OCEANOGRAPHY 101

Miracosta College

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Oceanography 101

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About this Book

This textbook outlines the major processes and features of the world's oceans. Content starts with a review of important fundamentals of the natural and physical science related to oceanography. Following chapters focus on Earth history and evolution of life through time.

Concepts related to geology and structure of the solid Earth are presented in chapters on plate tectonics, and physiography of the ocean basins, including information about earthquakes, volcanoes, and sediments deposited in ocean basin.

A chapter on the physics and chemistry seawater sets the stage for chapters on atmospheric circulation (including weather and climate), the global ocean circulation system, and the dynamics of waves, tides, and coastlines.

The final section reviews marine life from the base to the top of the "food chain." Chapters focus on the characteristics of primary food production in the marine environment and how the physical and chemical characteristics of ocean environment impact sea life. Final chapters review dominant and important life forms in the ocean, including invertebrates that dominate the sea floor (benthic environments), and vertebrates (including fish, reptiles, and marine mammals) that dominate open ocean environments.

Throughout the chapters are discussion that explore the oceans as a resource for people, and considers human impacts on marine environments.

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CHAPTER OVERVIEW

1: Introduction to Oceanography

1.1: What is Oceanography?

What is oceanography?

Oceanography includes the branches of science that deal with the physical and biological properties, and observable phenomena of the world **oceans** and **seas**. This oceanography course covers many aspects associated with other disciplines including **physical geography**, **geology** (including **earth history** and **astronomy**), **chemistry**, **meteorology**, **biology** and **ecology**. Perhaps most important, **human interactions**, include general history, exploration, exploitation, and some of the many environmental factors affecting our modern global civilization.

Figure 1.1. Earth is an oceans planet!

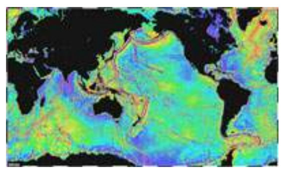


Figure 1.2. Map of the ocean basins of the world.

What do ocean scientists do?

- Ocean scientists study all aspects of the marine physical environment (geology, chemistry, biology).
- Oceanographers map the seafloor and work with navigation and remotely sensing ocean basin regions.
- Marine geologists study seafloor rocks and sediments.
- Marine scientists work in environmental fields: climate change, waste management, resource protection.
- Marine engineers work in construction and engineering: archeology, foundations, offshore drilling.
- Marine scientists serve in national security and are involved in public health and safety.
- Marine scientists study coastal erosion hazards, waves, currents, storms.
- Marine biologists study study all aspects of the marine food chain from microbes to megafauna.
- Marine scientist are involved in all forms of shipping, port management, and marine-related industries.
- Ocean scientists in education: schools, parks, museums, and media

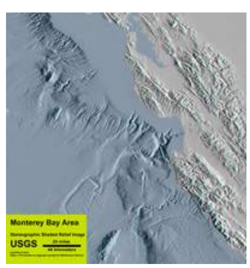


Figure 1.3. Image of coastal and marine **bathymetry** and land **topography** of the central California region showing San Francisco Bay, Monterey Bay and Monterey Canyon offshore.

Many states and cities also have agencies that employ marine scientists. Scientists are involved in all aspects of management of water resources, coastal and marine wildlife resources and fisheries. They conduct natural hazard investigations. They work for organizations involved with with offshore energy extraction and with shipping and port management. Many teachers in public schools and colleges have degrees in marine sciences! For instance, in California, many marine scientists are employed are employed by the CA Department of Conservation, and are employed by the branches of the University of California marine research programs.

Federal organizations conduct oceanographic research and employ many marine scientists. Note that the abbreviations for these agencies are used throughout this website.

Name and Abbreviation	website
National Oceanic and Atmospheric Administration (NOAA)	www.noaa.gov
US Geological Survey (USGS)	www.usgs.gov
Fish & Wildlife Service (FWS)	www.fws.gov
National Park Service (NPS)	www.nps.gov
National Atmospheric and Space Administration (NASA)	www.nasa.gov
Department of Agriculture (DOA)	www.usda.gov
Department of Defense (DOD)	www.dod.gov
Department of Energy (DOE)	www.doe.gov
Environmental Protection Agency (EPA)	www.epa.gov
Center For Disease Control (CDC)	www.cdc.gov

1.2: The World Oceans

The World Oceans: Basic Geography Facts

- Oceans cover 71% of Earth's surface.
- Oceans are interconnected (meaning that all water circulates through one world ocean).
- Oceans have huge size and volume (97% of Earth's water).

The four principal oceans:

- Pacific (largest and deepest), Atlantic, Indian, Arctic (smallest and shallowest)
- Plus one: Southern Ocean (or Antarctic Ocean) - extension of oceans around Antarctica below 60° South latitude

Seas are:

- Smaller than true oceans
- Composed of salty water of varying salinity
- Partially or fully enclosed by land. For example the Yellow Sea is connected to the Pacific Ocean and the Red Sea to the Indian Ocean, whereas the Salton Sea and Caspian Sea are fully landlocked.

Selected seas (discussed in this course) include: Mediterranean Sea, Adriatic Sea, Black Sea, South China Sea, Red Sea, Dead Sea, Persian Gulf, Caspian Sea, North Sea, Caribbean Sea, Bering Sea, and Sargasso Sea. Note there are many other "seas!" In addition, around North America are large oceanic embayments including the Gulf of California, Gulf of Alaska, Gulf of Mexico, and Hudson Bay.

Figure 1.4. Map of World Oceans and Seas

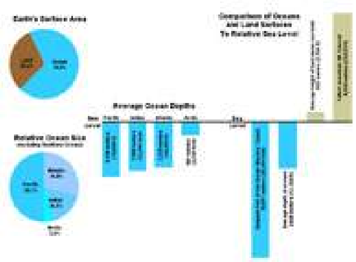


Figure 1.5. Oceans depth and surface area compared with land.

Comparison of Ocean Basins and Continents

• Average depth about 3688 m (12,100 ft)
• Deepest area of the ocean: Mariana Trench in the Pacific: 11,022 m (36,161 ft)
• Average elevation of continents: 840 m (2,756 ft)
• Highest mountain: Mt. Everest 8850 m (29,935 ft)

See: Volumes of the World's Oceans (NOAA)

Topography is the measurement of the elevation on land. **Bathymetry** is the measurement of depth of water in oceans, seas, or lakes. Both topography and bathymetry are measure relative to the global average of **sea level.**

1.3: Early Exploration of the Oceans

Early Exploration of the Oceans

Ancient World Explorations: Many ancient cultures traveled the oceans for exploration, trade and conquest. Selected important highlights in history include:

* **Ancient Egyptians** used reed boats on the Nile River as early as 4,000 BC. Shipbuilding was known to the Ancient Egyptians as early as 3000 BC. Egyptian shipping trade extended throughout the eastern Mediterranean and the Red Sea, extending south around the Horn of Africa (modern Somalia).
* **Minoan** seafaring culture centered on the island of **Crete** and other islands in the western Mediterranean region (2600 to 1400 BC).
* **Phoenician** seafaring culture centered along coastal regions along with is now Lebanon, Syria, and Israel from about 1500 BC to 300 BC. Their shipping trade networks extended throughout the Mediterranean region into coastal waters of southern Europe and Northern Africa.
* **Chinese** exploration began as early as 3000-2500 BC, some by ship. China's maritime economic development began in the Zhou Period (1030-221 BC).
* **Mayans** traveled by boat throughout the Caribbean region (800 B.C-1521 AD).

Figure 1.6. An Egyptian ship.

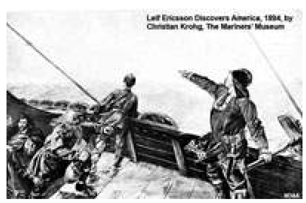


Figure 1.7. **Leif Ericsson** on a Viking exploration voyage

Pacific Islanders
Pacific Islanders are descendants of ancient seafaring peoples that navigated and settled remote islands throughout the **South Pacific region (Oceania)** dating back 1000s of years.
• These people settled on many remote islands in what is now modern Micronesia, Polynesia, and Melanesia.
• Hawaii was inhabited around 500 AD explored from Marquesa Islands (and inhabited them around 300 AD).

The Middle Ages
• **Vikings** explored the North Atlantic Ocean
• Norse seafaring peoples colonized Greenland and Iceland.

Early European navigators
• Explored the Mediterranean Sea, coastal Africa, and the Middle East.
• Developed a method to determine latitude using star navigation.

Age of Discovery (1492-1522)
• **Christopher Columbus** made landfall in the Caribbean Sea in 1492 (He never set foot on North America.)
• Many journeys were undertaken to explore and exploit resources to the **New World**.
• Most exploration involved searching for new trade routes to Eastern Asian sources of precious spices & textiles.
• **Ferdinand Magellan's** ship crew was first to circumnavigate the globe 1519. (Magellan didn't survived the journey, he was killed during a tribal skirmish on Mactan Island in the Philippines.)

Voyaging for science (1768-1780):
• Explorer **Captain James Cook** was a navigator and cartographer (map maker) for the British Royal Navy.
• Explored and traveled through all oceans on 3 different voyages
• Determined outline of the Pacific Ocean on 3rd voyage
• Modified shipboard diet to eliminate scurvy
• Used **John Harrison's chronometer** (a timing device invented to determine longitude)

Figure 1.8. Map of the Atlantic Gulf Stream compiled by Ben Franklin, published in 1769 is an example of early oceanographic research. Ponce de Leon first observed the Gulf Stream in 1513. Ben Franklin first charted the Gulf Stream with the help of a Nantucket sea captain.

Figure 1.9. *View of a Whale Fishery* from Captain Cook's voyage journal, 1790.

1.4: Essential Science Review Concepts for Oceanography

Essential Science Review Concepts for Oceanography

The following sections provide a brief overview of important concepts that are important to discussions in all subsequent chapters. These discussions are a mix of essential concepts provided in introductory courses in physical science, chemistry, biology, physics, and earth science.

The Scientific Method

The scientific method is how scientific ideas are tested and validated and applies to research conducted in nearly all professions.

The scientific method involves:

- Collection of data and observations leads to multiple hypotheses (educated guesses).
- Each hypothesis is rigorously tested and it fails (rejected) or passes (and become a theory).
- Tests/experiments must be thoroughly researched and accurately reported.
- Tests/experiments result must be reproducible.

Define science, observation, hypothesis, fact, theory, scientific law, and scientific methods.

Science is the systematic knowledge of the physical or material world gained through observation and experimentation. The overall goal of science is to understand how the natural world works. The fundamental assumption of science is that the natural world behaves in a consistent and predictable manner.

The **scientific method** involves the observation of phenomena, the formulation of a hypothesis concerning the phenomena, experimentation to demonstrate the truth or falseness of the hypothesis, and a conclusion that validates or modifies the hypothesis.

Observation is the act of noting and recording something, such as a phenomenon, with instruments, in order to gain information. An example is the collection for data for temperature, oxygen levels, and pollutants in seawater at different depths in a harbor to monitor water quality for sea life protection.

A **fact** is knowledge or information based on real occurrences; something demonstrated to exist or known to have existed.

A **hypothesis** is a tentative explanation for an observation, phenomenon, or scientific problem that can be tested by further investigation. An example of the testable hypotheses: Observed high levels of certain types of bacteria in seawater samples from a harbor might be linked to an influx of raw sewage leaking from a nearby sewage treatment facility.

A **theory** is a set of statements or principles devised to explain a group of facts or phenomena, especially one that has been repeatedly tested or is widely accepted and can be used to make predictions about natural phenomena. Note that in science the word *theory* means something far more certain and concrete than the popular use of the word, which we can define as an assumption based on limited information. Established scientific theories are based on vast amounts of information and knowledge, giving us high confidence that they are correct.

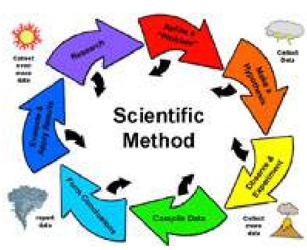


Figure 1.10. The **Scientific Method** involves an ongoing cycle of inquiry.

Figure 1.11. NOAA research ship, the Ronald H. Brown, illustrates one of perhaps hundreds of vessels around the world involved

in marine research and investigations.

Figure 1.12. The **Alvin**, a deep-sea exploration submersible.

Making Assumptions Can Be A Dangerous Thing.

An **assumption** is a thing or idea that is accepted as certain to happen, **without proof**. Misinterpreted observations can easily be used as proof or evidence in helping to establish a fact or resolve the truth of a statement. However, assumptions are often used as guiding principles in decision making when proof or facts are not resolved or accepted. Classic assumptions in history include ideas such as ***the Earth is flat***, or ***the Earth is the center of the Universe***. Throughout history, political, religious, economic special interests, and strongly-held societal beliefs have been used as underlying assumptions; sometimes they hold true, others are often proven wrong by new scientific evidence. The term **educated guess** (a hypothesis based on some related knowledge and experience, and therefore likely to be correct) may be no more than an assumption.

1.5: Try the Scientific Method! Two Simple Exercises To Illustrate

Example 1: Attendance vs. Grade (This example is a very valuable start to a college course!)

Use the **scientific method** to evaluate the data on this table comparing **two variable factors**: student **attendance** (number of classes missed in an introductory science class) compared with **final grades** of students in three classes. Discuss **observations, facts, assumptions, hypotheses, and theories**. How can these hypotheses be tested? What other factors not listed might explain observable facts?

What would it take to make these hypotheses into a proven theory?

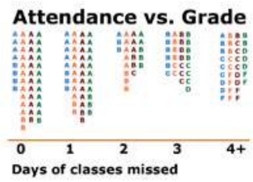


Figure 1.13. Data: Attendance vs. Grade

Example 2: Beach Sand vs. River Sand

A common assignment used in introductory geology courses is to examine and describe characteristics (similarities and differences) in the nature of river sand and beach sand.

Use the **scientific method** to make observations using these four microscope images of sand samples (2 from river deposits, 2 from beach deposits). Use observations to make hypotheses about why the sample have identifiable characteristics unique to their origin.

Can you make some hypotheses about some of the changes that occur as sand gradually migrates from source areas in upland regions to where sand accumulates on beaches along coastlines?

Can you come up with suggestions for experiments to test these hypotheses that would support a theory of the character and origin of sand in different environmental settings?

Special note: this topic is covered in more detail in later chapters.

	
Figure 1.14. River sand (CA)	Figure 1.15. Beach sand (TX)

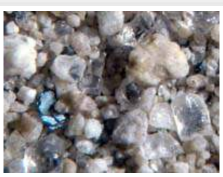



Figure 1.16. **River sand** (OH)	Figure 1.17. Beach sand (CA)

1.6: Essential Chemistry and Physics Concepts for Oceanography

Aspects of chemistry and physics are discussed in nearly every chapter on oceanography. Below are highlights of important concepts.

What is Matter?

Basic concepts of chemistry are essential to understanding the physical and chemical properties of matter, particularly **natural earth materials** (rocks, seawater, air, organic matter, etc.). The chemical characteristics of earth materials reveal information about the environments how and where they are formed, Their characteristics also determine their potential fate when exposed to chemical changes over time. For instance, rocks formed deep underground may not be stable in the surface environment where they are exposed to water, air, temperature changes, and other physical and chemical conditions.

Basic chemistry concepts needed to be understood for this oceanography course include:

- **All matter is made up of atoms**, and atoms are made up of atomic particles (**electrons, protons, and neutrons**). An **atom** is the smallest unit of a chemical **element**. Atoms have a **nucleus** composed of neutrons & protons and has a positive charge. Negatively charged electrons orbit around the nucleus in shell-like layers.
- A chemical **element** is a pure chemical substance consisting of one type of atom distinguished by its **atomic number**, which is the **number of protons in its nucleus**. Elements have equal balance in numbers of positively charged protons and negatively charged electrons. Common examples of elements are iron, copper, silver, gold, hydrogen, carbon, nitrogen, and oxygen.
- An **element** is a substance that cannot be broken down into simpler substances by chemical means.
- An element is composed of atoms that have the same **atomic number**, that is, each atom has the same number of protons in its nucleus as all other atoms of that element.
- The **Periodic Table** is a list of known chemical elements arranged in order from smallest to largest and by group chemical properties. It is a list of 118 known elements arrange by atomic number. Of these, 92 are **naturally occurring** (prior to development of artificial nuclear research and development; elements 95 to 118 have only been artificially created and are highly unstable). The lightest element, hydrogen, has one proton, whereas the heaviest naturally occurring element, uranium, has 92 protons. In general elements on the left side of the periodic table are metals, and elements on the right (shown in blue in Figure 1.15) are nonmetals.
- Atoms bond together to form **molecules**. A **molecule** is a group of atoms bonded together, representing the smallest fundamental unit of a chemical compound that can take part in a chemical reaction.
- A **chemical compound** is a pure chemical substance consisting of two or more different chemical elements that can be separated into simpler substances by chemical reactions. Chemical compounds have a unique and defined chemical structure; they consist of a fixed ratio of atoms that are held together in a defined spatial arrangement by chemical bonds. All minerals are chemical compounds, but by comparison relatively few compounds are naturally occurring minerals!
- Types of molecular **bonds** include **metallic** (for metals), **ionic** (compounds that dissolve easily), **covalent** (most others).
- A **mixture** is a combination of two or more pure substances in which each pure substance retains its individual chemical properties. Examples of mixtures include rocks, magma (molten rock) air, and seawater.
- **Chemical formulas** are used to describe **compounds** such as H2O (for water), NaCl (for salt), CO2 (for carbon dioxide)

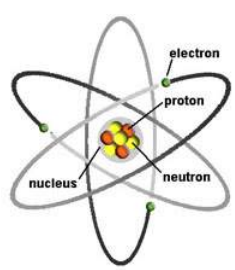


Fig. 1-18. Structure of an atom: this example is the element lithium composed of a nucleus of 3 protons, 4 neutrons, and an outer shell of 3 electrons spinning around the nucleus.

The **most abundant elements** in our **physical environment** are: **H, C, N, O, Na, Mg, Al, Si, P, S, Cl, K, Ca, Fe** (Be prepared to name these elemental symbols! -- see Figure 1.15).

These elements are:

- ingredients of common rocks and sediments (**solids**)
- components of seawater and air (**liquids** & **gases**)
- essential nutrients for life (**organic compounds**)

Fig 1-19. The periodic table with essential elements highlighted.

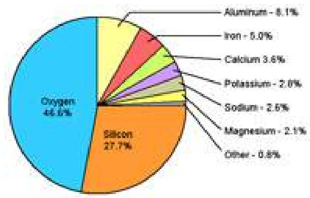


Figure 1.20. Composition of the crust. Rock samples collected from around the world show that the chemical composition of the Earth's crust is not uniform, but certain elements are much more abundant than others. **Silicon and oxygen** are the two most abundant elements in the crust.

1.7: Chemical Bonds

Chemical Bonds

Molecular compounds are held together on an atomic level by chemical bonds. Three types of chemical bonds include **ionic bonds**, **metallic bonds**, and **covalent bonds**. The types of chemical bond influence the physical properties of the molecular compounds they form.

Molecular compounds held together by **ionic bonds** are **salts**. *An ionic bond is a chemical bond between two oppositely charged ions*. Typically, metals lose valence electrons (loose electrons in their outer shell of orbiting electrons) to become positively charged **cations**, whereas the nonmetal accepts electrons to become negatively charged **anions**. For example, common salt (NaCl) has ionic bonds between sodium (Na^+) has a positive charge and chlorine (Cl^-) has a negative charge. Salts readily dissolve in water as their charged ions are attracted to parts of water molecules that can also have positive and negative charges. As water evaporates, the ions dissolved in water will precipitate again as salts. Natural salts like halite (NaCl) and gypsum ($CaSO_4$) are generally soft minerals and can dissolve in water.

Figure 1.21. **Salt** crystals are held together by **ionic bonds**. Salt compounds **dissolve** in and **precipitate** from water.

Figure 1.22. This view shows salt crystals precipitating on a dry lakebed in Death Valley, California.

Metals are held together by **metallic bonds**. *Compounds with metallic bonds transmit electricity.* With metallic bonds, the valence electrons disassociated from orbiting a single atom and become more of a cloud electrons that surround the positively charged nuclei of interacting metallic ions. Metalloids are intermediate between those of metals and solid nonmetals. Although most elements are metals (all those on the left and center parts of the Periodic Table), only a few elements occur naturally in metallic form including gold, platinum, copper, iron, and mercury (in liquid form). Some minerals are **metalloid compounds** including pyrite (FeS_2), magnetite (Fe_3O_4), and galena (PbS).

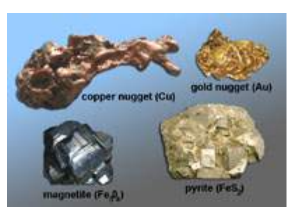


Figure 1.23. **Metallic bonds** occur in metallic minerals (like native copper and gold) and metalloid minerals (like magnetite and pyrite).

Molecular compounds held together by **covalent bonds** are *non-metallic* compounds. Covalent bonds occur when two or more atoms share orbiting electrons, creating more stability in the valence shell of electrons between the bonding elements. These materials can form crystal complexes and do not transmit electricity and tend to be harder, more durable compounds. For instance, most gem minerals are non-metallic compounds with covalent bonds. The mineral **quartz** (SiO_2) is a non-metallic crystalline compound (see Figure 1.24).

Figure 1.24. Most minerals are non-metallic crystalline compounds held together by **covalent bonds** (and will not transmit electricity). [Quartz]

Van der Waals forces (bonds) are weak, nonspecific forces between molecules and include attractions and repulsions between atoms, molecules, and surfaces. Van der Waals forces are responsible for **friction** and what makes water ***sticky***.

1.8: Isotopes (and Radioactivity)

Isotopes (and Radioactivity)

Many **elements** have one or more **isotopes**. Isotopes are of the same element that contain equal numbers of protons but different numbers of neutrons in their nuclei, and hence differ in relative atomic mass but not in chemical properties. Some isotopes are not stable and ultimately break down or change into other elements. We call such isotopes r**adioactive**. Many elements have both stable and radioactive isotopes. For example, the element **carbon** has 3 isotopes: ^{12}C and ^{13}C are stable, whereas ^{14}C is unstable and will undergo **radioactive decay**. All there isotopes have 6 protons, but have 6, 7, and 8 neutrons, respectively.

Figure 1.25. Radioactive **elements** that occur in rocks and minerals include isotopes of potassium, thorium, radium, and uranium. and may display measurable radioactivity. A **geiger counter** us used to measure materials for radioactivity.

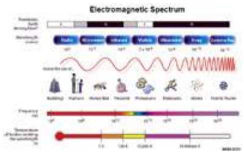
In the natural environment there are 80 different elements that have one or more isotopes. Of these, at least **254 stable isotopes** that have never been observed to decay. Another 50 are radioactive. With the invention of nuclear weapons, and the numerous nuclear bomb test through the 1950s to the present, there are now many more radioactive isotopes loose in the environment. The mixing of these radionuclides in the air, water, and sediments dilute their concentrations, but also disperse them to all regions of the world.

For example, the March 2011 Fukushima Daiichi nuclear disaster associated with the massive earthquake and tsunami in Japan released large amounts of radiation into the marine environment.

1.9: Energy

Energy

Energy exists in several forms such as heat, kinetic energy (mechanical), light, potential energy, electrical, or other forms. **All physical and chemical reactions involve either the loss or gain of some form of energy.**



Electromagnetic energy from the Sun is the force behind all motion of the atmosphere and the oceans. The Sun's electromagnetic energy comes from nuclear fusion in the Sun's core. The immense pressure in the Sun's core fuses hydrogen atoms into helium atoms, a process that gives off vast amounts of energy and causes the Sun and other stars to glow. **Geothermal energy** is the driving force for motion within the planet (including plate tectonics, earthquakes, and volcanoes). Both solar electromagnetic energy and geothermal energy are utilized to support life and ecosystems within the marine environment.

Fig 1-26. The **electromagnetic spectrum is** the range of wavelengths or frequencies over which electromagnetic radiation extends.

All natural materials either transmit, reflect, or absorb electromagnetic energy in different ways. Solar energy that is absorbed by the atmosphere, oceans, and land is converted to **heat** or other energy forms. An equivalent amount of energy is radiated back into space. Some of the energy is used to move the oceans and atmosphere, and support life in the process over time.

1.10: Gravity, Mass, and Density

Gravity, Mass, and Density

Gravity is the weak force that attracts a body toward the center of the earth, or toward any other physical body having mass.

Mass is the property of matter that measures its resistance to acceleration. Roughly, the mass of an object is a measure of the number of atoms in it. Gravity is the force that holds Earth in orbit around the Sun, and the Moon in orbit around the Earth. Mass is often confused with **weight**. Weight is a measure of an amount of mass under the influence of gravity. For instance, a 150 pound person on Earth would only weigh 25 pounds on the moon because the Moon only has 1/6 the gravity of Earth.

Density is the ratio between mass and volume. It is a measure of how much matter an object has in a unit volume (such as cubic meter or cubic centimeter).

• **Density = mass/volume**
• Usually defined in **grams per cubic centimeter - gm/cm^3**

Density Stratification
• The earth and oceans have layers based upon density differences, they are density stratified.

Examples of the density of earth materials:
• Air ~0.1 gm/cm^3
• Freshwater 1.0 gm/cm^3
• Saltwater ~1.001-1.03 gm/cm^3
• Surface rocks ~3 gm/cm^3
• Center of earth ~16 gm/cm^3

Calculate the change in density when we add 1% salt to freshwater: (.99)(1.0 gm/cm^3) + (0.01)(3.0 gm/cm^3) = 1.02 gm/cm^3

Seawater has an average density of **1.027 gm/cm^3**, but this varies with temperature and salinity over a range of about 1.020 to 1.029 gm/cm^3.

1.11: Zones of the Earth Climate System

Zones of the Earth Climate System

On any location on the planet, the slow progress of seasonal changes are related to observable migration that the path the Sun follows through the sky over the cycle of one year. **Seasons** occur because:
a) the Earth spins (rotates) on its axis marked by the north and south poles; and,
b) the axis of the spinning Earth is tilted about **23.5°** relative to **ecliptic** plane. (The ecliptic plain flat circular path the Earth follows as it **revolves** around the Sun in the orbital plane)(Figures 1-27 and **1-28**).

Only twice a year, on the **spring and fall equinoxes** is the Sun directly above the **equator (0°)**. The **summer solstice** occurs on June 21 when the Sun is directly overhead at noon along the latitude **23.5° north** (a circle on the globe called the Tropic of Cancer). Likewise, the winter solstice occurs on December 20 when the is directly overhead at noon along the latitude **23.5° south** (a circle on the globe called the Tropic of Capricorn).

The **tropics** are the region of the world between the parallels of latitude about **north (Tropic of Cancer)** and **23°5′ south (Tropic of Capricorn)** on opposite sides of the **equator (0°)**.

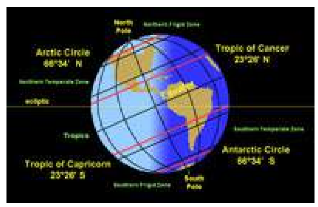


Figure 1.27. Location of **tropics**, **temperate**, and **polar** zones.

The term **polar** is used to describe the high latitude cold regions surrounding the Earth's north and south poles. The **Arctic Circle** runs **66.33° north** of the equator. North of this line is the **North Frigid Zone** (also known as The Land of the Midnight Sun where the Sun never sets on the summer solstice). The **Antarctic Circle** is parallel of latitude approximately **66.33° south** and defines the northern boundary of the **South Frigid Zone**. The Antarctic Circle marks the approximate limit south of which the Sun remains above the horizon all day on the summer solstice.

The regions between the tropics and the polar regions are called **temperate** zones (North Temperate Zone and South Temperate Zone).

Figure 1.28. **Seasons** are caused by the tilt in Earth's axis as it orbits around the sum.

1.12: Understanding Maps

Understanding Maps

Maps are perhaps the most important tools for navigation and evaluating features on the land's surface, underwater, or even underground. Maps are used for many issues involving land use and natural resource management. Maps have been used back into prehistoric times. However, the evolution of maps in the modern digital world has changed map making—enhancing their use in nearly all aspects of modern science, technology, and culture. Modern maps are created with **geographic information systems (GIS)**. A GIS is a computer-based map-generating program that can merge geographic (spatial) information with many kinds of topical themes in database format. Such themes may consist of medical information (such as disease outbreak data), water resources, roads, buildings and civic infrastructure, power grid information, agricultural and biological information, etc.). Satellite data are increasingly used for nearly all aspects of mapping of the land, oceans, and weather patterns.

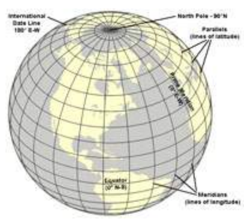
Figure 1.29. **Maps** show thematic information in a geographic context. The theme of this map shows human migration routes on a world map base.

Many maps display **relief** or elevation information . Relief relates to height and shape characteristics of a landscape (such as high relief, low, relief, gentle relief, rugged relief, etc. **Shaded-relief maps** show changes in elevation (topography and bathymetry) using shades of gray or color.

What are Latitude and Longitude?

Locations on the Earth's surface are defined using latitude and longitude coordinate system (Figure 1.30).

Latitude is the angular distance of a place north or south of the earth's **equator**, usually expressed in degrees and minutes. Lines of latitude are called **parallels**. Latitude lines parallel the Equator. Each degree of latitude is approximately 69 miles (111 kilometers) apart. Latitude in the Northern Hemisphere can be determined by sighting on the North Star (which lies directly above the North Pole) and determining the angle of the star above the horizon (subtract it from 90°).



Longitude
is the angular distance of a place east or west of the
Prime Meridian
usually expressed in degrees and minutes. In order to make an accurate map of the stars for use in ship navigation, in 1884, a location indicating the precise location of
0° East-West
was designated in the cross hairs of a telescope in the Royal Observatory (now located on the grounds of the National Maritime Museum) in Greenwich England. This line marks the reference location of the
Prime Meridian
now used in all global mapping (including GPS location systems). The
International Date Line
is on the opposite side of the earth located
180° east or west
of the Prime Meridian.

Figure 1.30. Longitude and **Latitude** projected on a globe

A **meridian** is a circle of constant longitude passing through a given place on the earth's surface and the terrestrial poles. Longitude lines (of equal spacing measured in degrees) are widely spaced at the equator but converge at point at the North and South Poles. The Prime Meridian is designated 0° (zero degrees). Meridian lines east of the Prime Meridian are designated *positive* values (0° to 180° east); whereas meridian lines west of the Prime Meridian are designated *negative* values (-0° to -180°). At 180° east or west is the **International Date Line**. A degree of longitude is widest at the equator at 69.172 miles (111.321) and gradually shrinks to zero at the poles. At 40° north or south the distance between a degree of longitude is 53 miles (85 km).

Defining locations with a latitude-longitude coordinate system—any location on the planet surface can be defined by a number in **degrees, minutes,** and **seconds** north or south of the Equator and east or west of the Prime Meridian. (Compare to hours, minutes, seconds on a clock!)

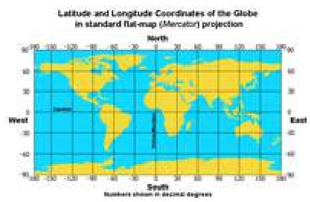


Figure 1.31. Map of the world showing latitude and longitude in a Mercator (flat) projection

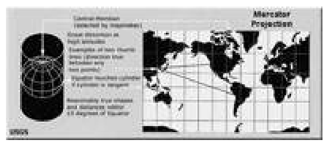


Figure 1.32. Map of world showing with **Mercator Projection** - notice distortion in high latitudes because longitude lines are not converging

Figure 1.33. Map of North America with **Lambert Conic Projection** - on this scale distortion of America is minimal, but look at South America.

Example: Location of the Statue of Liberty in New York Harbor

The **standard coordinates** (in degrees, minutes, and seconds) of the Statue of Liberty are:
Latitude: **40°68′92"N**
Longitude: **74°04′ 45"W.**

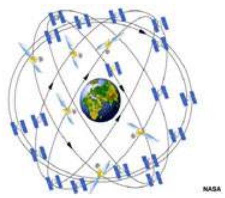
Described in **decimal degrees** the coordinates of the Statue of Liberty are:
Latitude: **40.689758° N**
Longitude:**-74.045138° W**.

An example from San Diego, California
The monument on top of Mount Soledad in La Jolla is located:
Latitude: **32.8398° N**
Longitude: **117.2523° W.**

Fig. 34. A globe view is the only way to have perfect map projection!

Find the latitude and longitude of any named location or landscape feature on the GeoNames website.

The earth is round (a sphere like a globe) but maps are flat. As a result, maps that show large regions are distorted. **Map projections** are attempts to portray a portion of the Earth on a flat surface (examples are shown in Figures 1-31 to **1-33**). The flattening of a map always causes some distortions of distance, direction, scale, and area. Large scale maps (such as a map of a continent or a world show much distortion, however, maps on small scales (such as a map of a town or neighborhood) have relatively little distortion. There are many map projection systems, each serves different purposes and has some variety of distortion. Learn more about map projections at the **U.S. Geological Survey's Map Projections website.**



A

Global Positioning System (GPS)

is a space-based global navigation satellite system that provides reliable location and time information in all weather and at all times and anywhere on or near the Earth when and where there is an unobstructed line of sight to four or more GPS satellites (Figure 1.35). GPS is now used for nearly all forms of digital map navigation.

Figure 1.35. Satellite network of the Global Positioning System.

1.13: Geologic Time Scale

Geologic Time Scale

Geological time refers to the time of the physical formation and development of the Earth (especially prior to human history). Geologic time also applies to the age and history of the Universe. Geologists have subdivided periods in Earth's history is measured periods spanning **millions or billions of years**. The Geologic Time Scale has been established to name segments of time periods to help define the chronology of events (such as mountain range formation), the formation of rock units (such as the age of a lava flow), the age of fossils, organizing geologic map units, and other purposes. Figure 1.30 is a standard geologic time scale listing names of major time periods with time span information. Names of geologic time periods (like Late Cretaceous or Pleistocene) are used for organizing geologic map units, charting the age or petroleum-bearing rock layers underground, and perhaps hundreds of other purposes.

Figure 1.30. Geologic Time Scale showing major geologic events in Earth history and the evolution of life on earth. New scientific discoveries are refining knowledge about the chronology and impacts or significance of events through deep Earth time.

College courses in ***historical geology*** examine what is currently known about the age of the Earth and the events as they are known or inferred to have occurred. For this course, the name of geologic time periods are used to explain the age of when rocks or sedimentary deposits formed, and where and how they occur in relation to other rocks and deposits associated with them. For example, rock layers containing dinosaur bones will correlate to the specific time period that the dinosaurs lived in the geologic past.

Every rock has a history! The geologic time scale used today has evolved through the past two centuries as new scientific discoveries have been made and new technologies for dating the age of earth materials have become available. The most recent version of the geologic time scale is released on a Geological Society of America website as updated versions become available.

Note that the notions that the Earth being old (measured in billions of years) has not been all that popular with some religious groups throughout the ages. The primary arguments about the age of the Earth and the observable universe have been resolved by the global scientific community, but paradigms have ways of shifting as new discoveries are made and new information becomes available, and those ideas are tested by scientific methods. Vast periods of time in earth history are fundamental parts of understanding biological evolution of life on earth (*paleontology*), understanding genetics, particularly related to human evolution, and in astronomy explaining the vastness and age of the observable universe.

Fossils are traces or remains of prehistoric life now preserved in rock.
- **Paleontology**: study of fossils
- Fossils are mostly found in sedimentary rocks
- Where found, fossils aid in interpretation of the geologic, geographic, and environmental past
- Fossils serve as important time indicators
- Fossils allow for correlation of rocks from different places

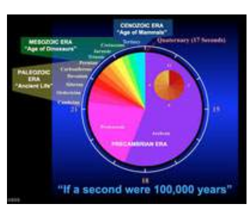


Figure 1.31. If a second were 100,000 years - this classic diagram shows the distribution of different ages of time as if it were all squeezed into a 24 hour day. All of human history would fit in the last fraction of a second!

1.14: Earth's Place in the Universe

Earth's Place in the Universe

Many aspects of **astronomy** have contributed to the knowledge of the origin and geologic history of planet Earth. Meteorites have been found, collected, and studied for centuries. Telescopes on the ground and now in space, satellites, robotic and manned missions to space, the Moon, and other planets and moons in our Solar System objects have greatly expanded the collective knowledge about the origin of our planet and objects in the Solar System—all of which have evolved to their current state over billions of year. So far, life is only known to exist on Earth, but it could possibly exist elsewhere, even within our Solar System. We just haven't proven it yet.

Figure 1.32. Like this giant redwood in Big Basin State Park, California. All physical materials, including life on Earth, have an origin connected to the formation of elements that formed from events that happened in space many billions of years ago!

Discoveries Leading To Modern Astronomy

Claudius Ptolemaeus (~100-170 CE), also know simply as **Ptolemy**, was an Egyptian astronomer, geographer, and mathematician (of Greek descent) who became well known in the Alexandria philosophical community in the 2nd century. Although Ptolemy made a variety of important, if not interesting, contributions to knowledge of his times, perhaps his most significant, and long lasting, was his observations of the orbits of planets and constellations. He promoted the geocentric model, that Earth was the center of the observable Universe. The ancient Greek, Roman, and Muslim astronomers followed the **geocentric model** (or **Ptolemaic system**) that described the Universe with the Earth at its center.

1.15: Early Astronomers- Copernicus, Galileo, Kepler, and Newton

Early Astronomers: Copernicus, Galileo, Kepler, and Newton

The geocentric model wasn't seriously challenged until **Nicolas Copernicus** who published a report in 1543 suggesting that the Sun, not the Earth, was the center of the Universe (called Copernican heliocentrism). **Nicolaus Copernicus** (1473-1543) was the first to explain the observed ***retrograde, looping phenomena*** of planet motion by replacing previously held theories of **geocentrism** (Earth being the center of the Universe) with **heliocentrism** (the Sun being the center of the observable Universe).

However, the Copernican system was also discovered to be flawed as **telescopes** were developed to see farther into space and astronomers began to grasp the immense scale of time and distance between our Solar System and other objects in our Milky Way Galaxy and the Universe beyond.

Italian physicist and astronomer, **Galileo Galilei** (1564-1642) used an early **telescope** and discovered four large moons of Jupiter (Figure 1.33). He also promoted the **Heliocentrism Theory** that the Sun, not the Earth, was the center of our Solar System. In 1615 he was subjected to the Roman Inquisition for his scientific inquiries. He was forced to publicly recant his beliefs and subjected to house arrest for the remainder of his life. (Note that the Roman Catholic Church eventually accepted his theory and officially forgave him in 1992!)

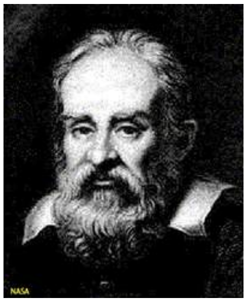


Figure 1.33. **Galileo Galilei** first used a telescope to examine the night sky.

1.16: Gravity

Gravity

Gravity is a weak but measurable force, but becomes observable when dealing with objects on the scale of moons, planets, and satellites launched into space. Understanding the very mysterious force of gravity is fundamental to characterizing the mechanics of the orbits of planets and moons within the Solar System (and objects moving throughout the universe). Using research by earlier astronomers, between 1609 and 1619, **Johannes Kepler** presented scientific laws that describe to character of the **elliptical motion** of planets around the sun. **Isaac Newton** used Kepler's laws to mathematically resolve the nature of gravity which he presented in 1687 as his **Law of Universal Gravitation** which states "a particle attracts every other particle in the Universe using a force that is directly proportional to the product of their masses, and inversely proportional to the square of the distance between them" (Figure 1.34). Gravity is a weak but measurable force, but becomes observable when dealing with objects on the scale of moons, planets, and satellites launched into space.

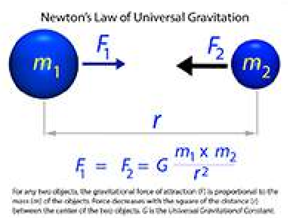


Figure 1.34. Newton's Law of Universal Gravitation.

1.17: Determining the Expanse of Space

Determining the Expanse of Space

From the time of Galileo to the beginning of the 20th century, the telescope technology advanced, and the night sky with it stars, planets, gas and dust clouds (nebula), and other objects were charted in great detail. The problem was that we could see lots of stars, but had no way of knowing how far away there were because stars vary in their brightness in addition to their distance. Astronomers have developed several methods to directly or indirectly measure the distance to object is space.

It was in 1923 that **Edwin Hubble** found dozens of uniquely identifiable ***variable stars*** in the ***Andromeda nebula*** and then determined that Andromeda was at least 10 time more distant than the most distant stars in the Milky Way. He was first to determine that Andromeda was a separate system which he named a **galaxy**. The **Milky Way** is an obvious band of densely distributed stars and clouds of dust visible as a band in the clear night sky (Figure 1.35)**.** Before Hubble's discovery, it was thought to be the Milky Way represented the entire Universe, and that unusual shaped ***spiral nebulae*** (galaxies) were part of the Milky Way. With Hubble's discovery, it became evident that Earth and the Sun's Solar System was within the greater Milky Way Galaxy.

Figure 1.35. The **Milky Way** as photographed on a clear night sky. The Milky Way is the main plane of the galaxy where stars are concentrated.

The **Andromeda Galaxy** is a **spiral galaxy** (Figure 1.36). It is the closest large galaxy to our **Milky Way Galaxy** and is one of the few visible to the naked eye. It is the most distant object in space that can be seen without magnification.

The Andromeda Galaxy can be seen in the northern hemisphere on clear autumn nights. It is located about 2.25 million light-years away from Earth. (A **light year** is the astronomical distance that light can travel in a year; approximately about 9.4607 x 10^{12} kilometers or about 6 trillion miles.) Andromeda is estimated to contain about 1 trillion stars. Astronomers estimate that the Milky Way and Andromeda galaxies will eventually collide (merge) in about 4.5 billion years in the future.

Figure 1.36. **Andromeda Galaxy**

1.18: Galaxies

Galaxies

A **galaxy** is a system of millions to trillions of stars, together with gas and dust, held together by gravitational attraction. Deep-space observing telescopes show distant **field of galaxies**—galaxies and clusters of galaxies can be seen in all directions in distant space. The distance to these objects are in the range of thousands to billions of **light years** away from Earth.

Figure 1.37 shows a field of galaxies observed in on small region in deep space. Using images like this, astronomers estimate there may be 100 billion galaxies within the **Observable Universe**.

Galaxies appear as many shapes and sizes, but there are three general classes: **spiral**, **elliptical**, and **irregular galaxies**, but each of these groups are subdivided into classes (Figures 1-38 to 1-40). Small elliptical galaxies are the most common, and unlike spiral galaxies their stars do not seem to revolve around their **galactic centers** in an organized way. The galactic center is where the greatest mass and concentration of stars exist in a galaxy. Irregular galaxies take on many shapes, and many are interpreted as galaxies that have collided or merged under gravitational attraction.

The **Milky Way Galaxy** is probably a spiral galaxy.

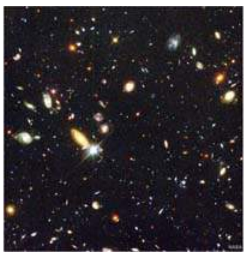


Figure 1.37. A **field of galaxies**.

Figure 1.38. A spiral galaxy.

Figure 1.39. An elliptical galaxy

Figure 1.40. An irregular galaxy

1.19: Earth's Place In the Observable Universe

Earth's Place In the Observable Universe

- *The Moon revolves around the Earth every 27.32 days.*
- *The Earth-Moon System revolves around the Sun every 365.242 days (1 year).*
- *It takes the Sun about 230 million years to make one complete orbit around the center of our Milky Way Galaxy (traveling about 828,000 km/hr). Our galaxy is about 100,000 to 120,000 light-years in diameter and contains over 200 billion stars. Our Solar System resides roughly 27,000 light-years away from the Galactic Center.*
- *The Observable Universe is the part of the greater universe that can be observed by the naked eye or by modern telescopic methods. The light we observe from object in space has travel great distances (measured in light years). This means that distant objects in deep space we see on Earth today have long since changed or moved (Figure 1.41). What is beyond the Observable Universe is unknown.*

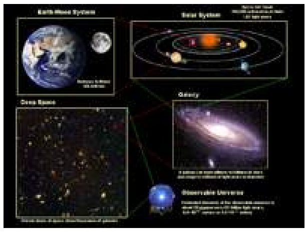


Figure 1.41. Earth's place in the **Observable Universe**.

1.20: The Big Bang Theory

The Big Bang Theory

In the 1927, a French astronomer, **Georges Lemaître**, proposed the idea that in the distant past that the Universe started as just a single point in space, and as the Universe has been expanded as a great explosion to what is observable now. Two years later in 1929, Edwin Hubble reported that the most distant observable galaxies are moving away at a faster rate than ones closer to Earth. This observation, and much other evidence, now supports a **Big Bang Theory**.

The **Big Bang Theory** is a cosmological theory holding that the **Observable Universe** originated approximately **13.8 billion years ago** from the violent explosion of a very small agglomeration of material of extremely high density and temperature (Figure 1.42). Current scientific though is that originally the material ejected from the Big Bang was too hot for subatomic particles with measurable mass to exist. It was probably many thousands of years after the Big Bang that it got cool enough for sub atomic particles and then atoms to form, and that gravitational attraction could influence the newly forming matter. Early in the history of the Universe matter began to condense and with time gravitation attraction pulled materials together to form galaxies.

In 2016, the Hubble Space Telescope was able to capture an image of the furthest distant galaxy known, estimated at about 13.4 billion light years away from Earth.

What is beyond the Observable Universe is unknown. See a NASA website about the Big Bang Theory.

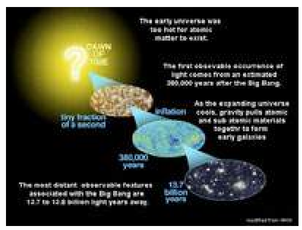


Figure 1.42. A very brief story of the **Big Bang** and the evolution of the **Observable Universe** over an estimated **13.8 billion years.**

1.21: Stars

Stars

A **star** is a self-luminous celestial body consisting of a mass of gas held together by its own gravity. Stars exist in a balance—their internal energy generated by nuclear fusion reactions results in an outflow of energy to the star's surface. This outward flow of directed gas and radiation pressures is balanced by the inward-directed gravitational forces.

Since ancient times, astronomers have been charting stars into **constellations**—recognizable grouping of starts that appear in the night sky and move with the seasons as the Earth orbits the Sun (Figure 1.43). Although stars in constellation often appear in association by appearance, they may be large distances apart and very greatly in brightness (intensity). In addition, stars exist in a wide range of colors, most obvious when observed through telescopes or from space (Figure 1.44). Many stars are clustered together, often sharing a common stellar history (Figure 1.45). Some stars orbit each other relatively close to one another as binary systems (Figure 1.46). Some star systems have multiples stars in orbit around each other.

Figure 1.43. A **constellation chart** of stars visible in the fall night sky.

Figure 1.44. A view of stars of many different colors in the Alpha Centari region. **Color** is a reflection of how hot stars are: blue are hottest, red are cooler. White and yellow are intermediate.

Figure 1.45. The **Pleiades** star cluster, perhaps the most recognizable constellation, contains over 3000 stars and is about 400 light years away and about 13 light years in diameter.

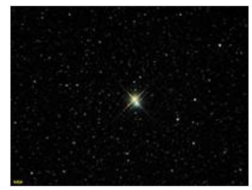


Figure 1.46. **Albireo** is the name of a binary star system visible about 380 light years distant.

Among the millions of stars observable in our galaxy, astronomers have been classifying them by size, color, and brightness (intensity) . Most stars in our galaxy fall into a class called the **main sequence** of which our Sun belongs (Figure 1.47). Astronomers have developed theories about star formation and the life cycle of stars in their different classes. With years of observation, abundance of knowledge has been gained about the life cycle of stars (Figure 1.48).

Life Cycle of Stars

Stars form in giant molecular clouds called **nebula**. A nebula is an interstellar cloud within a galaxy consisting of gas and dust, typically glowing from radiant energy from stars nearby within them (Figures 1-49 to **1-54**). Nebulae are the birth place of both stars and other objects within solar systems. Nebula can form from the explosion of stars at the end of their life cycle, resulting the creation of a new generation of stars and solar systems.

As stars form, gravity draws material in (mostly gas) and it mass increases until the internal heat and pressure is enough to start nuclear fusion reactions (converting hydrogen into helium). As stars age, they consume their fuel and eventually run out of nuclear fuel. Stars like the Sun may take billions of years to consume their nuclear fuel. When the fuel runs out, stars collapse under the weight of their own gravity. However, the fate of a star depends upon its mass.

Stars up to about seven times the mass of the sun fall within the "main sequence" grouping of stars. These go through stages as they consume their fuel. Young stars fuse hydrogen into helium. When stars run out of their hydrogen, the force of gravity causes them to collapse, which increases the heat and pressure within its core. During this phase of a star's life it will expand and become a **red giant**. Once the helium in the core of a star is consumed, stars in the main sequence will shed much of their mass into space (creating nebula), and the remaining core will shrink and cool and shrink to become a hot remnant called a **white dwarf**.

Fate of Supergiant Stars

Stars with masses greater than about seven times the mass of the Sun experience a more spectacular fate. More massive stars will burn through their fuel much faster than stars of the main sequence because their cores are hotter and under greater pressure. One these massive stars burn through their hydrogen and helium, this increase in heat and pressure allows fusion to convert helium into carbon, then carbon into neon, and then into iron. As the star continues to burn through it's fuel it eventually shuts down because it the fusion process of creating iron actually consumes more energy than it produces and the star looses it balance and collapses under it own gravity. The collapsing core reaches temperatures in the range of 100 billion degree and the core recoils as a massive explosion called a **nova**. Great star collapses produce supernova where a star may shed the majority of it mass into space. What happens to the core depends on the mass of the star. Stars about 7 to 20 times the mass of the Sun produce massively dense objects called neutron stars (their density is so great that electrons and protons collapse to form a great mass of neutrons). Stars with masses greater than about 20 times the mass of the Sun collapse to form **black holes**. Black holes of so dense that their gravity prevents light from escaping from within their "event horizons" where matter is pulled into an inner space where nothing escapes.

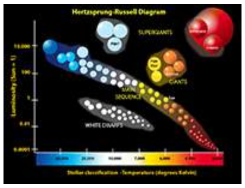


Figure 1.47. The **Hertzsprung-Russell Diagram** illustrates classification of stars based on star size, temperature, and intensity. The life cycle of stars depends primarily on their mass and composition.

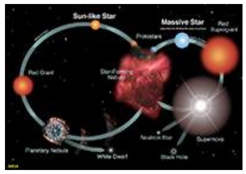


Figure 1.48. Illustration of the life cycle of stars from their formation in nebulae to their ultimate fate of collapsing and exploding to form white dwarfs, neutron stars, or black holes, depending on their mass.

Figure 1.49. Carina Nebula, a part of our Milky Way Galaxy where new stars are forming and emerging from a gas and dust cloud in what is commonly called a "stellar nursery."

Figure 1.50. Supernovas are great explosions that partially to completely demolish aging massive stars, releasing new matter and gas to create a new generation of stars in newly created nebula.

Figure 1.51. The **Horsehead Nebula**, located in the constellation Orion, is mostly dust. Bright spots in the nebula are associated with newly forming stars.

Figure 1.52.The **Crab Nebula** is the remnant of a supernova recorded in 1054 A.D. The Crab Nebula now spans about 10 light years and has a neutron star at its center.

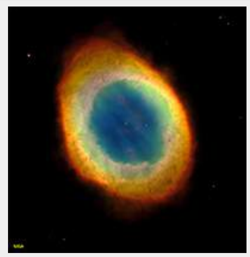


Figure 1.53. The **Ring Nebula** is located about 2,000 light years from Earth. The nebula is a gas shroud about a light year in diameter that surround a dying star.

Figure 1.54. **The Hour Glass Nebula** (discovered by the Hubble Telescope) is an unusual young planetary nebula located about 8,000 light years away.

1.22: The Solar System

The Solar System

The **Solar System** is the system containing the Sun and the bodies held in its gravitational field, including the planets (**Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune**), planetary moons, the asteroids, comets, and other interstellar bodies and matter (Figure 1.55).

Most planets and planet systems (planets with orbiting moons) orbit the Sun in the **ecliptic plane**—an imaginary plain containing the Earth's and other planets' orbit around the Sun.

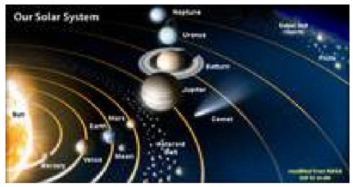


Figure 1.55. Our **Solar System** originated from gas, dust, and other matter that gravity pulled together in a stellar nebula about 5 billion years ago.

1.23: The Sun

The Sun

- By mass, the Sun is composed of hydrogen (70.6%) and helium (27.4%), all other elements are trace by comparison.
- The Sun's average diameter is about 864,000 miles (about 109 times the size of Earth).
- The Sun rotates on its axis in an unusual way. The rotation period at the Sun's equator is about 27 days, but is about 36 days at it poles.

Figure 1.56. The Sun (our **star**), is one of billions of stars in our **Milky Way Galaxy**.

Structure of the Sun

The Sun's internal structure is inferred to be subdivided into several zones (Figure 1.54).

- **Core**—The internal temperature of the Sun's is estimated to be about 27 million degrees Fahrenheit, hot enough to drive the **nuclear fusion** process of **converting elemental hydrogen into helium**, the source of **solar energy**.
- **Radiative zone**—Above the core where fusion occurs, slowly radiates upward through the massive radiative zone.
- **Convection zone**—The temperature is estimated to drop to about 3.5 million degrees Fahrenheit, where convection of "great bubbles of dense plasma (ionized matter) rise toward the surface in a convective manner (like a pot of boiling soup).
- **Photosphere**—A 300 mile thick layer of hot gas makes up the surface of the Sun where most of the Sun's energy radiates into space. The Sun's surface temperature is about 10,000 degrees Fahrenheit, hot enough to radiate solar energy in the visible light spectrum.
- **Chromosphere** and **Corona**—The outermost layer of the Sun is a thin solar atmosphere (the chromosphere) which extends as streaming plasma deep into space (the corona). The region is not a hot as the underlying photosphere, but is heavily influence by magnetic forces generated deeper in the Sun. Features of the chromosphere are only visible with special sun-observing telescopes. However, the corona is visible during solar eclipses when the disk of the Moon's shadow temporarily blocks the intense light form the photosphere (Figure 1.55).

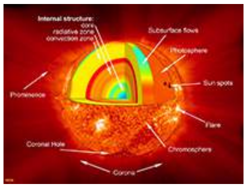


Figure 1.57. Internal structure of the Sun.

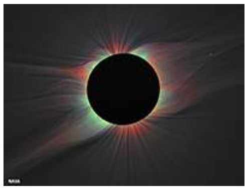


Figure 1.58. The Sun's corona is visible during a solar eclipse.

1.24: Sunspots, Coronal Mass Ejections, and the Solar Wind

Sunspots and Coronal Mass Ejections

Sunspots are relatively dark patches that appear temporarily on the Sun's photosphere (Figures 1-59 and **1-60**). Sunspots are cause by a flux in magnetic fields that appear to inhibit convection. Sunspots usually occur in pairs, like the two ends of a U-shaped magnet. Sunspots last a few days to a few months before they dissipate. The concentration of sunspots on the solar surface tend to follow an 11 year cycle that also flows a small variation is the total amount of solar energy output.

Coronal mass ejections are unusually large eruptions of streaming plasma and radiation (composed of charged particles) under the influence of solar magnetism. Eruptions result in the formation of **solar flares** and **prominences** (arching flares) that erupt from the Sun's surface (Figures 1-61 and **1-62**).

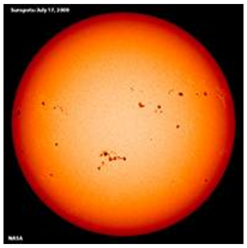


Figure 1.59. **Sunspots** appear as dark splotches on the Sun's surface.

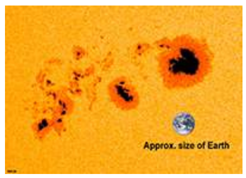


Figure 1.60. Comparison of the relative size of sunspots to the size of the Earth.

Figure 1.61. A **solar flare** erupting on the Sun's surface.

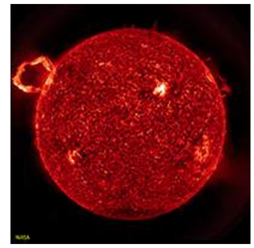


Figure 1.62. A large solar **prominence** erupting on the Sun's surface.

The Solar Wind

The **solar wind** is a stream of energized, charged particles (mostly electrons and protons) flowing outward from the Sun's upper atmosphere. The ionized particles are released into space from the Sun's corona and by coronal mass ejections (prominences and flares). The solar wind moves through solar system at speeds roughly 500 miles per second (800 km/sec); about 10 days from Sun to Earth) and can reach temperatures of about 1 million degrees (Celsius). The solar wind is what blows a ***tail*** away from the bodies of comets as they go through the solar system. Estimates suggest the Sun loses the equivalent of ***one Earth mass*** about every 150 million years (which isn't much considering the size of the Sun). Large **corona mass ejections** from the Sun's surface result in **solar storms** that frequently impact Earth and other planets.

The Earth's **magnetic field** shields the planet from the erosive effects of the solar wind (Figure 1.63). Particles trapped by Earth's magnetic field flow into the upper atmosphere producing the **aurora borealis** (Northern Lights) and **aurora australis** (Southern Lights) (Figure 1.64). Over geologic time, the solar wind also erodes the atmosphere of planets with weak magnetic fields (this includes Mercury, Mars, and the Moon). Strong auroras have been observed on the gas planets (Jupiter, Saturn, Uranus, and Neptune)—all of which have a dense atmosphere and a strong magnetic field.

Solar storms associated with coronal mass ejections can interfere with radio communications, cause damage to satellites, and impact electrical transmission lines and facilities (resulting in power outages). During strong solar storms long lines of metal (like electrical power lines, pipelines, and railroad lines in northern regions can overload with electrical charges which and spark to nearby objects and have been reported to have started brush fires. Because massive solar ejections can be observed, the possible impacts of solar storms can be predicted.

Figure 1.63. Coronal mass ejections result in the **solar wind** which is deflected and captured by the Earth's magnetic field.

Figure 1.64. The **aurora borealis** are streaming light displays in the northern hemisphere.

1.25: Planets and Planetary Systems of the Solar System

A **planet** is a large spherical celestial body moving in an elliptical orbit around a star. A **planetary system** is a set of gravitationally bound celestial objects in orbit around a star or star system. Planets with orbiting moons are planetary systems. The Solar System consists of four inner **rocky planets**, four outer **gas planets**, and orbiting belts of **asteroids**, **comets**, **planetesimals**, and other objects under the gravitation influence of the Sun.

The 4 Inner Rocky Planets			

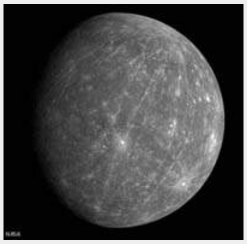
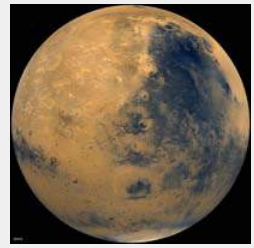

			

Figure 1.65. Mercury	Figure 1.66. Venus	Figure 1.67. Earth	Figure 1.68. Mars
• a rocky planet • no atmosphere • no moons • **planet radius**: 1,516 miles (2440 km) • **average distance from sun**: 36 million miles (58 million km) • **orbital period**: 88 days • **gravity**: 3.7 m/sec2	• a rocky planet • hot atmosphere, mostly CO_2 (with a sulfur-rich cloud cover) • no moons • **planet radius**: 3,760 miles (6050 km) • **average distance from sun**: 67.24 million miles (108 million km) • **rotation (day)**: -243 day (it rotates backwards!) • **orbital period**: 224.7 days • **gravity**: 8.87 m/sec^2	• a rocky planet with oceans, ice cap, and atmosphere • supports life! • one moon (the Moon!) • **planet radius**: 3,959 miles (6370 km) • **average distance from sun**: 92.96 million miles (150 million km) • **rotation (day)**: 24 hours • **orbital period**: 365.24 days • **gravity**: 9.8 m/sec^2	• a rocky planet • has ice caps at poles • thin atmosphere, mostly CO_2 • 2 small moons: (**Phobos** and **Deimos**) • **planet radius**: 2,106 miles (3390 km) • **average distance from sun**: 141.6 million miles (228 million km) • **rotation (day)** 24.67 hours • **orbital period**: 687 days • **gravity**:

The 4 Outer Gas Planets (or Planetary Systems)			
			
Figure 1.69. Jupiter	Figure 1.70. Saturn	Figure 1.71. Uranus	Figure 1.72. Neptune

• largest of the gas planets • mostly hydrogen and helium • has **67 moons**, of which 4 are much larger than other moons. • very active storms are visible in its atmosphere. • **planet radiu**s: 43,441 mile 70,000 km) ***average distance from sun**: 483.8 million miles (779 million km) • **orbital period**: 12 years • **rotation (day)**: 9 hr, 56 min	• a gas planet famous for its visible rings (mostly dust, ice, and rock fragments). • Currently has **62 moons**, including **Titan**, the largest in the Solar System. • **planet radius**: 36,184 miles (36,200 km) • **average distance from sun**: 888.2 million miles (1.42 billion km) • **orbital period**: 29 years • **rotation (day)**: 10 hr, 42 min	• a gas planet • has 5 medium-sized moons (many smaller ones too) • **planet radius**:15,759 miles (25,400 km) • **average distance from sun**: 1.784 billion miles (2.87 billion km) • **orbital period**: 84 years • **rotation (day)**: 17 hr, 14 min	• the outermost gas planet • has 13 known moons • **planet radius**: 15,299 miles (24,620 km) • **average distance from sun**: 2.795 billion miles (4.5 billion km) • **orbital period**: 165 years • **rotation (day)**: 16 hr, 6 min

1.26: Earth's Moon

Earth's Moon

Earth's **Moon** is the fifth largest of at least 168 known moons orbiting planets in the Solar System (Figure 1.73).

Figure 1.73. **The Moon**
moon radius: 1,079 miles (1,736 km)
orbital period: 27 days
average distance from Earth: 238,855 miles (383,300 km).
gravity: 1.622 m/s^2

The Moon rotates ate the same rate that it revolves around the Earth (a synchronous rotation that keeps the same side of the Moon facing Earth).

The Moon lacks an atmosphere, and does not display any active geologic activity (such as earthquakes or volcanic eruptions). Like Earth, the Moon has a core, mantle, and a crust; geophysical data suggest the part of the Moon's core and mantle may be molten. The lack of atmosphere has helped to preserve geologic features that date back to early stages in the formation of the Solar System.

Most of what we have learned about the physical environment, composition, and origin of the Moon comes from the **Apollo Missions** (between 1961 and 1975) which culminated in a series of manned Moon landings between 1969 and 1972. Rock and lunar soil sample collected during those missions have helped resolving many questions and supporting theories about the origin of the Earth and Moon within the Solar System (discussed below).

1.27: Asteroids and Comets

Asteroids and Comets

An **asteroid** is any of the thousands of small irregularly shaped bodies of stone, metal, and ice that revolve about the sun. In our Solar System, asteroids typically range in size from about one-mile (1.6 km) to about 480 miles (775 km) in diameter (Figure 1.74). Most asteroids orbit the Sun in the **Asteroid Belt** located between Mars and Jupiter. However many large objects have been observed passing through Earth's orbital path. Asteroid collisions with Earth were frequent in Earth's early history, but are now extremely rare events. The extinction of the dinosaurs and many other species is mostly blamed on the environmental catastrophe created by an asteroid impact about 65 million years ago, defining the end of the Cretaceous Period (and Mesozoic Era).

A **comet** is a celestial body thought to consist chiefly of if ices of ammonia, methane, carbon dioxide, and water, and dust (Figure 1.75). Comets are observed only in that part of its orbit that is relatively close to the sun, having a head consisting of a solid nucleus surrounded by a nebulous cloud of gas and debris (a coma) up to 2.4 million kilometers (1.5 million miles) in diameter. The coma turns into an elongated curved vapor tail arising from the coma when sufficiently close to the sun. There may be more than 100 million comets in the outer Solar System.

A **meteor** is a bright trail or streak that appears in the sky when a meteoroid is heated to incandescence by friction with the earth's atmosphere.

A **meteorite** is a stony or metallic mass of matter that has fallen to the Earth's surface from outer space (Figure 1.76).

Asteroids and Comets

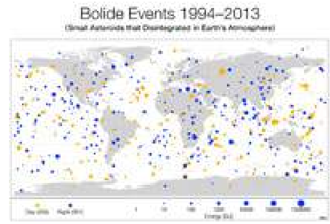
Figure 1.74. Asteroids are solid objects in space consisting mostly of rock, dust, some metals, and possibly ice.

Figure 1.75. Comets are like asteroids (mostly frozen gases and ice, dust, some rocky material) that leave a trail of material as they are heated as they approach the sun.

Figure 1.76. An **iron-nickel meteorite** is **magnetic**.

A **bolide** is a large meteor (or asteroid or comet) that explodes in the atmosphere (Figures 1-77 and **1-78**). About a dozen significant (recorded) bolide events happen each year. A recent bolide explosion involved the Chelyabinsk meteor that blew up over Russia on February 15, 2013. The explosion occurred high in the atmosphere, but the atmospheric shock wave blew out windows, doors, and injured over a thousand people on the ground (see YouTube video).

An **atrobleme** is an eroded remnant of a large crater made by the impact of a comet or asteroid (large meteorite). Because of weathering and erosion processes, impact craters are relatively short lived on the Earth's surface (with exceptions for large impacts or in arid regions). Currently there are almost 200 known craters distributed on all continents. Others have been discovered by oil drilling through sedimentary cover.

	
Figure 1.77. Bolide (meteor fireball) over Oklahoma Panhandle, 9/30 2008	Figure 1.78. Map of reported bolide events 1994-2013.

Can you explain why are there so many craters on the surface of the Moon but not on surface of the Earth?

1.28: The Outer Solar System

The Outer Solar System

The region beyond to orbit of Neptune is called the **Kuiper Belt**. It is the circumstellar disc at the outer margin of the Solar System beyond the planets. It is similar to the Asteroid Belt, but far larger (wider) and many times more massive. The belt extends from Neptune (at about 30 AU [astronomical units] to about 50 AU - **one AU** is the average distance of the center of the Earth to the center of the Sun.

There are more than **100,000 Kuiper Belt Objects** (KBO). The Kuiper Belt includes three recognized **planetesimals** (or **dwarf planets**) including Pluto, Haumea, and Makmake. KBOs are probably mostly composed of frozen volatile compounds (ices of methane, ammonia, and water). Pluto's status as a ***planet*** has been argued for years - Figure 1.79. **Pluto** does not behave like other planets; it does not orbit the Sun within the ecliptic plane, and sometimes Pluto's orbit puts it closer to the sun than Neptune.)

Beyond the Kuiper Belt is the hypothetical **Oort Cloud** - a region that may contain an abundance of icy planetesimals and objects that may surround the Solar System at a distance of between 50,00 and 200,000 AU. The Oort Cloud may be the source of most of the long-period comets that have been observed.

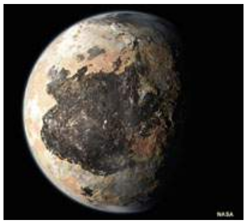


Figure 1.79. Pluto was formerly classed as a planet, but now it is called a **planetesimal**, or a **dwarf planet** in the **Kuiper Belt**. Pluto has 5 moons.

1.29: Nebular Hypothesis of the Origin of the Solar System

Nebular Hypothesis of the Origin of the Solar System

Many billions of years before the formation of the Solar System there were probably several generations of star formation and destruction occurred in our region of the Milky Way. Ancient **supernova explosions** in the distant past produced the elements we observe in our Solar System today (an example of a fairly recent supernova explosion is shown in Figure 1.80). **Nuclear fusion** in stars coverts hydrogen into helium and other elements up to the atomic mass of iron. Elements heavier than iron are only created by intense energy in **supernova explosions**. Gas, dust, and other matter from previous supernova explosions became part of a nebula (Figures 1-81). Gravity gradually condenses material in nebulae into new star systems (see example in Figure 1.82).

Figure 1.80. Supernovas are great explosions that partial to complete demolish aging stars, releasing new matter and gas to create a new generation of stars.

Figure 1.81. Nebula, the birthplace of stars; some are formed from the explosion of other more ancient stars, some thousands to millions time larger than the Sun.

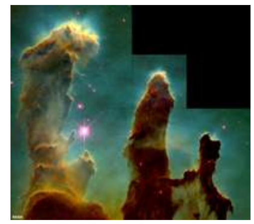


Figure 1.82. Pillars of Creation, a part of Eagle Nebula in our Milky Way Galaxy where new stars are forming and emerging from a gas and dust cloud—a stellar nursery.

An ancient nebula in the Milky Way Galaxy was the birthplace of our Sun and Solar System. Currents of material (gases, dust, asteroids, etc.) under the influence of gravity consolidated into the **proto suns** and **proto planets** of new star systems within the nebula, one of which became our Sun and Solar System. Because all matter is influenced by gravity, matter within nebulae gradually is pulled toward areas with more matter. As matter moves toward a location with greater density it may be caught in a spinning current around a center of accumulating matter that may become a sun or a planet.

• The combination of gravity and spin results in the formation of a flat, disk-shaped stellar cloud with the Proto Sun (or **pre Sun**) at the center. The increasing mass and gravity of the Sun grabs most of the matter in the evolving Solar System (Figure 1.83).

• The Sun eventually gains enough mass that nuclear fusion can begin, creating the intense energy that it radiates into space.

• The massive release of energy from the new Sun heats the surrounding stellar region, combined with the force of high energy plasma (the solar wind) pushes the light elements (mostly hydrogen and helium) out of the inner Solar System region. As a result:

• Inner planets form from the accumulation mostly of metallic and rocky substances (dust). Lighter gas materials are pushed to the outer regions of the Solar System.

• Larger planets in the outer part of the Solar System began forming from gases (mostly hydrogen) and fragments of ice (H_2O, CO_2, and other gases).

• The Sun and its Solar System gradually formed by the gravitational attraction of materials within a stellar nebula beginning almost 5 billion years ago.

• The evolving Solar System assumes a flat, disk shape of condensing gases and dust with the Proto Sun (or pre Sun) at the center. The consolidation of matter under gravitational attraction causes the surrounding nebular cloud to flatten and spin.

• After **solar ignition** (initiation of the Sun's internal nuclear fusion reactions), the Sun's intense solar energy and solar wind begins to drive gases away from the inner Solar System.

• Inner planets begin to form from metallic and rocky substances (dust).

• Larger outer planets began forming from fragments of ice (H_2O, CO_2, and others).

Figure 1.83. A brief explanation of how the Solar System came to be through the process of stellar evolution.

Proto-Earth Formed

Studies of meteorites and samples from the Moon suggest that the Sun and our Solar System (including **proto-planets**) condensed and formed in a nebula before or about **4.56 billion years** ago. A recent Scientific American article places the current assumed age of the Earth is about **4.56 billion years** old. Currently, the oldest samples of ***Early Earth*** rock samples from the Jack Hills region of Australia that contain crystals of the mineral zircon dated to an age of about **4.4 billion years.**

Earth also formed through gravitational attraction of interstellar dust, gases, small asteroids and larger objects (planetesimals) within the early Solar System consolidating within the Sun's stellar nebula and within its orbital belt around the Sun.

- Initially, the Earth was probably homogeneous in composition, eventually becoming extremely hot and mostly molten within.
- Proto-Earth was probably under constant bombardment by asteroids, comets, and planetary dusts and debris.
- Current thought is that the **Proto-Earth** grew to a larger in size than today's Earth.

Formation of the Earth-Moon System

Proto-Earth experienced a great planetary collision resulting in formation of the Moon.

Studies of the rocks brought back from the **Apollo Missions** show that the Earth and Moon have similar mineral and isotopic compositions. Such an impact probably vaporized much of the upper portion of the Proto-Earth, throwing much of it into space. Gravity eventually consolidated the material into the Earth-Moon system. This, and the fact that the **Earth has a tilted axis**, and the **Moon's orbit is not in the ecliptic plane**, suggest that the Moon may have formed from the collision of another small planet-sized object with the Earth early in the history of the Solar System (Figure 1.84). It is this tilt to Earth's axis that gives rise to the **seasons** as it orbits the Sun.

The Moon's surface displays a heavily cratered surface, many of the craters are massive in scale. Dark-colored **maria** are regions on the lunar surface where molten material flooded the surface, filling in depressions created by massive impacts. The lighter-colored highland regions on the Moon are rugged mountainous regions consisting of heavily cratered moonscapes and tectonic features that formed early in the Moon's history when the mantle was more molten and lighter material floated to the surface to crystallize and form the lunar crust. The cratering was a result of asteroids and comets collisions, mostly within the first billion years of the Moon's history.

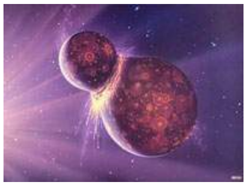


Figure 1.84. Proto Earth colliding with another object

1.30: Evolution of Earth’s Layered Structure

Evolution of Earth’s Layered Structure

Earth has a layered structure, having an outer rocky crust and mantle overlying a molten and solid metal core, however, this internal layered arrangement did not exist early in Earth's history (Figure 1.85).

• Early in Earth's history the composition of the planet was probably more homogeneous. However, just like oil and water don't mix, metals separated from non-metal substances, and as metals are denser, gravitation forced them to sink toward the planet's core.
• Likewise, molten material rich in dissolved gases and lighter silica-rich matter is less dense and over time it gradually migrated upward accumulating in the mantle and thin crust where some of it reached the surface, resulting in volcanism and massive degassing.
• Despite intense asteroid bombardment, early crust began to form.
• Chemical segregation under the influence of gravity established the basic divisions of Earth’s interior (core, mantle, and crust). This process also happened with other planets, moons, and planetesimals in the Solar System.

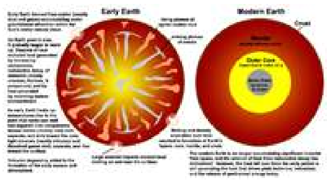


Figure 1.85. Formation of the early Earth and the eventual development of its internal layered structure: core, mantle, and crust. Volcanic degassing and accumulating gases from space led to the formation of Earth's atmosphere and oceans.

1.31: Origin of Earth's Atmosphere and Oceans

Origin of Earth's Atmosphere and Oceans

The study of meteorites and material in space suggest the early Earth probably had large quantities of water, organic compounds, and other gases trapped in the accumulating material forming the planet. As a result, as rocks melted large amounts of **volcanic outgassing** took place. This volcanic outgassing contributed to the atmosphere forming around the planet. Volcanic outgassing from the Earth's interior is still taking place as illustrated by gas emissions from volcanic eruptions such as those on Hawaii or on Iceland where the source of molten material is known to be rising to the surface from the mantle (Figure 1.86).

• Current thought is that large volumes of water vapor and carbon dioxide formed Earth's primitive atmosphere. The atmosphere was also rich in nitrogen, methane, and ammonia.

Figure 1.86. Volcanic outgassing of the interior of the planet is still taking place, as illustrated by volcanic eruptions on Hawaii.

• Early in Earth history the Earth probably had a thick, hot atmosphere. The surface of the planet was probably hotter than the boiling point of water, so much of the planet's water was trapped as water vapor in the atmosphere.

• Early on, no continents or oceans probably existed (at least no trace of them are preserved from that time), and no evidence of life on Proto-Earth has been discovered.

• Eventually the surface cooled enough for early crust to began to form. With a solid crust and reduced surface temperatures, rainfall could begin to accumulate in depression on the surface. As more and more water was released from the atmosphere oceans began to form.

• By about **4 billion years ago (BYA) t**he Earth's oceans were essentially in place. Oldest rocks from Canada are of this age.

• Nearly 2 billion years ago, life had advance enough for photosynthesis to take place, gradually consuming the vast reservoirs of carbon dioxide in the atmosphere and dissolved in the oceans, while releasing oxygen to accumulate in the atmosphere (discussed in Chapter 2).

1.32: What Are Minerals? and What Is the Difference Between a Rock and a Mineral?

Basic Geologic Principles

Some basic geologic concepts are helpful for explaining the origin of rocks that formed in ocean basins or are observable in rocky outcrops along coastlines. Rocks form in many ways, and because the Earth is so old, rocks that may have formed in one location may have been altered or moved long distances from its place of origin.

What Are Minerals? What Are Their Significance?

A **mineral** is a **naturally occurring**, **inorganic** (never living) **solid** with a **definite internal arrangement of atoms** (crystal structure) and has a **chemical formula that only varies over a limited range that does not alter the crystal structure**.

Currently there are about **4,000 known minerals** of different chemical composition and internal atomic crystal arrangements (discussed below). However, slightly more than a dozen are considered "**common minerals**" because of their abundance on the earth surface. Figure 1.87 shows **common rock-forming minerals**.

In contrast, minerals considered **gems** are, mostly, exceedingly rare. **Most minerals are chemical compounds** consisting of two or more elements, however, some elements naturally occur in mineral form including gold, copper, platinum, sulfur, and iron.

Figure 1.87. Common rock-forming minerals are the most abundant minerals found on our planet Earth.

What Is the Difference Between a Rock and a Mineral?

A **rock** is a relatively hard, naturally formed aggregate of mineral matter or petrified matter. Rocks are **mixtures** and may consist of one or more minerals, but may include organic matter and other non-mineral substances, such as gases and water. Rocks are what makes up the materials of the solid Earth and other rocky planets and moons in the Solar System. The word **stone** is another common term used to describe rock.

Rocks consist of one or more minerals. Figure 1.88 shows how minerals can be combined to form different kinds of rocks that form under different environmental conditions.

Figure 1.88. Combinations of common minerals occur in different kinds of rocks. The kind of rock depends on the geologic setting where they form: igneous, sedimentary, or metamorphic.

The mineral composition of a rock reflects the physical environment and geologic history where a rock formed. Rock form in a variety of geologic setting ranging from locations on or near the earth surface, deep underground, or even in outer space. Most of the rocks we see on the surface of our planet formed by processes that happened long ago. However, we can see these processes that form rocks actively taking place in many places today. Rapid rock formation can be seen happening such as lava cooling from a volcanic eruption in places like Hawaii or Iceland. However, most rocks we see around us form very slowly in settings that may not be visible on the land's surface. Slow processes creating rocks can be inferred by observing reefs growing and accumulating in the oceans, or sediments being carried by flowing water in streams or moved by waves crashing on beaches. We can see sediments being deposited, but we cannot see them turning into stone because the process may take thousand or even millions of years.

The mineral composition of a rock reflects the physical environment and geologic history where a rock formed.

1.33: General Classification of Solid Earth Materials

General Classification of Solid Earth Materials

Igneous rocks are rock formed from molten materials. These include **intrusive rocks** (rocks cooled from **molten material [magma]** below the surface) and **extrusive rocks** formed on the Earth's surface by **volcanism**.

Sediments are solid fragments of inorganic or organic material that come from the weathering of rock and soil erosion, and are carried and deposited by wind, water, or ice.

Sedimentary rocks are rocks that formed through the deposition and solidification of sediment, especially sediment transported by water (rivers, lakes, and oceans), ice (glaciers), and wind. Sedimentary rocks are often deposited in layers, and frequently contain fossils.

Metamorphic rocks are rocks that were once one form of rock but has changed to another under the influence of heat, pressure, or fluids without passing through a liquid phase (melting).

1.34: Igneous Rocks

Igneous Rocks

• The term **igneous** applies to rocks or minerals that have solidified from molten material.
• Molten material underground is call **magma**; when it erupts and flows on the surface it is called **lava**.
* When molten material cools, it **crystallizes** into rock.
• When magma intrudes other rocks underground and cools it forms **intrusive igneous rocks** (examples include granite, diorite, and gabbro). Slower cooling times underground result in bigger mineral crystals. These rocks typically have acrystalline texture from interlocking crystal grains.
• Lava that extrudes on the surface as a volcanic eruption cools quickly, forming **extrusive igneous rocks** (examples include rhyolite, andesite, and basalt).

Igneous rocks are generally classified by their color and size of their crystals, and more specifically classified by their mineral composition. Study of igneous rocks has played an important role in deciphering the origin of rocks beneath and around ocean basins (discussed in Chapters 3 and 4).

Figure 1.89. Intrusive (plutonic) igneous rocks

Figure 1.90. Extrusive (volcanic) igneous rocks.

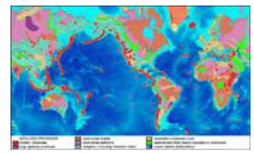


Figure 1.91. Igneous regions of the world.

Figure 1.92. **Basalt** volcano: Pu'u'o'o volcano on Hawaii's Big Island.

Figure 1.93. Andesite volcano: Mount St. Helens in the Cascade Range, Washington..

Figure 1.94. Granites exposed in core of Sierra Nevada Range.

1.35: Sediments and Sedimentary Rocks

Sediments and Sedimentary Rocks

Sediments are solid material that has settled from a state of suspension in a fluid (water, ice, or wind).
• When **lithified** (**consolidated** or **cemented**) becomes a **sedimentary rock**.
• Sediments are derived from **weathering** and **erosion** of pre-existing rocks.
• Sediments and sedimentary rocks can help tell the geologic history of an area (discussed in Chapter 5 about marine sediments).
• Sedimentary deposits are classified by grain size and source.
• Sedimentary deposits may contain **fossils**.

Sediments and sedimentary rocks cover much of the seafloor around the world. Most sedimentary rocks observed on land were deposited in ocean settings, along coastlines, or in shallow seaways that flooded onto the continents in the past. Sedimentary deposits and the fossils they contain have been important sources of information for resolving questions about Earth history and climate change.

Figure 1.95. Common sedimentary rocks include conglomerate, sandstone, shale, limestone, gypsum, and marl

1.36: Metamorphic Rocks

Metamorphic Rocks

• Metamorphic rocks are formed by “changing” pre-existing igneous, sedimentary or other metamorphic rocks.
* Metamorphic processes involve changes caused by exposure to heat, pressure, and chemically-active fluids.
• Driving forces are increased heat and pressure as rocks are buried deep into the earth in association with mountain-building periods.
• They typically develop a fabric or texture that differentiates it from the original rock it formed from (called a **protolith**).
• Commonly found in ancient crustal rocks exposed in mountain ranges and in the core of continental landmasses.

Examples: quartzite, slate, marble, gneiss, schist, and serpentinite (the State Rock of California)

Figure 1.96. Common metamorphic rocks

1.37: The Rock Cycle

The Rock Cycle

The **rock cycle** is a conceptual model of how earth materials form and change in the Earth's crust over time. The rock cycle represents the series of events in which a rock of one type is converted to one or more other types and then back to the original type. Both **products** (rocks and sediments) and **processes** (such as melting, cooling, erosion, deposition, metamorphism, remelting) are part of this idealized cycle. The **passage of geologic time** is the essential component, although some processes are much faster than others. Note that all these types of processes are taking place simultaneously, but at different locations on and within the crust. It is important to note that rock cycle processes also occur on other rocky planets or moons, but rates may vary due to the presence (or lack of) atmospheric gases or fluids (including water) or availability of heat enough to melt rocks.

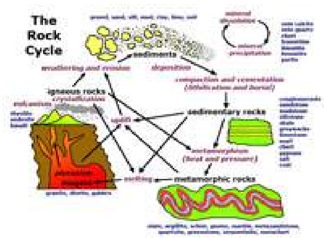


Figure 1.97. The Rock Cycle is a conceptual model that portrays **processes** and **products** changing over time

1.38: Uniformitarianism

Uniformitarianism

The concept of the rock cycle is attributed to a Scottish physician, **James Hutton** (1726-1797), who studied rocks and landscapes and coastlines throughout the British Isles. Hutton's concepts were later promoted in a book entitled *Principles of Geology* by the Scottish geologist **Charles Lyell** (the book was released in 3 volumes in 1830-1833). Hutton and Lyell are considered the founders of modern geology. Hutton also promoted the theory of uniformitarianism. **Uniformitarianism** emphasizes that all geologic phenomena may be explained as the result of existing forces having operated uniformly from the origin of the Earth to the present time. Uniformitarianism is commonly summarized: "**The present is key to the past.**"

Hutton fearlessly debated that the Earth was very old, measured in millions of years rather than thousands of years as promoted by the religion organizations of his times.

Many scientists in Hutton's time promoted an alternative theory of **catastrophism**. **Catastrophism** is a theory that major changes in the Earth's crust result from catastrophes rather than evolutionary processes. The theory of catastrophism was more in line with religious doctrine common in the 17th and 18th centuries.

It is interesting that today, uniformitarianism still applies to most geologic and landscape features, but discoveries have show that the Earth, or large regions of it, have experience great catastrophes, such as asteroid impacts, great earthquakes, collapse of continental shelves (causing massive underwater landslides and tsunamis), super storms, great floods, or volcanic events. However, these events can be scientifically viewed within the greater context of modern geology. Uniformitarianism explains how observable processes taking place over long periods of time can change the landscape. Examples include:

* earthquakes only happen occasionally, but in an area taking place over millions of years can result in the formation of a mountain range.
* the deposition of silt from annual floods over millions of years can built a great river delta complex.
* the slow growth and accumulation of coral and algal material over time can build a great barrier reef.

1.39: Rock Formations

Rock Formations

Stratigraphy is a branch of geology concerned with the systematic study of bedded rock layers and their relations in time and the study of fossils and their locations in a sequence of bedded rocks. A **stratum** is a bed or layer of sedimentary rock having approximately the same composition throughout (plural is **strata**).

James Hutton also contributed to a theories about rock formations. A **rock formation** is the primary unit of stratigraphy, consisting of a succession of strata useful for mapping or description. A rock formation typically consists of a **unique lithology** (rock type) that has a relatively defined geologic age and is considered **mapable** (occurs throughout area or region, both on the surface and in the subsurface).

Rock formations preserved information about what conditions were like when the original sediments were deposited, such as on a river delta, a coastal beach environment, a ocean setting, or a massive dune field. Rock formations can also consist of igneous rocks, such as ancient lava flows or massive volcanic ash deposits. Rock formations typically represent materials that accumulated over period of hundreds of thousands, to many millions of years.

Figure 1.98. **Strata** exposed along a reservoir shoreline. Each layer represents sediments deposited under unique environmental conditions over a period of time (days, years, centuries).

Figure 1.99. Layers of sedimentary **rock formations** of the Cenozoic Era are exposed in many locations US coastlines. These are Calvert Cliffs on Chesapeake Bay, Maryland.

1.40: Methods For Determining the Age of Earth Materials and Features

Methods For Determining the Age of Earth Materials and Features

Geochronology, the branch of earth sciences concerned with determining the age of earth materials and events through geologic time.

How do geoscientists determine the age of rocks or fossils? How do they figure out how long ago and in what order did geologic processes or events take place? For instance how do they know how often a volcano erupts or how often earthquakes take place. Geologists now have many ways to determine the age of materials using **absolute** and **relative dating methods**.

Absolute and Relative Dating Methods

Absolute dating is a general term applied to a range of techniques that provide estimates of the age of objects, materials, or sites in real calendar years either directly or through a process of calibration with material of known age. There are many methods of absolute dating rocks or other ancient materials. The methods of absolute dating used depends on whether suitable samples are available for testing.

Relative dating is the science of determining the relative order of past events, without necessarily determining their **absolute age** (see below).

1.41: Decay of Radioactive Isotopes Used For Absolute Dating

Decay of Radioactive Isotopes Used For Absolute Dating

Unstable isotopes emit particles and energy in a process known as **radioactive decay**. A **parent isotope** is an unstable radioactive isotope. A **daughter product isotope** results from the decay of a parent.

Radioactive decay occurs at known rates and using this you can determine the age of certain types of rocks.

Dating of materials that contain naturally-occurring **radioactive isotopes** is possible because the rates of decay are known. The radiation decay ***clock*** starts the moment a mineral in a rock forms (or for **^{14}C** when an organism dies).

A **half-life is the time required for one-half (50%) of the parent to change to daughter product**. The next half-life is when only a quarter of the original parent radionuclide remains, and so on. Age determinations can be determined by comparing the ratio of the parent and daughter isotome in a new (fresh) sample with the percentage in the old sample material being tested (Figure 1.100).

Commonly referenced studies of absolute dating utilize the radioactive decay of:		
Parent Isotope	**Daughter Isotope**	**Half Life**
^{238}U (unstable uranium isotope)	**^{206}PB** (stable lead isotope)	~ 4.5 billion years
^{40}K (unstable potassium isotope)	**^{40}Ar** (stable argon isotope)	~ 1.25 billion years
^{14}C (unstable carbon isotope)	**^{14}N** (stable nitrogen isotope)	5,730 years
Note there are many other radionuclides used for absolute dating methods.		

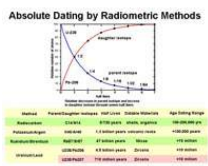


Figure 1.100. Absolute dating methods. Different isotopes are used to study different materials and geologic time ranges.

Sources of error in Absolute dating. Error can be caused by a variety of misinterpretation. Do we have a general good idea of the geologic history of the sample? (See **Relative Dating** below). Factors include:

The sample has been within a closed system, meaning no parent or daughter atoms have entered or the sample. This is best assured by using fresh, unweathered rock samples.

• Decay rate is constant over geologic time.

Not all rocks can be dated by radiometric methods

• **Detrital sedimentary particles** are not the same age as the rock in which they formed
• **Metamorphic rock age** may not necessarily represent the time when the rock formed
• **Datable materials** (such as volcanic ash beds and igneous intrusions) are often used to bracket ages
• Bracketing sedimentary ages using **igneous rocks**

Figure 1.101. Nuclear bomb testing release large quantities of radionuclides into the global environment. Atmospheric and oceanic nuclear testing began with the first test on July 16, 1945 (Trinity Site in New Mexico). Most atmospheric testing ended in 1980, but (sadly) still continues underground.

1.42: Radiocarbon Dating and Relative Dating

Radiocarbon Dating

Radiocarbon dating is one of the most used method of absolute dating because of its useful **dating window** encompassing the past 100,000 years (it is especially useful for studying archeological features and young sedimentary deposits). ^{14}**C** (isotope carbon -14) is a unstable radioactive isotope (radionuclide). **Radiocarbon dating** (using ratios of the isotopes of radioactive isotope ^{14}**C** to stable isotopes ^{12}**C** and ^{13}**C** derived from buried or isolated organic or carbonate materials. The **half life** of ^{14}**C** [unstable isotope carbon-14] is about **5,730 years**. Radiocarbon dating has extensively used in archeological investigation and the study of climate change over the last several hundred thousand years, and precision methods now available make radiocarbon dating highly reliable. Radiocarbon dating is highly effective for extracting ages of organic materials (bone, tissues, wood, etc.) that have been isolated by burial and is effective for dating materials materials from ancient human activities going back for many thousands of years.

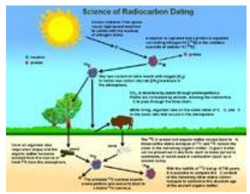


Figure 1.102. The science behind the **radiocarbon absolute dating method.**

Relative Dating

Relative dating is the science of determining the relative order of past events, without necessarily determining their **absolute age** (see above). Relative dating involved the study of fossils and the correlation or comparison of fossils of similar ages but from different regions where their age is known. Microfossils derived from sediments and cores from wells help in the subsurface exploration for oil and gas.

Relative dating is useful and relatively easy compared with absolute dating
• Not all rocks can be dated with radioactivity (see above).
• This is the way we tell the ages of rock layers relative to each other.

Basic Geologic Principles Used For Relative Dating

These basic principles are easily observed in geologic outcrops, but have value for any number of scientific and technical applications beyond geology. Figure 1.105 and **1-106** illustrates the **four laws** that are used in resolving the age of rocks and the order in which they formed or geologic events occurred. The three laws are as follows:

Law of Original Horizontality—this law states that most sediments, when originally formed, were generally laid down horizontally. However, many layered rocks are no longer horizontal.

Law of Superposition—this law states that in any undisturbed sequence of rocks deposited in layers, and the oldest on bottom the youngest layer is on top. Each layer being younger than the one beneath it and older than the one above it.

Law of Cross-Cutting Relationships—this law states that a body of igneous rock (an intrusion), a fault, or other geologic feature must be younger than any rock across which it cuts through.

Law of Inclusions
• An inclusion is a piece of rock within another rock.
• The rock containing the inclusion is younger

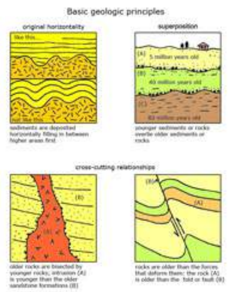


Figure 1.103. **Basic geologic principles** illustrated.

Fig.1-104. Example of a **basalt inclusion** in **granite**. The granite is younger than the basalt.

1.43: Unconformities- Gaps in the Geologic Record

Unconformities: Gaps in the Geologic Record

Following on the **Law of Original Horizontality** and **Law of Superposition**, both Hutton and Lyell recognized erosional boundaries preserved between rock layers that represent *gaps in the geologic record*. They named these gaps **unconformities**. An unconformity is a surface between successive strata that represents a missing interval in the geologic record of time, and produced either by: a) an interruption in deposition, or b) by the erosion of depositionally continuous strata followed by renewed deposition. It should be noted that the unconformable gaps in the geologic record in one region may be represented by sedimentary deposits in another region. Through time, geologists and paleontologists have been able to correlate rock formations and associated unconformities across large regions and even across oceans to other continents. Research over the past two centuries have provided information that in many of the gaps, making a more complete history of the geologic record.

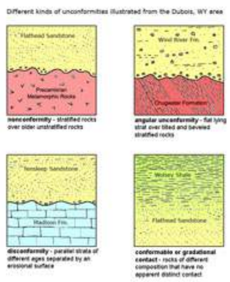


Figure 1.105. Types of **unconformities** (boundaries between layered rocks).

Fig. 106. Layered sedimentary rocks in a sea cliff in Encinitas, CA showing an **angular unconformity** (evidence of a gap in the geologic record).

Several types of unconformable boundaries are recognized (Figure 1.107):

- **nonconformity**—an unconformity between sedimentary rocks and metamorphic or igneous rocks when the sedimentary rock lies above and was deposited on the pre-existing and eroded metamorphic or igneous rock
.
- **angular unconformity**—an unconformity where horizontally parallel strata of sedimentary rock are deposited on tilted and eroded layers, producing an angular discordance with the overlying horizontal layers
.
- **disconformity**—an unconformity between parallel layers of sedimentary rocks which represents a period of erosion or non-deposition.
- **conformable boundary**—an arrangement where layers of sedimentary strata are parallel, but there is little apparent erosion and the boundary between two rock layer surfaces resemble a simple bedding plane.

Figure 1.107. **Rock formations** exposed in the Grand Canyon were originally deposited in different stages during the **Precambrian** and **Paleozoic Eras**. Some layers were deposited in shallow oceans, others layers accumulated on land.

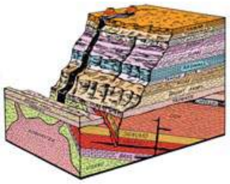


Figure 1.108. A block diagram of the Grand Canyon shows the names of **rock formations** separated by **unconformities** (representing gaps in time when sediments were not deposited). Can you spot an **angular unconformity**?

Figure 1.109. Rock formations like these in Utah record information about 100 million years of **Mesozoic Era** of the region. These sedimentary rock layers were originally deposited horizontally, but were tilted by later mountain-building (tectonic) activity.

Figure 1.110. Layers of sedimentary **rock formations** with unconformities are exposed in many locations along the California coastline. For example, these sedimentary rock formations are exposed at the Dog Beach in Del Mar, CA.

How Do Unconformities Form?

Unconformities are caused by relative changes in sea level over time. Wave erosion wears away materials exposed along coastlines, scouring surfaces smooth. On scales of thousands to millions of years, shorelines may move across entire regions. Erosion strips away materials exposed to waves and currents. New (younger) material can be deposited on the scoured surface. Shallow seas may flood in and then withdrawal repeatedly. Long-lasting transgressions can erode away entire mountain ranges with enough time.

A **transgression** occurs when a shoreline migrates landward as sea level (or lake level) rises.

A **regression** occurs when a shoreline migrates seaward as sea level (or lake level) falls (Figure 3.111).

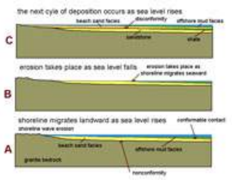


Figure 3.111. **Unconformities** can form by the rise and fall of sea level. Erosion strips away materials exposed to waves and currents. A rise in sea level causes a **transgression** which creates space underwater for sediments to be deposited. New (younger) material is deposited on the scoured surface. When sea level falls it causes a **regression**, and sediments are not deposited or are eroded away.

Sea level changes may be caused by region uplift or global changes in sea level, such at the formation or melting of continental glaciers. Whatever the cause of sea level change, when sea level falls, sediments are eroded from exposed land. When sea level rises, sediments are typically deposited in quiet water settings, such as on shallow continental shelves or in low, swampy areas on coastal plains.

Some unconformities represent great gaps in time. For example, the **Great Unconformity** in the lower Grand Canyon illustrates where a great mountain range existed in the region during Precambrian before erosion completely stripped the landscape away back down, eventually allowing seas to flood over the region again in Cambrian time (see the angular unconformity below the Tapeats Formation in Figure 1.108). The *gap in the geologic record* in some locations along the Great Unconformity represents billions of years.

1.44: Quiz Questions - Chapter 1 - Introduction to Oceanography

Quiz Questions - Chapter 1 - Introduction to Oceanography

1. Oceans cover 71 percent of the earth surface and have an average depth of about:
a. 2,444 feet (745 meters)
b. 12,100 feet (3688 meters)
c. 22,124 feet (6743 meters)
d. 29,935 feet (8850 meters)
e. 26,161 feet (11,022 meters)

2. The overall goal of science is:
a. to create better technology.
b. to develop hypotheses and theories.
c. to discover the origins of humans.
d. to find the origin of the universe.
e. to discover underlying patterns in the natural world.

3. Which of the following is a well-tested and widely accepted view that best explains certain observable facts?
a. theory
b. scientific method
c. rule
d. hypothesis
e. observation

4. A pure chemical substance consisting of one type of atom distinguished by its atomic number is called:
a. an atom.
b. an element.
c. a nucleus.
d. a proton.

5. Except for a simply hydrogen atom, the nucleus of atoms are made up of:
a. protons and neutrons.
b. neutrons and electrons.
c. electrons and protons.
d. none of the above.

6.The number of known elements listed on the Periodic Table is 118. Of these, how many are naturally occurring?
a. 64
b. 78
c. 92
d. 108

7. There are 16 elements that are considered most abundant in Earth's physical environment. What two elements are most abundant in Earth's crust?
a. oxygen and silicon.
b. aluminum and iron.
c. hydrogen and oxygen.
d. carbon and oxygen.

8. Chemical substances classed as **salts** are held together by:
a. covalent bonds.
b. ionic bonds.
c. metallic bonds.

d. Van der Waals bonds.
e. none of the above.

9. Isotopes of an element have:
a. the same number of protons and neutrons.
b. the same number of neutrons, but different number of protons.
c. the same number of protons, but different number of neutrons.
d. different numbers of electrons, neutrons, and protons.

10. Which of the carbon isotopes undergoes radioactive decay?
a. ^{12}C
b. ^{13}C
c. ^{14}C
d. All carbon isotopes are not stable and will undergo radioactive decay.

11. What part of the electromagnetic spectrum listed below has the ***greatest energy*** (based on highest frequency or shortest wavelength)?
a. UV (ultraviolet rays)
b. visible light
c. thermal infrared rays
d. microwaves
e. radio waves

12. Density is usually defined as a measure of mass (in grams) divided by the volume (in cubic centimeters, or cm^3). What is the average density of seawater?
a. 0.917 grams/cm^3
b. 1.0 grams/cm^3
c. 1.027 grams/cm^3
d. 0.986 grams/cm^3

13. The tilt in Earth's axis is theorized to have been caused by the collision of a Mars-sized object with the Proto Earth early in the formation of the Solar System. As a result, the Earth has 4 seasons. The day of the year when the north pole axis points closest to the Sun on the longest day of the year in the northern hemisphere is the:
a. winter solstice.
b. spring equinox.
c. summer solstice.
d. fall equinox.
e. summer equinox.

14. The angular distance of a place north or south of the Earth's **equator**, usually expressed in degrees and minutes, and is called:
a. latitude.
b. parallels.
c. longitude.
d. meridians.

15. One degree of **latitude** near the south pole or near the equator is approximately:
a. zero miles.
b. 53 miles (85 kilometers).
c. 69 miles (111 kilometers).
d. 100 miles (161 kilometers).

16. In order to make an accurate map of the stars for use in ship navigation, in 1884, a point indicating the precise location of 0° East and West was designated in the cross hairs of a telescope in the Royal Observatory (located on the grounds of the National

Maritime Museum in Greenwich England). This line marks the reference location of the Prime Meridian now used in all global mapping (including GPS location systems). The line on the opposite side of the globe at 180° from the Prime Meridian is called:
a. the Equator.
b. the Baseline.
c. the International Date Line.
d. Tropic of Cancer.

17. It is difficult to make a flat map of the spherical globe. A commonly used type of map of the Earth that projects lines of longitude and latitude as a perpendicular grid of squares (and does not show lines converging at the north and south poles) is called a:
a. Lambert conical projection map.
b. Mercator projection map.
c. Quadrangle projection map.
d. all of the above.

18. Who was first to provide evidence that explained Heliocentrism Theory that the Sun, not the Earth, was the center of our Solar System?
a. Aristotle
b. Nicolaus Copernicus
c. Galileo Galilei
d. Johannes Kepler
e. Isaac Newton

19. Which scientist used observational information from earlier scientists to resolve the Law of Universal Gravitation?
a. Aristotle
b. Nicolaus Copernicus
c. Galileo Galilei
d. Johannes Kepler
e. Isaac Newton

20. A **light year** is the astronomical measure of:
a. the distance that light can travel in a year.
b. approximately 9.4607 x 10^{12} kilometers .
c. about 6 trillion miles.
d. all of the above.

21. The Milky Way is thought to be:
a. a spiral galaxy.
b. an elliptical galaxy.
c. an irregular galaxy.
d. the Observable Universe.

22. According to the Big Bang Theory, the current estimates put the age of the Observable Universe is about:
a. 13.8 billion years.
b. 11,000 thousand years.
c. 6,000 years.
d. 4.56 million years.
e. 4.56 billion years.

23. The birth place of stars and solar systems are interstellar clouds called a:
a. nebula.
b. constellation.
c. red giant.

d. nova.

24. The outermost layer of the Sun is:
a. the radiative zone.
b. the convection zone.
c. the photosphere.
d. the chromosphere and corona.

25. What causes solar wind and solar storms?
a. large solar flares.
b. large solar prominences.
c. coronal mass ejections.
d. all of the above.

26. What are the 4 gas planets in our solar system?
a. Mercury, Venus, Jupiter, and Saturn
b. Mercury, Venus, Earth, and Mars
c. Earth, Mars, Jupiter, and Saturn
d. Jupiter, Saturn, Uranus, and Neptune

27. Which planets do not have moons?
a. Mercury and Venus
b. Mercury, Venus and Mars
c. Mercury, Venus, Jupiter, and Saturn
d. Mercury, Venus, Neptune, Uranus, and Neptune

28. The Asteroid Belt is located between:
a. Venus and Earth.
b. Earth and Mars.
c. Mars and Jupiter.
d. Jupiter and Saturn.
e. Uranus and Neptune.

29. An object that enters the atmosphere and explodes with great force is called a:
a. galaxy.
b. comet.
c. asteroid.
d. bolide.
e. meteorite.

30. According to the Nebular Hypothesis of the Origin of the Solar System, the current estimate put the age of the Earth is about:
a. 13.8 billion years.
b. 11,000 thousand years.
c. 6,000 years.
d. 4.56 million years.
e. 4.56 billion years.

31. Which of the moons orbiting a planet in the outer solar system it thought to have twice as much water (volume of oceans) than planet Earth?
a. Titan
b. Europa
c. Ganymede

d. Enceladus

32. A substance that in considered a **mineral** must have which of the following characteristics:
a. It must be naturally occurring in the environment.
b. It must be an inorganic (never living) solid.
c. It must have crystal structure with a definite internal arrangement of atoms.
d. all of the above.

33. What is true about a **rock**?
a. A rock can be a mixture.
b. A rock may be composed of one or more minerals.
c. A rock may include non-mineral substances, such as water, gases, or organic matter.
d. b and c.
e. all of the above.

34. What are the three types of rocks?
a. igneous, sedimentary, and metamorphic.
b. minerals, soils, and rocks.
c. weathering, transportation, and deposition.
d. igneous, sedimentary, and molten.

35. What is the name of theory that states that ***the physical, chemical, and biological laws that operate today have also operated in the geologic past***, or more simply stated, "**The present is key to the past**."
a. hypothesis
b. superposition
c. uniformitarianism
d. historical geology
e. catastrophism

36. A branch of geology concerned with the systematic study of **bedded rock layers** and their relations in time, and the study of **fossils** and their locations in a sequence of bedded rocks is called:
a. stratigraphy.
b. assumption.
c. chronology.
d. catastrophism.

37.Which of the following is **not** a form of **relative dating** of geologic features?
a. using radioactivity to find the age of a rock.
b. using the law of superposition to compare the ages of rock layers.
c. comparing fossils found in rock layers from different locations.
d. placing events in their proper sequence or order without knowing their exact age in years.
e. answers b, c and d above.

38. The law that states that in any undisturbed sequence of rocks deposited in layers, and the oldest on bottom the youngest layer is on top is:
a. the Law of Original Horizontality.
b. the Law of Superposition.
c. the Law of Cross-Cutting Relationships.
d. the Law of Inclusions.

39. The relative age of a volcanic intrusion exposed in the side of a canyon might be determined by:
a. the Law of Original Horizontality.
b. the Law of Superposition.

c. the Law of Cross-Cutting Relationships.
d. the Law of Angular Unconformities.

40. The arrow in this view of the Grand Canyon (below) points toward:
a. a disconformity.
b. an angular unconformity.
c. a nonconformity.
d. a conformable contact.

CHAPTER OVERVIEW

2: Evolution of Life Through Time

2.1: A Brief Summary of the Evolution of Life on Earth through Time

This chapter is a brief summary of the evolution of life on Earth through time.

Historical geology is the science that examines concepts of **evolution** and **geologic time** as preserved in the ***fossil record***. Historical geology is relevant to all other sciences that involve studies of the physical environment!. This chapter is a very brief summary of the history of life and discussions about some major geologic events shaping planet Earth. Figure 2.1 highlights many of the key geological and biological events that occurred, impacting life, leading to the present.

Earth formed from the accumulation of dust, gases, asteroids, and small planetesimal in the stellar nebula (as discussed in **Chapter 1**). During this early period in Earth history conditions on the surface of the planet were probably too hot for oceans to exist. However, over time the surface cooled enough for oceans to form and persist. However, the oceans and atmosphere were chemically very different than what exists today. The Early Earth had no significant free oxygen in the air or oceans, and the oceans were rich in organic compounds, essential for the development of evolution and life. ***The oldest sedimentary rocks on Earth preserve evidence of biological activity***, but only on a primitive microbial level. Early evolution was taking place on the molecular, intercellular, and microbial scales for the first 3 billion years of Earth's history. Eventually primitive life forms began to use photosynthesis as a source of energy, and gradually (over a billion years) the atmosphere and oceans became an oxygen-rich environment allowing more complex life forms to evolve.

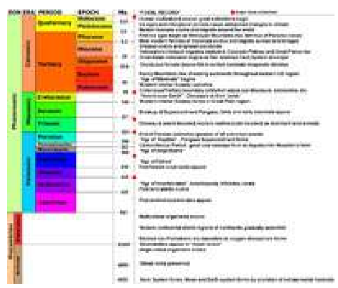


Figure 2.1. Geologic Time Scale with highlights in evolution and events in Earth history.

2.2: Key Developments In Understanding the Origin Of Life On Earth

Key Developments In Understanding the Origin Of Life On Earth

Carl Linnaeus was a Swedish botanist, physician, and zoologist (lived 1707-1778), who laid the foundations for the modern scheme of **binomial nomenclature**. Lineaus is considered a founder of modern **taxonomy** and **ecology** (Figure 2.2). For instance, **humans** are called ***Homo sapiens*** in binomial nomenclature.

Figure 2.2. Carl Linnaeus (1707-1778) is considered founder of modern **taxonomy** and **ecology**.

Linnaeus's system of classification grouped organisms based on ***shared characteristics***. Modern taxonomy attempts to connect taxonomy to the evolutionary framework of shared common ancestors (commonly referred to as the ***evolutionary tree of life***). In the past three centuries, millions of species have been identified and classified, but the lineages of different species are constantly being revised as new information becomes available.

Charles Darwin (1809-1882), a scientist/explorer, is credited with presenting the first published work dedicated to **natural selection** in his book entitled ***Origin of Species*** (published in 1859) (Figure 2.3). Darwin's **theory on natural selection** is now considered among be the main processes that brings about **biological evolution**. Darwin's book is a compilation of his observations and thoughts about plants, animals, and fossils initially gathered during a five-year voyage around the world studying nature onboard the Royal Navy ship, the ***HMS Beagle***. **Natural selection** is the processes whereby organisms that are better adapted to their environment tend to survive and produce more offspring. Note: Darwin did not release his research for nearly two decades after the expedition largely out of fear of repression, but his work arguably became one of the world's greatest scientific works of modern times.

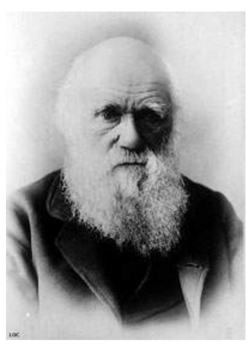


Figure 2.3. Explorer, **Charles Darwin** (1809–1882) published his **theory of natural selection** in a book titled ***Origin of Species*** in 1859.

Gregor Johann Mendel (1822-1884) was an Austrian geneticist/researcher (and monk) who conducted experimental research on creating hybrids of garden peas. In 1865 and 1866, he published his research on how **hereditary characteristics** are passed from parent organisms to their offspring. **Mendelian Theory** is fundamental to much of what is known about modern **genetics theories** (Figure 2.4).

Over the past two centuries, many scientific discoveries and technological innovations have advanced our knowledge of biochemistry, cell structure and processes, and genetic evolution. In 1951, **James Watson** and **Francis Crick** discovered and reported the double helical structure of the **DNA molecule** (Figure 2.5). Today, the entire genetic structure of human DNA has been mapped and reported via the **Human Genome Project (2001)**. **Genome mapping** is now central to many kinds of biological and medical research.

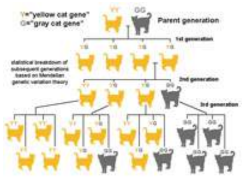


Figure 2.4. Statistical genetic variation illustrated by Mendel's research (applied to cats).

Figure 2.5. DNA occurs within **chromosomes** within a **cell nucleus** (illustrated).

2.3: Evolution

Evolution

Evolution means (in general usage) ***the gradual development of something, especially from simple to more complex forms***. In **biological sciences, evolution** involves the processes by which different kinds of living organisms are thought to have developed and **diversified** from earlier forms during the history of the Earth.

Biological evolution also involves changes in **heritable genetic traits** within biological populations over successive generations (first described by **Gregor Johann Mendel** in 1865). Evolution occurs at many scales including the molecular level, cell level, organism level, species level, and ecosystem community level.

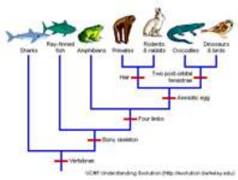


Figure 2.6. Evolution and **classification** of living things (illustrated) based of shared or identifying characteristics.

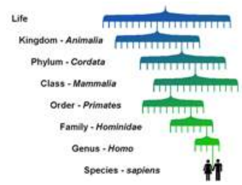


Figure 2.7. Human taxonomy illustrated within the ***hierarchical classification of living things*** (kingdom, phylum, class, order, family, genus, and species).

Figure 2.8. Classification (taxonomy) of a house cat.

Figure 2.9. Classification (taxonomy) of a dog.

Evolutionary Theory Highlights

Evolutionary theory is a an essential component of the knowledge supporting the current geologic time scale.
• Evolution supports an old earth (~4.56 billion years).
• The different time periods represented on the geologic time scale have uniquely defined populations of fossil species representative of those ages.

• **Natural selection (Darwinism)**: The strongest and best adapted organisms survive and produce offspring.

Divergent Evolution
• Populations that are separated environmentally can develop different features based upon an adaptation to their environment.
• One group of organisms can ***radiate*** (or ***diversify***) into many different groups and species.
• Divergence leads to different and distinct populations and communities of organisms.

Convergent Evolution
Populations can develop similar features based upon a utilizing a similar environment and living habits. The term **niche** is used in biology to define an organism's role in an ecosystem.

Examples of Convergent Evolution:
• Both fish and marine mammals developed streamline bodies to swim efficiently.
• Marine mammals developed fur/thick blubber to protect them from cold waters.
• Modern marine mammals share many of the same physical traits and life habits that ancient marine reptiles had before their disappearance from a mass-extinction event at the end of the Cretaceous Period (about 66 million years ago; discussed below).
• Birds, bats, flying squirrels, insects, and flying fish all independently developed means in order to take flight.
• Marsupial mammals in Australia adapted similar characteristics of mammal elsewhere (see table to right).

Populations that evolve in separate settings may develop similar traits (convergence)

Examples: (niches)	Marsupial mammals in Australia	Mammals elsewhere
Birthing manner	Marsupial	Placental
Grazers	Kangaroo	Deer
Carnivores	Tasmanian wolves	Wolves/Dogs
Climbers	Koalas	Monkeys

How Evolution Works

The **life mission** of individuals in any species is to **eat**, **survive**, and **reproduce** (Figure 2.10).
While living, individuals must deal with **competition** (**within a population** of their own species, or **with other species**).
Individuals must also adapt to **environmental changes** (changes in living space, availability of food resources, climate changes, catastrophes, etc.).
As time passes, species with either **adapt** to changing situations (and **evolve**), or they face **die offs** or **extinction**.

Figure 2.10. How **evolution** works.

All species have a role within an ecosystem.

The term **niche** refers to the specific area inhabited by an organism. The term niche also refers to the role or function of a species within an ecosystem, involving the interrelationships of a species with all the biotic and abiotic factors affecting it. All species fill a niche, ranging from limited, small micro-environments to a distribution on a regional or even global scale in a multitude of environmental settings.

2.4: Essential Concepts of Historical Geology and Evolution

Essential Concepts of Historical Geology & Evolution

The **geologic time scale** is a systematic and chronological organization of time related to the history of the Earth and Universe used by scientists (geologists, paleontologists, astronomers) to describe the timing and relationships between events that have occurred (see **Figure 2.1**).

Paleontology is the scientific study of life forms existing in former geologic periods, as represented by their **fossils**; the science involves reconstructing the physical characteristics of organisms, life habits, and the environments where they lived (**paleoecology**).

A **fossil** is a remnant or trace of an organism of a some earlier geologic age, such as a skeleton or leaf imprint, embedded and preserved in sedimentary deposits. Few things living today will survive to become fossils (see table to right on how fossils form).

The term **fossil record** is used by geologists and paleontologists (scientists who study paleontology) to refer to ***the total number of fossils that have been discovered, as well as to the information derived from them***. Many species that we see today do not get a chance to be preserved as fossils, but we can still learn about them by comparing them to fossils that have been found and properly recorded.

Fossilization is the processes that turn plant or animal remains eventually to stone.

A **trace fossil** is a fossil impression of a footprint, trail, burrow, or other trace of an animal rather than of the animal itself.

Review of how fossils form **(or how they survived destruction)**
After an organism dies, its remains must: **1.** survive being **eaten** (at least partially eaten). **2**. must survive **transport** to site of preservation. **3.** survive **burial** in sediments or volcanic materials. **4.** survive **bioturbation** (being chewed up underground by burrowing organisms). **5.** survive **microbial decay**. **6.** survive **compaction** with burial. **7.** survive **chemical changes** associated with lithification. **8.** survive **uplift, weathering** and **erosional exposure**. **9.** be **discovered** and **identified**. **10.** be **researched**, **reported**, and **curated** to be useful.

2.5: Sedimentary Sequences Preserve the Fossil Record

Sedimentary Sequences Preserve the Fossil Record

The history of the evolution of life is partly preserved in sedimentary rocks found around the world. The ancient history of a species is also preserved in the DNA of living organisms. Although the fossil record is extensive, there are many ***gaps*** in the fossil record where sediments of different ages have not been preserved in many regions, and much has been erased as ocean crust is destroyed in the processes involving plate tectonics (discussed in Chapter 4). Also, ancient sedimentary deposits on continental are destroyed by erosion. Despite these issues, sedimentary deposits representing all geologic ages are preserved and exposed in different places around the world. The fossil record is best preserved and represented by sedimentary deposits associated with ancient shallow marine and coastal environmental settings preserved and exposed in continental settings.

Transgressions and Regressions of Ancient Shallow Seas

Figure 2.13 shows how sea level rose and fell through the ages across North America. A **transgression** occurs when sea levels rise and shallow seas ***advance*** onto the margins of a continent. When sea level falls, the seas ***retreat*** and land is exposed—a process called a **regression**. For much of the last billion years shallow seaways transgressed onto the North American continent. Many minor transgressions and regressions also occurred, and shallow seas intermittently covered large portions of the continent. When sea level rose, sediments were deposited blanketing large regions of the continents. These deposits are preserved as sedimentary rock formations that accumulated in terrestrial, coastal, and marine depositional environments. Groups of these rock formations are parts of **sedimentary sequences** that preserve the **fossil record**.

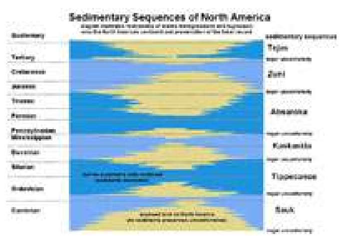


Figure 2.13. Major sedimentary sequences of North America preserve some of the evidence of the ***fossil record*** (after Sloss, 1931). The **Sauk Sequence** is the oldest containing shell fossils of the Cambrian Period. Each sequence represents a major advance (**transgression**) of shallow seas and coastal environments. Major unconformities represent periods of **regression** (dominated by erosion when the seas withdrew).

Each of the sequences rests on the eroded surface on top of a previous sequence represented by a **major regional unconformity** (also called a **sequence boundary**, as illustrated in **Figure 2.13**). **Six major sequences** (with their **underlying unconformities**) are recognized throughout North America, with equivalent sequences and sequence boundaries on other continents. Each sequence represents a major marine advance (a **transgressions**) of shallow seas , replacing coastal plains and terrestrial environment. The major unconformities represent periods of **regression** (when the seas withdrew and coastal and terrestrial environmental setting replaced shallow marine environments).

Each of the sequences preserve fossils and evidence of biological activity that occurred when the sediments were deposited and preserved. Erosion through time has stripped away these deposits in many regions, but portions of each sequence are still still preserved and exposed in different parts of the continents. For example, part of four of the great sequences are exposed in the Grand Canyon (Figure 2.14). Sedimentary rocks bearing fossils from all geologic-time periods have been identified in locations scattered around the world.

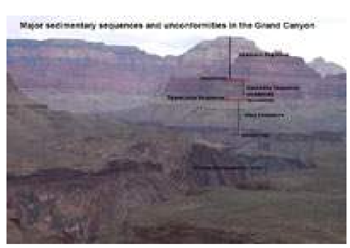


Figure 2.14. Paleozoic-age sedimentary sequences exposed in the Grand Canyon, Arizona include portions of the **Sauk**,

Tippecanoe, **Kaskaskia**, and **Absaroka sequences** (shown in Figure 2.13). Each sequence is bounded (above and below) by unconformities. The oldest sequence bearing an abundance of fossils is the Sauk Sequence that rests on top of the **Great Unconformity,** an erosional boundary between rocks of Precambrian and Cambrian age exposed in the deepest parts of the Grand Canyon**.**

2.6: Ecological Succession- How Species and Ecosystem Populations Change Over Time

Studies of the fossil record show that extinctions in Earth's history vary from a disappearance of a species (an **extinction**), to the disappearance of entire lineages and populations within regional communities or globally (a **mass extinction**). Paleontologist have scoured outcrop areas and made extensive collection of fossils. Their investigations have have revealed information about the appearance, changes, and extinction of many species. In many cases, they have made detailed analysis of fossil population and distributions across a region where rock layers of a particular age are preserved—one example involves extensive in sedimentary rock formations like the Triassic-age Chinle Formation in Painted Desert region of Arizona that contain an abundance of well preserved fossils (Figure 2.11).

Figure 2.11. Outcrop area of the Triassic-age Chinle Formation in the Painted Desert, Arizona is an example of an ideal study area that has an abundance of fossils preserved in many layers of strata over a large region.

The changes in species structure of an ecological community over time is called **ecological succession**. Ecological succession takes place on time scales ranging from decades (such as what happens to forest community after a massive wildfire or catastrophic superstorm) or even millions of years during an ice age or a mass extinction event. Figure 2.12 shows an interpretation of the changes in the species populations in within an ancient ecosystem over time as revealed by fossils preserved is successive layers of sedimentary strata. Changes in ancient species populations and ecosystems can be inferred from the abundance the fossil preserved (or missing), the character of the fossils themselves, and sometimes information can be inferred from the sediments surrounding fossils or trace fossils in the sedimentary layers investigated in a study area. Studies show that species appear, populations grow, and then decline and vanish, sometimes returning, or are often replaced by other species that either have out-competed them, or simply replaced them when climate changes or other processes occurred that changed an ecosystem community setting over time.

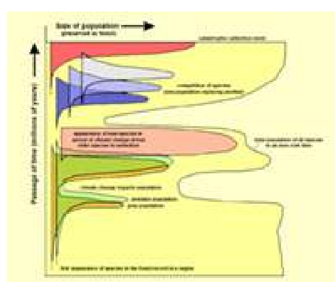


Figure 2.12. **Population changes in a local ecosystem over time** (select species and total population of all species). Interpretations like this may be made from exhaustive studies of fossil collections from an area like in Figure 2.11.

2.7: Precambrian Eon

Geologic History and Biological Evolution

The following sections of this chapter is a review of major geologic events, biological evolution, and selected important concepts related to Earth history, starting with the most ancient events and appearance of life forms in the fossil record and leading to the Present.

Precambrian Eon

Precambrian is the general name for the geologic time period between when the Earth formed in the Solar System (in Hadean Time about 4.56 billion years ago) and the beginning of **Phanerozoic Eon** (about 540 million years ago). The oldest rock on Earth are Precambrian age. The Precambrian is subdivided into three Eons:
• **Hadean Eon** (before about 4 billion years ago)
• **Archean Eon** (between about 4.0 and 2.5 billion years ago)
• **Proterozoic Eon** (between about 2.5 billion and 540 million years ago).

The Precambrian encompassed all of early Earth history and rocks from that time preserve evidence of the **evolution of life forms on a microbial level**. In biology, **cell theory** states that a **cell** is the fundamental structural and functional unit of living matter, and that the an **organism** a multicellular body composed of autonomous cells with its properties being the sum of those of its cells. **Multicellular organisms** (animals and plants) do not appear in the fossil record until late in Precambrian (Late Proterozoic) time.

The **Phanerozoic Eon** began after the end of the Proterozoic Eon about 540 million years ago, and marks the change when fossil remains of multicellular organisms began to appear in great abundance in the fossil record (discussed below).

Geologic Time		**Highlights of Biological Evolution**
PRECAMBRIAN	About 4.56 billion years ago	Formation of Earth and Moon within the Solar System nebula (Figure 2.15). (This is discussed in detail in Chapter 1).
	About 4 billion years ago	Evidence of earliest cell-based life of Earth (**prokaryotes**).
	About 3 billion years ago	Evidence of **photosynthesis** and first eukaryotic cells capable of **oxygen-based respiration.**
	About 3.0 to 1.8 billion years ago	World-wide deposition of **banded-iron formations** fundamental to the gradual conversion of Earth atmosphere rich in **carbon dioxide (CO_2)** to **oxygen (O_2)** (discussed below). This conversion took nearly a billion years. Once there was enough free oxygen in the atmosphere, this allowed the development of an **ozone layer** to protect Earth from deadly solar **ultraviolet radiation** (**UV**). UV destroys many organic organic compounds. Without an ozone layer, intense solar UV probably would have killed life in the shallow ocean waters.
	About 1.8 billion years ago	**Sexual reproduction** fully established in **eukaryotes**. Sexual reproduction increased the rate of mutation in species, leading to increased **biodiversity**.
	About 1 billion years ago	Earliest evidence of **multicellular organisms** (**metazoans**). Early multicellular organism were very ***primitive*** but diversified very quickly through geologic time.
PHANEROZOIC EON ⬇	**Cambrian Period** Beginning about 540 million years ago	The beginning of the **Cambrian Period** started a ***radiation of species*** preserved in the fossil record. This is, in-part, because many organisms began to develop the first **hard skeletal material** as part of defensive and functional body plans. The diversity of species preserved in Cambrian sediments is partly because soft-bodied organisms were not preserved in Precambrian-age sediments. Significant changes happened in the global physical environment in Cambrian time. Formation of the ozone layer created hospitable habitats and new space for organisms to move up and utilize shallow, warm sea environments that followed a major transgression onto the continents. Organisms were finally able to adapt to this new environment by allowing them to utilized **calcite ($CaCO_3$)** for ***hard body parts*** are (shells and exoskeletons). Organisms with ***calcareous*** body parts were selectively or preferentially preserved in Cambrian and younger sedimentary rocks. The selective preservation of calcareous body parts has therefore made it easier to find evidence of life forms today preserved as fossils. **Sediments** composed of the skeletal remains of organisms (with shells and exoskeletons rich in $CaCO_3$) is called **lime**, which turns into a sometimes quite fossiliferous rock, **limestone.**

Figure 2.15. Current thought is that th the debris created by the collision of a object with the **ancestral Earth** (or **P** history of the Solar System about 4.5 l

Early Evidence of Life on a Global Scale

Banded-iron formations (BIFs) are sedimentary mineral deposits consisting of alternating beds of iron-rich minerals (mostly hematite) and silica-rich layers (chert or quartz) that formed about 3.0 to 1.8 billion years ago (Figure 2.16). Theory suggests BIFs are associated with the **capture of free oxygen** released by photosynthetic processes by **iron dissolved in ancient ocean water**. The ancient oceans were enriched in CO_2 (just like the atmosphere). Iron easily dissolves in **CO_2-rich water** — this is easy experiment to illustrate: ***drop and iron nail in a bottle of soda*** and it will dissolve completely in a few days! The early oceans must have been rich in iron (similar to **salt** is today)! Once nearly all the free iron dissolved in the ancient seawater was consumed, oxygen could gradually accumulate in the atmosphere. Once enough oxygen was free in the atmosphere, an ozone layer could form.

BIF deposits of Precambrian age are preserved in many locations around the world, occurring as massive and widespread deposits, hundreds to thousands of feet thick. The BIFs we see today are only remnants of what were probably every greater and more extensive deposits. During Precambrian time, BIF deposits probably extensively covered large parts of the ancient global ocean basins. Today, BIFs are ***the major source of the world's iron ore*** and are found preserved on all major continental shield regions.

Figure 2.16. A sample of Precambrian **banded-iron formation** (**BIF**) from Fremont County, Wyoming.

Cell Theory in Evolution

Cell Theory dictates that all known living things are made up of one or more **cells** (the fundamental structure and functioning living unit in all living things. All living cells arise from pre-existing cells by processes involving cell division.

Cells are divided into two main classes: prokaryotic cells and eukaryotic cells.

Prokaryotic cells include (bacteria and related organisms). **Prokaryotes lack a *nucleus*** (or ***nuclear envelope***) and are generally smaller, structurally simpler, and less complex genomes (genetic material) than **eukaryotic cells** (Figure 2.17).

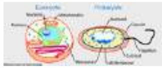


Figure 2.17. Cell structures of **Prokaryotes** and **Eukaryotes**

Eukaryotic cells contain ***cytoplasmic organelles*** or a ***cytoskeleton***, and **contain a *nucleus*** in which the genetic material is separated from the cytoplasm. **Eukaryotes** include fungi, plants, animals, and some unicellular organisms. Eukaryotic cells are capable of **sexual reproduction** (Figure 2.17).

The oldest known prokaryote fossils are about 3.5 billion years old.
The oldest known eukaryote fossils are about 1.5 billion years old.

The same basic molecular processes are involved in the lives of both prokaryotes and eukaryotes, suggesting that **all present-day cells are descendant from a single primordial ancestor.**

Endosymbiosis is a theory that suggests **organelles** evolved in eukaryotic cells and occurred when one type of cell became incorporated into another type of cell, creating a **symbiotic relationship** to the benefit of both (such as **chloroplasts** in plants, and **mitochondria** in animals).

Viruses are ***non-living*** organic structures capable of genetic self replication that are not classified as cells and are neither unicellular nor multicellular organisms; viruses lack a metabolic system and are dependent on the host cells that they infect to reproduce. Viruses likely have influenced evolution on a cellular level in Precambrian time, just as they impact species evolution today.

A **stromatolite** is a mound of calcareous sediment built up of layers of lime-secreting **cyanobacteria** (blue-green bacteria, algae and other ***more primitive*** eukaryotic life forms) that trap sediment, creating layers accumulations (Figure 2.18). Stromatolites are found in Precambrian rocks and represent some of the **earliest known fossils**. Stromatolites are known from all geologic time periods and are still occurring today, with exceptional examples resembling ancient life forms still being formed today in places like Shark Bay, Australia (Figure 2.19).

Figure 2.18. **Stromatolites**, fossils of cyanobacterial algae mats, occur in rocks dating back to early Precambrian time, but can still be found living in some aquatic environments today.

Figure 2.19. **Stromatolite** of Shark Bay, Australia, are modern living examples of stromatolites that resemble fossils from the Precambrian Eon.

Life in Late Precambrian Time (Late Proterozoic Eon)

Evidence of the first sexual reproduction appear in the fossil record about **1.2 billion years ago**. Many eukaryotic organisms including **protista** (both unicellular and colonial forms), fungi, and multicellular organisms (including plants and animals) reproduce sexually.

Metazoans are multicellular animals that have cells that differentiate into tissues and organs and usually have a digestive cavity and nervous system. Metazoans appeared on Earth in **Late Precambrian** time (Late **Proterozoic Eon**) consisting of cells that with growth would differentiated into unique tissue or organs used for special purposes, such a locomotion, feeding, reproduction, respiration, tissues able to ***sense*** the environment, etc.

Late Precambrian life forms have been discovered, but fossils from this period are scarce and poorly preserved because they did not contain hard parts (skeletons, teeth, etc.). Impression is sediments are dominantly **trace fossils** (tracks, trails, resting and feeding traces) and rare body impressions have been found.

A group of ancient fossil organisms called the **Ediacaran fauna** is one of the earliest known occurrence of multicellular animals is the fossil record. They were named for the Ediacaran Hills of South Australia where they were first discovered. Traces of Ediacaran fauna has been found worldwide in sedimentary rocks of about 635 to 541 million years (very late Precambrian age) and consisted of frond- and tube-shaped, soft-body organisms, mostly sessile life forms (***sessile*** meaning attached to the seabed). Many of the fossils from this time period share similar characteristics of some ***families*** or ***classes*** of organisms still found on Earth today (including segmented worms, jellyfish, chordates, and other invertebrates).

2.8: The Paleozoic Era

The Paleozoic Era

The **Paleozoic** is the era of geologic time spanning about 541 to 248 million years ago. **Paleozoic** means ***ancient life*** (even though evidence of microbial life extends well back in time to some of the earliest sedimentary rocks still preserved and discovered on Earth). The Paleozoic Era follows the Precambrian Eon and precedes the Mesozoic Era. The term Paleozoic is used to describe the age of rocks that formed and accumulated in that time period. Highlights include:

• Dominant large animals: Invertebrates dominate early; fish and amphibians appear in the middle Paleozoic, and reptiles appear even later.
• Continents were mostly clustered together throughout the Paleozoic Era.
• Large, warm, clear, shallow seas covered large portions of continents.
• Similar animal and plant species existed on each continent.
• Continents were mostly low with little relief. Few large mountain ranges existed on and around most continental landmasses (compared with today).
• The combined Appalachians and Atlas Mountains formed 350 to 400 MYA (between what was North America and Africa before the opening of the Atlantic Ocean basin).

2.9: Cambrian Period (540-485 million years)

Highlights of the Early Paleozoic Era

Evolution of early plant and animal life (dominated mostly **marine invertebrates**) is revealed in the fossil record of the early part Paleozoic Era. Primitive land plants, insects, and the first vertebrates also appear.

Cambrian Period (540-485 million years)

The **Cambrian Period** is the oldest of the named geological periods of the **Paleozoic Era**. At the beginning of the Cambrian Period the combination of tectonic forces and erosion of the landscape allowed shallow seas to gradually cover much of North America. Shallow seas covered most of what is now the Great Basin, Rocky Mountains, and Great Plains in the west, and much of East Coast, Appalachian region, and most of the Midwest. The shallow seas withdrew at the end of Cambrian time, but what was left behind was a blanket of Cambrian sedimentary rocks, collectively called the **Sauk Sequence** (see **Figures 2-20** and **2-21,** also see **Figure 2.13**). The base of the Sauk Sequence rests on an eroded surface of ancient Precambrian-age (mostly metamorphic and igneous rocks of the core of more ancient mountain systems). This sequence boundary is called the **Great Unconformity**. The Great Unconformity is exposed in many places throughout the western United States, and is particularly well known from exposures along the base sedimentary rocks of Cambrian age exposed in the Grand Canyon within the canyons Inner Gorge (see Figure 2.14). The Great Unconformity can be traced across most of North America wherever the base of the Cambrian-age Sauk Sequence is exposed.

Figure 2.20. The **Great Unconformity** is an erosional boundary at the base of the **Sauk Sequence** throughout much North America. This view is in Wind River Canyon, Wyoming.

Figure 2.21. The fossiliferous Bright Angel Shale of Cambrian age is one of the rock formations of the **Sauk Sequence** exposed throughout the Grand Canyon region.

Calcareous skeletal shell remains first appear in the Cambrian Period.

The term ***Cambrian explosion*** refers to evidence in the fossil record which shows that **all major phyla** were established in the transition from latest Precambrian to the Early **Cambrian Period** (about 700 to 541 million years ago) (Figure 2.22). The cause of this radiation from earlier metazoan life forms is uncertain, but it may have been driven by global climate changes (hot to cold cycles) and the establishment of unique habitats (**niches**) which allowed species to evolve separately from common ancestors. In Cambrian time, escalation of predator-prey relationships and increased competition appears to have driven rapid evolution of new species (along with extinctions). In Cambrian time, **shelled organisms** first appear in abundance in sedimentary deposits preserved from that time period. The fossil record from Cambrian time show that organisms with **chitonous** and **calcareous shells** and **exoskeletons** appeared and diversified. Many Cambrian-age organisms have eyes, legs (or pods), spinal chord-like features, segmented body plans, and other unique body parts and characteristics. Representatives of all phyla from the *Cambrian Explosion* still exist in the world today (Figure 2.22). Sedimentary rocks from Cambrian Period are typically rich in evidence of life activity. They preserve an abundance of **bioturbation features** (also called ***trace fossils***) even if the life forms that created them are not preserved (an example of bioturbation is shown in **Figure 2.23**).

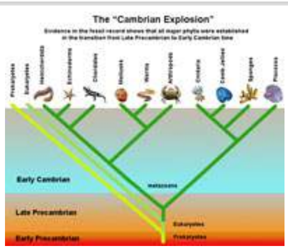


Figure 2.22. The **Cambrian explosion** refers to the diversification of life forms that began near the end of the Precambrian Eon.	Figure 2.23. **Invertebrate tracks and trails** appear in abundance in Cambrian-age sediments (Tapeates Sandstone) in the lower Grand Canyon in Arizona.

Invertebrates dominate the fossil record in the early Paleozoic Era. An **invertebrate** is an animal lacking a ***backbone*** (spinal column or spinal chord), such as an arthropod, mollusk, annelid worm, coelenterate, echinoderm, and many others. The classification of invertebrates constitute a division of the animal kingdom, comprising about 95 percent of all animal species and about 30 different ***known*** phyla.

By the end of the Cambrian Period several groups of invertebrates were well established in shallow marine environments, perhaps most notably were **trilobites**, **brachiopods**, **crinoids**, **bryozoans**, **sponges**, and **gastropods** (snails) are locally common fossils preserved in Cambrian sedimentary rocks (Figures 2-24 and **2-25**). At the end of the Cambrian Period, **sea level fell** and a long period of **exposure** and **erosion** occurred throughout North America and the other continents worldwide.

	
Figure 2.24. **Trilobites** are common shelled fossils in sedimentary rocks from the Cambrian Period.	Figure 2.25. **Cambrian fossils**: trilobites, brachiopods, gastropods, and other invertebrates

2.10: Ordovician Period (485-444 million years)

Ordovician Period (485-444 million years)

Shallow seas once again flooded across much of North America through much of the **Ordovician Period**. Deposition of sediments during this marine transgression resulted in the **Tippecanoe Sequence** which rests **unconformably** on top of the **Sauk Sequence** (see **Figure 2.13**). However, when sea level rose again (millions of years later) and shallow seas returned to cover large portions of the continents, communities of life forms in the oceans had significantly changed.

Trilobites no longer dominated the fossil record, but other life forms began to proliferate in warm, shallow marine environments. Communities similar to some modern reef-like settings appear in the fossil record. **Corals** (unrelated to modern varieties), **crinoids**, **cephalopods**, **brachiopods**, **bryozoans** and other fossil life forms with calcareous skeletons dominate the fossil record. Their abundance reflects their ability to live, proliferate, and upon death, survived burial and **fossilization** processes). Rare early examples of jaw-less, armored fish and land plants have been discovered in sediment deposits of Ordovician age. Sedimentary rocks of Ordovician age crop out in many locations around the country, but they are perhaps best known from the **Cincinnati Arch** region (of Ohio, Kentucky and Indiana) where a great abundance of well preserved fossils occur in strata preserved from that time period (Figures 2-26 to **2-28**).

Figure 2.26. Fossil-rich sedimentary rocks of the **Tippecanoe Sequence** are perhaps most famous from the Cincinnati Arch region.

Figure 2.27. Fossil brachiopods on a layer of Ordovician limestone from Brookville Indiana (on the Cincinnati Arch).

Figure 2.28. Common fossils of the Ordovician Period

2.11: Silurian Period (444-419 million years)

Silurian Period (444-419 million years)

Few rocks of Silurian age are preserved in North America's fossil record (they are either not preserved or are not exposed at the surface). Some sedimentary rocks of Silurian age are preserved in upstate New York, around the Cincinnati Arch, and around the margins of the Michigan Basin are notable exceptions. Large fossil ***pinnacle reefs*** occur around the margins of an ancient sea basins that covered what is now the state of Michigan. The fossil record shows that the Silurian world was dominated by marine invertebrates, but the first ***fish-like*** **chordates** appear. Simple and primitive forms of **land plants** began to flourish and diversify during Silurian time. Plants on land became a food source allowing the first animals to emerge onto dry land (including early insects,arachnids and centipedes, and scorpions)(Figure 2.29). The first jawed fishes and freshwater fishes appear in Silurian. Large marine, scorpion-like creatures called ***eurypterids*** grew up to nearly 7 feet long (much larger than anything like it that exists like it today). Early vascular plants evolved in the Silurian Period, setting the evolutionary stage for terrestrial ecosystems that followed.

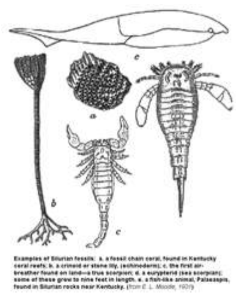


Figure 2.29. Common and unusual fossils of the Silurian Period.

2.12: Devonian Period (419 to 359 million years)

Highlights of the Middle and Late Paleozoic Era

The Middle to Late Paleozoic Era is highlighted by the development of forest ecosystems and the development of vertebrate species on land, and rise of large fish in the oceans.

Devonian Period (419 to 359 million years)

On land, free-sporing **vascular plants** adapted and spread across the landscape, allowing the **first forests** to cover the continents. By the middle of the Devonian several groups of plants had evolved leaves and true roots, and by the end of the period the first **seed-bearing plants** appeared. Terrestrial **arthropods** began to flourish. In the marine world, early ray-finned and lobe-finned **bony fish** and **sharks** appear and flourish as revealed in the fossil record. The first coiled-shelled **ammonoid** mollusks appeared. Holdover families of marine **invertebrates** from earlier times persisted, including trilobites, brachiopods, cephalopods, and reef-forming tabulate and rugose corals flourished in shallow seas (Figure 2.30).

The current oil and gas boom in the United States is largely because of the **fracking technologies** used to extract **petroleum** from the **tight (**meaning ***low permeability***), **black shales** associated with ***organic-rich*** muddy sediments deposited in inland seas of Devonian and Mississippian age. These black shales underlie large regions of the **Appalachians**, the **Mid continent**, and northern **Great Plains** regions in the United States. These deposits are part of the **Kaskaskia Sequence** (see **Figure 2.13**).

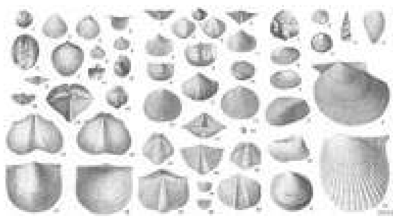


Figure 2.30. Devonian Period brachiopods and common fossils from Kentucky

2.13: Carboniferous Period (359 to 299 million years ago)

Carboniferous Period (359 to 299 million years ago)

The **Carboniferous Period** got its name from the abundance of **coal deposits** in rocks of Late Paleozoic age in **Europe**. In the United States, the **Carboniferous Period** is ***subdivided*** into the **Mississippian Period** and **Pennsylvanian Period.** An abundance of coal deposits of these ages also exist in eastern and central United States. During the Carboniferous the world was very different than today. The Earth's atmosphere was much thicker, having as much as 40% more oxygen and a more uniform global environment than exists today by some estimates.

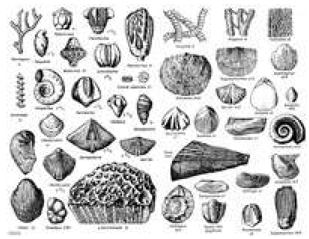


Figure 2.31. Mississippian Period marine invertebrate fossils from Pennsylvania.

2.14: Mississippian Period (359 to 323 million years ago)

Mississippian Period (359 to 323 million years ago)

Sedimentary rocks of **Mississippian** age in North America are dominated by marine sediments preserved as limestones rock formations when shallow, warm seas covered much of North America. Massive fossiliferous limestone rock formations of Mississippian age exposed throughout the Midcontinent (Mississippi Valley), and throughout the Appalachian and Rocky Mountain regions (Figure 2.31). For example, the Redwall Limestone in the Grand Canyon region is about 800 feet thick (Figure 2.32). Mississippian rocks throughout these regions are host to many cavern systems (such as **Mammoth Cave** in Kentucky). Mississippian rocks are part of the **Kaskaskia Sequence** (see Figure 13.16).

The southern Appalachian Mountains began to rise in Mississippian time, and terrestrial lowlands and coastal swamps began to replace shallow seas on the North American continent. Coastal swamps along the margins of rising mountain ranges rising above the shallow seas began to support forests. **Amphibians** became the dominant marginal-land vertebrates in Mississippian time (they still requires water to lay their eggs).

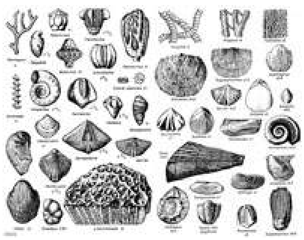


Figure 2.31. Mississippian Period marine invertebrate fossils from Pennsylvania.

Figure 2.32. The massive Redwall Limestone of Marble Canyon and the Grand Canyon formed in the Mississippian Period.

2.15: Pennsylvanian Period (323 to 299 million years ago)

Pennsylvanian Period (323 to 299 million years ago)

The Pennsylvanian Period is named for the coal-bearing region in the Appalachian Plateau and Mountains region**).** Great coastal forests and swamplands covered large regions of North America and parts of Europe. Great **coal** deposits formed from extensive swamps that trapped organic sediments in locations around the world. Pennsylvanian rocks are perhaps best know for their **coal-bearing basins** in the Appalachians and Midwest regions (Figures 2-33 and **2-34**).

Figure 2.33. Pennsylvanian age coal-bearing basins in the eastern United States are part of the Absaroka Sequence.

Figure 2.34. Reconstruction of a swamp forest of the Pennsylvanian Period.

Perhaps the greatest evolutionary innovation of the Carboniferous Period was the development of **amniote egg** which allowed lizard-like tetrapods to advance. **Reptiles** evolved and became the first totally terrestrial vertebrates, descendant from amphibian ancestors. With the abundance of vegetation on land, arthropods flourished, including species of insects that are much larger than any found on Earth today (Figure 2.31). In Pennsylvanian time, glaciation cycles in the Southern Hemisphere caused repetitious rise and fall in sea levels. The **Appalachian** and **Ouachita Mountain** systems also began to develop as ancient forms of the continents of Africa, South America, and North America began to collide with one-another.

It was during the Pennsylvanian Period that the world's continents assembled together to form the supercontinent of **Pangaea** (discussed in **Chapter 4**). The unconformable boundary between the **Kaskaskia Sequence** and the overlying **Absaroka Sequence** is the boundary between sedimentary rocks Mississippian and Pennsylvanian age (see **Figure 2.13**).The Absaroka Sequence includes sediments deposited during Pennsylvanian, Permian and Triassic Periods (see below).

2.16: Permian Period (299 to 252 million years)

Permian Period (299 to 252 million years)

The last period of the Paleozoic Era was a time of colossal changes. All the continents of the world had combined to form the supercontinent of Pangaea. In the fossil record, a group of **tetrapods** (lizard-like, four legged animals with backbones or spinal columns) called ***amniotes*** appeared, capable of living on dry land and producing terrestrially adapted **eggs**. All modern land species are descendant from a common ancestral group of amniotes. Reptiles adapted and flourished in the more arid conditions.

During the Permian, the expansive fern forests that existed during the Carboniferous disappeared, and vast desert regions spread over the North American continental interior. Seed-bearing conifers (gymnosperms) first appear in the Permian fossil record.

In Permian time, seawater began to flood the great rift valleys associated with the opening of the Atlantic Ocean basin and the separation of North America and South America. One arm of the sea flooded westward into an inland sea basin located in the West Texas and New Mexico region (Figure 2.35). **Great reef tracks** developed in around this basin Figure **2-36**). Eventually the Permian Basin (as it is called) completely filled in with massive accumulations of salts (gypsum and evaporite).

The end of the Permian Period (and Paleozoic Era) is marked by the **greatest mass extinction** in Earth history.

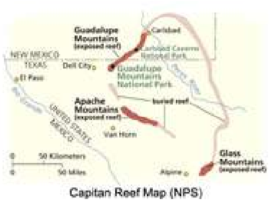


Figure 2.35. Map of the Permian Reef complex in Texas and New Mexico

Figure 2.36. Permian reef track exposed in Guadalupe National Park, Texas

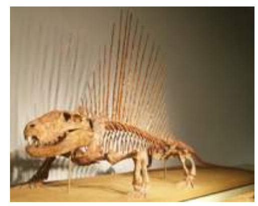


Figure 2.37. ***Dimetrodon***, a mammal-like reptile from the Permian Period on display at the Chicago Field Museum

2.17: Evidence of Large Mass Extinctions Preserved In the Fossil Record

Evidence of Large Mass Extinctions Preserved In the Fossil Record

Extinction is the state or process of a species, family, or larger group being or becoming **extinct** (ceasing to exist).

Extensive studies of **microfossils** in deep well cores extracted from around the world show that the appearance and disappearance (extinction) of species has happened continuously through geologic time, but the rate was not constant.

As climates and landscapes changed, new species evolved to fit ever changing ecological ***niches***; older species fade away.

A **mass extinction** is an episode or event in earth history where large numbers of species vanish from the fossil record nearly simultaneously. The causes of mass extinctions are debated, but some are linked to possible global climate changes associated with asteroid impacts, massive volcanism episodes, onset of ice ages, or a combination of effects that affected environments globally. Many questions remain about the causes of the great mass extinctions (because they may shed light on what is happening or may happen to the world related to human activities impacting the modern environment).

Current estimates are that **90 percent of all species** that have ever lived on Earth are now **extinct**. However, the **rate of extinction** has not been constant. Mass extinctions have occurred at least five times in the last 500 million years. With each mass extinction much as about 50 to 90 percent of previously existing species on Earth had disappeared in very short periods of geologic time (Figure 2.38).

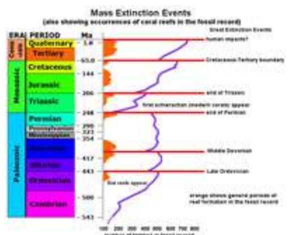


Figure 2.38. **Great mass extinction events** in the **fossil record** (***species diversity*** compared with the geologic time scale).

The Permian/Triassic (P/T) Boundary Extinction—The Greatest Of All Mass Extinctions

The **greatest mass extinction** event occur at the end of the Permian Period (about 252 million years ago). Most families of organisms that existed in the Paleozoic Era vanished at the end of the Permian Period. A 2008 report published by the Royal Society of London provided estimates that as much as 96 percent of marine species and about 70 percent of terrestrial vertebrates that existed in Late Permian time vanished during the end of the Permian extinction event. This occurred during the assembly and breakup of the supercontinent **Pangaea**. Great amounts of volcanism are known from that period associated with the rifting and opening of the Atlantic Ocean basin. However, other causes, such as glaciation, ocean circulation collapse, or possibly asteroid and comet impacts, extraterrestrial radiation events, and others have been pondered. The problem with studying mass extinctions like the one associated with the Permian-Triassic boundary is that the world has significantly changed since that time. Bedrock of Permian and older age under all the world's ocean basins have be subducted back into the Earth's mantle or heavily altered by mountain-building processes. In addition, much of the sedimentary record associated with exposed land of that time were stripped away by erosion before sediments began to be deposited and preserved in Triassic Period. Whatever the cause, it took many millions of years after the **P/T extinction event** (or events) for the **biodiversity** of the planet to return to levels that existed before in the Late Paleozoic Era. When this biodiversity returned, the world was host to completely different varieties of species and ecological communities, many replacing or occupying the same life habits (***niches***) and environments occupied by organisms that disappeared before the P/T extinction.

Great extinction events created opportunity for new life-forms to emerge. For instance, **dinosaurs** and many other life forms appeared only after the mass extinction at the end of the Permian Period (about 252 million years ago). The same is true for when mammals replaced dinosaurs when they went extinct at the end of the Cretaceous Period.

Perhaps the most studied extinction event has been the **Cretaceous-Tertiary Boundary** where strong evidence suggests at least one asteroid collided with earth in the vicinity of the Yucatan Peninsula in Mexico (about 66 million years ago)(Figure 2.39, see Figure 2.58 below). This extinction killed off the dinosaurs and many other families of organism that lived in the oceans and on land. However, the catastrophe made room for mammals and other groups of organisms to rapidly **diversify** and **evolve**. Unlike the P/T extinction which has limited exposure around the world from 252 million years ago, there are many locations world wide and on all continents and within sediments extracted from the sea floor that reveal information about what happened at the end of the Cretaceous Period about 66 to 65 million years ago (discussed below).

Figure 2.39. An massive asteroid impact ***can ruin your day*** (and your species, and many others).

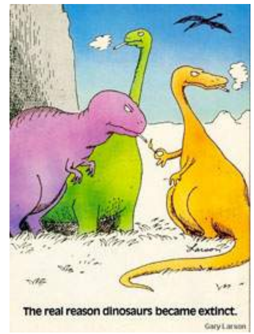


Figure 2.40. A classic *Far Side* cartoon by Gary Larson.

Are humans causing a sixth great mass extinction?

Many scientists believe evidence suggests that another mass extinction is currently under way. Global **climate change,** the **growth of the human population,** and the expansion of **human activity** into previously wild habitats are largely to blame. Some estimates suggest that human activities such as land clearing (for agriculture), pollution, mining, urban development, and over fishing may drive ***more than half*** of the world's marine and land species to extinction possibly within the next century. This extinction event perhaps began during the end of the last ice age when humans spread around the globe and their populations expanded when the global climate was drastically changing. Many species of large land animals and birds have vanished in the past 10,000 years, but the rate of changes has drastically increased in the past 100 years with the tremendous expansion in the global human population.

2.18: Mesozoic Era

Mesozoic Era

The **Mesozoic Era** is the era between the Paleozoic and Cenozoic Eras, comprising the **Triassic**, **Jurassic**, and **Cretaceous Periods**. The Mesozoic Era is commonly referred to as the ***Age of Reptiles.*** Highlights of the Mesozoic Era include:

• Dominant large animals: **Reptiles** and **dinosaurs**; **birds** and **mammals** appear.
• Increased mountain building occurred in many regions around the globe, and with that, lots of sediments were generated from erosion.
• The ancient supercontinent, **Pangaea,** begins to breakup at about 200 million years ago (Pangaea is discussed in Chapter 4).
• With the breakup of Pangaea, continents began moving apart. This caused isolation of species and communities, and as a result, created more diversity in plant and animal species through ***divergent evolution***.
• The ***ancestral*** **Rocky Mountains** and **Cordilleran Ranges** formed in western North America between about 120 to 66 million years ago.

2.19: Triassic Period (252 to 201 million years)

Triassic Period (252 to 201 million years)

Following the great extinction event at the end of the Permian Period, life on Earth gradually reestablished itself both on land and in the oceans through succession. ***Scleractinians*** (modern corals) replaced earlier forms as dominant reef-forming organisms. On land, reptilian ***therapsids*** (an order related to the distant ancestors of mammals) and ***archosaurs*** (ancestors of dinosaurs and modern crocodillians) became the dominant vertebrates. New groups evolved in the middle to late Triassic Period including the **first dinosaurs**, primitive **mammals**, and flying vertebrates (***pterosaurs***) but these families did not flourish until after another global extinction event at the close of Triassic time. Current thought is that ancestral forms of both **mammals** and **dinosaurs** first appear in the fossil record in Late Triassic time, about 200 million years ago.

During the middle Triassic, the supercontinent of **Pangaea** began to rift apart into separate landmasses, **Laurasia** to the north and **Gondwanaland** to the south. With the breakup of Pangaea, terrestrial climates gradually changed from being mostly hot and dry to more humid condition. Another mass extinction in the fossil record marks the end of the Triassic Period.

Figure 2.43. **Red beds** of the Chugwater Group of formations of Triassic age exposed near Lander, Wyoming.

Red beds are oxidized, iron-rich sedimentary deposits that occur extensively throughout western North America that were deposited in coastal terrestrial and nearshore environments during the Triassic Period. Red beds of Triassic age are well exposed in west Texas, throughout the Colorado Plateau and Rocky Mountain region, and in the Newark and Connecticut Basins on the East Coast. These are associated with the **Absaroka Sequence** that accumulated while Pangaea was still assembled and hot and dry climate conditions prevailed across most of North America.

Figure 2.41. Dinosaur tracks in Late Triassic sedimentary rocks, Dinosaur State Park, Connecticut.

Figure 2.42. Extensive coniferous forests covered coastal regions at illustrated by the massive deposit of fossil wood preserved in Triassic-age sedimentary rocks in and around Petrified Forest National Park, Arizona.

Figure 2.44. ***Desmatosuchus***, an ***archosaur*** from the Triassic Period found in West Texas

Figure 2.45. ***Placerias***, a large mammal-like reptile from the Triassic Period from Petrified Forest National Park, Arizona

2.20: Jurassic Period (201 to 145 million years)

Jurassic Period (201 to 145 million years)

The cause of the mass extinction at the end of Triassic is still unclear, but evidence shows that it was associated with rapid and massive amounts of volcanism that was taking place with the **breakup of Pangaea** (created by the opening of the Atlantic Ocean basin as North and South America gradually split away from the African and European continents).

With other life forms out of the way, dinosaurs adapted and diversified into a wide variety of groups. Although ***pterosaurs*** were the dominant flying vertebrates during the Jurassic Periods, the first **birds** appeared—having evolved from a branch of **theropod dinosaurs**. Rare small mammals occur in the fossil record during the Jurassic Period, but remained insignificant compared to the dinosaurs that dominated the landscape. Large marine reptiles including ***ichthyosaurs*** and ***plesiosaurs*** dominated the oceans.

Figure 2.48. Massive sandstone cliffs of the Navajo Sandstone of Jurassic age are well exposed in Zion National Park, Utah

Sedimentary rocks of the **Zuni Sequence** are well preserved and throughout the Colorado Plateau region. During the late Jurassic Period a great coastal sand desert covered much of the western part of the continental United States. This ancient sand desert would rival the large deserts of the Sahara or Arabian Peninsula that exist today. Through time, the desert conditions gave way to more humid coastal conditions with river systems and coastal swamplands (home to a variety of dinosaurs of the Jurassic and following Cretaceous Periods). The massive white cliffs of Zion National Park preserve evidence of this great sand desert in the western United States (Figure 15.48).

Figure 2.46. Dinosaur tracks in Jurassic-age rocks near Tuba City, Arizona.

Figure 2.47. Dinosaur bones preserved in ancient river bed sediments, Dinosaur National Monument, Utah.

Figure 2.49. Reconstruction of ***Stegasaurus***, a Jurassic-age vegetarian dinosaur with unusual spinal plates. Dinosaur National Monument, Utah.

Figure 2.50. Skeleton of ***Allosaurus***, a massive carnivorous dinosaur from the Jurassic Period. Dinosaur National Monument, Utah.

2.21: Cretaceous Period (145 to 66 million years)

Cretaceous Period (145 to 66 million years)

During the Cretaceous Period the Earth was relatively warm compared to the world today. There were no glaciers on the planet and sea level was as much as 200 feet higher that today. Fossils of warm-water organisms are found in rocks that are arctic regions today. The dinosaurs that survived into the Cretaceous Period diversified and evolved into many unusual forms. Large marine reptiles called ***Mosasaurs*** were the dominant organism in the ocean. Sediments deposited in shallow sea flooding onto the continents had an abundance of ***ammonites***—squid-like organisms that had calcareous shells similar to modern nautilus species. Cretaceous gets its name for ***Creta***—Latin for the word **chalk**. The shallow warm seas of the Cretaceous Period were locations where the calcareous skeletal remains of planktonic organisms called ***coccoliths*** accumulated, forming great accumulations of chalk, such as exposed in the **Great White Cliffs of Dover**, England. In many places in the equatorial realm oyster-like organism called ***rudists*** formed great reefs. **Flowering plants** also first appear in the fossil record, **birds** existed in Cretaceous time but were insignificant compared to flying non-avian ***pterosaurs***. Small **mammals** first appear in abundance in the Cretaceous Period, but they were still generally insignificant compared with more dominant reptile and dinosaur species that existed around them.

During Late Cretaceous time, a large mountain range and volcanic arc developed along the western margin of North America as the Atlantic Ocean basin began to rapidly expand. The rising mountains in the west forced an isostatic down warping of the central part of the North American continent, allowing the shallow **Western Interior Seaway** to flood across much of the region extending from Arctic Ocean in Alaska and Canada to the Texas Gulf Coast region (Figure 2.56).

Figure 2.53. Jurassic- and Cretaceous-age rock formations in Capitol Reef National Park in central Utah (sedimentary layers of the Zuni Sequence).

Sedimentary rocks of the **Zuni Sequence** are well preserved and throughout the Colorado Plateau region. During the late Jurassic Period a great coastal sand desert covered much of the western part of the continental United States. As Pangaea broke apart, a great volcanic arc system began to form along the western margin of North America (called the **Cordilleran Range**). At the same time, shallow seaways began to expand across the central North America Seaways eventually merging to form the ancient **Western Interior Seaway**. This ancient seaway extended from Texas to Alaska by Cretaceous time and covered what are now the Great Plains and Rocky Mountain regions of the United States and Canada (Figure 2.54)

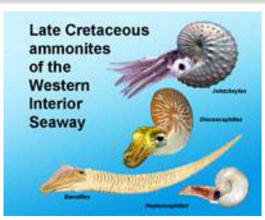


Figure 2.51. Late Cretaceous **ammonites** of the **Western Interior Seaway** - an ancient seaway that existed in the Great Plains and Rocky Mountain region during Cretaceous Time.

Figure 2.52. *Triceratops*, a Late Cretaceous herbivore dinosaur. Chicago Field Museum.

Figure 2.54. ***Parasaurolophus***- a Late Cretaceous dinosaur with a crested skull.

Figure 2.55. Dinosaur Sue, a famous ***Tyrannosaurus rex*** fossil on display at the Chicago Field Museum. ***T. rex*** was a large carnivorous dinosaur of the Late Cretaceous Period.

2.22: The Cretaceous-Tertiary Boundary (or K/T Boundary) Extinction

The Cretaceous-Tertiary Boundary (or K/T Boundary) Extinction

The **Cretaceous-Tertiary boundary** is associated with one of the most investigated mass extinction events. The age of the K/T boundary is currently estimated to be about 66 million years based on absolute dating methods. It is has been well investigated partly because it is the youngest of the large extinctions that totally changed the nature of life on Earth. It is also well exposed in many locations on land around the world and has been studied extensively in core samples from deep-sea drilling projects.

The **K/T extinction event** is believe to have been caused by a massive asteroid impact in the Yucatan region of Mexico, although other possible sites of large impacts are being considered. What is known is that all species of dinosaurs on land, and marine reptiles and ammonites in the marine realm vanished.

The massive asteroid impact and following shock waves, monstrous tsunamis, firestorms, ash clouds, toxic gas clouds, and global winter-like condition that followed caused ecosystem collapse and failure of the food chains and webs in both the oceans and on land.

It is important to note that all species that exist today are descendant of the limited number of species that survived the global catastrophe... small mammals, birds, invertebrates, reptiles, amphibians, fish and other surviving groups had evolutionary advantages that allowed them to survive. With the dinosaurs, pterosaurs, large swimming reptiles and other large animals of the Cretaceous Period out of the way, the surviving species proliferated and moved into empty and new niches that allowed them to prosper and diversify.

The K-T boundary occurred near the end of the **Zuni Sequence Cycle** when sea level also fell around the globe (see **Figure 2.13**). In the following Cenozoic Era many changes continued to occur including the uplift of the Rocky Mountain region and the withdrawal and disappearance of shallow inland seas and great lakes that previously flooded the Western Interior region.

Figure 2.56. Western Interior Seaway and locations of plausible asteroid impact sites around North America.

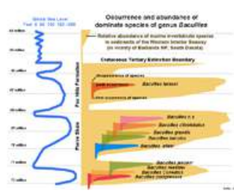


Figure 2.57. Appearance, expansion, decline and extinction of Late Cretaceous ammonite genus *Baculites.* Diagram shows changes in sea level and abundance of marine species.

The person is pointing toward a zone of disrupted bedding that corresponds to the zone where many terrestrial and marine species vanished from the fossil record at the end of the Cretaceous Period.

Figure 2.58. A layer of highly disrupted sediments corresponds with the mass extinction horizon associated in marine sediments located along the Cretaceous-Tertiary Boundary exposed in and around Badlands National Park, South Dakota.

2.23: Cenozoic Era

Cenozoic Era

The Cenozoic is commonly referred to as the ***Age of Mammals***. The Cenozoic Era began with the mass extinction event associated with the **K/T Boundary** (discussed above). Highlights of the Cenozoic Era include:

• Dominant large animals: **Mammals.** Mammals diversified, gradually replacing the niches held by dinosaurs wiped out by the K/T extinction.

• Mountain building continued, especially around the Pacific Ocean; the Himalayan Mountains, the Alps, and mountain ranges throughout southern Eurasia begin to form. The Rocky Mountains and Cordilleran Ranges in western North America continued to form.

• Lots of erosion of existing mountains fed sediments to coastal plains and ocean margin basins.

• The youngest **Tejas Sequence** began to accumulated in the early Cenozoic Era and continues to the present day, forming the Atlantic and Gulf Coast regions.

<table>
<caption>The Cenozoic Era is generally divided into two (or three) periods:</caption>
<tr><th>Era</th><th colspan="2">Period</th><th>Time Range</th></tr>
<tr><td rowspan="3">Cenozoic</td><td rowspan="2">Tertiary</td><td>Paleogene</td><td>66 million to 23 million years ago</td></tr>
<tr><td>Neogene</td><td>23 million to 2.6 million years ago</td></tr>
<tr><td colspan="2">Quaternary</td><td>2.6 million years ago to the present</td></tr>
</table>

The older name, **Tertiary Period,** in now subdivided into two periods: **Paleogene Period** and **Neogene Period**.
The periods of the Cenozoic Era are also subdivided into time periods called **epochs.**

2.24: Paleogene Period (66 to 23 million years ago)

Paleogene Period (66 to 23 million years ago)

Period	Epoch	Notes	Time Range
	Paleocene Epoch	The mass extinction at the end of the Cretaceous Period left many of the niches filled by dinosaurs and large swimming reptiles empty. **Mammals** with **placental-type live birth** appear. Shallow seas of the Cretaceous period withdrew or were gradually replaced by lakes. In North America, the Rocky Mountains began to rise. See more about the Paleocene: American Museum of Natural History	66 to 56 million
Paleogene	**Eocene Epoch**	Modern-like forms of mammals appear and diversify in the fossil record during the Eocene Epoch. The Eocene was a warm period with an expanded tropical realm. The end of the Eocene period is marked by a mass extinction that may have involved asteroid collisions in Siberia and in the vicinity of Chesapeake Bay. See more about the Eocene: American Museum of Natural History	56 to 33.9 million
	Oligocene Epoch	The Oligocene was a time of transition when older life forms were replace with life forms that dominate the world today. The warmer, more tropical environments of the Eocene Epoch gave way to dryer landscapes dominated by grasslands, whereas broad-leaf forests became more restricted to the equatorial realm. See more about the Oligocene: American Museum of Natural History	33.9 to 23.0 million

Figure 2.59. Eocene lake deposits crop out as the Chadron Formation in Bryce Canyon National Park, Utah

Figure 2.60. Eocene-age sediments fill many of the basins throughout the Wyoming region.

Figure 2.61. Eocene through Miocene sedimentary rocks crop out in Badlands National Park, South Dakota.

Figure 2.62. Eocene and younger rock formations exposed at the Del Mar Dog Beach, California.

2.25: Neogene Period (23 to 2.6 million years ago)

Neogene Period (23 to 2.6 million years ago)

Period	Epoch	Notes	Time Range
Neogene	**Miocene Epoch**	Animals and plants of the Miocene Epoch are approaching modern life forms in diversity and appearance. Earth was warmer with expanded tropical realms compared to the modern world. The Himalayan Mountains begin to rise as the Indian continental landmass began to collide with Asia. See more about the Miocene: American Museum of Natural History	23 to 5.3 million
	Pliocene Epoch	Global climates cooled and became dryer with the **onset of glaciation cycles**. Most families of animals and plants found in the world had ancestral forms during the Pliocene, including humans. Greenland's ice sheet starts to form. South America and North America became linked at the Isthmus of Panama, allowing the cross migration of many species between continents; but also shutting off the migration of species from the Atlantic to the Pacific oceans. The same kind of interactions took place when Africa collided with Europe. See more about the Pliocene: American Museum of Natural History	5.3 to 2.6 million

			
Figure 2.63. Miocene-age sedimentary rocks exposed along Chesapeake Bay at Calvert Cliffs, Maryland.	Figure 2.64. Pliocene-age sedimentary rocks exposed in sea cliffs near Santa Cruz at Wilder Ranch State Park	Figure 2.65. Pliocene-age sedimentary basin fill rocks exposed in Death Valley National Park, California	Figure 2.66. Neogene-age sedimentary rocks (Miocene to Pleistocene) crop out in Anza Borrego State Park, California

2.26: Quaternary Period (2.6 million years ago to Present)

Period	Epoch	Notes	Time Range
Quaternary	**Pleistocene Epoch**	Time period of major **ice ages** where continental glaciation advance and retreated; glaciers covering much of northern North America and Europe during cold periods. Modern human species appears in the fossil record. Many species of large land mammals went extinct at the end of the Pleistocene Epoch. Learn more about the Pleistocene of California preserved in the La Brea Tar Pits, Los Angeles (UC Berkeley Museum of Paleontology website).	2.6 million to 11,000 years
	Holocene Epoch	End of the Wisconsinian ice age to the present. Includes a 400 foot-rise in sea level and the rise of human civilizations. Humans rise to become the dominant species on Earth. Learn more about the Holocene: American Museum of Natural History	11,500 years to present

Figure 2.67. A thick sequence of coastal and nearshore deposits of Pleistocene age are exposed in the sea cliffs of Thornton State Beach south of San Francisco, California.

Figure 2.68. Big Bone Lick State Park, a source of Pleistocene-age **megafauna** fossils in northern Kentucky is the ***birthplace*** of North American vertebrate paleontology.

Figure 2.69. **Glacial till and outwash** exposed at Caumsett State Park, Long Island, New York. Long Island is underlain by unconsolidated Pleistocene-age glacial deposits.

Figure 2.70. **Glacial moraine** at Montauk Point on Long Island, New York is part of the southern terminal moraine of the Wisconsin glaciation at the end of the Pleistocene Epoch.

2.27: Evolution of Humans and the Rise of Modern Civilization

Evolution of Humans and the Rise of Modern Civilization

Some 15 to 20 different species of ***early human*-like species** (**humanoids**) are currently recognized. However, not all scientists studying human evolution agree how these species are related or how or why they died out. The majority of early human species left no living descendants. Scientists also debate over how to identify and classify particular species of early humans, and about what factors influenced the evolution and extinction of each species or sub-species.

Humans are included in the family of **primates** (which include modern monkeys, apes, and humans). Primates are descendant from an earlier monkey-like group called ***prosimians*** that appear in the fossil record in Eocene to Oligocene time. Primate species appear in abundance in many locations around the world during the Miocene Epoch (between 23 to 5.7 million years ago).

Fossils of earliest recorded human-like ancestors come from sediments of 6-7 million years ago in western Africa; the species had chimpanzee-sized brains and were able to walk upright on two legs. Fossils of 6 to 3 million years recovered in eastern Africa (Ethiopia) show species with ape-like features that walked upright and lived in forested environments. By 4 million years ago, early human species lived in near open areas in forested environments; bone structures show they were able to walk upright (bipedal) and still climb trees. The famous ***Lucy*** skeleton (about 3 million years show species had ape-like proportions of face, brain case, strong arms [for climbing], but walked upright on arched feet.

The **oldest stone tools** have been found in sediments deposited 2.6 million years ago. ***Homo habilis*** (2.4-1.4 million years ago) species thought to represent the first stone toolmaker.

Multiple species of the genus ***Homo*** have been discovered from the time period of about 2 to 1 million years ago; some sharing the same environments. Human use of **fire** began about 800,000 years ago. Evidence suggests fire was used for warmth, cooking, socializing, and safety from predators. ***Homo erectus*** is known from ages about 1.89 million to 143,000 years ago, and fossils have been recovered from places as distant as eastern to southern Africa; western Asia (Republic of Georgia), China and Indonesia. The species used fire and ate meat, and evidence suggest that they took care of old and weak members of their clans.

A rapid increase in human brain size took place from 800,000 to 200,000 years ago, giving humans better survival skills the ability to adapt to changing environmental conditions (such as the onset of ice ages and interglacial warm and dry periods).

Our species, ***Homo sapiens***, first appear in the fossil record about 200,000 years ago in Africa, but spread out into Europe and Asia by at 100,000 years ago (Figure 2.71). We now inhabit land everywhere on the planet and we are the sole surviving species of a once diverse group of ancestral family of human-like species. As human populations spread around the world, populations became isolated and developed characteristics associated with major **races** of humans that exist throughout the world today.

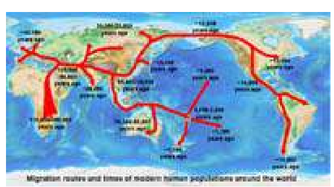


Figure 2.71. Routes of human evolution and **migration** around the world beginning in late Pleistocene time.

Climate change associated with the ice ages must have had significant impacts on the survival and extinction of human and human-like species. In addition, populations were impacted by massive volcanic episodes, such as the by the Toba Super Eruption in Sumatra that occurred about 75,000 years ago.

Although new discoveries are constantly being made, current though is that humans first came to Australia within the past 60,000 years and to the Americas within the past 30,000 years. Use of agriculture methods and the rise of the first civilizations developed within the past 12,000 years. As the human species has expanded, diversified, adapted, and populated. In contrast, many other species have already gone extinct due to human predation, isolation, and habitat destruction. The modern human population has benefited from advances in medicine, agriculture, and transportation. The world's population has doubled in the last 40 years, but the rate of population growth has declined by almost half in that time (but not enough to stop population growth)(Figure 2.73). However, this success is countered by the demands of land and resources that lead to war and conflicts between populations. Population growth is not evenly distributed around the world (Figure 2.74).

Figure 2.72. Within the past century, human activity has completely changed large regions of the planet's physical environment.

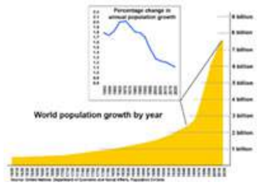


Figure 2.73. World population growth 1600 to 2017 and rate of population growth 1950 to 2017 from United Nations data.

Figure 2.74. World population density map of the world for 2015. Note that large populations have developed in regions of high agricultural productivity where water is abundant (and perhaps the most valuable resource to a region).

Human Evolution Time-line Interactive (Smithsonian Institution website)
http://humanorigins.si.edu/evidence/human-evolution-timeline-interactive

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2.28: Refugia- How Life Goes On After Environmental Calamities

Refugia: How Life Goes On After Environmental Calamities

Even after any number of the great mass extinctions, life returned and flourished in abundance. Once the environmental calamity that caused the great mass extinction at the end of the Cretaceous Period ended, this allowed for the succession of living things from life forms that survived in place, or survived in refugia. A **refugia** is an area in which a populations of organisms can survived during an extended period of unfavorable conditions. Refugia are isolated or ***protected*** environmental setting that survive major climate changes—examples include:

• an unglaciated area on a south-facing mountain slope where plants and animals survive in isolation, surrounded by advancing continental glaciers.
• species surviving an isolated mountain peak cool and wet enough to allow some species to survive when surrounding lowlands change from forests to desert conditions.
• plants and animals that become isolated on islands when sea level rises, and relative species elsewhere are wiped out by disease and/or predation.
• a an isolated community surviving in a canyon with continuous water supply in a region of long-term extended drought.
• species living in an isolated bay far away from the annihilation caused by a massive asteroid impact elsewhere on the planet.

Many question remain why some species survive a mass extinction event. What was it about species turtles, snakes, crocodillians, birds, and mammals that allowed them to survive the K/T extinction event when all dinosaurs and other organisms did not?

Refugia In Our Modern Era

With the advance of human civilizations, we are witnessing unprecedented extinctions as cities and croplands replace forests and coastal plains. Some species are hunted to extinction, or environmentally sensitive species loose their refugia. Human activities, such as building interstate highways and expansion of urban corridors, are isolating populations that would otherwise be a part of a continuous breeding population across an area or region. For some species, surviving member of species now only exist in zoos or on isolated park lands and wildlife preserves. On the other hand, ***useful species***, such as dogs, cats, goats, cows, chickens, etc., are protected, but are increasingly being genetically modified to suit the needs and interests of their human hosts.

2.29: Evolution and Adaptation To Extremes

Evolution and Adaptation To Extremes

Adaptation is the driving force of evolution on many levels (microscopic to massive organisms; individual species to diverse communities). Environmental changes over time force species and communities (ecosystems) to adapt to special **niches**. Figure 2.75 shows the evolution and diversification of plants through geologic time. Some species able to spread across large regions by adapting to variable climate conditions that match their reproductive and feeding cycles. Ancient lineages that have survived extinction are often better adapted to living in harsh environments (such as lichens, mosses, and club mosses living in barren, rocky settings, Figure 2.76). Species like the Giant Sequoias that live in isolated communities in California's Sierra Nevada Range are remnant populations was once a much more widespread forest community that existed during the last ice age (Figure 2.77).

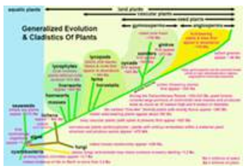


Figure 2.75. Evolution involving competition and adaptations have led to a diversification of plants through geologic time.

Figure 2.76. Ancient lineages of early plants (such lichens, mosses, and club mosses) have adapted to harsh environments on rocky settings.

Figure 2.77. Giant Sequoias (the world's largest trees) in Yosemite National Park, CA are adapted to local climate conditions.

Organisms that have adapted to living in vernal pools illustrate adaptation to extreme environmental conditions. A **vernal pool** is a small pool or pond that forms temporarily, such as after a summer thunderstorm, seasonal precipitation (Figure 2.79). During a short period when water is present, a variety of species have adapted to completing their entire life cycle in a matter of days to weeks before the water dries up or becomes too salty. Amazingly, species like tadpole shrimp, fairy shrimp, and other desert species have adapted to these extreme environmental conditions. Tadpole shrimp have fossil ancestry dating back to marine environments in middle Paleozoic time. Tadpole shrimp have basically survived longer than any known species by being able to adapt to a variety of extreme environment conditions (Figure 2.80).

Figure 2.78. Healthy coral reef communities are adapted to a stable yet limited range of environmental conditions: clear, shallow, warm seawater with good circulation. Today, reef communities worldwide are threatened by rapidly changing environmental conditions largely influenced by human activities (pollution, heat from global warming, and resource exploitation).

Figure 2.79. **Vernal pools** like this one form in after a desert summer thunderstorm. Within days, species such as tadpole shrimp hatch, feed on limited food supply, grow to adult size, reproduce (producing cysts and eggs, both sexually and asexually) before dying off when the water dries up, sometimes for many years between periods of precipitation.

Figure 2.80. **Tadpole shrimp** are brachiopod crustaceans that appeared in the marine fossil record about 400 million years ago, but are only found today in vernal pool habitats. Their body plan has remained more or less consistent over the course of the past 250 million years. These species have adapted to survive some of the harshest climate extremes on Earth.

2.30: The Anthropocene Epoch (1865 AD to present)?

- ## The Anthropocene Epoch (1865 AD to present)?

Page ID 9799

The name **Holocene Epoch** has been applied to the time period extending from the end of the last ice age, encompassing the rise of human civilizations up to the present time. However, the name **Anthropocene** has been suggested to designate the current geological age, viewed as the period during which ***human activity has become the dominant influence on climate and the physical environment***. Some question are: When did this happen? And, how will generations of consciously aware descendants of our times (human and otherwise) be able to recognize it from landforms and layers with sedimentary deposits? Many suggestions have been made, and deposits in one region may not completely match characteristics in another region. (This is an excellent discussion topic for examining other extinction boundaries in the geologic past!) Here are points to consider: **when did the Anthropocene begin**?

• Many scientists think the beginning of the Anthropocene began with the **Industrial Revolution** in the 1850s; the logical start starting point to the modern era. The start of the Industrial Revolution marks when major extraction of mineral resources began (coal, iron, and other metals), the spread transportation networks, the growth and expansion urban development.
• Durable pollen from eucalyptus trees imported from Australia and New Zealand to support expansion or the railroads start to appear in sediments throughout California sedimentary basin deposits starting in the 1850s.
• Mass production and distribution of durable glass, porcelain products, and lead bullets started in the 1850s, beginning the contribution to *throw-away society* materials that can be found in abundance wherever humans went. Durable man-made products began to accumulate as trash in the environment.

Figure 2.81. The Washington Monument is a possibly a good choice for a **type section** for the **Holocene/Anthropocene Boundary.** The lower part of the monument was built (by slaves) before the Industrial Revolution began. The upper part of monument was completed in a second construction phase after the Civil War (by free men) after the Industrial Revolution was well in progress.

Interestingly, the H/A Boundary level depicted on the Washington Monument approximately marks the level that sea level will rise to if most of the ice on Greenland and Antarctica were to melt due to global warming (as has already occurred in the geologic past).

A later start to the Anthropocene Epoch is suggested for post World War II. Sediments from this period include:
• A universal boundary world-wide where radioactive isotopes and byproducts of the surface testing of nuclear weapons can now be identified as a boundary in sedimentary deposit around the world.
• Durable plastics, construction materials, porcelain tiles, composite materials, and other durable trash of the modern era released intentionally or accidentally (such as damaging effect caused by superstorm damage, tsunamis, floods, or other disasters) are now distributed throughout the environment.
• Construction of sprawling urban area, mining regions, transportation routes (such as interstate highways) , and agricultural activities have significantly modified the landscape in many regions that will have lasting effect on the landscape for many millennium into the future. Some estimates suggest that human activities are moving more materials than all the rivers, wind, ocean currents, and other natural geologic processes combined.
• Landfills will be a long-lasting time stamp on the landscape worldwide.
• Introduction of exotic species have completely changed the environment in many regions.

This discussion has many intriguing manifestations. Can humans organize and adjust to what might be considered **sustainability**? Or, perhaps without hope, are we destined to an apocalyptic fate as describe by **Thomas Malthus** (1766-1834)**,** an English economist and demographer who proposed a theory that human population growth will always tend to outrun the food supply. Malthus suggested that the betterment of humankind is impossible without strict enforcement of limits on reproduction. So far in our modern era, it seems that some of the limitations on what might be considered sustainable have been addressed by advancing technology and changing social norms (globally). The question is, can we collectively achieve sustainability without enduring war, disease, and famine?

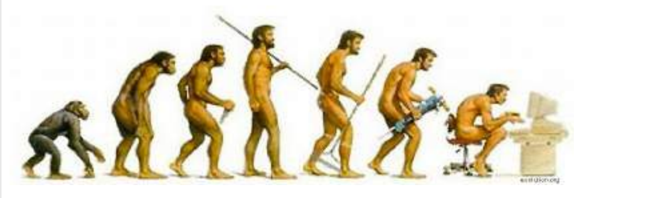


Figure 2.82. A famous cartoon depicting human evolution. Many people agree that humans are greatly altering our global environment with potentially catastrophic consequences without drastic changes in how we use our planet's limited resources. We need to learn how to manage and sustain our world's natural resources and manage our populations in any way while avoiding catastrophe.

2.31: Concepts of evolution, refugia, and succession provide a valuable lesson about modern society.

Concepts of evolution, refugia, and succession provide a valuable lesson about modern society.

In our life times we can witness the progress of evolution in many ways, and hopefully, learn. The advance of technology illustrates these concepts. Classic examples illustrate:

- cars and displacing or replacing trains and horse-drawn carts as primary means of transportation.
- cell phones replacing telephones, which replaced telegraphs and mail services as primary means of communication.
- cable television replacing radio/TV broadcasting.
- cities grow through **succession** following the changes in politics, industry, and development of infrastructure.

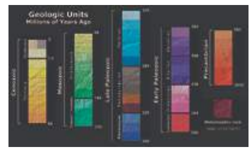
So, should calamity happen, and an area or region should loose electrical power or access to liquid fuels, what would survive? Populations would need to migrate, adapt, or face famine. Electric- and gas-power tools and equipment would be rendered useless, but hand-powered tools like hammers, water pumps, shovels, saws and axes would be increasingly valuable!

In the business world, evolution provides particularly important concepts. It is an interesting study to see how businesses and corporations survive economic calamities caused by wars and depressions, and the rise of competing new technologies. ***It is a jungle out there***.

2.32: Where are rocks of different ages exposed in the United States?

Where are rocks of different ages exposed in the United States?

Rocks of all geologic ages are exposed in different parts of the United States. Figure 2.83 is a geologic map of the conterminous United States, and Figure 2.84 is the geologic map legend that shows colors associated with regions where rocks of different ages are exposed at the surface. Earth scientists use geologic maps like these to locate areas where they may go study the fossil record where rocks of different ages (and the fossils they contain) occur. Each region of the country has unique fossil record. The best place to start an investigation is to visit museums, universities, and government organizations that host fossil and rock collections in the vicinity where rocks are exposed. Learn more about the regional geology and natural resources of the United States on this link: **Regional Geology of the United States**.

	
Figure 2.83. Geologic map of the United States.	Figure 2.84. Geologic ages of bedrock on the geologic map.

Selected comprehensive websites for paleontology and evolution:

U.C. Berkeley Museum of Paleontology website
http://www.ucmp.berkeley.edu/exhibits/index.php

American Museum of Natural History
https://www.amnh.org/our-research/paleontology

Smithsonian Institution, Department of Paleobiology
http://paleobiology.si.edu/

2.33: Quiz Questions - Chapter 2 - Evolution of Life Through Time

1. Who was get credit for publishing a theory of natural selection, the fundamental concepts for the modern science of evolution?
a. Carl Linnaeus
b. Charles Darwin
c. Gregor Johann Mendel
d. James Watson and Francis Crick

2. The theory that populations that are separated environmentally can develop different features based upon an adaptation to their environment is called:
a. heredity.
b. natural selection.
c. divergent evolution.
d. convergent evolution.

3. For a species to avoid extinction, individuals must:
a. eat, survive, and reproduce.
b. deal with competion (within their own species or with other species).
c. be able to adapt to environmental changes.
d. all of the above.

4. "The total number of fossils that have been discovered, as well as to the information derived from them" is referred to as:
a. the geologic time scale.
b. the science of paleontology.
c. the fossil record.
d. fossilization.

5. Groups of these rock formations are parts of **sequences** that preserve the fossil record. Each of the sequences rests on the eroded surface on top of a previous sequence represented by a ***major regional unconformity*** (also called a ***sequence boundary***). **How many sequences** (with their **underlying unconformities**) are recognized throughout North America (with equivalent features on other continents)?
a. two
b. four
c. six
d. eight

6. When geologic evidence suggest that photosyntheses and the first eukaryotic cells capable of oxygen-based respiration first appear on Earth?
a. about 4.56 billion years ago
b. about 4 billion years ago
c. about 3 billion years ago
d. about 1.8 billion years ago

7. When does it appear that sexual reproduction was fully established in eukaryote organisms?
a. about 4.56 billion years ago
b. about 600 million years ago
c. about 3 billion years ago
d. about 1.8 billion years ago

8. A mound of calcareous sediment built up of layers of lime-secreting **cyanobacteria** (blue-green bacteria, algae and other ***more primitive*** eukaryotic life forms) that trap sediment, creating layers accumulations is called:
a. a stromatolite.
b. a metazoan.

c. endosymbiosis.
d. Ediacaran fauna.

9. The earliest period of the Paleozoic Era when shelled organisms first appear in abundance in the sedimentary record is called the:
a. Precambrian Eon.
b. Cambrian Period.
c. Ordovician Period.
d. Devonian Period.
e. Jurassic Period.

10. When bony fishes and sharks first flourish in abundance in the Paleozoic Era?
a. Precambrian Eon
b. Cambrian Period
c. Ordovician Period
d. Devonian Period
e. Jurassic Period

11. What period did amphibians first appear in abundance in the fossil record?
a. Ordovician Period
b. Devonian Period
c. Mississippian Period
d. Permian Period
e. Triassic Period

12. During what period did great forested swamps exist that became the source of most of the extensive coal deposits through the Appalachians and Midwest regions of North America?
a. Devonian Period
b. Pennsylvanian Period
c. Permian Period
d. Triassic Period
e. Cretaceous Period

13. The greatest mass extinction occurred at the end of this period, possibly wiping out about 96% of marine species and 70% of land species that existed previously.
a. Ordovician Period
b. Devonian Period
c. Mississippian Period
d. Permian Period
e. Jurassic Period

14. The ***Age of Reptiles*** best applies to which time range?
a. Mesozoic Era
b. Paleozoic Era
c. Cenozoic Era
d. Permian Period
e. Tertiary Period

15. The dinosaurs first appear in what geologic period?
a. Pennsylvanian Period
b. Permian Period
c. Triassic Period
d. Jurassic Period

e. Cretaceous Period

16. When do birds first appear in the fossil record?
a. Pennsylvanian Period
b. Permian Period
c. Triassic Period
d. Jurassic Period
e. Tertiary Period

17. Small mammals and flowering plant first appear in abundance in which geologic period?
a. Jurassic Period
b. Permian Period
c. Triassic Period
d. Cretaceous Period
e. Tertiary Period

18. A great mass extinction, including the disappearance of dinosaurs and many forms of marine life, is believed to have been associated with a massive asteroid impact in the Yucatan region of Mexico. This occurred at the end of which period?
a. Jurassic Period
b. Permian Period
c. Triassic Period
d. Cretaceous Period
e. Tertiary Period

19. When did mammals with placental-type live birth appear in the fossil record?
a. Jurassic Period
b. Cretaceous Period
c. Paleocene Epoch
d. Eocene Epoch
e. Quaternary Period

20. The Ice Ages are associated with which geologic period?
a. Jurassic Period
b. Quaternary Period
c. Triassic Period
d. Cretaceous Period
e. Miocene Epoch

21. What is the name of the geologic epoch when human civilizations with cities first developed around the world?
a. Quaternary
b. Holocene
c. Anthropocene
e. Weshouldhavecene

CHAPTER OVERVIEW

3: Structure of the Earth

3.1: Introduction

This chapter reviews the major concepts of the **structure of the Earth** and describes the dynamic processes associated the formation of distinct layers within the earth. This is essential information to understand **plate tectonics** (discussed in **Chapter 4**). Plate Tectonics Theory explains how the Earth's surface is broken up into large plates of rock whose slow movements create earthquakes, volcanoes, and mountains, changing the way the Earth looks over geologic time.

While much has been discovered about the character and natural resources of our planet since the time of Christopher Columbus's first voyage, little was know about the internal character of the Earth until the Cold War era following World War II. Although studies of the internal structure of the earth were first reported in the late 19th century using seismic wave data from great earthquakes, it was the data from testing, spying, and verification of underground nuclear explosions that provided a clearer, more detailed picture of the internal structure of our planet. The earth is composed of several zones, including a central **core**, a **mantle**, and a **crust** (Figure 3.4 and **3-5**). **Oceans (hydrosphere)** and **atmosphere** rest on the surface of the crust. All parts are held together and have their character based on the force of gravity, their chemical composition, and largely how they formed and changed through geologic time. These same factors apply to other planets and moons as well. The **solid earth** has a central **core** (both solid & liquid), a **mantle** (mostly solid though capable of slow flow by heat convection), and the **crust** (solid).

The appearance of the world as we see it today is a result of the accumulative effects of all geologic processes that have happened in the past. Some of these processes occur rapidly (such as volcanic eruptions, earthquakes, great storms and flood, and occasional asteroid impacts). However, most features we see on the landscape or in a region (or larger features like continents) involve processes that are far grander, operating both near and deep below the surface, and taking place gradually over long periods of time (in spans measured in millions to hundreds-of-millions of years). For instance, the coast lines of northwest Africa and the eastern United States are currently moving apart at a rate of about 2-4 inches a year. However, about 200 million years ago the two continents were joined together before the opening and formation of the Atlantic Ocean basin! Plate tectonics theory helps explain most of the processes and grand landscape features we observe around the world today, both on land and beneath the oceans.

Figure 3.1. Nearly all geologic processes observed on Earth fit in some way into **Plate Tectonics Theory.**

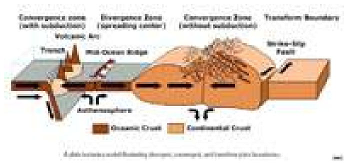


Figure 3.2. A simplified model of plate tectonics showing types of **lithospheric plate boundaries**.

3.2: The Atmosphere

The Atmosphere

The atmosphere is a gaseous mass or envelope surrounding the Earth, and retained by the Earth's gravitational field. The Earth's atmosphere is subdivided into levels:

* The **troposphere** is the lowest portion (up to about 6-8 miles [10-13 km]) where all weather takes place and contains about 80% of the atmosphere's mass and 99% of its water vapor.

* The overlying **stratosphere** extends up to about 31 miles (50 km). It contains an abundance of ozone which absorbs ultraviolet radiation, protecting life on land and in the shallow ocean .

*The **mesosphere** is the part of the earth's upper atmosphere above the stratosphere in which temperature decreases with altitude to the atmosphere's absolute minimum.

* The **thermosphere** the region of the atmosphere above the mesosphere and below the height at which the atmosphere ceases to have the properties of a continuous medium (about 60 miles [100 km]). The thermosphere is characterized throughout by an increase in temperature with height. Here where the charged atomic particles of the solar wind interacts with atmospheric gases.

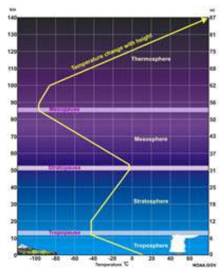


Figure 3.3. **Structure of the Earth's atmosphere.**

3.3: The Solar Wind Impacts the Upper Atmosphere

The Solar Wind Impacts the Upper Atmosphere

The **solar wind** is a stream of energized, charged particles (mostly electrons and protons) flowing outward from the Sun's upper atmosphere. The ionized particles are released into space from the Sun's corona and by solar mass ejections (prominences and flares). The solar wind moves through solar system at speeds roughly 500 miles per second (800 km/sec); about 10 days from Sun to Earth) and can reach temperatures of about 1 million degrees (Celsius). The solar wind is what blows a comet's tail away from the bodies of comets as they go through the solar system. Estimates suggest the Sun loses the equivalent of "one Earth mass" about every 150 million years (which isn't much considering the size and mass of the Sun). Large **corona ejections** from the Sun's surface result in **solar storms** that frequently impact Earth and other planets.

The Earth's **magnetic field** shields the planet from the erosive effects of the solar wind (Figure 3.4). Particles trapped by Earth's magnetic field flow into the upper atmosphere producing the **aurora borealis** (Northern Lights) and **aurora australis** (Southern Lights) (Figure 3.5). Over geologic time, the solar wind also erodes the atmosphere of planets with weak magnetic fields (this includes Mercury, Mars, and the Moon). Strong auroras have been observed on the gas planets (Jupiter, Saturn, Uranus, and Neptune)—all of which have a dense atmosphere and a strong magnetic field.

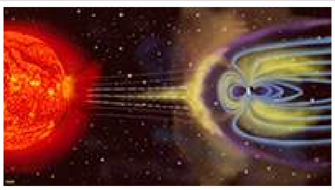


Figure 3.4. Coronal mass ejections result in the **solar wind** which is deflected and captured by the Earth's magnetic field.

Figure 3.5. The **aurora borealis** are streaming light displays lights in the northern hemisphere.

Solar storms associated with coronal mass ejections can interfere with radio communications, cause damage to satellites, and impact electrical transmission lines and facilities (resulting in power outages). During strong solar storms long lines of metal (like electrical power lines, pipelines, and railroad lines in northern regions can overload with electrical charges which and spark to nearby objects and have been reported to have started brush fires. Because massive solar ejections can be observed, the possible impacts of solar storms can be predicted.

3.4: The Hydrosphere, Cryosphere and Biosphere

Hydrosphere and Cryosphere

The hydrosphere includes all the waters on the Earth's surface, such as oceans, lakes, rivers, streams, and groundwater. 97% of all water on earth is **seawater** (discussed in Chapter 7).

The **cryosphere** is the frozen water on Earth including glaciers, sea ice, snow, freshwater ice, and frozen ground (permafrost).

The **hydrologic cycle** illustrates the movement of water through the **hydrosphere** and **cryosphere**. The movement of water and ice erodes the land surface and provides ocean basins with sediment. Dissolved materials become the salt in seawater. Salts in seawater are concentrated as water evaporates and later falls as precipitation, with most of it falling back into the ocean. The rest falls on land and becomes ice, runoff, groundwater, or is absorbed and released by living things, mostly plants.

Figure 3.6. The **hydrologic cycle** illustrates the movement of water through the **hydrosphere** and **cryosphere**.

The Biosphere

The term **biosphere** is the regions of the Earth occupied by living organisms. Life as we know it requires liquid water. So far, a biosphere is only known on Earth. Earth's biosphere encompasses the land's surface, oceans and surface waters (including the seabed in the deepest parts of the ocean basins). Life is found in the lower atmosphere (considering birds, flying insects, and wind-blown pollen and microbes), and deep underground,such in caverns, and even deeper where microbes have been found in groundwater and in porous spaces between mineral grains of solid rock deep in the subsurface. Microbes can tolerate the near boiling temperatures and extreme acidic conditions of hotsprings and thermal pools in Yellowstone National Park and other hydrothermal settings around the world. Microbes are found consuming and degrading oil reserves in petroleum reservoirs deep underground. One of the most sought goals in space exploration is to find evidence of biospheres on other planets and moons.

3.5: Subdivisions of the Structure of the Solid Earth

Subdivisions of the Structure of the Solid Earth

The Earth consist of several parts: a **core**, a **mantle**, and a **crust**. Other planets and moons in our Solar System share some of these characteristics:

-The **crust** is the outermost solid shell of a rocky planet or moon, which is chemically distinct from the underlying mantle. The crust is mostly composed of relatively low-density silicates minerals rich in aluminum. The crust is a comparatively thin outer skin that ranges from about 2 miles (3 km) thick at the oceanic ridges to 40 miles (70 km) under some mountain belts. Gravity measurements show that the crust is separated into thin **oceanic (3.0 gm/cc)** and thicker **continental crust (2.7 gm/cc).** The crust is more rigid than the underlying mantle, it is brittle, and hosts earthquakes.
-The **mantle** is an inner layer of a terrestrial planet or other rocky body large enough to have differentiated in composition by density. On Earth, the mantle is a highly viscous layer between the crust and the outer core. • Composed of higher-density silicates rich in iron and magnesium that extends to a depth of about 1800 miles (2900 km). • Large portions can flow slowly and are near melting.
-The **core** is the innermost part of the earth is believed to be a magnetic iron-nickel rich sphere that consists of a 758 mile (1220 km) thick solid and very dense **inner core** that is overlain by 1400 miles (2250 km) of dense molten material in the **outer core**. The outer core is liquid, and heat convection here creates currents in the liquid metal that generate Earth's magnetic field.

Other rocky planets and moons have also cores, mantles, and crusts, hydrospheres, and atmospheres. So far, only Earth is known to have a biosphere.

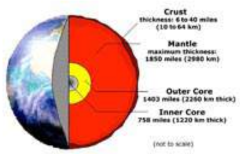


Fig 3-7. The **asthenosphere** is a part of the upper mantle that behaves in a more fluid-like manner than the overlying **lithosphere**. The lithosphere is cooler, and behaves in a more rigid or brittle manner. The lithosphere includes uppermost part of the mantle and overlying crust. It is the region where all earthquakes take place. Rocks in the asthenosphere are hot and will deform rather than fracture under pressure.

3.6: Layers Of the Earth As Defined By Physical Properties

Layers Of the Earth As Defined By Physical Properties

With increasing depth, Earth's interior is characterized by gradual increases in temperature, pressure, and density.
Depending on the temperature and depth, a particular Earth material may behave like a brittle solid, deform in a plastic–like manner, or melt and become liquid. Figure 3.8 illustrates the structure of the Earth highlighting the physical properties of the different layers.

Figure 3.8. Structure of the Earth

Lithosphere (sphere of rock)

The term **lithosphere** is used to describe the rigid outer part of the Earth, consisting of the crust and upper mantle. Compared with other layers of the Earth, the lithosphere is a relatively cool, rigid shell and averages about 60 miles (100 km) in thickness, but may be about 155 miles (250 km) or more thick beneath the older portions of the continents. The lithosphere is broken up into moving plates, and the movements of these plates are responsible for all the large-scale features observable on the surface—including ocean basins, continents, and mountain ranges.

Asthenosphere (weak sphere)

The term **asthenosphere** refers to a semi-fluid layer beneath the lithosphere (within the **upper mantle**), between about 60 to 400 miles (100-650 km) below the outer rigid lithosphere (oceanic and continental crust) forming part of the mantle. The asthenosphere, although solid, is very hot and is thought to be able to flow vertically and horizontally, enabling sections of lithosphere to undergo movements associated with plate tectonics. Geologist use the term **plastic** to describe how hot solid materials, including rocks, can deform and flow slowly.

Mesosphere (or Lower Mantle)

This region is a rigid layer between the depths of about 400 to 1800 miles (650 km and 2900 km), but the rocks at these depths are very hot and capable of gradual flow. Heat from the core drives mantle gravitational convection.

Earth's Core

Earth's core is subdivided into to zones based on their geophysical properties: an outer core and an inner core. Outer core: As discussed in section 3.6, the outer core is a liquid layer composed mostly of an iron-nickel alloy (a mixture with similar composition to metallic meteorites). Convective flow within the outer core generates Earth's magnetic field.

Inner core: Geophysical studies show that the inner core behaves like a solid, but is very dense, around 16 gm/cc (similar to the physical properties of an iron-nickel meteorite).

Figure 3.9. An iron-nickel meteorite is magnetic and has a similar density as the metallic core of our planet.

How do we know the structure of the Earth?

By indirect **geophysical methods**! **Geophysical methods** use technical applications and equipment to collect information about the earth, oceans, and atmosphere that are not directly observable by our senses. Examples include:

Geophysical Method	Instruments Used
Magnetic measurements	**magnetometers**
Gravity measurements from the surface or from precise measurements from satellites orbiting a planet or moon	**gravitometers and satellites**
Seismic waves from earthquakes or large explosions	**seismographs**

Figure 3.10. Gravity can be precisely measured from orbiting satellites.

The sections that follow explore the types of information we can learn from these three methods.

3.7: Magnetism Measurements Reveal the Earth's Metallic Core

Magnetism Measurements Reveal the Earth's Metallic Core

Earth's magnetic field is believed to be formed by the convection of hot, molten iron in the outer core. There must be significant amounts of iron for Earth to have such a strong magnetic field.

The **Geographic North Pole** is the axis of Earth's rotation. It is is currently offset from the **Magnetic North Pole** by about **11.5 degrees** (same with the South Poles). The magnetic poles are very slowly wandering relative to the geographic poles. This wondering of the magnetic poles is caused by gradual changes of Earth's magnetic field. Current thought is that shifts in Earth's magnetic field are probably caused by changes in gravity-driven flowing currents in the planet's liquid-metallic outer core.

Magnetic Reversals: The Earth’s magnetic field reverses, causing the locations of the north and south magnetic poles to switch. If a magnetic reversal were to occur today, then a magnetic compass would point to the South Magnetic Pole instead of the North Magnetic Pole. Geologists and geophysicists have determined that magnetic reversals have happened many times through geologic time. Magnetic reversals are preserved in the “**paleomagnetic record**” - preserved as weak magnetic fields locked into rocks bearing magnetic minerals at the time they form (see the ***Paleomagnetism*** discussion below). We think that the magnetic reversals are probably caused by shifting currents in Earth's liquid metallic outer core. When a magnetic reversal occurs, basically what happens is the north magnetic pole becomes the south magnetic pole, and vice-versa. This switching of magnetic poles can last for periods ranging from thousands millions of years. Hundreds of magnetic reversals are recorded in the geologic records, observed in rocks on continents and the seafloor in many regions around the globe where rocks of all ages are preserved.

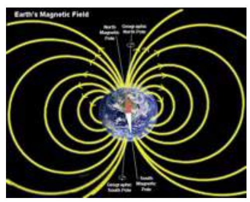


Figure 3.11. Earth's magnetic field extends from the core and far out into space.

3.8: Gravity Measurements

Gravity Measurements

Gravitometers are devices that measure very tiny differences in Earth's gravitational field from one place to another. Gravity measurements are also calculated measuring subtle changes in the paths of Earth orbiting satellites. Orbiting satellites are pulled closer to Earth over regions of higher gravity.

Gravity measurements reveal that there must be denser material deeper in the Earth. Rocks at the surface of the planet are not dense enough to account for the overall higher amount of gravitational attraction that exists between objects on the surface and objects orbiting the planet. Variations in gravitational forces also reveal subtle differences in the density and thickness of the crust in different regions of the world. Figure 3.12 shows variations in the Earth's gravitational field as revealed by satellite gravity measurements. The map shows that older and colder crust, such as under regions in the oceans, is denser (having higher gravitational attraction) than where new ocean crust is forming along mid-ocean ridges. Gravitation is less where the crust is less dense, such as beneath continental regions and where rocks are hotter (associated with regional volcanism).

Gravity Anomaly Map

Figure 3.12. NASA's gravity anomaly map shows subtle differences in the Earth's gravitational field in different portions of the world.

Gravitational forces increase with increasing mass and decreases with distance. The greater the mass between to objects (such as moons or satellites orbiting planets), the greater the gravitational attraction. In addition, the closer two objects (such as moons and planets), the greater the gravitational attraction.

3.9: Earthquakes, Faults, and Earthquake Faults

Earthquakes, Faults, and Earthquake Faults

An **earthquake** is ground shaking caused by a sudden movement on a fault, by a volcanic disturbance, a landslide, or a explosion (natural or man made).

A **fault** is a fracture or crack along which two blocks of rock slide past one another. This movement may occur rapidly, in the form of an earthquake, or slowly, in the form of **creep**.

Earthquakes occur somewhere around the world every hour of every day. Most are too small to even feel. However, large-magnitude, damaging earthquakes happen somewhere around the world almost every year. Large earthquakes can cause widespread chaos, destruction, and death. Earthquakes are associated with **faults**, but not all faults currently generate earthquakes (some faults may have been active long ago, but are now inactive). Faults range is size from small fractures in a local outcrop to great fault systems that can extend for thousands of miles.

Features Associated With Faults

A **fault** is a fracture or crack along which two blocks of rock slide past one another. This movement may occur rapidly, in the form of an earthquake, or slowly, in the form of creep (Figure 6.18). Types of faults include strike-slip faults, normal faults, reverse faults, thrust faults, and oblique-slip faults. Faults can be small to large complex systems of interlinking faults and may change form one kind of fault in one location to another kind somewhere else. Many faults are associated with folds. Faults split, bifurcate, merge, or can peter out over distances, sometime forming complex systems of fractures.

The relative motion of faults (one side to the other) is described in terms of relationship of a **hanging wall** and **foot wall** (see normal fault and reverse fault examples in **Figure 3.13**).

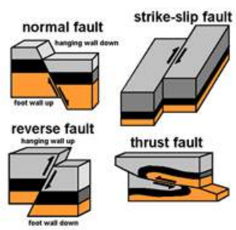


Figure 3.13. **Block diagrams** illustrating common types of faults**: normal fault, reverse fault, strike-slip fault, and thrust fault**. Offset strata illustrates the relative motion of the **foot wall** to the **hanging wall** of each type of fault.

A foot wall is the underlying block of a fault having an inclined fault plane.

A hanging wall is the block (rocks) on the upper side of an inclined fault plane.

Simply described here—if a fault is exposed well enough to see that the fault plane is inclined, the side you could ***stand on*** is called the **foot wall**. The side you could ***hang from*** without your feet touching the ground is the **hanging wall**. For instance, on a normal fault, the hanging wall has moved down relative to the foot wall. On a reverse fault, the hanging wall has moved up relative to the foot wall.

Terms Used To Describe Earthquakes

A rupture zone is the area of the Earth through which fault movement occurred during an earthquake. For large earthquakes, the section of the fault that ruptured may be several hundred miles in length. Ruptures may or may not extend to the ground surface.

A **focus** is the point below the Earth's surface where seismic waves originate during an earthquake (Figure 3.14).

An **epicenter** is the point on the Earth's surface above the point at depth in the Earth's crust where an earthquake begins.

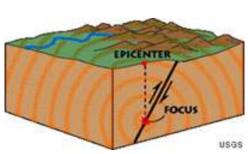


Figure 3.14. Diagram illustrating the **focus** and **epicenter** of an earthquake along a fault.

Seismic Waves

Seismology is the study of **earthquake shock waves** as they pass through the earth. Seismology is the science that helped resolve many questions about the internal structure of the earth.

Seismic waves are shock wave and vibrations in the Earth which issue from the **focus** of an **earthquake**. Seismic waves are a result of an earthquake, impact, or explosion, or some other process that imparts low-frequency acoustic energy into the earth. (Figures 3-14 and **3-15**).

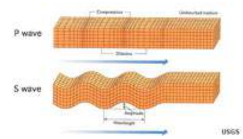


Figure 3.15. **Earthquake waves** include:
P-compression waves and
S-shear waves.
P-waves move faster than S-waves and are first to be felt. The S-waves arrive next and produce the majority of shaking in an earthquake.

Two Types of Seismic Waves: **Surface Waves** and **Body Waves**

• **Surface waves** travel on the surface.
• **Body waves** travel through the earth.

There are two types of body waves: **P waves** and **S waves**

P (primary) waves are **compressional** and cause rocks to move back-and-forth **parallel** to the direction of wave movement.
• **P waves travel faster than S waves** through denser and more compact elastic materials (solid, liquids, gases).

S (shear) waves have a shear effect and cause rocks to move back-and-forth **perpendicular** to the direction of wave movement.
• **S waves are slower than P waves** and travel only through solid mater, not liquids or gases. S wave speed varies depending on materials, but typically they only move about 60-70% as fast as P waves in the upper part of the Earth's crust. The fact that S waves travel through all parts of the Earth except the outer core tell us that the outer core is the only part of the Earth's interior that is fully liquid.

Locating Earthquakes With Seismographs

A **seismograph** is a device used to record earthquake shaking and is used to determine the **distance from an earthquake focus**, and the **magnitude** and **intensity** of earthquakes. Data from numerous seismographs linked together in networks are used to determine the focus, epicenter, extent of rupture**,** and amount of shaking in a region caused by an earthquake. A minimum of 3 seismographs are needed to determine the **epicenter** of an earthquake (Figure 3.15).

Figure 3.15. At least three seismographs are needed to locate the epicenter of an earthquake. A single seismograph can only tell you how far away an earthquake occurred, but not in which direction.

Note that the Global Seismographic Network consists of thousands of seismographs around the world, so information about earthquakes can be calculated quite precisely.

In earthquake-prone regions, many seismographs have been installed, along with related fault motion sensors that measure stress and strain buildup along faults or the extremely slow creep of some faults, and even changes in the gas content, water level changes, and electrical properties of rocks in the vicinity of fault zones. The more measurement devices, the better detail can be determined about the nature of earthquake-prone fault systems.

Describing Earthquakes: Earthquake Magnitude and Earthquake Intensity

Earthquake magnitude (M) is a numeric measure that represents the size or strength of an earthquake, as determined from seismographic observations. The **Richter scale** is a numerical (logarithmic) scale for expressing the magnitude of an earthquake on the basis of seismograph oscillations. Today earthquake intensity is recorded with a **Moment Magnitude Scale (MMS)** which is based on the seismic moment of the earthquake, which is equal to the rigidity of the Earth multiplied by the average amount of slip on the fault and the size of the area that slipped. Richter scale and moment magnitude scales are similar, but the MMS scale is more precise **(Figure 3.13)**.

Earthquake intensity (I) is a measure of ground shaking describing the local severity of an earthquake in terms of its effects on the Earth's surface and on humans and their structures. The **Modified Mercalli Intensity (MMI)** scale, which uses Roman numerals, is one way scientists measure intensity **(Figure 3.16)**.

Figure 3.16. Comparison of earthquake **magnitude (MMS)** and **intensity (MMI)** scales (USGS)

Video: Historic Earthquakes compared (Pacific Tsunami Warning Center)

Video: Earthquakes of the First 15 Years of the 21st Century (US NWS Pacific Tsunami Warning Center)

3.10: How does seismic wave data reveal the internal structure of the Earth?

How do seismic wave data reveal the internal structure of the Earth?

Earthquake Shadow Zones: Extensive study of shock waves of earthquakes and the global monitoring of underground nuclear bomb testing reveal information about the internal structure of the Earth. P and S waves both go through solids. S waves do not go through non-solids, so only P waves are received on the opposite side of the Earth. Zones of **seismic wave shadows** occur in the regions shown in Figure 1.17 between about 105° to 140° on the opposite side of the globe from a seismic shock. These shadow zones shows us that part of the Earth's core is liquid material (molten material). In contrast, the inner core is believed to consist of solid metal, possibly similar in composition of iron meteorites.

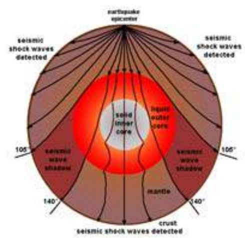


Figure 3.17. Seismic shock wave provide information about the structure of the Earth.

What can seismic (P and S) waves data tell us?

• Parts of the earth are not solid.
• The depth and location of an earthquake.
• The relative strength of an earthquake.
• The average density of Earth.
• The density of each layer in the Earth.

3.11: Earth's Major Boundaries Revealed By Seismic Waves

Earth's Major Boundaries Revealed By Seismic Waves

The *Moho* (Mohorovicic discontinuity): (Discovered in 1909 by Andriaja Mohorovicic)

• The Moho is the boundary between the crust and the mantle. It separates less dense crustal rock from underlying denser mantle rock.

• Identified by a change in the velocity of P waves

The core-mantle boundary (CMB): (Discovered in 1914 by Beno Gutenberg)

• Based on the P-wave shadow zone

• No P waves from 105 to 140 degrees

• The fact that S waves do not travel through the outer core provides evidence for the existence of a non-solid layer beneath the mantle

• Showed existence of liquid outer core and overlying mantle

Lehmann Discontinuity (Predicted by Inge Lehmann in 1936)

• Boundary between outer and inner core defined by an increase in seismic wave velocity from outer to inner core and by seismic wave reflection off the solid inner core.

The locations of the **Moho**, **CMB**, and **Lehmann Discontinuity** are shown in Figures 3-8 and **3-17**.

3.12: Seismic Wave Data Used To Map the Lithosphere

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Seismic Wave Data Used To Map the Lithosphere

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Earthquake data also reveals the location of major **fault zones** of the world (Figure 3.18). Many of the fault systems are associated with **lithospheric plate boundaries** (see discussion below).

Fault systems evolve and change over time—driven by plate tectonic forces associated mantle convection influencing the rigid lithosphere. Fault systems are often associated with volcanic regions. Faults may form and remain active for long ages before becoming inactive, and then may become reactivated again in some later period. Tectonic forces within the Earth deform rocks through processes of folding and faulting, producing mountains, valleys, and may other landscape features.

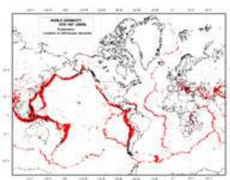


Figure 3.18. **Map of earthquakes of the world** (USGS record for 1978 to 1987).

3.13: The Mantle

Mantle Convection

Gravitational heat convection in the mantle is the source of forces that move, bend, and break rocks in the Earth's lithosphere (Figure 3.19). Heat in the Earth is produced by radioactive decay of unstable isotopes as well as heat left over from when the Earth formed billions of years ago in the solar system's nebula.

Motion within the mantle is responsible for deep crustal stretching (**extension**) and **compression**. Motion in the mantle is produced by **gravitational heat convection**—hot rocks expand and rise whereas cooler (hence denser) rocks sink. Thicker, less dense, continental crust floats higher than thinner, denser ocean crust below ocean basins. **Gravity-driven heat convection** within the Earth is the conclusive power source driving plate tectonic motions.

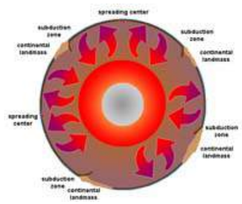


Figure 3.19. **Mantle convection** is the driving force of movement in the Earth's lithosphere.

Behavior of the Lithosphere (rigid crust and upper mantle) and Asthenosphere (upper mantle)

Subdivisions used in geologic discussions relating to **Plate Tectonics Theory** (discussed below) include:

The **Lithosphere** is the rocky outer portion of the Earth, consist of the crust and upper mantle (about the upper 60 miles [100 km] below the Earth's surface). It is the solid (more brittle) zone of the earth where earthquakes occur.

The asthenosphere is the upper portion of the mantle underlying the lithosphere where heat and pressure is great enough for materials to flow slowly. This movement is driven by the heat derived from within the deeper parts of the mantle and core that cause materials to flow by **gravitational heat convection** (see Figure 3.19). Gravitational convection works as follows—Adding heat causes materials (solid and molten) to expand, loose density, and rise; whereas cooling material shrinks and increases in density, and sinks. The asthenosphere is a semi fluid layer of the Earth, between about 40 to 80 miles (100-200 km) below the outer rigid lithosphere (oceanic and continental crust) forming part of the mantle and thought to be able to slowly flow vertically and horizontally, enabling sections of lithosphere to subside, rise, and undergo lateral movement associated with plate tectonics.

Another important distinction within the lithosphere are the differences between what is known as **oceanic crust** and **continental crust**. The rocks exposed on continental land masses are different than those found in the crust beneath the ocean basins.

Ocean crust is part of Earth's lithosphere that underlies ocean basins. Oceanic crust is primarily composed of **mafic rocks** (chiefly basalt and other rocks rich in iron and magnesium). These rocks are more dense than the rocks that underlie continents (continental crust rocks are less dense and are enriched in silica and aluminum). In addition, ocean crust around the world is significantly younger (less than 200 million years). In contrast, rocks that are found within continental landmasses are generally less dense and much older than rocks found beneath ocean basins. Land masses composed of continental crust have typically accumulated very slowly through the natural refining processes associated with plate-tectonics over many hundreds of millions to several billion years.

Continental crust is the relatively thick parts of the Earth's crust that forms the large landmasses. Continental crust is generally older, thicker, and less dense than ocean crust. Continental crust is also typically, more complex than oceanic crust, Continental landmasses are dominantly composed of igneous and metamorphic of granite or more **felsic** composition (rocks are enriched in silica and aluminum).

In general, rocks found within continental crust are less dense and thicker than the rocks beneath the ocean basins. This difference in thickness and density of the two types of crust helps explain the geography of the planet as well as explaining many aspects of the tectonic forces changing the landscapes of our planet over time. Just like blocks of wood floating in water, where the continental crust is thicker and less dense, the land masses isostatically float higher on the asthenosphere. Where the continental crust is thick enough it rise above the surface of the oceans (Figure 3.20). Oceans fills in the lower regions on the Earth's surface underlain by thinner, denser ocean crust.

Isostacy illustrated	
Figure 3.20. Isostasy: floating wooden blocks of different sizes illustrate how oceanic and continental crustal rocks are at relative isostatic equilibrium floating on the mantle. There would have to less dense crust under mountain ranges than under oceans. As geophysical studies reveal, **continental crust is typically thicker and less dense than ocean crust.**	Figure 3.21. Crustal thickening in the Himalayan Mountains and Tibetan Plateau is illustrated in this photograph from space.

3.14: Isostasy

Isostasy

Isostasy is the state of *balance*, or *equilibrium*, which sections of the Earth's lithosphere (whether continental or oceanic crust) are thought ultimately to achieve when the vertical forces upon them remain unchanged. In the early days of "modern geology" the variations in elevations on land (topography) and the depth of the oceans (bathymetry) were mapped around the globe. Investigations lead to the hypothesis of isostasy, that continents were floating on a more fluid mantle, much the way that wood blocks or icebergs float on water. With wood or ice blocks, the thicker they were, the higher they rose above the water (Figure 3.20). This lead to the belief that the crust beneath the continents—especially beneath mountain ranges—is thicker and less dense than the crust beneath the ocean basins. For example, the crust beneath the Himalayan Mountains must be much thicker that the crust beneath the Indian mainland, and much thicker than the crust beneath the Indian Ocean (Figure 3.21)**. Isostatic equilibrium** is the state of balance which sections of the Earth's lithosphere (whether continental or oceanic crust) are thought ultimately to achieve when the vertical forces upon them remain unchanged. The lithosphere floats upon the semi-fluid asthenosphere below (see Figure 3.19).

Geologic Examples of Isostasy

An iceberg floating on the ocean is a perfect illustration of isostasy (Figure 3.22). At Earth's ocean surface, solid freshwater glacier ice is about 10.7% less dense than cold seawater; as a result, ice floats. The amount of ice rising above the ocean surface is in equilibrium with the buoyant ice below the surface. As icebergs melt, the amount of ice above the surface adjusts to the buoyant volume below the surface. The ratio of the amount of ice above and below the surface remains the same as the ice melts.

Figure 3.22. Iceberg showing isostasy. Ice below the surface is in equilibrium with buoyant ice below the surface. As the ice melts, the iceberg floats lower and lower in the water.

Isostasy determines the elevation of the land surface on continents and the depth of ocean basins. The thickness and density of lithosphere determines how high mountains rise above surface on continents and on the ocean floor. In addition, thickness and density of lithosphere determines how deep ocean basins are.

Isostasy also causes **vertical movement** of the crust. For example, If a section of lithosphere is loaded, as by ice of a continental glacier, it will slowly subside to a new equilibrium position. When the continental glacier melts, the removal of the weight allows to slowly **rebound** back to isostatic equilibrium. Parts of northern North America and Europe that were covered by continental glaciers during the last ice age are now slowly rising eventually back to isostatic equilibrium (this action is called glacial rebound) (Figure 3.21).

The crust is always readjusting to changing forces from below and above. If a section of lithosphere is reduced in mass, as by erosion, it will slowly rise to a new equilibrium position. Increases in heat flow from the mantle cause crustal rocks to warm, expand, and rise. Old ocean crust becomes cold and shrinks, and with its mafic composition becomes denser and sinks back into the mantle.

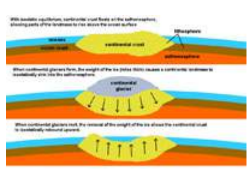


Fig-23. Isostatic rebound caused by the melting of continental glaciers reveals the fluid-like behavior of the asthenosphere.

Isostasy and the Age and Evolution of Continental Landmasses

Many hypotheses were put forward to try to explain the evolution of landscapes—isostasy was one of them. Early hypotheses focused on what was easily observable. Continents around the world shared a variety of large physiographic features: mountain ranges, coastal plains, plateau regions, and inland lowlands. Some of these lowland regions are underlain by what appeared to be ancient rocks that were once to core of mountain ranges in the distant past. These regions were located near the center of most of the continents and have became known as **shields** (such as the **Canadian Shield** of North America, see Figure 3.24). In most cases, these shields are surrounded by belts of mountain ranges that were composed of rocks that appeared younger than the shield regions. Also, some of these mountain ranges appeared much younger than other mountain ranges. This lead to conclusions that landscapes could be classified as *youthful*, *mature*, or *old age* —assuming that all mountain ranges form about the same way, and that youthful mountain ranges, like the Himalayan or Rocky Mountains eventual erode way (becoming more mature with age, like the Appalachian Mountains). Eventually almost all elevated features (mountains, hills) completely erode away, producing "old age" landscapes, similar to what is seen in shield regions (see Figure 3.24). The erosion of material from continental region contribute mass to the submerged regions along continental margins. In many regions along the continental margins the weight of additional sediments are casing them to sink (such as near the mouth of rivers, such as the Gulf Coast near the Mississippi River delta).

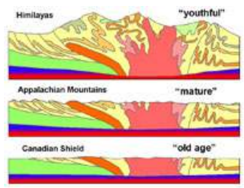


Figure 3.24. **Isostasy** and the hypothesis of landscapes evolving through ***youthful***, ***mature***, and ***old age*** stages. Evolution of a landscape over time involves uplift, erosion, and isostasy.

The assumption is that as materials erode away, the crust readjusts itself to maintain an **isostatic equilibrium**. As material is removed the crust rises. Over time, material that were once deep within mountain ranges eventually becomes exposed at the surface by erosion. Over time, the assumption was that isostatic adjustments eventually cease, and the mountains would completely erode away to a flat plain and eventually sink below the waves. Unfortunately, there were too many cases where the isostatic adjustment hypotheses didn't match all the observable facts. Not all old shield regions were low plains (as illustrated with the Scandinavian region of Europe and much of Africa). In addition, some regions, such as the Colorado Plateau, had characteristics that fit into all three categories, youthful, mature, and old age, all at the same time. In addition, there was very little to explain how mountain ranges and continents formed in the first place! Why do some mountain ranges have volcanoes and other don't? What would explain the composition and distribution of volcanic mountain ranges around the world, and what in the world could explain what chains of volcanoes like the Hawaiian archipelago were doing in the middle of the Pacific Ocean? These questions (and more) were finally resolved with the development of Plate Tectonic Theory.

3.15: Plate Tectonics Theory

Plate Tectonics Theory

Plate Tectonics is a unifying collection of concepts that explains most things geological on Earth, and other planets and moons as well. (**Note: Plate Tectonics is the focus of Chapter 4**). Plate Tectonics theory explains the structure of the Earth's crust and many associated phenomena as resulting from the interaction of rigid lithospheric plates that move slowly over the underlying mantle.

Plate Tectonics (definition) (Illustrated in Figure 3.25.)
• A theory that states that the earth's solid outer shell (lithosphere) broken into large, rigid pieces called **plates** that can move relative to each other by sliding atop the non-solid asthenosphere.
• Plates are thought to move due to a combination of convection in the asthenosphere and gravity. These forces are discussed in more detail in Chapter 4.
• Most volcanoes and earthquakes occurs where the solid lithospheric plates meet.

Figure 3.25. General model representing essential concepts presented by **Plate Tectonics Theory** (discussed in Chapter 4).

Deformation is the action or process of changing in shape or distorting, especially through the application of pressure. In geologic terms, deformation refers to changes in the Earth's crust related to tectonic activity, particularly **folding** and **faulting**.

Heat from inside the earth drives mantle convection (hot material rises, cool material sinks, Figure 3.19). The rise and fall of masses of material in the mantle create forces that move the rocks in the cool and brittle lithosphere near the Earth's surface. These motions exert great forces, strong enough to rip continents apart, but the rate of movement is extremely slow on an annual basis (measurable in inches or centimeters per year).

Whereas the fluid-like state of rocks in the asthenosphere move slowly, the solid, brittle material in the lithosphere builds up great pressure (stresses) and the rocks will strain under the pressure until the point that they rupture, causing earthquakes that propagates as a shock waves through the Earth.

3.16: Historical Observations leading up to Plate Tectonics Theory

Historical Observations leading up to Plate Tectonics Theory

Much of the background work related to the modern theory is the culmination of hundreds of years of world-wide exploration and geologic observations that go back several centuries. Highlights include:

* **Early Maps of the World**: Maps compiled by early global explorations resulted in the observation of the matching shapes of the coastlines on opposite sides of the Atlantic Ocean. These similarities were noted from early maps by by a Flemish cartographer named **Abraham Ortelius** in 1596 who first suggested that it looked like the continents had drifted apart. Geographers preparing maps noted that charts of land masses that the shape continents of the world fit together like a jig-saw puzzle. It took centuries before an organized effort started to analyze the data!

* Observations of the location of the **world's volcanoes** (maps) and lead to the recognition of the **Ring of Fire (Figure 3.26).** As we will see in the next chapter, the volcanoes of the Ring of Fire relate directly to Plate Tectonics Theory.

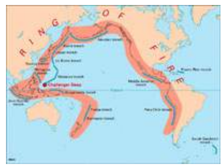


Figure 3.26. The **Ring of Fire** is a zone of volcanoes, numerous earthquakes, and offshore deep trenches.

Continental Drift

The **Continental Drift Hypothesis** was a prelude to the modern Plate Tectonics Theory.

The **Continental Drift Hypothesis** was proposed by a German astronomer and meteorologist named **Alfred Wegener** (1880-1930), but based on research by other earlier observers. The Continental Drift Hypothesis was based on observations that the continental coastlines on either side of the Atlantic Ocean seemed to match up. More importantly, the drift hypothesis was supported by similarities of fossils, rocks, and mountain belts on both sides of the Atlantic, as explained further below.

Wegener's hypothesis was that all the observable continents bordering the Atlantic and Indian Oceans had once assembled into a single supercontinent that he named **Pangaea**. He determined that this great landmass began to break apart about 200 million years ago (Figures **3-27 to 3-29**). He said that these continents started moving about 200 million years ago (MYA) and they are still moving. This is amazing because Wegener proposed this more than 100 years ago and it remains correct today. However, the theory was rejected by most scientists at the time.

Figure 3.27. Geographers noted that the continents fit together like a jig-saw puzzle.

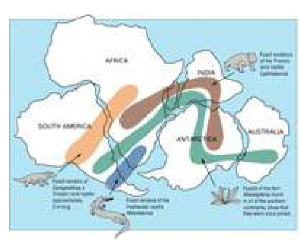


Figure 3.28. Fossil evidence connecting lands of Pangaea about 260 million years ago)

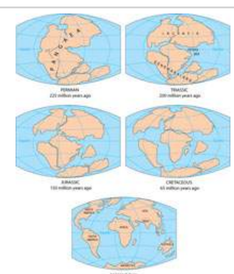


Figure 3.29. The formation and breakup of **Pangaea** over 300 million years.

Pangaea—a supercontinent comprising all the continental crust of the earth, theorized to have assembled from other continental land masses in middle to late Paleozoic time. The assembled landmass, Pangaea, existed through late Paleozoic and through early Mesozoic times before the continents separated and gradually migrated into their current configuration.

Geologic and fossil evidence indicated that some land masses which are now separated may have been together at some point in time. However, nobody could provide a mechanism for the continents to move.

Fossil evidence supporting Continental Drift includes:

• Similar fossil sites occur on different continents, when Pangaea was together. Examples include Mesosaurus and Glossopteris fossils (Figure 3.28). **Mesosaurus** is a reptile from the Early Permian of southern Africa and South America. **Glossopteris** are fossilized woody plants from the Permian and Triassic Periods.

• Fossils and organic deposits in sedimentary rocks provide information about the geologic features, the climate, and flora and fauna for an area through geologic time.

• In many regions, fossils are found presently in climates and locations that could not have supported them. Example: fossil corals found in marine sediments of northern Alaska. This is because continents drifted from one climate zone to another, carrying fossils with them.

• Fossils show that marked **divergent evolution** occurred at times when the continents were split apart. This can account for the **present-day distribution** of plants and animals around the globe (especially marsupial mammals).

Geologic features supporting Continental Drift include:

• **Old mountain ranges** cross continental boundaries that are now separate but were once together. (Examples: The **Appalachian Mountains** in eastern US and **Atlas Mountain** of northwest Africa).

• The formation of rocks in climates that could not support those types of rocks. Example: Permian-age rocks displaying evidence of **glaciation** in found in southern India.

The **Sedimentary Rock Record** in many regions around the world reveals the progression of changes that took place as continental landmasses split apart. For example, When Africa pulled apart from South America the sediments reveal:

• First, the land was uplifted, **rifted apart**, and a very large lake filled in the low region.
• The rift partially opened to the ocean from the north.
• Finally, it opened completely to the open ocean to the south.
• This occurred between 60 and 100 million years ago.

* Similar processes are occurring in the African **Rift Zones** and **Red Sea** region today!

3.17: The Atlantic-Pacific Paradox

The Atlantic-Pacific Paradox

Early exploration of Atlantic Ocean basin showed that it is surrounded mostly by gentle coastal planes and old, worn down mountain ranges, and had relatively little volcanic or earthquake activity in other regions. In contrast, the Pacific and other ocean regions were much less understood. In contrast, early exploration of the Pacific Ocean basin brought awareness of the region described as the **Ring of Fire** (see **Figure 3.26**). In most places around the Pacific Rim's Ring of Fire the transition zones of the continents to the deep ocean has large numbers of active or recently active volcanoes. This region also experiences large numbers of tremendous earthquakes. In most places where volcanic arcs (island belts and mountain ranges composed of volcanoes) appear on land, there are also very deep-water trenches located not too far offshore of the coastline.

Why was Continental Drift rejected by the Scientific Community?

Although Continental Drift intrigued the scientific community, it was largely rejected because there was no data to explain all the observable facts about how or why continents moved across ocean basin. This was largely because in the early 20th century very little was known about the nature of the world's ocean basins nor the physical characteristics of the structure of the Earth's asthenosphere and lithosphere. Many other hypotheses existed in the scientific community well into the late 20th century, but these conflicting ideas have faded in significance with the advances of the newer Plate Tectonics Theory. Wegener's hypothesis was rejected because he proposed a mechanism for continental drift, which turned out to be wrong.

• His mechanism was complicated and involved the force of the earth spinning and the tides.
• He was dismissed as a crank and his detractors said that he carefully picked his data to fit his hypothesis.
• At this point in time the entire Earth was solid, so it was difficult to formulate a mechanism for continental drift.

3.18: Seafloor Discoveries in the 20th Century

Seafloor Discoveries in the 20th Century

Although using sound to measure the depth of water was invented early in the 19th century, advanced methods were not widely used to intentionally map the seafloor until WWI and used in association with ship and submarine warfare activities. **SONAR** (short for **SO**und **NA**vigation & **R**anging) is a system for detecting objects under water and for measuring the water's depth by emitting sound pulses and detecting or measuring their return after they reflect off the seafloor. Sonar investigation revealed the extent of the **Mid-Atlantic Ridge** in the center of the Atlantic Ocean basin (Figure 3.30).

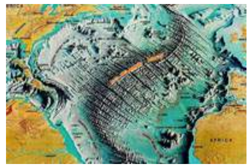


Figure 3.30. Seafloor bathymetry of the Atlantic Basin (mapped with SONAR) showing the **Mid-Atlantic Ridge**, a submarine mountain chain in the middle of the Atlantic Ocean.

Seismology has revealed important aspects of how lithospheric plates interact with each other, how plates form and are destroyed. **In the 1930's** a Japanese scientist, **Kiyoo Wadati**, thought that deep earthquakes and volcanoes in Japan (and the Pacific Rim) could be explained by continental drift motions. Over time, as earthquake detection equipment (**seismographs**) were set up around the world and data collections were compiled, it became apparent that there were patterns that showed that nearly all earthquakes occurred in zones where chains of volcanoes and mountain ranges were most actively forming around the **Ring of Fire**, across southern Europe into east Asia, and along narrow belts beneath the oceans associated with mid-ocean ridges (Figure 5.30). **Hugo Benioff** (a USGS earthquake scientist) expanded on Kiyoo Wadati's ideas and plotted the location of deep earthquakes to delineated large geologic structures associated with the Pacific's Ring of Fire. It was recognized that earthquakes and volcanoes did not occur at random but at specific and concentrated spots on and within the Earth's crust (Figure 3.31).

Earthquakes under Japan reveal a pattern.

Figure 3.31. Earthquakes under Japan revealed a pattern named a Benioff-Wadati Zone.

3.19: Paleomagnetism and the Study of the Seafloor

Paleomagnetism and the Study of the Seafloor

Earth's magnetic field has been a curiosity since ancient times. The magnetic **compass** was first invented as early as the Chinese Han Dynasty (about 206 BC). The compass was used during China's Song Dynasty for military navigation by 1044 AD, and for maritime navigation by about 1117 AD. Today, the source of the magnetic field is presumed to be from the movement of molten iron and metals in the earth's core. The spinning of these liquid metals produces electric currents in the same manner as an electric coil produces a magnetic field. The magnetic field extends into space (see **Figure 3.11**). Over time, these currents fade, change direction, or intensify elsewhere, causing the magnetic poles to migrate or reverse the magnetic polarity of the entire planet (events called **magnetic reversals**).

Magnetometers (devices used to detect and measure the strength of magnetic fields) were used in World War II to search for submarines. It was noted from these investigations that the seafloor preserved large magnetic anomalies that lined up parallel the **Mid-Atlantic Ridge (Figure 3.32)**. These investigations showed that the Earth's magnetic field has reversed many times through Earth history; magnetic reversals happened over periods ranging from thousands to millions of years. The chronology of magnetic reversals through geologic time are now well know.

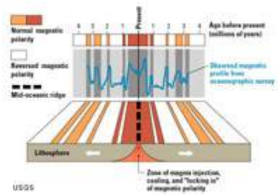


Figure 3.32. Mapping of the seafloor with magnetometers revealed lines of magnetic reversals on opposite sides of mid-ocean ridges. (USGS)

Paleomagnetism is the study of the fixed orientation of a rock's magnetic minerals as originally aligned at the time of the rock's formation (simply, ***old magnetism***). Paleomagnetism is usually the result of **thermoremanent magnetization** (magnetization that occurs in igneous rocks as they cool below a certain temperature (called the **Curie Point**). As rocks (with iron in them) solidify, the magnetism direction points to the magnetic pole (which is currently north).Igneous rocks may keep their magnetic orientation they obtain at the time they form (if they are not altered). This magnetic signature is preserved, even if the landmass the magnetic rocks are on is moving. Mapping of the seafloor with magnetometers revealed lines of rock preserving history of **magnetic reversals** running **parallel to the mid-ocean ridges** [first published by Vine & Matthews, 1963] **(Figure 3.33)**. With decades of studies of paleomagnetism of seafloor rocks and volcanoes around world the chronology of magnetic reversals through geologic time are now well known.

Paleomagnetism studies provide important data for resolving the age of rocks, where they formed, and where they have traveled over time. Fundamental information about the formation of new oceanic crust and explains the migration of landmasses over time. Paleomagnetism studies are fundamental to the theory of **seafloor spreading**.

Seafloor Spreading

Seafloor spreading is the processes associated with the formation of new areas of oceanic crust, which occurs through the upwelling of magma at mid-ocean ridges and its subsequent outward spreading movement on either side. As new rock forms along spreading centers it becomes attached to the lithospheric plates on either side of the **spreading centers**. Because the Earth's magnetic field is reversing frequently through geologic time, the rocks forming and moving away from spreading centers preserve the pattern of preserved magnetic orientation. This pattern turns out to be mappable (Figures 3-32 and **3-33**).

Paleomagnetic studies of the world ocean basin resulted in the discovery of mid-ocean ridges and spreading centers. These undersea mountain ridges extend for 10s of thousands of miles beneath portions of the global ocean basins (**see Figure 3.18**, **3-30,** and **3-36** below). Seafloor spreading became a mechanism to explain continental drift. However, seafloor spreading alone does not explain the formation of continental landmasses through geologic time.

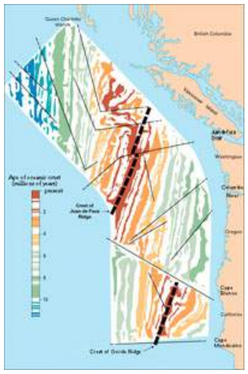


Figure 3.33. West Coast **magnetic reversals** reveal the location of spreading centers and fault boundaries in the ocean basin offshore of California, Oregon, Washington, and British Columbia

3.20: Another Geologic Paradox- The Rocks of the Ocean Floors are Much Younger than the Rocks of the Continents

Another Geologic Paradox: the rocks of the ocean floors are much younger than the rocks of the continents

In the late 1940's methods of **radiometric-age dating** were developed. After WW2, samples of ocean crust and sediments were collected from the sea floor throughout the world ocean basins and analyzed using both **radiometric-age dating** (decay of radioactive isotopes) and **relative dating** (using **microfossils** derived from seafloor sediment coring samples). Geologic data indicated a relatively young sea floor (**ocean crust**), where the oldest is about **200 million years old**. However, data also indicated very old continents, where the oldest was more than **3 billion years old**!

- Continental crust is made up of rocks measured into the **billions of years**, especially in the stable **craton** cores of **continental shields** (mostly in the central region of continental landmasses) (Figure 3.34).
- The **oldest ocean crust is about 200 million years (Figure 3.35)** The oldest ocean crust is found in locations near continental land masses (such as the east coast of North America) and near volcanic island arcs along the western side of the Pacific Basin.

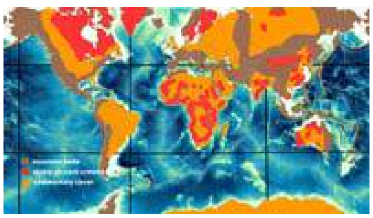


Figure 3.34. Map of the world showing **continental mountain belts** (brown) and stable **ancient cratons or shield regions** (orange and red, the oldest rocks being red). Ocean bathymetry (in shades of blue) show mountain ranges **(mid-ocean ridges)** beneath the oceans.

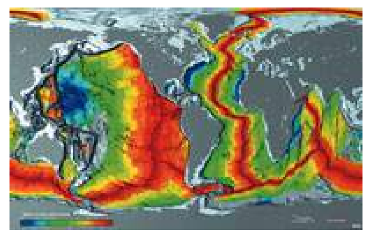


Figure 3.35. Geologic and geophysical mapping show that the crustal rocks beneath the modern oceans are less that 200 million years, with the youngest rocks (and some actively forming) occur along **mid-ocean ridges**.

As shown in Figures 3-33 to **3-36,** the maps shows the bathymetry and geologic ages of the ocean basins, highlighting long undersea mountain ranges (**mid-ocean ridges**) that extend thousands of miles near the middle of the Atlantic and Indian Oceans, and part of the eastern Pacific Ocean basin. Although early oceanographic studies revealed mountains hidden beneath the oceans, a complete map of the ocean floor wasn't compiled in detail until starting in World War II as part of naval research for submarine warfare. Although some data regarding the age of continental rocks was partly known before the war, much detail of the geology of continental regions wasn't available until global energy and mineral resource mapping was conducted in the decades following the war.

What was discovered was that, in general, most of **the oldest rocks found in the Earth's crust occur in the center of continental landmasses**, such as in the **Canadian Shield** region of North America, Greenland, the central parts of Africa, South America, Australia, and Siberia, and the peninsula of India (Figure 3.34).Thee regions have rocks that range in age to typical **over a billion years** to the oldest know rocks of about **4.4 billion years** (from Australia). These regions are called **continental shields**. Note that it is within these regions that most of the world's most economically significant gem and precious metal deposits are found!

Surrounding the **continental shields** on most of the continents are belts of mountain ranges and coastal plains that contain rocks younger that a billion years in age. The higher mountain ranges, including the Himalayan, Andes, Alps, and Rocky Mountains are considered to be actively forming and are dominated by rocks that have formed after the breakup of the supercontinent Pangaea (mostly after about 300 million years ago). There are some older mountain ranges, like the Appalachian Mountains in eastern North America, that appear more worn down, and the areas are relatively inactive geologically (having fewer earthquakes and little recent volcanic activity). By comparison, the landscapes within the shield regions are nearly completely worn down and are no longer geologically active. However, these shield regions display characteristics of having once been parts of mountain ranges that existed a billion or more years ago. In many areas parts of the shield regions, ancient mountain ranges have formed, eroded away, and reformed again and again, but today, in contrast, there is very little geologic activity (volcanoes or earthquakes).

Figure 3.35 is a map showing the age of rocks found in the crust beneath the ocean basins of the world. Again, beginning in earnest during World War II and culminating in the Cold War, geophysical mapping and sampling of materials from the sea floors around the globe showed that rocks on the ocean basins were very significantly younger that rocks found on the continents, with ages ranging in only about **200 million** for the oldest rocks beneath ocean basins! In all cases, the age of seafloor grows progressively younger approaching **the mid-ocean ridges**. Using seismic data and deep-sea submersible exploration craft, the mid-ocean ridges were discovered to be belts of undersea volcanic areas. **New ocean crust** was (and is) forming along the mid-ocean ridges (Figure 3.36). In contrast, **old ocean crust** is sinking back into the mantle or being added onto some continental margins (discussed in **Chapter 4**).

Figure 3.36. Map showing the location of the world's **mid-ocean ridges**. These undersea mountain ranges are the longest on earth. Mid-ocean ridges (where new ocean crust is forming) is found beneath portions of all the world's ocean basins.

3.21: Quiz Questions - Chapter 3 - Structure of the Earth

1. What layer of the atmosphere does all weather take place?
a. thermosphere
b. mesosphere
c. stratosphere
d. troposphere

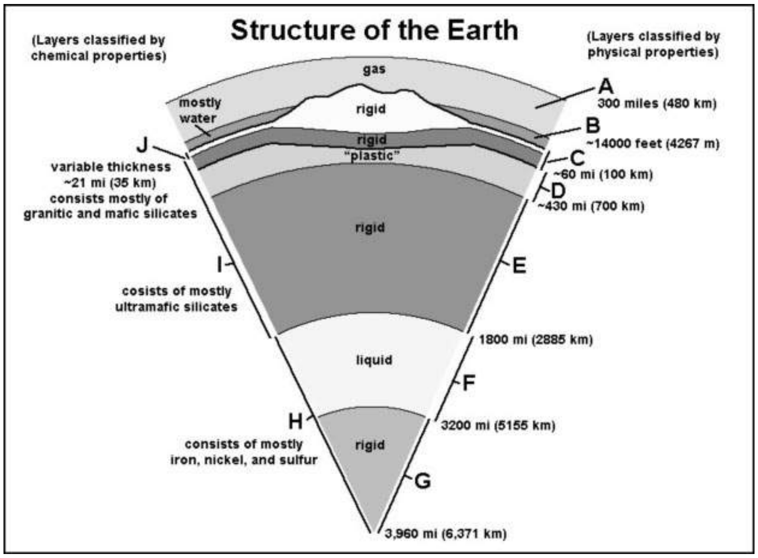
2. The solar wind is a stream of energized, charged particles flowing outward from the the Sun's upper atmosphere (the corona). When these particles encounter the Earth's magnetic field they are deflected toward the polar region where the stream into the atmosphere causing the night sky to light up. In the southern hemisphere these light patterns in the sky are called:
a. the aurora borealis
b. a corona ejection
c. the aurora australis
d. a solar storm

3. The part of the Earth that includes all the frozen water (including glaciers, sea ice, snow, freshwater ice, and frozen ground [permafrost]) is called:
a. the asthenosphere.
b. the hydrosphere.
c. the troposphere.
d. the cryosphere.

4. The name given to the regions of the Earth occupied by living organisms is called:
a. the hydrosphere.
b. the biosphere.
c. the troposphere.
d. the mesosphere.

5. The rigid outer part of the earth, consisting of the crust and upper mantle. is a relatively cool, rigid shell and averages about 100 km in thickness and called the:
a. asthenosphere.
b. lithosphere.
c. stratosphere.
d. cryosphere.

Questions 6-9 apply to the **Structure of the Earth Diagram** below.
Note: layers on left are classified by chemical properties, layers on right are physical properties.



Match letters (A to J) to features on the Structure of the Earth diagram.
6. Which layer represents Earth's crust?
7. Which layer represents the lithosphere?
8. Which layer represents the asthenosphere?
9. Which layer or layers represent the core?

10. **Magnetic reversals** have happened many times in Earth's past. What is something we might observed if a magnetic reversal were to happen today?
a. A magnetic compass would point to the South Magnetic Pole instead of the North Magnetic Pole.
b. Earth would flip on its rotational axis.
c. Earth's magnetic field might suddenly runs east/west instead of south/north.
d. All choices are correct.

11. Studies of the alignment of iron-rich minerals in old volcanic lava flows around the world have shown that:
a. the Earth's magnetic poles may have moved.
b. the Earth's magnetic poles have switched alignment many times in the past.
c. the continents have moved over time.
d. All choices are correct.

12. On a reverse fault:
a. the hanging wall moves up relative to the foot wall.
b. the foot wall moves up relative to the hanging wall.
c. the foot wall moves horizontally relative to the hanging wall.
d. the hanging wall moves down relative to the foot wall.

13. The location below the Earth's surface where an earthquake rupture starts is called:
a. the epicenter.
b. the focus.
c. the fault line.
d. All choices are correct.

14. Which of the follow statements is NOT true?
a. An earthquake fault is an active fault that has a history of producing earthquakes.
b. Not all faults are active or are considered earthquake faults.
c. All faults are actively capable of producing earthquakes.
d. Active earthquake faults can produce both earthquakes and creep.

15. A **seismograph** is a device used to record earthquake shaking and is used to determine:
a. the distance from an earthquake focus.
b. the magnitude of an earthquake.
c. the intensity of an earthquake.
d. All choices are correct.

16. The first to arrive at a distant location from an earthquake is:
a. a shear (S) wave.
b. a compression (P) wave.
c. a sound (S) wave.
d. a rupture.
e. none of the above.

17. The measure of ground shaking describing the local severity of an earthquake in terms of its effects on the Earth's surface and on humans and their structures is called:
a. earthquake magnitude.
b. Richter scale.
c. earthquake intensity.
d. P-waves and S-waves.

18. What can seismic (P and S) waves data tell us?
a. Parts of the Earth's interior are not solid.
b. The depth, location, and relative strength of an earthquake.
c. The average density of each layer in the Earth.
d. All of the above.

19. The Mohorovicic discontinuity (or Moho) is:
a. the boundary between granitic continental crust and basaltic oceanic crust.
b. the boundary surface between the Earth's crust and the mantle, lying at a depth of about 6–7 miles (10–12 km) under the ocean bed and about 24–30 miles (40–50 km) under the continents.
c. the boundary between Earth's rigid mantle and the liquid core.
d. a fault boundary between two plates in a subduction zone.

20. Isostasy allows continental crust to rise above sea level because it is:
a. thinner and denser than ocean crust.
b. mostly composed of volcanic basalt in composition compared with ocean crust.
c. thicker and contains more granitic rocks than ocean crust.
d. all of the above.

21. This extensive region that surrounds an ocean basin gets its name because experiences more major earthquakes and volcanic eruptions than other regions of the world.
a. Himalayan Mountains.
b. The Atlantic Ocean basin
c. The Arctic Ocean basin
d. The Ring of Fire

22. The **theory of continental drift** (a theory proposed by Alfred Wegener in 1912) was supported by what kind of evidence?
a. Matching fossils occur on different continents on opposite sides of ocean basins.
b. The shapes of continent margins on opposite sides of ocean basins appear to fit like a jigsaw puzzle.
c. Rocks of similar age and composition and mountain ranges on different continents appear to match on opposite sides of ocean basins.
d. all of the above

23. The most conclusive proof for continental drift was provided by:
a. the coastlines of continents on a world map.
b. evidence that sea-floor spreading creates new ocean crust beneath ocean basins.

c. identical fossils and rocks found on two separate continents.
d. similar climate patterns on opposite sides of ocean basins.

24. The ancient supercontinent in Alfred Wegener's continental drift hypothesis when all the continents were assembled into a single landmass was called:
a. Panthalassa.
b. Pangaea.
c. Gondwanaland.
d. Laurasia.

25. Geologic mapping of the world shows that much of the bedrock on all continental landmasses around the world range in ages that are exceedingly old (hundreds of millions to billions of years). However, the oldest rocks found in the ocean crust beneath the world’s ocean basins are:
a. about 2 million years and younger.
b. about 20 million years and younger.
c. about 200 million years and younger.
d. about 2 billion years and older.

CHAPTER OVERVIEW

4: Plate Tectonics

4.1: Plate Tectonics

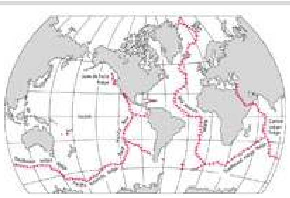
This chapter reviews the major concepts of **Plate Tectonics Theory**. Concepts of plate tectonics evolved as questions about the "**structure of the Earth**" and the age of the ocean basins were resolved over time (discussed in Chapter 3). **Plate tectonics** is a fundamental theory that captures the science of how the earth works: why "things" are where they are, how they formed, and how they evolved, over time, to become features within the world that we see today.

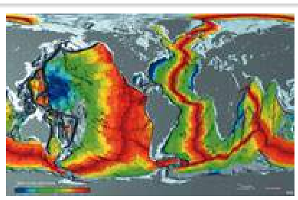
The appearance of the world as we see it today is a result of the accumulative effects of all geologic processes that have happened in the past. Some of these processes occur rapidly (such as volcanic eruptions, earthquakes, great storms and flood, and occasional asteroid impacts). However, most features we see on the landscape or in a region (or larger features like continents mappable on a global scale) involve processes that are far grander, operating both near and deep below the surface, and taking place gradually over long periods of time (in periods measured in millions to hundreds-of-millions of years). For instance, the coast lines of northwest Africa and the eastern United States are currently moving apart at a rate of about **2-4 inches a year**. However, about 200 million years ago the two continents were joined together before the opening and formation of the **Atlantic Ocean Basin**! Plate tectonics theory helps explain most of the processes and grand landscape features we observe around the world today, both on land and beneath the oceans.

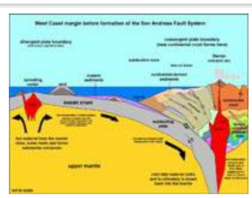
Figure 4.1. Nearly all geologic processes observed on Earth "fit" in some way into "**Plate Tectonics Theory.**"

Over time, the newly formed ocean crust cooled and moved slowly away from the **mid-ocean ridges (Figure 4.2)**. These areas where new crust is forming and moving apart are called **spreading centers**. New ocean crust forms and moves away from spreading centers over time (Figure 4.3). Since new ocean crust is forming, old crust has to be disappearing somewhere, and it turned out that the old crust was sinking back into the mantle along extensive fault zones associated with the **deep ocean trenches**. These great fault systems are called **subduction zones** (illustrated in two **plate-tectonics models**, Figures 4-4 and **4-5**). Subduction zones are locations where cool and dense ocean crust sinks back into the **mantle (asthenosphere)**, as it sinks it heats up. Water and gases trapped in the sinking crust cause partial melting (forming magma) which rises (due to its lower density through zones of weakness in the **lithosphere**. Some of this rising magma accumulates in **magma chambers**, whereas some of it may actually rise all the way to the surface to form **volcanoes**. Earthquakes caused by friction along the subduction zone reveal that crust is slowly sinking back into the mantle.

Figure **4-34** is a map of Earth's **lithospheric plates** (the **inferred** plate boundaries around the world). Figure 4.35 illustrates the basic components of the **plate tectonics model**. These diagrams illustrate where new crust is forming along spreading centers along mid-ocean ridges, and where old ocean crust is being destroyed or recycled into new continental crust along subduction zones. Spreading centers and subduction zones are mapped as **plate boundaries**, but there are features that are also considered plate boundaries where crust is neither forming or being destroyed but are rather moving past each other or crushing into each other. These regions have earthquakes but little or no volcanic activity.







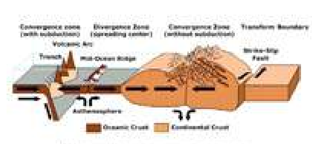


Figure 4.2. Map showing the location of the world's **mid-ocean ridges**. These undersea mountain ranges are the longest on earth. Mid-ocean ridges (where new ocean crust is forming) is found beneath portions of all the world's ocean basins.	Figure 4.3. Geologic and geophysical mapping show that the crustal rocks beneath the modern oceans are less that 200 million years, with the youngest rocks (and some actively forming) occur along **mid-ocean ridges**.	Figure 4.4. Plate tectonic model	Figure 4.5. A simplified model of plate tectonics showing types of **lithospheric plate boundaries**.

In 1962, a classic paper written by **Harry Hess** (a geologist and Navy submarine commander during World War II) who described that the continents did not plow through the oceanic crust (as proposed by **Wegener's [1915] Continental Drift Theory**), but instead, proposed that they were riding with the oceanic crust like a conveyor belt. This idea was combined with the works of others including: Vine and Matthews (1963) (see Figure 3.23), and **Tuzo Wilson** (who first reported his theory about the origin of plate boundaries in the early 1960s). Many any other contributions from scientists around the world to put the The**ory of Plate Tectonics** together.

4.2: Plate Tectonics Theory

Plate Tectonics Theory

Today, **Plate Tectonics Theory** explains the large-scale motions of Earth's **lithosphere**. Plate tectonics theory builds on concepts of "continental drift." It was the global efforts of seafloor exploration following World War II resulted in the development of **seafloor spreading theories** in the late 1950s and early 1960s. This exploration effort involved perhaps many thousands of scientists within the "global geoscience community" (geologists, oceanographers, paleontologists, and geophysicists, assisted by world leaders) who systematically gathered information and mapped the world, both on land and underwater. The mechanics of Plate Tectonics Theory were largely resolved as large quantities of data about the age and distribution of rocks beneath the ocean basins were compiled from ocean drilling programs and geophysical studies of the ocean crust from around the world. Seafloor mapping, along with the study of volcanoes and earthquakes provided the evidence to support plate tectonics theory.

Plate Tectonics Theory helps to explains to some degree almost "*all things geological*" in the observable world, past and present. Plate tectonics expounds that Earth's outer shell (**lithosphere**) is composed of several large, thin, relatively rigid "**plates**" that move relative to one another. Movements along fault systems that define **Lithospheric plate boundaries** produce **most observed earthquakes**.

Figure 4.6. Map showing the location of **lithospheric plates** and **plate boundaries** of the world. Boundaries shown in yellow are divergent boundaries, Those in orange are convergent boundaries. Note that some plates include both continental and oceanic crust.

Watch a video about the **Pacific Ring of Fire and Its Earthquakes (and Volcanoes)** (YouTube video)

4.3: Three Types of Lithospheric Plate Boundaries

Three Types of Lithospheric Plate Boundaries (see Figures 4-4 to 4-6)

Divergent boundary (where plates are pulled apart by tensional forces)**—**When plates diverge, spreading centers form creating new oceanic crust. Examples include mid-ocean ridges in world's ocean basins. Spreading centers occur where continents are pulling apart. Examples include the Africa rift zones, Red Sea basin, Iceland, and North America's Great Basin region including the Gulf of California (see discussions below).

Convergent boundary (where plates are pushed together by compressional forces**)**—When lithospheric plates collide... mountains belts form - examples include the Himalayas, Alps, and ancient Appalachian Mountains when the ancient continent of Pangaea formed. When continents collide with ocean crust... subduction zones with deep ocean trenches and volcanic arcs form - examples include the Andes Mountains, Aleutian Islands, Japan, Philippines, Indonesia, the ancient Sierra Nevada and modern Cascades Range in northern California, Oregon, and Washington.

Transform boundary (where plates slide past or are rotational**)—**When plates slide past each other creating fault systems along plate margins. Examples include the San Andreas Fault in California and major faults in Pakistan, Turkey, and along the Jordan River/Dead Sea.

4.4: Divergent Plate Boundaries

Divergent Plate Boundaries

Divergent plate boundaries are locations where tensional forces are pulling things apart. In locations where lithospheric plates are diverging, the rates of divergent motion range from 2 to 17 cm/year.

Spreading Centers along Divergent Plate Boundaries

A **spreading center** is a linear area where new crust forms where two crustal plates are moving apart, such as along a mid-oceanic ridge. Spreading centers are typically seismically active regions in ocean basins and may be regions of active or frequent volcanism (Figure 4.7). Spreading centers are associated with divergent plate boundaries.

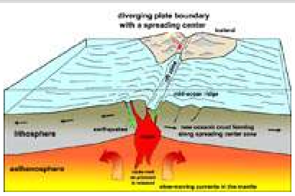


Figure 4.7. **Formation of new oceanic crust** along a **spreading center** associated with a **mid-ocean ridge**. Some spreading centers appear on land. For example, a portion of the **Mid-Atlantic Ridge** is exposed on **Iceland**.

Figure 4.8. Iceland's is an exposed portion of the North Atlantic spreading center. Iceland is splitting along a rift zone where new crust is forming. Of 130 volcanoes on the landmass, 30 are currently considered active.

Seafloor spreading and formation of new ocean crust

Seafloor spreading features and processes include:
• Involves **oceanic crust (OC)** only.
• Tensional forces pull oceanic crust apart (forming faults that split deep into the newly forming ocean crust).
• This forms a **mid-oceanic ridge (MOR)**.
• Volcanic activity along faults and fracture zones allows magma to rise cool on or near the seafloor surface.
• This volcanic activity generates new seafloor/oceanic crust,
• New oceanic crust moves away from spreading center as more is formed.
• Youngest oceanic crust is found near the ridge, oldest (and colder)crust is far away from ridge.
• Uplifts occurs as it is rifted, so MORs are the shallowest part of deep ocean basins.
• The MOR is symmetrical about the ridge.
• Magnetic reversals preserved in volcanic rocks are found along MORs worldwide.
• Sediments thicken away from the ridge (discussed in Marine Sediments chapter).• Hydrothermal vents (i.e.: vents of hot water

called "black smokers") are found in spreading centers.

Ocean Rises vs. Ridges

Spreading center are active at different rates, resulting in different physical characteristics.
A **rise** spreads faster and is less steep, a **ridge** is steeper and spreads slower.
Examples:
• **East Pacific Rise** (see Figures 4-2, 4-3, **4-6**, and **4-9**)
• **Mid-Atlantic Ridge** (see Figures 4-2, 4-3, 4-6, and **4-7**)

• On **Iceland**, the **MOR** rises to the land surface, its rate of spreading is about **15 cm/yr** (Figure 4.8).

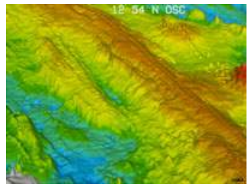


Figure 4.9. The **East Pacific Rise** is a rapidly forming **spreading center** (a mid-oceanic ridge that separates the Pacific Plate to the west from (north to south) the North American Plate, the Rivera Plate, the Cocos Plate, the Nazca Plate, and the Antarctic Plate. See Figure 4.6.

Continental Rifting

Continental Rifting occurs where divergent boundaries form within continental landmasses:
• Involves **rifting** (pulling apart) of **continental crust (CC)** only.
• Forms possibly from **convection** in the **asthenosphere**
• Large amounts of sediments are usually produced in **continental rifting zones**.

• Initially, when a continental rift forms it has *continental processes* such as the formation of large lakes, rivers, and beaches. Later, as it pulls farther apart it can become an **oceanic rift** when sea water floods in. It then becomes a **MOR**.

Present continental rifts include:
• **Red Sea** and East **African Rift System** (Figure 4.10 and **4-11**).

* The **breakup of Pangaea** began with continental rifting starting about 200 million years ago with Africa pulling apart from North and South America. It eventually flooded with seawater and became the new Atlantic Ocean Basin.

Figure 4.10. **Continental rifts** along the Red Sea and Sinai Peninsula (Jordan River, Dead Sea)

Figure 4.41. Africa rift zones are zones where the African continent are being pulled apart. The African Rift basins are spreading centers that are the location of large inland lakes and much volcanic activity. One day in the distant future become seas like the modern Red Sea.

Crustal Extension and Continental Rifting

Crustal extension occurs where a divergent plate boundary develops under a continental landmass on a large scale, associated with **continental rifting (Figure 4.12).**

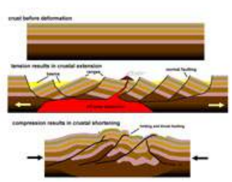


Figure 4.12. Crustal extension and crustal compression.

Both crustal extension and continental rifting are occurring in northern Gulf of California and throughout North America's Great Basin region under Nevada, Arizona and eastward into the Rio Grand River rift valley in New Mexico (Figure 4.13). As the Atlantic Ocean opened, the North American continent was pushed over a spreading center that is now the entire region of Utah, Nevada, Arizona, and parts of New Mexico. Baja California and the Peninsular Ranges of San Diego and Orange counties have been rifted away from the Mexican coastline gradually over about 23 million years. Baja will continue moving northward, eventually crushing into southern Alaska in the distant future!

Figure 4.13. Gulf of California and Great Basin—a region where crustal extension is occurring.

4.5: Convergent Plate Boundaries

Convergent Plate Boundaries

Convergent Plates move together and collide so you have **compressional** forces. They are associated with **active margins**—locations where mountain building is occurring, resulting in numerous earthquakes and andesite (explosive) volcanoes.

A **subduction zone** is a plate boundary along which one plate of the Earth's outer shell descends (subducts) at an angle beneath another (Figure 4.14). A subduction zone is usually marked by a deep **trench** on the sea floor. An example is the Cascadia Subduction Zone offshore of Washington, Oregon, and northern California (see Figure 4.19 below). Most **tsunamis** are generated by subduction-zone-related earthquakes.

Figure 4.14 illustrates how earthquake data reveals the geometry of a **subduction zone**. This diagram show the location and intensity of earthquakes over a period of time in the vicinity of the Tonga Islands in the South Pacific Ocean. A deep ocean **trench** runs along the southeast side of the island chain. Earthquake data shows that a major fault system descends at an angle, extending eastward beneath the Tonga Island and extends of hundreds of kilometers at a steep angle deep into the upper mantle (asthenosphere) where it is presumed that earthquakes cease because rocks are too hot and under intense pressure that it easier for them to fold and flow plastically than to fracture as brittle rock. The earthquake data suggests that the eastern edge of the Australian Plate is being over run by the western edge of the Pacific Plate, and that rocks of the Australian Plate are descending into the upper mantle.

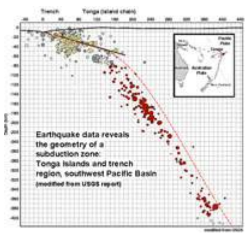


Figure 4.14. Earthquake data reveals the geometry of a subduction zone in the region of Tonga.

Three types of Convergent Plate Boundaries: OC/CC, OC/OC, & CC/CC

Three types of convergent plate boundaries are recognized: .
a) Subduction of ocean crust (OC) beneath continental crust (CC)
b) Subduction of ocean crust (OC) beneath ocean crust (OC)
c) Continental Collisions: continental crust (CC) colliding with continental crust (CC).

a) Subduction of ocean crust (OC) beneath continental crust (CC).

• Denser, thinner OC is pushed or subducted beneath less dense and more buoyant CC.
• A chain of volcanoes formed, called a **continental volcanic arc**.
• Subduction produces both deep and shallow focus earthquakes (with tsunami potential); the largest ever--9.5 magnitude in Peru/Chile Trench in 1960.
• Volcanoes of the **andesite** (explosive) type. Examples include the Andes and the Cascade Range , etc.
• Deep **trenches** form around continents margins. Trenches are especially well developed in regions far away from spreading centers (where the ocean crust is old, cold, and denser, and therefore sinks more rapidly).
• Subduction reduces amount of (and destroys) OC.
• Rates of subduction are up to 15 cm/yr in the active margins of the Pacific Basin.

Examples:
• Andes in South America **(Figure4-15**)
• Cascades in United States (include such volcanoes as Mt. St. Helens, Mt. Rainier, Mount Shasta, Crater Lake and many others)

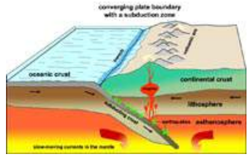


Figure 4.15. **Subduction zone geometry (OC/CC)** is revealed by the location of earthquakes and volcanic activity. Subduction zones are where oceanic crust is destroyed and new continental crust forms. Subduction zones associated with ocean trenches surround much of the Pacific Ocean Basin.

b) Subduction of ocean crust (OC) beneath ocean crust (OC).

• Many similar features as above [OC/CC].
• Denser, older, cooler OC is pushed or subducted beneath less dense, warmer, younger OC.
• Forms island volcanic arcs.
• Deep and shallow (tsunami potential) focus earthquakes
• Volcanoes not as explosive as above with OC/CC, as there is no mixing of CC rocks (called granites). Volcanic rocks are mostly basaltic in composition.
• Subduction reduces amount of (destroys) OC.

Examples:
•**Japan, Tonga Islands**, and **Aleutian Islands** (Alaska)(Figures 4-16 and **4-17**)

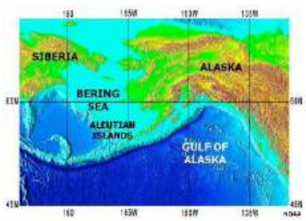


Figure 4.16. **Aleutian Islands** and **Aleutian Trench**.

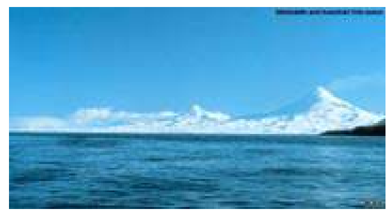


Figure 4.17. Volcanoes of the Aleutian Islands arc.

c) Continental Collisions: continental crust (CC) colliding with continental crust (CC)

When continents collide with other continental landmasses:
• Neither of the CC are subducted,
• Both are very buoyant and want to "float" or ride high.
• This is where you form the very large mountain chains.
• Mountain building occurs with lots of earthquakes; massive erosion also occurs.

Examples
• **Himalayas** (India) beginning 45 million years ago) (Figure 4.18)
• **Alps Mountains** are being pushed up by collisions between Africa (and Italian Peninsula) with Europe.
• **Appalachians Mountains** in the eastern United States (formed when North America collided with Africa about 350-400 million years ago (before the Atlantic Ocean opened later).

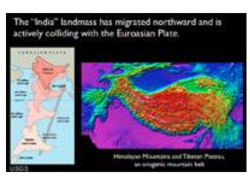


Figure 4.18. Migration of "India" away from ancient Pangaea has led to the collision of continental land masses resulting in the rise of the Himalayan Mountains. In this region, the continental crust on both sides of the plate boundary are too light to sink into the mantle.

4.6: Transform Boundaries

Transform Boundaries

Transform boundaries are locations where one plate is sliding past another.
• Can occur in any crustal type (OC or CC)
• Crust is neither produced or destroyed

Continental Transform Faults

• In continental crust, transform faults can be large destructive faults like the **San Andreas Fault System** in California (Figure 4.19).
• Earthquake magnitudes up to 8.5 have been measured.
• Rates on the **San Andreas Fault (SAF) average 2-5 cm/yr** or LA will be adjacent to SF in about 20 million years!
• Compression(and **uplift**) or tension (and **down-warping**) can occur. The high mountains in Southern California are a result of this kind of compression along the SAF including the San Gabriels, San Jacinto, and San Gorgonio Mountains.

Oceanic Transform Faults
• In ocean crust, smaller transform faults occur perpendicular to the spreading centers.
• They have smaller earthquakes associated with them, when compared with their continental cousins.
• These faults occur where there is a bend or change in the rate of spreading along the MOR.

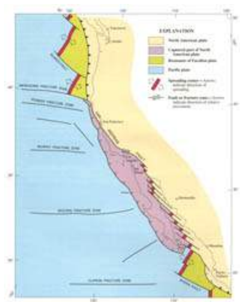


Figure 4.19. The San Andreas Fault system is part of a complex **transform plate boundary** along the West Coast of North America.

4.7: Review- Examples of Plate Boundaries

Convergent boundaries	Divergent boundaries	Transform boundaries
When continents collide mountains belts form. Examples: • Himalayas • Alps • ancient Appalachian Mountains	When plates diverge, spreading centers form creating new oceanic crust. Examples: • mid ocean ridges in world's ocean basins • The African Rift Zones and the Red Sea • The Great Basin and Rio Grande Rift Zone	When plates slide past each other creating fault systems along plate margins. Examples: • San Andreas Fault • Pakistan • Turkey • Jordan River/Dead Sea

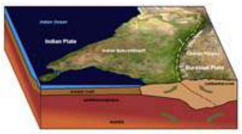
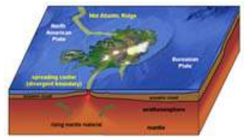

	

Figure 4.20. Himalayan Mountains are a convergent plate boundary	Figure 4.21. Mid Ocean Ridge in Iceland is a divergent plate boundary	**Fig 4-22. San Andreas Fault system is a transform plate boundary**
When continents collide with ocean crust trenches with subduction zones and volcanic arcs form - examples: • Andes Mountains • Aleutian Islands • Japan, Philippines, Indonesia, etc. • Ancient Sierra and modern Cascades	Spreading centers occur where continents are pulling apart. Examples: • Africa rift zones • Red Sea • Iceland • North America's Great Basin	**Transform faults** also occur within plates, but are related to movements that shape the seafloor. Examples: • Dead Sea fault zone, Jordan • India/Pakistan boundary fault • North Anatolian Fault, Turkey

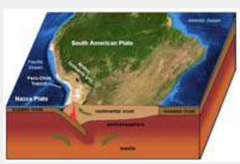
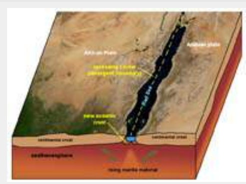
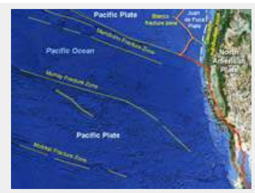

		

Figure 4.23. Convergent boundary along the west coast of South America	Figure 4.24. **A divergent boundary forming in the Red Sea area**	Figure 4.25. **Transform fracture zones offshore of California are within the Pacific Plate**

Important! Continental margins may or may not be plate boundaries! For example, the **East Coast** is in the middle of the North American Plate. **Why?** When North America first split away from Africa and Europe, there was first a continental rift valley; it became a plate boundary between the three expanding lithospheric plates. As new crust formed along the Mid Ocean Ridge spreading center, it became attached to the plates on either side. **Today the North American Continent is part of the larger North American Plate! (**See **Figure 7.29.)**

4.8: Hotspots and Mantle Plumes

Hotspots and Mantle Plumes

A hotspot is a place in the upper mantle of the Earth at which extremely hot magma from the lower mantle upwells to melt through the crust usually in the interior of a tectonic plate to form a volcanic feature.
• These are hotspots beneath the lithosphere caused by rising plumes of hot mantle material.
• Can form volcanoes on surface (examples include **Hawaii** and **Yellowstone hotspots** (Figures 4-26 and **4-27**).
-Volcanoes are mostly **mafic (basaltic**) as these lavas are very hot and very fluid from deep sources.
-Less common are **felsic (rhyolitic)** magmas as they are thicker and less prone to flow.
• Hotspots can occur beneath any crustal type (OC or CC).
• Where they form a trace consisting of a chain of volcanoes (like in Hawaii's **Emperor Seamount Chain, Figure 4.26**)
• Hotspots can exist in about the same place for 10's of millions of years
• The **Hawaiian Hotspot** has existed for about 60 million years; the youngest part of the **Emperor Seamount Chain**.
• The oldest part of the Emperor Seamount Chain has already been subducted (destroyed).
• There are hundred of hotspots located around the world. Some are larger and more active than others.
• Most hotspots are located under the interior sections of lithospheric plates, but some occur near divergent plate boundaries.
• Paleomagnetism in rocks on the ocean floor associated with hotspots provides a method for determining speed and direction of plate motions.
• We are not sure of the exact mechanism that forms hotspots, there are some ideas (see below).

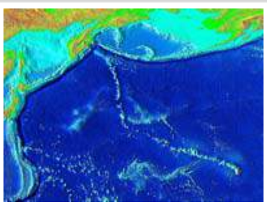


Figure 4.26. Map of the **Hawaiian Hotspot** and the Emperor Seamount Chain in the Pacific Ocean basin.

Figure 4.27. The **Yellowstone Hotspot** is beneath the North America continent and is slowly migrating eastward as the continent is moving westward.

Yellowstone National Park Hotspot:

• The Yellowstone hotspot currently under continental crust (Figure 7.50).
• Yellowstone is a very large and complex supervolcano.
The Yellowstone supervolcano is at the eastern end of a long chain of progressively older supervolcanoes that formed along the trace of the Snake River Plain (Idaho, Washington, and Oregon)
• The hotspot had formed volcanoes of both basaltic and rhyolitic composition.
• Has had large rhyolitic eruptions 3 times in the last 2 million years
• This hotspot appears to have been present for less time than the Hawaiian hotspot (about 17 million years).

Hot topic: Are hotspots related to "astroblemes" (large asteroid impacts)?

Earth has been hit by many asteroids throughout the geologic past. **If Earth didn't have an atmosphere and active plate tectonics it would appear heavily cratered like the moon!**

Current research suggests that massive asteroid impacts can deeply penetrate and fracture the lithosphere, allowing craters to flood with lava—the magma generated by both the impact and material flooding upward to the surface from deeper down. The question is, do **astroblemes** turn into **hotspots**? Also, it has been suggested that shock waves from a massive impact can travel through the Earth and will concentrate energy at the "**antipoles**" - resulting in deep fracturing of the lithosphere, resulting in massive volcanic eruptions. Examples of two possible "antipole" eruptions include the formation of the **Deccan Traps** in India (opposite the K/T boundary impact ~66 million years ago in the Yucatan region of Mexico. Another massive flood eruption occurred about 250 million years ago, forming the massive **Siberian Traps** (massive flood basalts that formed about the time of the great end-of-Permian extinction).

4.9: What drives plate motions?

What drives plate motions?

• Researchers agree that convective flow in the mantle is the basic driving force of plate tectonics (Figure 4.28).

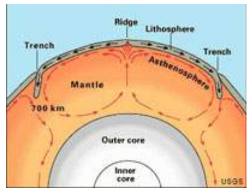


Figure 4.28. Mantle convection is the driving force of motion of lithospheric plates. Much of the convection motion may be in the upper mantle, but it is likely to extend deep into the earth's molten outer core.

Forces that drive plate motion:
• **Slab-pull** - the slow pull of mantle material where is moves from a rising location to a sinking location.
• **Slab-suction** - The high density of cold ocean crust sinking into the mantle pulls crust with it.
• **Ridge-push** - new ocean crust is warm and tends to rise above the ocean floor, pushing older cooler crust away

Plate tectonics model explains many aspects of the geometry of continents and ocean basins and the processes creating new oceanic and continental crust. Material that does not become incorporated into the lithosphere sinks and becomes incorporated back into the mantle.

Importance of plate tectonics
• The theory provides explanations for many of earth's major processes
• Explains the geologic distribution of earthquakes, volcanoes, and mountains
• Explains the distribution of ancient organisms and mineral deposits
• Plate tectonics are responsible large volumes of oil and gas deposits we enjoy today. Think about how your life and society would be different if we only had a mere fraction of the hydrocarbons we currently have and use.

4.10: How does Plate Tectonics explain why continental landmasses are so old (compared to ocean crust)?

How does Plate Tectonics explain why continental landmasses are so old (compared to ocean crust)?

The interior of the earth is very hot—the source of this heat is thought to be left over from the formation of the planet several billion years ago. As shown in Figure 4.28, the combined effect of the internal heat of the Earth and the force of gravity drive convection currents within the Earth . Heat things up, they expand, become less dense, and the material rises. Cool things down, they condense, increase in density, and the material sinks. This can be easily demonstrated the way hot air balloon rise and fall, or the way currents move when water is heated, or the way currents within a boiling pot of soup rises and sinks when it cools (Figure 4.29).

Figure 4.29. Currents in boiling soup demonstrates convection. The "**broth**" rises, cools, and sinks (like the formation and destruction ocean crust over time). In contrast, the bubbly "**froth**" builds up in patches over where cool soup sinks back into the pot. The buildup of froth in patches is similar to the way continents build up over time.

When new ocean crust forms in spreading centers, it is still hot for a time, but it eventually cools by having contact with the cold, deep ocean waters. As a result, old ocean crust is enriched in dense minerals. As it ages, it also absorbs water from the ocean and is becomes blanketed with marine sediments. Where subduction takes place, cold, dense ocean crust sinks back into the mantle. However, as the old crust sinks, it heats up and some of the materials within it melts (assisted by the presence of water and other gases). The materials that melt rise as hot fluids (magma and gases) through the overriding continental crust, forming large magma filled chambers that eventually crystallize into rock at depth, some of which erupts at the surface to form volcanoes. The new rocks that form along the continental margins are less dense than the original oceanic crustal rocks, therefore they eventually isostatically float and rise above the ocean surface, becoming land. Over time, more and more of this lighter rock accumulates first forming volcanic island chains. These volcanic arc and the sediments they shed eventually becomes scraped off and crushed onto the margin of continents—often pushed up as coastal mountain ranges. It this manner, continents grow slowly around their margins in a process called **accretion**. This process explains why the oldest rocks occur in the shield regions of continents and younger material occurs along continental margins.

Continental Accretion

Accretion is a process by which material is added to a tectonic plate or a landmass. This material may be sediment, volcanic arcs, seamounts or other igneous features, or blocks or pieces of continental crust split from other continental plates (Figure 4.30 to 4-31). Over geologic time (measured in millions of years), volcanic arcs form and may be crushed onto (or between) colliding continents along plate boundaries. Pieces of continental land masses may be ripped away and carried to other locations. For instance, Baja California and parts of southern California west of the San Andreas Fault are being ripped away from the North American continent and are slowly being carried northward. These rocks may eventually pass what-is-now San Francisco, and perhaps 70 to 100 million years from now will be crushed and accreted into the landmass currently known as Alaska!

The entire West Coast of North America is made up of massive fault-bounded blocks of crust (called terranes).A terrane is a fault-bounded area with a distinctive stratigraphy (collection of rocks), structure, and geologic history compared with surrounding terranes or land masses.

Another YouTube video:
Continents Adrift An Introduction to Continental Drift and Plate Tectonics. This video explains much of what this chapter reviews.

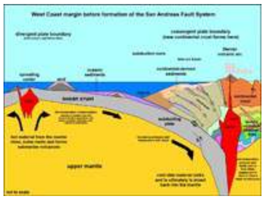


Figure 4.30. **Plate tectonic model**: **Subduction** introduces **oceanic crustal rocks** (including sediments) back into the **asthenosphere**. Water and gas helps low-temperature minerals to melt and rise as, forming new **continental crust** (less dense than oceanic crust). Floating on the Asthenosphere, the continental crustal materials accumulate, forming continents.

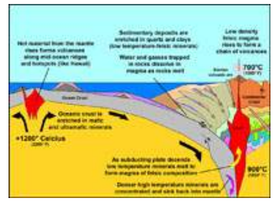
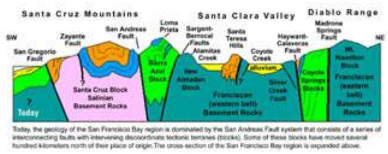


Figure 4.31.The processes associated with subduction lead to the **accretion** (growth) of continents over time. As ocean crust is recycled back into the upper mantle, the lighter material accumulates near the surface along continental margins. Pieces of lithosphere are sometimes scraped off one plate and crushed onto and added (accreted) to another plate.

Figure 4.32. Terranes in the San Francisco Bay area. This cross section of the Santa Clara Valley (south of San Jose, California) shows several fault-bounded terranes. Each of the large crustal blocks formed in locations far south of the Bay Area, but have gradually moved north along the fault system that bifurcates through the region. Over time, California has formed (assembled) by the accretion of terranes (small crustal landmasses) carried in by plate-tectonic processes slowly over geologic time.



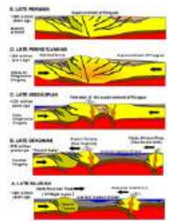
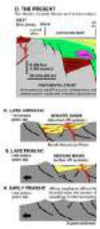
This page titled 4.10: How does Plate Tectonics explain why continental landmasses are so old (compared to ocean crust)? is shared under a not declared license and was authored, remixed, and/or curated by Miracosta Oceanography 101 (Miracosta)) via source content that was edited to the style and standards of the LibreTexts platform; a detailed edit history is available upon request.

4.11: Ancient Parts of Continents- Cratons and Shields

Ancient Parts of Continents: Cratons and Shields

A **craton** is a part of a continent that is stable and forms the central mass of the continent. The craton region of North America includes the region between the Rocky Mountains (to the west) and the Appalachian Mountains (to the east) and include the Canadian Shield.

A **shield** is a large area of exposed Precambrian-age crystalline igneous and high-grade metamorphic rocks that form tectonically stable areas. In all cases, the age of these rocks is greater than 570 million years and sometimes dates back 2 to over 4 billion years. For instance: the Canadian Shield is part of the North American craton region. Shallow inland seas have flooded over and retreated from North America's craton/shield region in the past billion years.

 Figure 4.33. Continental shields and cratons Continental shields contain the oldest rocks preserved in the cores of continental landmasses. These regions formed by processes associated with continental accretion billions of years ago, long before the continents of the modern world existed. These ancient shield are part of the stable parts of continents (cratons) and in many places are partially covered by younger sedimentary rocks (such as in the Great Plains and Midwestern Low Plateau regions of North America).	 Figure 4.34. Formation of Pangaea by closing of the "proto-Atlantic" Iapetus Ocean about 300 million years ago.	**Formation and Breakup of Pangaea** Through geologic time new continental crust forms and accumulates along the margins of continents. The "floating" continental crust eventually crashes into other land masses, and these terranes may assemble into larger continental crustal plates. For instance, the formation of the ancient supercontinent Pangaea assembled through continental accretion. Pangaea later gradually split apart by continental rifting forming the world's continental landmasses that exist today. The geologic story of the formation and breakup of Pangaea are preserved in the rock record all along the Atlantic Margin of North America, Europe, and Africa.	 Figure 4.35. Breakup of Pangaea Atlantic Ocean about 200 millio

4.12: California Geology and Plate Tectonics History

California Geology and Plate Tectonics History

California has been one of most studied geologic region of the world, and for good reasons: earthquakes!

Through its history, California has transitioned from a passive continental margin (before the breakup of Pangaea) to an active margin with the transition to subduction zone activity and the formation of the Cordilleran volcanic chain (during the Mesozoic Era). The Cordilleran Ranges is name for the volcanic arc that formed the Sierra Nevada Range and the Peninsular Ranges extending south in to Baja California). Subduction ended when the ancient **Farallon Plate** was overrun as North America moved westward, overriding the northern end of the spreading center in the Eastern Pacific basin (Figure 7.62). This lead to the formation to the modern transform plate boundary associated with the San Andreas Fault (part of the greater California fault system) and the opening of the Gulf of California.

Figure 4.36. Geologic map of California shows the complexity of the different regions within the state.

Figure 4.37. California earthquakes demonstrate that the region is an active margin

Figure 4.38. The San Andreas Fault System in California showing the locations impacted by major earthquakes.

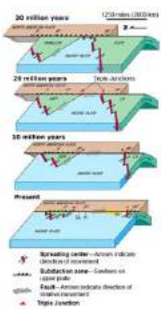


Figure 4.39. Formation of the San Andreas Fault caused by North America Plate overriding the ancient Farallon Plate. Remnants of the Farallon Plate exist as the Juan de Fuca Plate (offshore Oregon & Washington) and the Cocos Plate (off central America).

Assembling California:
California formed gradually over a billion years though processes involving subduction (forming island arcs) and by accretion (attachment of small land masses carried in for other parts of the Pacific Ocean basin). Before the opening of the Atlantic Ocean Basin, California was sometimes a passive margin.

Information about the geologic evolution of California:

Geologic History of Central California
A technical report about the San Andreas Fault System:
Wallace, Robert E., 1990, The San Andreas Fault System, California: U.S. Geological Survey, 283 p.

This historically significant report provides an overview of the history, geology, geomorphology, geophysics, a well known plate-tectonic boundary in the world.

Generalized California Plate Tectonic History:

No rocks older than ~1 billion years exist in CA - all materials in the CA region were subducted or moved e

~1 billion to ~250 million: CA was a mostly a **passive margin** or was accumulating as sediments on an active Periods of mountain building and other plate-tectonic-related activity moved small land masses along the West America moved westward and northward over time.

~250 to ~30 million: subduction and island-arc volcanism dominated the CA coast. An ocean trench existed al exists today, and a subduction-zone-related igneous activity created the great volcanic arc formed the core of t

~30 years ago to present: the San Andreas Fault System began to modify the coastline - transform faulting re

. Baja California split away from the Mexico. Uplift and erosion has exposed the core of the ancient volcanic a throughout the Sierra Nevada and Peninsula Range (Baja and San Diego region).

Supporting evidence of long-distance movement along the San Andreas Fault System.

Figure 4.40. The Pinnacles Volcano originally formed near Los Angeles nearly 23 million years ago. The western half (**Pinnacles Formation**) is now about 215 miles [350 km] north of the eastern half (**Neenach Formation**).

Figure 4.41. Granitic basement rocks in the **Coast Ranges** originally formed as part of an volcanic arc complex in the Mesozoic Era. They were ripped off of SoCal and carried northward by plate tectonics motion.

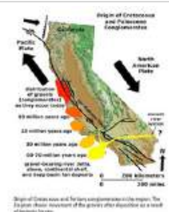


Figure 4.42. Cretaceous-age gravels deposited by an ancient river system in southern California were carried northward from their source area and are now scattered throughout the Coast Ranges.

4.13: Faults, Earthquake Faults, and Earthquakes in Southern California

Faults, Earthquake Faults, and Earthquakes in SoCal (Southern California)

Southern California is a very geologically active region. The maps below are very useful for understanding the nature of earthquake hazards in the region. Figure 4.43 shows the location of major historic earthquakes including regions where the major fault displayed surface ruptures and the number of years between major ground-rupturing events where they've been studied in important locations.

Figure 4.44 is a map showing SoCal's regional seismic activity as illustrated with the location of earthquake data recorded between the years of 1970 to 2010. It is interesting to study this map to see which faults, or fault systems were most active within this time window. Faults that do not show a lot of seismic activity on this map may indicate three possible scenarios: 1) the fault is no longer active, 2) the fault already experience an earthquake, and has released most of its stored up energy before 1970, or 3) the fault is *locked up* and is potentially going to possibly create a major earthquake in the future. It is interesting to study the landscape geography (both topography and bathymetry) relative to the location of the faults on this map. In most cases, the faults are associated with a mountain front (both on land and offshore).

Figure 4.45 shows a map of some of the major earthquake faults in Southern California, displaying characteristics of the faults below the surface. Faults shown as narrow lines are have a vertical orientation, whereas the wider lines show that the faults penetrate into the crust at a low angle (thrust faults). Many of the fault show a component of both horizontal or vertical segments. Almost all the faults are interconnected with other faults in the region. These maps show that the potential for major earthquake may occur both on land or offshore. The ones located offshore could possibly generate massive tsunamis along the SoCal coastline.

Figure 4.43. Map showing the location of California's major historic earthquakes including those that displayed significant ground rupture (before 2016).

Figure 4.44. Map showing the location of major faults and the epicenters of earthquakes (1970 to 2010) in Southern California. The base map of this image displays the rugged nature of the landscape associated with this fault zones as well as the bathymetry of the borderlands associated with islands offshore.

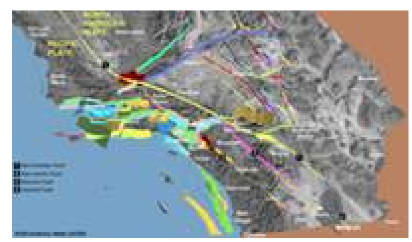


Figure 4.45. Map showing the detail of many of the faults in Southern California. The width of the color-shaded areas of the different faults shows the general angle that these earthquake faults descend into the crust. Vertical fault are narrow lines, whereas low-angle thrust faults are wider. Some faults show both low-angle and vertical components in different segments of the faults.

4.14: Recommend Reading

Recommend reading! Learn more about Plate Tectonics Theory at these online resources prepared by the Smithsonian Institution and U.S. Geological Survey:

This Dynamic Earth *(The Story of Plate Tectonics)* - this on-line booklet is used for teaching plate tectonics at schools and universities around the world. It has a companion map:

This Dynamic Planet *(World Map of Volcanoes, Earthquakes, Impact Craters, and Plate Tectonics*
(see Figure 4.66).

Crustal age of the Seafloor Map: National Oceanic and Atmospheric Administration, National Geophysical Data Center [large image]

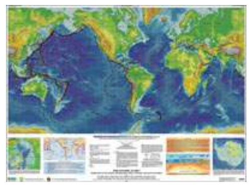


Figure 4.46. **Plate Tectonic Features Map from "This Dynamic Planet."**

Field guides to the San Andreas Fault and other regional faults in the San Francisco Bay region.

Where's the San Andreas Fault? A Guidebook to Tracing the Fault on Public Lands in the San Francisco Bay Region
Where's the Hayward Fault? A Green Guide to the Fault
Geology Field Trips To California's Central Coast

4.15: Quiz Questions - Chapter 4 - Plate Tectonics

1) Mid-oceanic ridges are sites with active volcanism, mild earthquakes, and:
a. they only have thin sediment cover because ocean floor is being newly formed.
b. the new crustal rocks consist of rocks of basaltic composition.
c. they are locations of hot water vents (called black smokers) on the seafloor.
d. all of the above.

2) The theory of plate tectonics helps explain the location of volcanoes and earthquakes. Which of these also describes the current theory of plate tectonics?
a. it combines elements of continental drift and seafloor spreading.
b. it suggests that the lithosphere is divided into pieces, called plates.
c. denser ocean crust sinks below less-dense continental crust along subduction zones.
d. all of the above.

3) A mid-ocean ridge is an example of what type of plate boundary?
a. convergent zone
b. divergent zone
c. transform zone
d. subduction zone

4) The youngest rocks on the ocean floor are typically located near what feature?
a. a mid-ocean ridge
b. a subduction zone
c. on an island arc
d. a deep-sea trench

5) A rift valley is evidence of which kind of plate boundary?
a. convergent boundary
b. transform boundary
c. divergent boundary
d. hotspot

6) What happens where an oceanic plate converges with a continental plate?
a. The denser oceanic plate slides on top of the less dense continental plate.
b. The denser oceanic plate slides under the less dense continental plate.
c. The less dense oceanic plate slides past the denser continental plate.
d. The less dense oceanic plate slides under the denser continental plate.

7) At what type of plate boundary are most high continental mountains formed?
a. convergent boundary
b. hotspots
c. divergent boundary
d. transform boundary
e. mid-ocean ridges

8) What kind of plate movement created the Himalayan Mountains?
a. convergence of oceanic crust with continental crust.
b. divergence between two continental crustal plates.
c. transform movement between oceanic and continental crustal plates.
d. convergence of two plates composed of continental crust.

9) According to the theory of plate tectonics:
a. the asthenosphere is divided into plates.
b. the lithosphere is divided into plates.
c. the asthenosphere moves over the lithosphere.

d. the asthenosphere is strong and rigid.
e. all of the above.

10) In plate tectonics theory, a plate can be made up of:
a. continental lithosphere only.
b. oceanic lithosphere only.
c. both continental and oceanic lithosphere.
d. both continental and oceanic asthenosphere.

11) What kind of plate boundary occurs where two plates grind past each other without destroying or producing new lithosphere?
a. divergent boundary
b. hotspots
c. convergent boundary
d. transform boundary

12) What type of boundary occurs where two plates move together, causing one plate to descend into the mantle beneath the other plate?
a. transform fault boundary
b. convergent boundary
c. divergent boundary
d. hotspots

13) Deep ocean trenches are associated with:
a. mid-ocean ridge systems.
b. transform fault boundaries.
c. subduction zones.
d. rift zones.

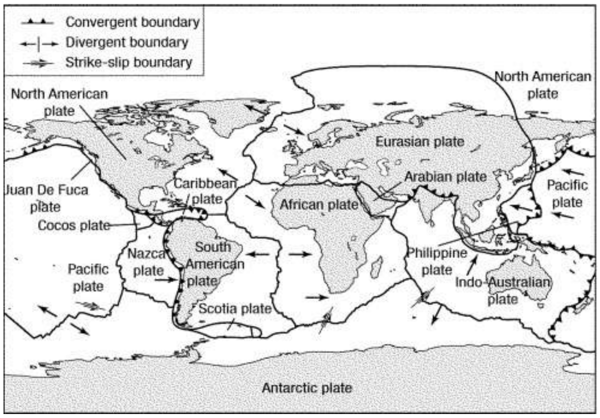
14) The Hawaiian Islands are associated with what type of volcanism?
a. intra-plate volcanism at a hotspot
b. subduction zone volcanism
c. volcanism at a divergent plate boundary
d. volcanism at a convergent plate boundary

15) Almost all deep-focus earthquake occur along or near what type of plate boundary?
a. convergent boundary
b. passive margin
c. transform boundary
d. divergent boundary

16) Which type of plate boundary is in the southern California region?
a. passive margin
b. divergent boundary
c. convergent boundary
d. transform boundary

17) Rift valleys, like the Great African Rift Valley, form as a result of:
a. crustal compression.
b. crustal extension.
c. stress and strain.
d. ductile deformation.

Questions 18 to 20 are related to the Plate Boundary Map below.



18) According to the Plate Boundary Map, what type of plate boundary occurs between the North American Plate and the Eurasian Plate?

a. transform boundary
b. divergent boundary
c. convergent oceanic-continental plate boundary
d. convergent oceanic-oceanic plate boundary

19) According to the Plate Boundary Map, what type of boundary occurs between the South American Plate and the Nazca Plate?

a. transform boundary
b. convergent continental-continental plate boundary
c. a convergent oceanic-continental plate boundary
d. convergent oceanic-oceanic plate boundary.

20) According to the Plate Boundary Map, which of the seven major lithospheric plates consists mostly of oceanic lithosphere?

a. Pacific Plate
b. Antarctic Plate
c. Indo-Australian Plate
d. South American Plate

CHAPTER OVERVIEW

5: Ocean Basins

5.1: Ocean Basins

Ocean Basins

Bathymetry is the measure of depth of water in oceans, seas, lakes, and rivers. Bathymetry data is used to create maps (called "**charts**") of the seafloor. Bathymetric charts are the equivalent of topographic maps on land.

In the past, the depth of water was measured by lowering weighted lines overboard.

Sonar invented in the 1920s and works by reflecting sound waves off the ocean floor. **SONAR** (short for "**SO**und **NA**vigation & **R**anging") is a system for detecting objects under water and for measuring the water's depth by emitting sound pulses and detecting or measuring their return after being reflected off the seafloor.

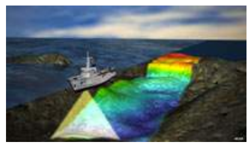


Figure 5.1. Ship equipped with sonar equipment scanning the seafloor.

Major provinces of the ocean floor

• **Continental margins** - these are regions that extend from the coast across shallow shelf regions to the edge of continents where the seafloor descends into deep water.
• **Deep-ocean basins** - This includes parts of the oceans where deep water prevails. Deep ocean basins cover the greatest portion of the Earth's surface.
• **Oceanic (mid-ocean) ridges -** nearly 12,000 miles (20,000 km) of mountain belts run through ocean basins and are associated with divergent plate boundaries (spreading centers).

Each of the major provinces are discussed in detail in the next sections.

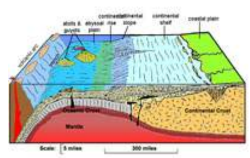


Figure 5.2. Submarine landscape features associated with a continental margin to deep-ocean basin.

5.2: Continental Margins

Continental Margins

Continental margins border continental landmasses are submarine geographic regions located between the shoreline and deep ocean. They are the submerged edge of continents. Continental margins include subregions and submarine geographic features:

- continental shelf
- continental slope
- continental rise
- submarine canyons

The width of continental margins varies: "passive margins" tend to be wider (like the East Coast) compared with " active margins" which tend to narrower (like the West Coast).

Continental margins are influenced by "continental processes" including tectonic uplift and subsidence, and erosion and deposition.

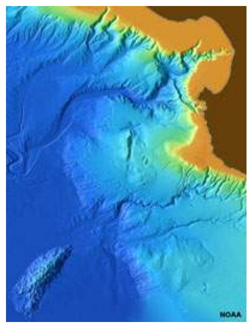


Figure 5.3. Bathymetric view of Monterey Canyon and other seafloor features along the central coast of California

5.3: Continental Shelf

Continental Shelf

A **continental shelf** is a submerged nearshore border of a continent that slopes gradually and extends to a point of steeper descent to the ocean bottom. Continental shelves are submerged extension of the continent.

Continental shelves typically have low relief: they usually have less than 1 degree of slope. Average is about one tenth of one degree.

Continental shelves are influenced by a variety of geologic processes, particularly associated with the erosion and deposition of sediments on beaches, deltas, and carbonates (coral reefs). Shallow water coastal and shelf environments are particularly influenced by the impact of large storms.

Continental shelves are commonly cut by submarine canyons.

Continental resources are areas with important natural resources, particularly fisheries, but also oil and gas, and sand and gravel.

During the peak of the last ice age, the world's continental shelves were mostly exposed coastal plain environments.

A **shelf break** is a general linear trend that marks the boundary between the relatively flat continental shelf and the drop-off into deeper water on the continental slope. **The shelf break generally follows the ancient shorelines that existed at the peak of the continental glaciation periods of the ice age when sea level was as much at 400 feet (120 meters) lower that present sea level.**

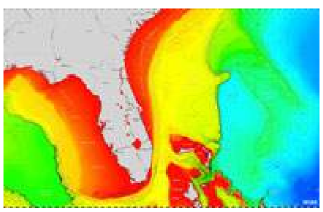


Figure 5.4. The continental shelf around Florida (shown in red) gradually transitions to the continental slope (yellow and green). Florida displays features of a typical "passive continental margin" having wide coastal plains, wide continental shelves, and gentle slopes extending into deep water.

5.4: Continental Slope

Continental Slope

A **continental slope** is the slope between the outer edge of the continental shelf and the deep ocean floor. The continental slope is cut by **submarine canyons** in many locations. The continental slope marks the seaward edge of the continental shelf.

Continental slopes typically follow the boundary between continental crust and oceanic crust.
Continental slope range in steepness from 1 to 25 degrees, average is 4 degrees.
• Pacific (active margin) average >5 degrees.
• Atlantic (passive margin) average about 3 degrees

Continental slopes are cut by submarine canyons. The dominant process influencing slopes are sediment deposition and erosion by turbidity currents (discussed below).

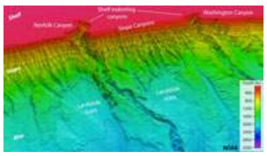


Figure 5.5. The continental slope off the coast of Virginia is cut by numerous submarine canyons that drain sediments to the continental rise at the base of the slope.

5.5: Continental Rise

Continental Rise

A **continental rise** is a wide, gentle incline from a deep ocean plain (abyssal plain) to a continental slope.

A continental rise consists mainly of silts, mud, and sand, deposited by turbidity flows, and can extend for several hundreds of miles away from continental margins. Although it usually has a smooth surface, it is sometimes crosscut by submarine canyons extending seaward of continental slope regions.

The continental rise is generally absent in regions where deep-sea trenches exist where subduction zones are active.

Continental rises feature **deep-sea fans**. In appearance they are much like alluvial fans on land found along the fronts of mountain ranges. Deep-sea fans are accumulations of sediment deposited by **turbidity currents** (called **turbidites**) at the foot of the continental slope. Turbidites are underwater landslide deposits. Over time they build up the large deep-sea fans that coalesce to form the continental rise along some continental margins.

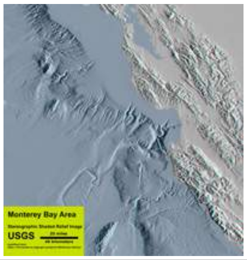


Figure 5.6. Bathymetry of the Monterey Bay offshore region highlights the character of the continental slope and rise.

5.6: Submarine Canyons

Submarine canyons are similar to river gorges carved in mountainous regions on land, however they tend to be both much larger and deeper. Characteristics of submarine canyons include:

• They generally form perpendicular to coastline.
• They are commonly associated with zones of weakness such as a fault or a ***drowned*** river valley (canyons flooded by sea level rise).
• They start on continental shelf and cut into (erode) shelf and upper slope, commonly near the mouth of a bay or river.
• They are carved by undersea erosion processes associated with **turbidity currents**. Turbidity currents transport sediment into deep ocean basins via submarine canyons.
• Turbidity currents moving down submarine canyons eventually slow down and deposit sediments on the continental rise as deep-sea fans.

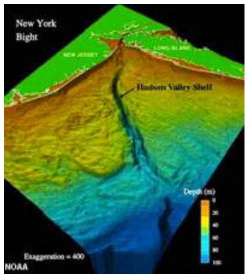


Figure 5.6.1: Hudson Canyon offshore of New York City

5.7: Turbidity Currents and Development of Submarine Canyons and Fans

Turbidity Currents and Development of Submarine Canyons and Fans

A turbidity flows is a turbid, dense current of sediments in suspension moving along downslope and along the bottom of a ocean or lake. In the ocean, turbidity currents can be massive episodic events. They typically form and flow down through a submarine canyon (carved by previous turbidity flows) and accumulate near the base of the continental slope on **deep-sea fans**. Turbidity flows produces deposits showing **graded bedding** (Figure 5.8). Slowing turbid currents drop their coarser fractions first (gravel and sand) and the finer silt and clay fractions settle out last.

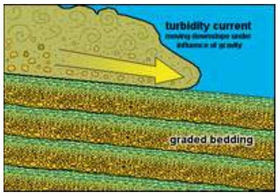


Figure 5.8. **Turbidity flows** are essentially underwater landslides or density-driven currents. Sediments laden with sediment are heavier than clear seawater.

Figure 5.9. Seas stacks composed of submarine channel deposits (mostly conglomerate) exposed at Gazos Creek State Beach, California

A **deep-sea fan** is a fan- or delta-shaped sedimentary deposit found along the base of the continental slopes, commonly at the mouth of submarine canyons. Deep sea fans form from sediments carried by turbidity flows (density currents) that pour into the deep ocean basin from the continental shelf and slope regions and then gradually settle to form graded beds of sediment on the sea floor. Deep-sea fans can extend for many tens to hundreds of miles away from the base of the continental slope and an coalesce into a broad, gently sloping region called a **continental rise**.

Graywacke is a fine-to-coarse-grained sedimentary rock consisting of a mix of angular fragments of quartz, feldspar, and mafic minerals set in a muddy base (commonly called a "dirty sandstone or mudstone" because of its mixed size fractions). Graywacke is the general term applied to sediments deposited by turbidity flows, and they commonly show graded bedding. Graywacke is common in the Coast Ranges of California and other active continental margin regions. It is exposed on land where tectonic forces push up rocks that originally formed in the deep ocean (examples in Figures 5-10 to **5-11**). "**Turbidites**" (deposits associated with turbidity flows) commonly appear as interbedded layers of sandstone and shale. Conglomerate typically occurs in thicker beds and were originally deposited as gravel and mud on ancient submarine fans closer to the mouths of submarine canyons or in channels carved into the seabed.

Figure 5.10. Cretaceous age turbidites exposed on Loma Prieta Peak, Santa Cruz Mountain, California

Figure 5.11. Cretaceous age **turbidites** (turbidity current deposits) at Bean Hollow State Beach, California

5.8: "Active" vs. "Passive" Continental Margins

"Active" vs. "Passive" Continental Margins

Continental margins typically fall into two classes: "active" and "passive."

An **active continental margin** is a coastal region that is characterized by mountain-building activity including earthquakes, volcanic activity, and tectonic motion resulting from movement of tectonic plates. Characteristics of active continental margins include:
• Found on mostly convergent plate boundaries
• Continental slope descends abruptly into a deep-ocean trench (no continental rise)
• Located primarily around the Pacific Ocean

The West Coast of the United States is an active margin that is characterized by rugged coastlines with narrow beaches and steep sea cliffs.

Passive continental margins occur where the transition between oceanic and continental crust which is not an active plate boundary. Examples of passive margins are the Atlantic and Gulf coastal regions which represent setting where thick accumulations of sedimentary materials have buried ancient rifted continental boundaries formed by the opening of the Atlantic Ocean basin. The Atlantic Coast of the United States is characterized by wide beaches, barrier islands, broad coastal plains (see features discussed below).

Figure 5.12. Active and passive margins of North America. The East Coast and North Slope are now passive margin regions located within the greater North American Plate.

Figure 5.13. Passive margin: North Carolina's Outer Banks region showing coastal plain, rivers, tidal estuaries, lagoon, barrier islands, and shallow Atlantic continental shelf

Emergent and Submergent Coasts

In some regions around the world, tectonic forces are pushing rocks up along coastal regions, mostly in regions associated with active continental margins. There areas are called **emergent coasts** and display features including sea cliffs and marine terraces (see below). Where sea level is rising faster than land is rising, or where coastal areas are sinking, it is called a **submergent coast**. Submergent coasts are associated with passive continental margins with wide coastal plains and continental shelves. Estuaries are associated with submergent coastlines formed when sea level rises and floods existing river valleys. Active margins can have both emergent and submergent coastlines in close proximity to each other.

Figure 5.14. Active margin: San Francisco Bay and Monterey Bay region has actively rising coastal range mountains and sinking coastal basins

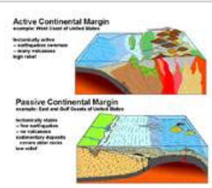


Figure 5.15. Comparison of active and passive continental margins. Passive margins are on the trailing edge of a moving continental landmass.

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5.9: Deep-Ocean Basins

Deep-Ocean Basins

Deep-ocean basins cover the greatest portion of the Earth's surface. Geographic features associated with deep-ocean basins include trenches, abyssal plains, ocean ridges and rises, and submarine mountainous regions.

Trenches

Trenches are long, relatively narrow canyon-like features that run parallel to continental margins. They are the deepest parts of ocean basins. Most trenches are located in the Pacific Ocean.

Trenches occur where mobile lithospheric plates plunge into the mantle (subduction zones). Trenches are associated with intense volcanic activity, usually in the form of volcanic arcs (or volcanic island chains) that develop above the descending side of the subducting plate associated with a trench.

Figure 5.16. An animated view of part of the Marianas Trench. See a NOAA animation.

Abyssal Plains

An **abyssal plain** is an underwater plain on the deep ocean floor, usually found at depths between 4500 and 6000 meters that extends from the continental rise (continental Lithogenous sediments accumulate along continental margins) to the distant deep ocean basin where continental-derived sediment deposition is not significant. Abyssal plains are large horizontal seafloor regions - typically some of the flattest places on the Earth's surface.

Abyssal plains are underlain by oceanic crust that formed and moved away from spreading centers associated with mid-ocean ridges and rises. Because they are so far from land they have very slow sedimentation rates. Some places less than 1 cm per 1000 years. The dominant geologic process is "Planktonic rain" which blankets seafloor with organic sediments.

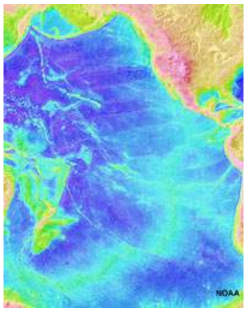


Figure 5.17. Abyssal plains dominate the Pacific Ocean basin.

Seamounts, Islands, Atolls, and Guyots

A **seamount** is any isolated mountain-sized feature that rises above the seafloor. A seamount may be a large tectonic block that separated from a large continental landmass or may be an ancient or even active submarine volcano. A submarine mountain that is partly exposed above the ocean surface is called an **island**. Many seamounts (and islands) are isolated volcanic peaks rising off seafloor. Many are part of mid-oceanic ridges or associated with oceanic hotspots (discussed below). For instance, the Hawaiian Islands are part of the Emperor Seamount Chain (see Figure 5.7). The South Pacific region is a region with numerous seamounts, of which many are islands, atolls, or guyots (Figure 5.40).

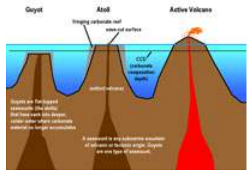


Figure 5.18. Formation of ocean-basin volcanoes, atolls, and guyots. Guyots are flat-topped seamounts that have sunk deep enough into cold water so that reefs cannot form.

An **atoll** is a ring-shaped reef, island, or chain of islands formed of coral, typical on a foundation of an extinct volcano in the ocean. The limestone ring forms along the margins of the volcano. Over time, the volcano either erodes away or sinks below the surface, but the limestone rim continues to grow and expand over time. A **guyot** is a submarine mountain (seamount) with a flat top. Most guyots are ancient submarine volcanoes that have been beveled by wave action before sinking into ocean depth and may lack the fringing limestone reefs associated with atolls.

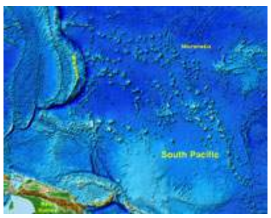
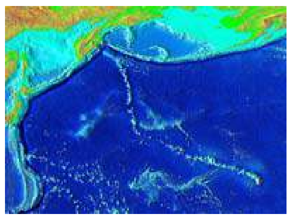
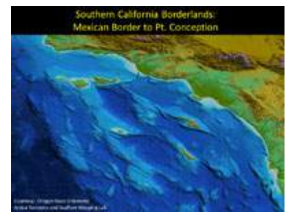
			

Figure 5.19. The South Pacific region has numerous islands, seamounts, atolls, and guyots. All of them started forming as undersea volcanoes.	Figure 5.20. Hawaii is the youngest volcanic island of the Emperor Seamount Chain. Many of the older seamounts were once volcanic islands but are now atolls or guyots.	Figure 5.21. A satellite view of an **atoll** displaying a fringing carbonate reef platform (with islands) surrounding an eroding central volcanic peak. Most atolls of the world are located in tropical regions of the South Pacific and Indian Oceans.	Figure 5.22. Seamounts and islands offshore of southern California. Many of these features are associated with active faults that are moving great blocks of crust across the seafloor.

Oceanic (Mid-Ocean) Ridges and Rises

Mid-ocean ridges (MORs) are broad, linear swells along divergent plate boundaries in ocean basins. They are associated with extensive faulting and small earthquakes, and along their crest there is high heat flow form new crust forming from the cooling of molten material derived from the mantle and remelting of the crust. Ocean Ridges are present in all ocean basins. They are the shallowest and youngest parts of deep ocean basins. Features associated with ocean ridges include volcanism (undersea volcanic features), hydrothermal vents, and undersea rift valley. As newly formed crust moves away from spreading centers, the crust gets older and layers of sediments thicken away from the mid-ocean ridges.

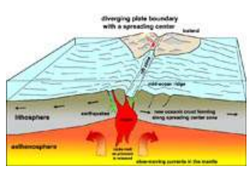


Figure 5.23. **Formation of new oceanic crust** along a **spreading center** associated with a **mid-ocean ridge**. Some spreading centers appear on land. For example, a portion of the **Mid-Atlantic Ridge** is exposed as Iceland.

What is the difference between a mid-ocean ridge and a mid-ocean rise?

The two features are basically the same except for their shape (topography) and how fast they form.
Topographic differences are controlled by spreading rates

- **Ridges** are steeper with slow spreading rates (1-5 centimeters per year) - Example: Mid-Atlantic Ridge
- **Rises** are flatter with fast spreading rates (greater than 9 centimeters per year) - Example: East Pacific Rise

Why are ridges and rises so high?

• Newly created oceanic lithosphere is hot and occupies more volume (less dense) than cooler older rocks
• As the oceanic crust travels away from the ridge crest it cools and becomes more dense and sinks

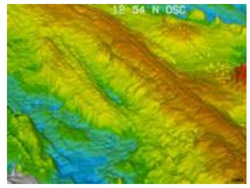


Figure 5.24. Bathymetric image of the spreading center on the East Pacific Rise.

5.10: Oceanic Lithosphere and Basins

Oceanic Lithosphere and Basins

Origin of oceanic lithosphere

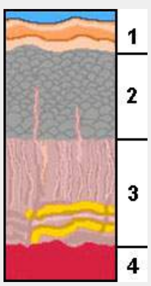
At mid-ocean ridges (spreading centers), lithospheric plates move apart. This creates space for magma to flow upward into the newly created fractures. Over time, more and more fractures form, fill with magma, and then cool and fracture. This process generates new oceanic lithosphere (ocean crust).

Zones of active rifting along mid-ocean ridges are typically 12 to 18 miles (20 to 30 km) wide. In some locations, the very hot, fluid lava migrating upward from the asthenosphere (upper mantle) reaches the surface of the seafloor resulting in formation of undersea volcanoes. These undersea eruption produce **pillow basalts** - pillow-shaped pods of basalt rock formed where the hot lava cools rapidly when exposed to seawater.

As new lithosphere forms, it gradually moves away from the mid-ocean ridge crest beyond the zone of active rifting and volcanism. Over time, the cooling crust gets denser and isostatically sinks lower where it is floating on the asthenosphere. Oceanic sediments gradually blanket the aging oceanic crust as it moves away from the spreading center. The layer of sediment grows thicker and thicker as it moves away from the mid-ocean ridge.

Structure of the oceanic lithosphere

Four distinct layers of oceanic lithosphere (combined are called an **ophiolite sequence**)



• Layer 1: sequence of unconsolidated sediments
Consists mostly of plankton remains and fine dust blown in from distance sources including from land (continental deserts sources) and meteorite dust.

• Layer 2: consisting of pillow lavas
Forms from basaltic lava erupting on the surface of the seabed, rapid cooling from exposure to seawater creates the pillow-like structure of the lava beds on the sides of underwater volcanoes.

• Layer 3: interconnected dikes called sheeted dikes
Newly cooled igneous rock formed at depth shrinks and fractures as it cool, allowing more magma to inject upward into new fractures in the expanding rift zone along the axis of a spreading center

• Layer 4: gabbro (like basalt but slowly cooled at depth)

Formation of oceanic lithosphere
• Magma (liquid material carrying crystals with it) originates from partially melted mantle forms **Layer 4**.
• Magma injected into fractures above the magma chambers creates the sheeted dike complex, forming **Layer 3**.
• Pillow basalts are from basaltic lava that is flash cooled in seawater, forming **Layer 2**.
• Sediments deposit on top of pillow basalts, forming **Layer 1**.

Aging of oceanic lithosphere results in chemical and physical changes
Once new oceanic lithosphere forms it begins to cool. The lithosphere is very warm relative to the cold ocean water above it. Large quantities of seawater sink into the new ocean crust and chemically reacts with it. These chemical process are a form of metamorphism. Ultramafic rock (rocks enriched in magnesium and iron) that formed deep in the upper mantle and oceanic lithosphere can gradually be altered into **serpentinite**. Large amounts of serpentinite are exposed in the Coast Ranges of northern California where old ocean crust has been pushed up and exposed in the mountain ranges.

			
Figure 5.25. Formation of an **ophiolite sequence** (ocean crust) near mid-ocean ridges.	Figure 5.26. Gabbro, a dominant crystalline igneous rock type formed in oceanic lithosphere.	Figure 5.27. Pillow basalts exposed near Avila Beach, central California.	Figure 5.28. Serpentinite (the State Rock of California) is a metamorphic rock derived from altered oceanic lithosphere (mostly Layer 4). This outcrop is part of a large mountain-sized block of oceanic crust exposed in the mountains near San Jose, California.

5.11: Formation and Destruction Cycle of Oceanic Lithosphere

Formation and Destruction Cycle of Oceanic Lithosphere

Continental rifting: The birth of a new ocean basin

• A new ocean basin begins with a the formation of a continental rift (example: the African Rift valleys, **Figure 5.29**).
• The Red Sea is an example of a rift valley that has lengthened and deepened into a narrow linear sea
• If spreading continues the Red Sea will grow wider and develop an oceanic ridge similar to the Atlantic Ocean.

Figure 5.29. Map and features associated with African continental rift zones.

Subduction: The destruction of oceanic lithosphere

• Oceanic lithosphere subducts because its overall density is greater than the underlying mantle
• Subduction of older, colder lithosphere results in **STEEP** descending angles of the sinking oceanic lithosphere.
• Younger, warmer oceanic lithosphere is more buoyant and angles of descent are **SHALLOW**.
• Research indicates that parts, or even entire oceanic basins, have been destroyed along subduction zones.

Destruction of oceanic lithosphere adds new material to continental crust

As oceanic lithosphere sinks back into the asthenosphere it carries large quantities of seawater and sediment with it. As it sinks, the increased heat and pressure forces water and gases out of the rock. This combination of trapped water and gases allows some of the material melt. The resulting magma that forms is depleted in iron and magnesium, but enriched in **aluminum** and **silica** (**felsic** in composition). This is because **mafic minerals** have both **higher melting temperatures** and **higher density** than **felsic minerals**.

As a result a natural refining process occurs... mafic material sinks back into the mantle whereas the molten felsic material (along with trapped water and gases) separate and work their way back to the surface. This results in the formation of volcanoes in the region above where subducting lithospheric slabs are sinking. This felsic material is less dense and becomes incorporated into new continental crust. Over long periods of time, enough felsic material accumulates to build continents, a process that may take billions of years.

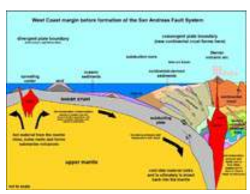


Figure 5.30. A plate tectonics model illustrating the formation and destruction of oceanic crust and the formation of continental crust.

5.12: Vents on the Seafloor- Black Smokers, White Smokers, and Deep-Sea Vent Communities

Vents on the Seafloor: Black Smokers, White Smokers, and Deep-Sea Vent Communities

Hydrothermal vents form where there is volcanic activity on or below the ocean floor, such as along the Mid-Ocean Ridge. Water seeps through cracks in the seafloor and is heated by hot rock deep below the ocean crust to as high as 400°C. This hot water is under too much pressure to boil, but it erupts as "smoky fountains" at vents on the sea floor. The hottest vent produce unusual chimney-like towers called "**black smokers**." The hot water contains dissolved metals (including iron, manganese, zinc, copper, sulfur, and others). When they encounter the cold ocean water, the minerals precipitate, making dark plumes of water and irregular deposits (including "chimneys") on the seabed. The rich supply of nutrients support chemotrophic bacteria (feeding on sulfur compounds) that support a complete food web of seafloor creatures, including tube worms, arthropods, fish, and other benthic life forms adapted to these harsh and temporary environments.

Cooler vents produce "**white smokers**" that are dominated by deposits of calcium-rich minerals, including anhydrite gypsum ($CaSO_4$) and calcite ($CaCO_3$). Minerals in ocean crustal rocks are rich in calcium, which dissolves easily on cold seawater. Where the warmed seawater rises back to the surface, the calcium-enriched water produces "white smokers" along with deposits of minerals that also host deep-sea bed communities.

Deep sea vents have been identified in many locations along mid-ocean ridges and along the flanks of undersea volcanoes. Current thought is that many of the major economic mineral deposits of the world may be associated with ancient deep-sea vent deposits.

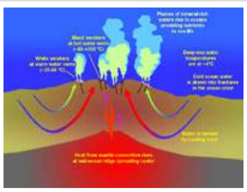


Figure 5.31. Deep-sea vents form from seawater convection in ocean crust.

Figure 5.32. Mineral-rich black smoker deposits are rich in copper, zinc, iron, and others

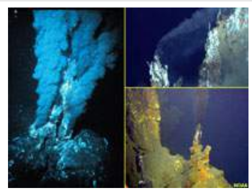


Figure 5.33. **Black smokers** venting very hot mineral-rich water on the seabed.

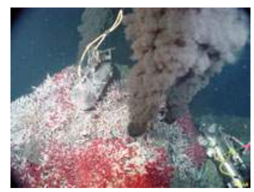


Figure 5.34. **Black smokers** with a deep-sea community around them.

Figure 5.35. White smokers with chimneys of the seabed.

Figure 5.36. White smokers with chimneys of the seabed.

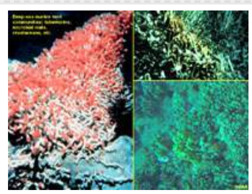


Figure 5.37. Deep-sea vents host rich benthic communities

Figure 5.38. Deep-sea vent community.

5.13: Coastal Plains, Climate Change, and Predicted Sea-Level Rise

Coastal Plains, Climate Change, and Predicted Sea-Level Rise

Climate change is a theory that has growing significance as overwhelming evidence shows that observable changes have been and are occurring in the atmosphere and oceans. Several factors are responsible. First, the **natural cycles of continental glaciation** associated with cyclic changes in the amount of solar energy the polar regions the Earth receives (ice ages are discussed in more detail in Chapter 9). The second factor is the modern impact of greenhouse gases on global warming created in the modern era of industrialization.

Impact of Melting Glaciers On Sea-Level Rise

Global warming has been taking place since the end of the last ice age, and the impact of sea level rise caused the melting of the massive continental glaciers is easily observable (this is discussed more detail in following chapters). The peak of the ***natural part*** of latest global warming cycle may have happened nearly 7,600 years ago, as warming of the atmosphere and the associated sea level rise drastically slowed down at about that time. The peak of the last ice age, about 26,500 years ago when massive continental ice sheets, ice caps, and alpine glaciers cover much of northern Europe and North America, more extensive glaciers in Antarctica (Figure 5.39). This displaced nearly 10 million cubic miles of ocean water onto the land to be stored as ice. Research shows that onset of deglaciation began about 20,000 years ago in the Northern Hemisphere with a massive rise in sea level starting starting about 14-15,000 years ago with deglaciation of the West Antarctic Ice Sheet. The location of **shelf breaks** around the world shows that sea level has risen about **400 feet (120 meters)** since the peak of the last ice age.

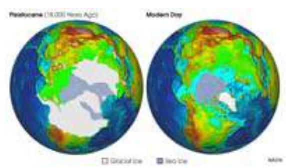


Figure 5.39. Extent of glaciers and sea ice during the peak of the last ice age and today in the Northern Hemisphere.

The effects of sea-level rise is very obvious on the landscape. Perhaps most obvious are that coastal river valley are now submerged in seawater in most locations around the world. If example, Chesapeake Bay and Delaware Bays were a river valleys about 400 feet deep at the peak of the last ice age; it is now submerged as salt-water estuaries (Figure 5.40).

Figure 5.40. Chesapeake and Delaware Bays (estuaries), and the Delmarva Peninsula. Sea-level rise has back filled river valleys draining into the Atlantic Ocean. Ridges on land became peninsulas.

Global Warming and Sea Level Rise have happened many times in the geologic past.

Figure 5.41 shows a map of the **Fall Line**. The map also shows the location of ***Fall-Line Cities*** along the inland margin of the Atlantic and Gulf coastal plains). The Fall line is an imaginary line, marked by waterfalls and rapids, where rivers descend abruptly from an upland to a lowland. Historically, it is the location that major cities became established because it was the farthest point up a river ships could travel before they encountered rapids, waterfalls, or conditions too shallow for ships to continue farther inland. In the Eastern U.S. the imaginary fall line is between the Appalachian Piedmont and the Atlantic coastal plain physiographic provinces. Similar fall lines can be observed along coastal plains in locations around the world. In the United States, the Fall Line boundary roughly follows an elevation of about **60 meters (200 feet) above sea level**, **This elevation is what sea level was before glacial ice started forming on Antarctica and Greenland when the Earth was ice free about 35 million years ago.** At that time, the entire **Atlantic and Gulf Coastal Plains** were submerged and were part of the **continental shelf**. Since then sea level has risen and fallen many times as continental glaciers have formed and melted. Sea level is now rising again, but cause of that increased rate is what is the problem.

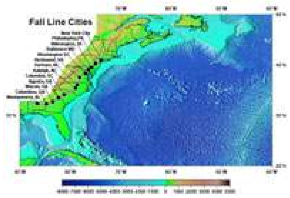


Figure 5.41. **Fall line cities** on along the inland margin of the Atlantic and Gulf coastal plains.

The Great Problem of Our Times: Accumulation of Greenhouse Gases In The Atmosphere

The demand for energy and agricultural resources by the world's expanding human population began to increase significantly since the beginning of the Industrial Revolution in the mid 1900s. Awareness of the environmental impact of this consumption began to become obvious most obvious when air pollution levels first began to intolerable in large urban regions around the world beginning in the 1960 (on into the present). With satellite technologies and collaborative international action in gathering of atmospheric and oceanographic data the Scientific Community is gathering and presenting evidence of active changes taking place around the world. These changes are caused by the introduction of vast quantities of greenhouse gases from the burning of fossil fuels (coal, oil, gas) and from deforestation and poor agricultural practices (soil destruction and livestock). The world's Scientific Community almost unanimously agrees that the effects of climate change are very real. Projections are being made about the plausible impacts climate change is going to have on the destruction of ecosystems, the rise in sea level.

The environmental impacts of climate change associated with greenhouse gas emissions are monumental. Here is a partial list:

• A summary of scientific research presented in 2013 by the United Nations' Intergovernmental Panel on Climate Change (summarized by by the Washington Post in 2016) suggests that sea level rise is estimated to rise between **0.52 and 0.98 meters (1.7 and 3.22 feet) by the year 2100**, with other estimates ranging higher. This report also suggest that melting of ice on Antarctica alone could cause seas to rise more than 15 meters (49 feet) by 2500.

• **Global temperatures have risen by 1.5° Celsius since the pre-Industrial Era began**, and this increase is projected to continue with the most significant rise happening in the past 20 years on an annual basis. A 2° Celsius rise alone is projected to have catastrophic impacts on ecosystems around the world. Warm-climate species will expand their ranges to the detriment of cold-climate species on all levels on of the world's food chains (oceanic and terrestrial). Estimate reported by the Natural Resources Defense Council suggest that global warming may cause the global temperature by as much at **8° Celsius by 2100** if the projected consumption of fossil fuels and other releases of greenhouse gases continues unmitigated.

• Global distribution of rain fall is expected to change, and major tropical storms are expected to increase in intensity.
• Increased level of CO_2 in the air is increasing the acidity of ocean surface waters, negatively impacting many species.
• Arctic regions are particularly experiencing climate change impacts involving the gradual disappearance of sea ice, the melting of permafrost, and the rapidly increasing rate of melting of glaciers.

Examples: The effects of sea-level rise are quite obvious in Louisiana (where the land is sinking and eroding, Figure 5.42). Figure 5.43 shows how the Gulf and Atlantic coastal regions will change with a rise of 1, 2, 3, and 4 meters. Figure 5.44 shows the 4 meter water line in Washington DC. It will be interesting to see how the ***political world*** will deal with these changes!

The political and economic consequences caused by inaction to stop potential calamities caused by climate change are staggering to ponder. The world faces economic crisis driven, in part, by the conflicting greed by international carbon-gas-producing industries, and largely by the increasing demand for energy and natural resources by individuals to entire nations that are unable or unwilling to accept their share of responsibility.

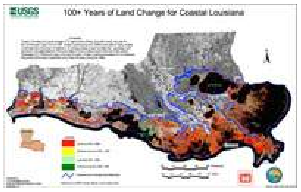


Figure 5.42. 50 years of land loss from sea level change and coastal erosion in Louisiana.

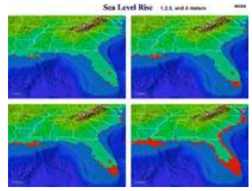


Figure 5.43. Projected changes from 1,2,3, & 4 meters of sea-level rise on the East Coast.

Figure 5.43. Projected flood zone of Washington DC if sea level rises 4 meters. Congress will have to paddle canoes to get to the White House!

Here is a quote the human impacts from climate change published by **Human Rights Watch [2018]** (a global environmental watch media organization):

"As the world urbanizes and industrializes, and as effects of climate change intensify, environmental crises will increasingly devastate the lives, health, and livelihoods of people around the globe. A lack of legal regulation and enforcement of industrial and artisanal mining, large-scale dams, deforestation, domestic water and sanitation systems, and heavily polluting industries can lead to host of human rights violations. Activists and ordinary citizens defending their rights to land and the environment may face intimidation, legal harassment and deadly violence. The primary victims of environmental harm are often impoverished and marginalized communities with limited opportunity to meaningfully participate in decision-making and public debate on environmental issues, and have little access to independent courts to achieve accountability and redress."

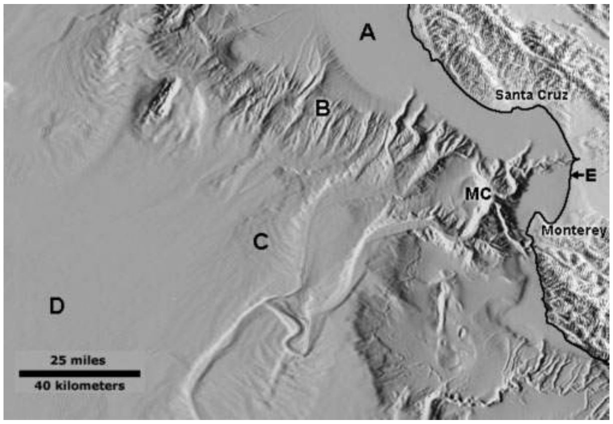
5.14: Selected Resources

Galapagos Regional Geology (NOAA) - The Galapagos Islands are an island chain on a spreading center in the Pacific Ocean basin.

Hawaii Lava Lake video (USGS) - This view of the fractures changing on the crust on a lava lake in Hawaii's Kilauea Volcano is a good proxy for the formation of spreading centers (on a smaller scale).

5.15: Quiz Questions - Chapter 5 - Ocean Basins

Questions 1 to 6 refer to the image below that shows a map of the coastline and the seafloor in a region including Monterey Bay—located between the coastal cities of Monterey and Santa Cruz and Monterey Canyon (shown as MC). On the image, the arrow for letter E points to the coastline along Monterey Bay.



1. On the seafloor, Letter A is located on:
a. continental rise.
b. continental shelf.
c. continental slope.
d. abyssal plain.

2. On the seafloor, Letter B is located on:
a. continental rise
b. continental shelf
c. continental slope
d. abyssal plane

3. On the seafloor, Letter C is located on the:
a. continental rise
b. continental shelf
c. continental slope
d. abyssal plane

4. An extensive flat section of the seafloor, Letter D is located on the:
a. continental rise.
b. continental shelf.
c. continental slope.
d. abyssal plain.

5. The “shelf break” is located:
a. between letters A and B.
b. between letters B and C.
c. between letters C and D.
d. at letter E

6. Monterey Canyon (shown as letters “MC”) is about twice the size of the Grand Canyon in Arizona. Submarine landslides and turbidity currents move sediments down submarine canyons to be deposited **mostly** on the:
a. continental rise
b. continental shelf.
c. continental slope.
d. abyssal plain.

7. An example of a passive margin is:
a. the coast of California, Oregon, and Washington.
b. the coast of southern Alaska.
c. the East Coast of the United States.
d. Hawaii.

8. Which of the following is NOT true about ocean trenches?
a. They are long, relatively narrow canyon-like features that run parallel to continental margins.
b. They are the deepest parts of ocean basins.
c. They usually occur in the ocean along volcanic island chains.
d. None of the above.

9. An ancient submarine volcano that has a flat top (beveled by wave action before sinking into ocean depths) and may lack fringing reefs is called:
a. an atoll.
b. a seamount.
c. a guyot.
d. a mid-ocean ridge.

10. The shallowest and youngest parts of deep, central ocean basins are typically:
a. mid-ocean ridges.
b. abyssal plains.
c. volcanic island arcs.
d. trenches.

11. As new ocean crust forms along mid-ocean ridges, what happens to the older ocean crust?
a. Older crust moves away from spreading centers.
b. The older ocean crust cools and sinks deeper into the ocean basins.
c. The ocean crust is blanketed with layers of ocean sediments.
d. Old, cold ocean crust eventually sinks into subduction zones.
e. all of the above.

12. Pillow basalts occur where:
a. sediments accumulate in beds on the seafloor.
b. lava erupts and cools quickly on the seafloor on submarine volcanoes, such as along mid-ocean ridges.
c. lava erupts from a volcano on an island arc chain.
d. fringing reefs form around an ancient volcano.

13. Serpentinite is the State Rock of California. It occurs in abundance throughout the coast ranges of Northern California. Serpentinite is a rock formed from:
a. the accumulation of the remains of ancient sea snakes.
b. a rock formed by the metamorphic alteration of ocean crustal rocks (basalt and gabbro) by exposure to seawater seeping into the ocean crust over time.
c. a rock formed from the accumulation of undersea landslide deposits.
d. all of the above.

14. As old ocean crust is destroyed in subduction zones, new continental crust forms as a result of:
a. water and gases released by increasing heat and pressure helps to melt some of the old ocean crust.
b. lighter, low temperature "felsic" minerals melt first and migrate upward, forming volcanoes and new continental crust.
c. denser, high temperature "mafic" minerals are concentrated in the old ocean crust that sinks back into the mantle.
d. all of the above.

15. Black smokers and white smokers are features are:
a. hydrothermal vents associated with volcanic activity on the seafloor.
b. most common along the rift zones associated with mid-ocean ridges.
c. host to biological communities that are supported by chemotrophic bacteria.
d. all of the above.

16. What is true about the relationship of coastal plains and continental shelves?
a. Coastal plains were part of the continental shelves that have been exposed by the fall of sea level.
b. Continental shelves are submerged portions of coastal plains that were exposed during the peaks of the ice ages.
c. The shelf breaks around the world roughly mark the locations of shoreline of the coastal plains at the peak of the last ice age.
d. All the choices are correct.

17. About 35 million years ago was the last time that Antarctica was ice free. Since then sea level has fallen and risen many times as continental glaciers advanced and retreated. During the peak of the high seas, the continental shelves extended inland, covering the coastal plains around the world. In North America, the hypothetical boundary between the Atlantic and Gulf coastal plains and upland regions is called:
a. the Fall Line.
b. the shelf break.
c. the Piedmont.
d. the continental rise.

18. According to a 2013 report by the United Nations Intergovernmental Panel on Climate Change, how much is sea level anticipated to rise by the year 2100?
a. Sea level is not changing.
b. Sea level is estimated to rise between 0.52 and 0.98 meters (1.7 and 3.22 feet).
c. Sea level is estimated to rise about 4 meters (13 feet).
d. Sea level is estimated to rise more than 15 meters (49 feet).

19. According to a Natural Resource Defense Council report (2017), how much will global temperatures rise by the year 2100 if current projections of fossil fuel consumption and other effects releasing greenhouse gases continues unmitigated?
a. Global temperatures will go down.
b. Global temperatures will not change.
c. Global temperatures could rise 2° Celsius.
d. Global temperatures could rise 8° Celsius.

20. According the Natural Resource Defense Council report (2017), What are some of the anticipated impacts if climate change effects from global warming continue unmitigated?
a. Global distribution of rain fall is expected to change, and major tropical storms are expected to increase in intensity.
b. Increased level of CO_2 in the air is increasing the acidity of ocean surface waters, negatively impacting many species.
c. Arctic regions are particularly experiencing climate change impacts involving the gradual disappearance of sea ice, the melting of permafrost, and the rapidly increasing rate of melting of glaciers.
d. All of the above.

CHAPTER OVERVIEW

6: Marine Sediments

6.1: Marine Sediments

Marine Sediments

This chapter is about the origin and distribution of **sedimentary deposits** (**sediments and sedimentary rocks**) with a focus on **marine sediments**.

The word "**sedimentary**" refers to materials consisting of sediments or formed by deposition; the word sedimentary also applies to both the **processes** and the **products** of **deposition** (Figure 6.1).

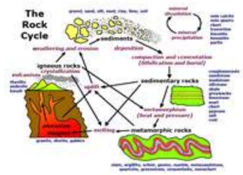


Figure 6.1. Sediments, **sedimentary rocks** and **sedimentary processes** are part of the **Rock Cycle**.

Sediment: Solid material that has settled from a state of suspension. **Sediments are transported and deposited by water (rivers, lakes, and oceans), ice (glaciers), and wind.**

Sedimentary rock is rock that has formed through the deposition and consolidation and solidification of sediment. Sedimentary rocks are often deposited in layers, and frequently contain fossils. Studies of sedimentary deposits can help tell the geologic history of an area.

Classification of Sediments and Sedimentary Rocks

Sediments (and sedimentary rocks) are classified in by **origin of source material** and by **grain size**.

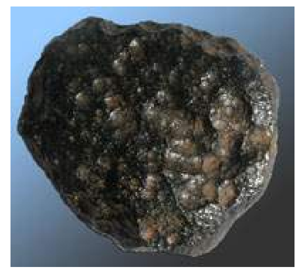
There are 4 sources of sediments (and sedimentary rocks):
a) Cosmogenous: material that falls to the Earth surface from outer space.
b) Hydrogenous: material precipitated directly seawater.
c) Lithogenous: material derived from erosion of other rocks, typically from continental sources.
d) Biogenous: material formed from the accumulation of remains of living organism.

6.2: Cosmogenous Sediments

Cosmogenous Sediments

Cosmogenous sediments originated from outer space. Scientists have used satellites to estimate how much material enters the earth's atmosphere. Current estimates from satellite data suggesting about 100 to 300 tons (mostly cosmic dust) hits earth each day. This is just a tiny fraction of the sediments generated on earth each day. However, early in the history of our Solar System, Earth and other planets, moons, comets and asteroids formed from the gravitational accumulation of extraterrestrial material, but by 4.5 million years ago, most of this cosmogenous accumulation had significantly diminished. However, cosmogenous materials including **iron-nickel** and **stony meteorites** can be found. Although a relatively insignificant source of sediment, meteor fireballs disintegrating in the atmosphere contribute dust that can accumulate measurable amounts in parts of some ocean basins.

Extraterrestrial impacts have changed life on Earth repeatedly, including the mass extinction at the end of the Mesozoic Era associated with the extinction of dinosaurs and many other forms of life on land and in the oceans. **Tektites** are silica glass generated by extraterrestrial impacts: asteroids exploding on the surface and molten material is ejected into the atmosphere where it condenses into a glass-like material.

		
Figure 6.2. A meteor fireball (a bolide) disintegrates in the night sky over Oklahoma.	Figure 6.3. Iron-nickel meteorite from the Diablo Canyon area, AZ (see below)	Figure 6.4. A tektite is a ball of glass-like material ejected by an asteroid impact.

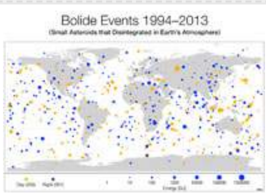



Figure 6.5. Known locations of bolide events (1994 to 2013). Bolides are meteor fireballs that explode when entering the atmosphere. Few reach the ground or oceans.	Figure 6.6. Meteor Crater (Diablo Canyon site) near Flagstaff Arizona is a 50,000 year-old asteroid impact site about a mile in diameter and 550 feet deep.	Figure 6.7. The Cretaceous-Tertiary extinction event is preserved in sediments in many locations around the world. This one is in South Dakota.

6.3: Hydrogenous Sediments

Hydrogenous Sediments

Hydrogenous sediments are sediments directly **precipitated from water**. Examples include rocks called evaporites formed by the evaporation of salt bearing water (seawater or briny freshwater).

Evaporites (Salts)

An **evaporite** is a rock composed of salt minerals left behind by the evaporation of salty water. Examples include minerals **halite** [**salt**] (NaCl) and **gypsum** ($CaSO_4 \bullet x\ H_2O$).

rock salt—a rock dominantly composed of sodium chloride (NaCl - the mineral **halite; Figure 6.8**). Rock salt is an evaporite formed in restricted basins with an inflow of seawater located in an arid environmental setting.

gypsum—a mineral composed of hydrous calcium sulfate ($CaSO_4$-$2H_2O$); an evaporite mineral used in the manufacture of plaster. Gypsum is deposited by concentrated seawater and by evaporation of freshwater in arid regions. Crystals of gypsum are common in soils in arid regions. If gypsum looses its water content, it is called **anhydrite** (Figure 6.9).

Figure 6.8. **Rock salt** (halite)

Figure 6.9. Anhydrite gypsum.

Salts are precipitated when sea water (or briny lake water) is concentrated by evaporation. Shorelines along the oceans in hot arid regions of the world are places where salt, gypsum and anhydrite are being deposited today. Places where salts (evaporites) are actively accumulation include around the Red Sea and Persian Gulf. Salt deposits are also forming in isolated, internally drained lake basins around the world including the Great Salt Lake in Utah and the Dead Sea.

Iron-manganese nodules form on the ocean bed (mostly in the deep Pacific) from the slow precipitation of metal oxides in the absence of other kinds of sediments. It may take many millions of years for an individual manganese nodule to grow on the deep seafloor. Deposits of them cover the seafloor only in regions located very far away from lithogenous sediment sources.

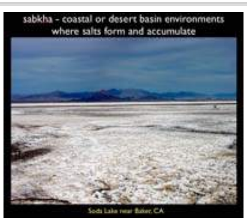


Figure 6.10. A **sabkha** is a desert coastal environment is where **salts, including halite and gypsum**, are commonly deposited.

Figure 6.11. Polygons of salt crystals (halite) being deposited on a salt pan on a dry lake bed in Death Valley National Park, California

iron-manganese nodule

Figure 6.12. An iron-manganese nodule forms very, very slowly from direct precipitation on the seafloor.

Figure 6.13. Iron-manganese nodules on the deep sea floor near the Puerto Rico Trench.

6.4: Lithogenous Sediments

Lithogenous Sediments

Lithogenous sediments form through the processes of **weathering and erosion** of materials exposed on **land and along coastlines**. Lithogenous sediments consist of solid fragments of inorganic or organic material that come from the weathering of rock and soil erosion, and are carried and deposited by wind, water, or ice. Lithogenous sediments are also commonly called "terrigenous sediments" because they are derived dominantly from terrigenous (land) sources. They are also called "**clastic sediments**" because they are made up of rock fragments derived from other rocks—a "**clast**" is a Greek word for a rock fragment.

Figure 6.14. Sand and gravel on SoCal beaches are typical lithogenous sediments. This view is of South Carlsbad State Beach, California.

Lithogenous sediments are:

• Mostly small pieces of broken rock transported to ocean from the land (wind, rivers, glaciers, coastal erosion, turbidity currents etc.)

• Generally form deposits rapidly (such as sand on a beach or a river delta)

• Can form in high energy environments and have coarse grain sizes (coarse sand, gravel, cobbles, and boulders).

• **Beach sand** is mostly composed of the **quartz (SiO_2)**, a mineral which very resistant to weathering.

• Most lithogenous sediments eventually are deposited along the margins of ocean basins.

• Some is deposited into the deep ocean by currents and underwater landslides near continents, and far offshore, lithogenous sediment of fine silt and clays, some as desert dust, forest-fire ash, or volcanic ash blown in by the wind.

6.5: Neritic and Pelagic Sediments

Neritic and Pelagic Sediments

The term **neritic** is used to described the shallow part of the ocean near a coast and overlying the continental shelf.
Neritic sediments are generally shallow water deposits formed close to land. They are dominated by lithogenous sources and are typically deposited quickly**. Neritic** sediments cover about ¼ of sea floor and are near landmasses.

The term **pelagic** means "of or relating to the open sea" particularly the upper layers of the ocean away from shore.
Pelagic sediments are generally deep-water deposits mostly oozes (see below) and windblown clays. They are typically finer-grained sediments that are deposited slowly. Because they are deposited far beyond the continental margins they are typically less lithogenous and more biogenous depending on biologic productivity. **Pelagic** sediments cover about ¾ of seafloor and are mostly in deep water.

The distribution of neritic or pelagic sediments is controlled by proximity to sources of **lithogenous sediments** (i.e.: landmasses) and the **productivity** of microscopic marine organisms.

6.6: Biogenous Sediments

Biogenous Sediments

Biogenous sediments are composed of the **remains of living organisms**, including microscopic phytoplankton (plants) and microscopic zooplankton (animals), terrestrial and aquatic plants, shells of invertebrates, and vertebrate material (teeth, bone), and associated organic residues. Coal, oil, and gas are derived from biogenous sediments. Biogenous sediments accumulate to form massive deposits associated with modern and ancient carbonate "reef systems" (such as the Australian Barrier Reef, South Florida, Keys, and the Bahamas, the Yucatan and reefs throughout the Caribbean Sea, and great reefs and atolls in thou gout the South Pacific, Indian Ocean, and many other locations. (See more on Biogenous Sediments below.)

Figure 6.15. Biological activity creates large volumes of sediment in some ocean regions.

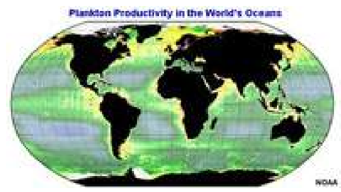


Figure 6.16. Oceanic plankton constitute the largest reservoir of biomass in the world's oceans

6.7: Volume and Distribution of Marine Sediments

Volume and Distribution of Marine Sediments

Of the 4 types of sediments, **lithogenous** and **biogenous** sediments are the most abundant on Earth today. Lithogenous sediment dominate the regions adjacent to continental landmasses (continental margins). The lithogenous sediment accumulations along continental margins can be many miles thick, especially where rivers have dumped large quantities of sediments for long periods of geologic time. Biogenous sediments accumulations can also be massive, particularly in locations where warn, shallow seas allow massive reef tracts to persist for long periods of time, such as with the Australian Great Barrier reef. Planktonic remains blanket the seafloor in large regions of the world's oceans. In contrast, cosmogenous and hydrogenous sediments are generally insignificant in comparison, but have important scientific and economic significance where they occur.

Sedimentary rocks are exposed throughout the world's continents, covering about half of the exposed land on the earth surface. This ***sedimentary cover*** blanketing continental areas was originally deposited mostly in coastal environments, in shallow seas flooding shallow continental basins, on continental shelves and in ocean basins along the margins of continents. Most of these sedimentary rocks that blanket much of the continents formed in the last several hundred million years. Even more massive quantities of sediments occur along continental margins in ocean basins. In many places around the world the thickness of sediments eroded from continental landmasses and volcanic chains and deposited in the adjacent ocean basin can be many miles thick! Sediments are thinnest or nonexistent on new ocean crust forming along **mid-ocean ridges**.

Most lithogenous sediments are on or near a landmass
• Coarser sediments accumulate closer to shore,
• Finer sediments are winnowed by waves and currents and are transported farther from shore to quieter water settings where they can settle out.

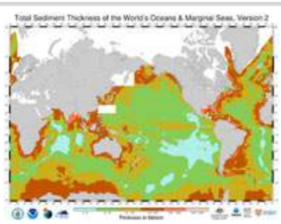


Figure 6.17. Thickness of sedimentary deposits along continental margins.

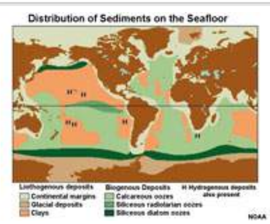


Figure 6.18. Distribution of sediments on the seafloor by type.

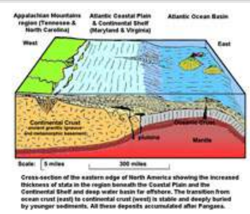


Figure 6.19. Continental margins are places where large quantities of lithogenous and biogenous sediments accumulate. They are thinnest or missing on new ocean crust forming on mid-ocean ridges.

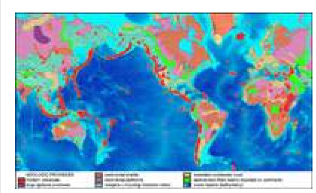


Figure 6.20. Map of geologic provinces of the world. Sediments and sedimentary rocks not only cover much of the world's seabed but also cover large regions of the continents that were once under water.

6.8: "High-Energy" and "Low-Energy" Depositional Environments

"High-Energy" and "Low-Energy" Depositional Environments

Flowing water is the dominant natural force causing erosion and deposition on Earth. The faster the water moves, the ***higher the energy*** in a physical setting. As flowing water increases in speed, the more it may become turbulent, increasing its ability to lift and move particles. Fast moving water can carry materials of different sizes ranging from boulders and gravel to finer materials (sand, silt, and clays). Flowing water also sorts sediments by size and density. **High-energy environments** include river channels, beach and shallow offshore environments with high wave action, and wave-battered coral reefs (Figures 6-21 to **6-22**). Fast flowing water from waves and currents may let larger materials settle and be deposited while finer materials are carried away and deposited in **quieter water** settings or what are considered **low-energy environments**. (Figures 6-23 to **6-24**). Low-energy environments on land include most lakes and swamps, and low-energy conditions exist in protected bays and lagoons, and in deeper-water setting in ocean in locations not significantly impacted by wave and strong current action.

Different sedimentary environments have different ***energy characteristics*** that may change from time to time. The forces of energy in a stream will increase as the volume of water increases, such as during flood. For most of a year, a stream will may be a calm environment, that changes during a flood, or during a ***flood season***. The same is true of beach and offshore bar environments. As wave energy increases, the greater the amount of energy translates into shoreline erosion and the moving of sediments to quieter and deeper offshore settings. Wave action separates sand from courser and finer fractions, building up or eroding beaches with changing conditions. A beach or offshore region can remain basically calm, relatively **low energy** for years until a hurricane comes along, and the setting becomes "high energy." One big storm event can move more sediments in a few days that might have moved for decades or even centuries. For example, Hurricane Camille did this to the coast of Alabama and Mississippi in 1969.

Deep-water environments far from shore tend to be low energy environments. However, in regions along continental margins quiet conditions can be suddenly disrupted by the rapid influx of sediments caused by massive underwater landslides or the effects of major storms on the nearby continental shelves.

High-Energy Depositional Environments

Coarse-grain sediments dominate. Weather (climate), currents, and wave energy are variable factors in "high-energy" environmental settings. Sediments are constantly being deposited or eroded in these settings.

Figure 6.21. Beaches

Figure 6.22. Coral reefs

Low-Energy Depositional Environments

Fine grained sediments dominate. Slow-moving currents prevent coarse-grained sediment from migrating into in low-energy settings. Fine materials can be carried long distances before they can settle out in the absence of waves and currents.

Figure 6.23. Lake (lacustrine) and swamp environments.

Figure 6.24. Tidewater marsh and estuary/lagoon settings.

Sedimentary deposits preserve aspects of the energy levels of the locations in which they were deposited.

In general, the particle size of sediments is larger in sedimentary deposit deposited in high-energy environments. Fine-grained sediments tend to erode in high energy environments, and tend to be deposited in low energy environments. In addition, the higher energy environments tend to have higher dissolved oxygen and nutrient concentrations, which influences the kind of organisms that live in such environments.

6.9: Sources of Lithogenous Sediments- Continental Weathering and Erosion

Sources of Lithogenous Sediments: Continental Weathering and Erosion

Rocks on or near the surface are exposed to physical and chemical interactions with air and water. The breakdown of earth materials due to exposure is called **weathering**. **Weathering produces sediments; erosion moves sediments.**

Lithogenous sediments are solid fragments of inorganic or organic material that come from the weathering of rock. On land and under water sediments are subjected to **gravitation forces** pulling them downslope. **Erosion** is the mechanical and chemical processes of weathering, wearing or grinding away materials on a landscape by the action of wind, flowing water, or glacial ice. **Deposition** is the process of sediments settling and accumulating from a moving fluid (wind, water, or ice). Once sediments have accumulated in a stable setting they can gradually undergo **compaction** and **cementation** to form sedimentary rocks.

Sediments can be **eroded**, **transported**, and **deposited, often over and over again.** Most sedimentary deposits preserve evidence about how, when, where, and why they were deposited!

Figure 6.25. Volcanic eruptions can produce large volumes of **ash** and other debris that can be eroded, transported, and deposited as marine sediments.

6.10: Weathering

Weathering

Weathering is the gradual destruction of rock under surface conditions. Weathering may involve **physical processes** (called **mechanical weathering**) or **chemical activity** (called **chemical weathering**). Biological activity can also result in weathering that can be construed as mechanical, chemical, or both.

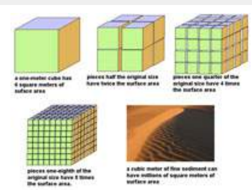
Weathering processes can begin long before rocks are exposed at the surface. This is true in most places on the earth surface where **rocky outcrops (bedrock)** is not exposed. In addition, weathering and erosion can take place simultaneously, perhaps most obviously in settings like rivers in flood, or waves crashing on a beach.

Mechanical Weathering

Mechanical weathering involves all processes that collectively **break rocks into smaller pieces**. Mechanical weathering includes all forms of **mass wasting**—a general name for processes by which soil and rock move downslope under the **force of gravity**. **Mass wasting**, a form of mechanical weathering, includes sudden events such as **rock falls**, **landslides**, **slumps**, and **avalanches**. These processes break "big pieces of rocks into smaller pieces."

Mechanical weathering can involve erosional grinding as fast-moving flood waters moves boulders and sediments down stream valleys and where wave action batters rocks into sand along a shoreline. Rocks are shattered by earthquakes and volcanic explosions, the expand and split when erosion unloads overburden on compressed rocks that were previously deeply buried. Rocks will split when water freezes and expands in cracks. Rocks exposed on the surface are subject to expansion and contraction caused by daily heating and cooling (particularly effective in arid environments). Mechanical weathering is also caused by organic activity—the breakdown and movement of rock and soil caused by expanding tree roots, burrowing, feeding activity, etc.

The mechanical breakdown of rocks increases the surface area (per unit area) increasing the available surface area where chemical weathering can take place (Figure 6.21).

		
Figure 6.26. Mechanical weathering is any process that makes "big pieces into smaller fragments."	Figure 6.27. **Glaciers** (moving ice) scours bedrock and produce and carry away large quantities of sediment.	Figure 6.28. **Gravity** drives **mass wasting**. In this case, a rock fall, breaks big pieces into fragments.
		
Figure 6.29. **Flood waters** can move all sizes of sediments, when the water slows down, sediments are deposited.	Figure 6.30. Coastal Erosion by wave, tides, and current is a major source of lithogenous sediments. This view is of the Thornton Beach coastal landslide area near San Francisco, California).	Figure 6.31. The mechanical breakdown of rocks **increases surface area** (per unit volume). Increased surface area increases the space for chemical weathering processes to take place.

Chemical Weathering

Chemical weathering involves the breakdown (decomposition, decay, and dissolution) of rock by chemical means. **Dissolution** is the action or process of dissolving or being dissolved, moving soluble components of materials into solution. **Leaching** is the process of dissolving and removing the soluble constituents of soil or rock near the land's surface. Water flowing under the influence of gravity carries dissolved materials away, ultimately adding to the saltiness of the oceans or they are deposited as salts, such a such as in an inland desert dry lake basin.

In most surface and near surface settings, mechanical and chemical weathering are taking place simultaneously.

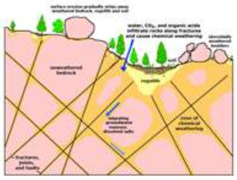


Figure 6.32. **Weathering** involves many processes occurring at or near the surface environment. Fractures allow water and air to penetrate into the bedrock allowing chemical weathering processes to take place.

Weathering and erosion are continuous processes in the surface environment, enhanced by the presence of water. Water is commonly called the **universal solvent** because so many compounds can be dissolved in it.

The journey of sediments can take a long time! The migration of sediments from upland regions to the ocean basins can take a very long time. Sediments can eroded and re-deposited many times along the journey.

Figure 6.33. Weathering is most intense where water is present (such as in upland areas that receive greater precipitation). This view shows Loma Prieta Peak near San Jose, CA.

Figure 6.34. **Flood waters carry sediments**: large particles (boulders, gravel, and sand) roll and bounce along on the stream bed; finer materials (fine sand, silt, and clay) can be carried in suspension.

Figure 6.35. **Flowing water** transports, grinds fragments, and erodes landscapes. Stream and river erosion are dominant forces changing mountainous landscapes. They contribute most of the sediments that build beaches and shoreline deposits.

Figure 6.36. Wave action along shorelines grinds rocks into fragments. Storm-driven currents in ocean and lake settings and wave action along coastlines can move tremendous amounts of sediments. (Año Nuevo State Beach, California)

Fate of soluble components of rocks: formation of seawater

As rocks weather and erode, they loose their soluble elemental components, they dissolve in groundwater and surface runoff and are carried away, eventually reaching the ocean. The high level of salt in seawater comes from\ the weathering and erosion of rocks on the surface or the seafloor. Salts dissolved in water flowing off of the continents or water flowing through sediments or rocks underground. **Evaporation** concentrates salt in seawater. Salt concentrations higher than seawater occur isolated lake basins in arid regions, such as in North America's Great Basin region. Salts end up being concentrated as salts on dry lake beds—or **brine** in basins such as Mono Lake (CA) or the Great Salt Lake (Utah). Over billions of years, rivers and streams, and groundwater flowing into the oceans have contributed to the saltiness of seawater. Salt in seawater is concentrated by the evaporation of water back into the atmosphere. (See **Why is the ocean salty?**)

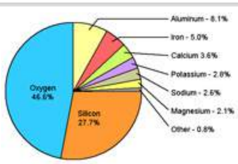


Figure 6.37. Composition of crustal rocks, some elements are more soluble and others.

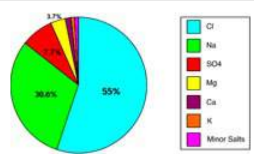


Figure 6.38. Elemental components of salts dissolved in seawater.

6.11: Sediments Classification Based On Grain Size

Sediments Classification Based On Grain Size

Sediments are solid fragments of inorganic or organic material that come from the weathering of rock and soil erosion, and are carried and deposited by wind, water, or ice. They range in size from large blocks to microscopic particles. Figure 6.39 shows the technical definition of sediment particles. However, general usage is as follows ranging from largest to smallest: **boulders, cobbles, gravel, sand, silt, and clays**.

Sediments form from the disintegration of rocks. They are transported, mostly by water, and in the process the fragments are abraded, with sharp edges worn down and the overall shape of particles increasing in roundness. Sediments derived from erosion on land are mostly **lithogenous sediments**.

Classification of clastic sediments and sedimentary rocks.

Clast Size	Size Class*	Sediment/Rock Name
>256 mm	boulders	sediment = gravel rock = conglomerate
64-256 mm	cobbles	
4-64 mm	pebbles	
2-4 mm	granules	
1-2 mm	very coarse sand	sediment = sand rock = sandstone
.5-1 mm	coarse sand	
.25-.5 mm	medium sand	
.125-.25 mm	fine sand	
.063-.125 mm	very fine sand	
.032-.063 mm	silt	sediment = mud rock = mudstone, siltstone and shale
<.032 mm	clay	

*Udden-Wentworth sediment size classification (Wentworth, 1922)

Figure 6.39. Classification of sediments by size of clasts (rock fragments)

Clastic sediments and sedimentary rocks

The word **clastic** is also commonly used to describe sediments or sedimentary rocks composed of fragments (or **detritus**) derived from older rocks. The word **clast** means rock fragment; the word is derived from the Greek word ***klastos*** which means ***broken***. Gravel, sand, and silt are examples of clastic sediments. Lithogenous sediments (described above) are mostly clastic sediments. A classification of clastic sediments and sedimentary rocks is illustrated in Figure 6.39 and with details discussed below.

How do sediments become sedimentary rocks?

Sediments can become **lithified** into sedimentary rocks once they've been deposited in a stable setting where burial, compaction, and cementation can take place. The processes, collectively called **lithification** (or **diagenesis**) typically takes place slowly over time but rates depend on many factors including the chemistry of the sediments and groundwater passing through the sediment, and how quickly or deeply burial takes place. Deposits of unconsolidated sediments typically have high **porosity—pores** are open spaces between grains filled with gas or fluids (water or in some cases, petroleum). **Compaction** is the process of gravitation consolidation of sediments, decreasing the volume of pore space between particles of sediment and increasing hardness. **Cementation** involves processes that harden sediments through the precipitation of minerals in pore spaces between grains of rock and mineral fragments, binding them together (Figure 6.40). Common minerals that form ***cement*** include **quartz**, **calcite**, **limonite**, **hematite**, and **clays**. The cementing minerals are slowly deposited between grains by groundwater.

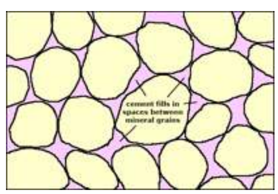


Figure 6.40. **Cementing** minerals fill in spaces between sediment grains as they turn to stone.

6.12: Clastic Sedimentary Rocks

Clastic Sedimentary Rocks

Rocks composed of grains of mineral and rock fragments derived from erosion of other rocks. Three general groups are coarse-grained, sand-size grained, and fine-grained ("mudrocks").

Coarse-grained sediments and sedimentary rocks

Gravel is rock particles that have been moved by moving water. Gravel usually consists of a mix of the more durable and most abundant rock types in the sediment source areas (Figure 6.41). Gravel deposits typically occur along stream valleys close to mountainous source areas and along rocky coastlines with high wave action.

Conglomerate is a sedimentary rock composed of cemented gravel. It consists of rounded to sub-angular fragments (larger than 2 mm in diameter) set in a fine-grained matrix of sand or silt, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent to gravel (Figures 6-42). The composition of grave reflects the rocks the general composition in the area where it comes from.

Figure 6.41. Wave action creates well rounded and sorted **gravel**.

Figure 6.42. **Conglomerate** formed from an ancient gravel deposit.

Sand-size-grained sediments and sedimentary rocks

Sand goes through degrees of refinement at it moves away from source areas. Sand deposits near mountain ranges may be enriched in feldspars. Volcanic regions may produce sand enriched in dark minerals. "Mature" sand that has traveled long distances in streams, blown by wind, or worked and reworked by waves will be enriched in quartz and individual grains will be very well rounded and well sorted (see below). Large sand deposit accumulate along stream valleys, on beaches, barrier islands, and offshore bars, and in dune fields in coastal areas and in desert environments.

Sandstone is a sedimentary rock formed by the consolidation and compaction of sand and held together by a natural cement, such as silica, calcite, and iron-oxide minerals (Figure 6.44). Most sandstone is dominated by the minerals **quartz**.

Figure 6.43. Sand is winnowed (sorted) and accumulates on a beach by wave action.

Figure 6.44. Sandstone outcrops exposed in Utah's Canyonlands National Park

Fine-grained sediments and sedimentary rocks ("Mudrocks")

Mud is a general term lumping together sediments consisting of a mix of clay, silt, and may contain sand. Mud is usually an unsorted mix of fine grain materials. Mud accumulates in quiet water settings separated from where coarser materials have settled out elsewhere (Figure 6.46). Most **soil** is mud. Mud-rich accumulations are common in river delta regions, swampy coastal regions, tidal flats, and in lake and deep water settings.

Mudstone is a fine-grained sedimentary rock formed from the compaction and cementation (lithification) of muddy sediments rich in **silt** (but may include percentages of fine sand and clay).

Shale is a soft, finely stratified sedimentary rock that formed from consolidated mud rich in **clay minerals** and can be split easily into fragile plates, such as along bedding plains. Shale forms from the compaction of sediment dominated by **clays**.

Clays are composed of any microscopic mineral particles. Most dust is clay sized particles. However, there are several types of **clay minerals. Clay minerals** are any of various hydrated aluminum silicates that have a fine crystalline structure and are components of clay (sediment). Clay minerals form from the weathering of feldspars and other silicate minerals and are the dominant sediment found on earth.

Figure 6.45. Certain kinds of **Clays** are used to make ceramic pottery. Clay is made up of clay minerals.

Figure 6.46. Mud accumulates in quiet-water environments as illustrated with these tidal flats.

Figure 6.47. Comparison of shale and mudstone. Shale tends to be flaky and splits into thin layers. Mudstone tends to form more massive layers.

Figure 6.48. Shale (blue gray) and **mudstone** (brown) outcrops in Utah's Capitol Reef National Park. Marine shales tend to be shades of blue, green, and gray.

Graywacke (or ***graywacke*** or ***grauwacke***, a German word signifying a gray, earthy rock) is a variety of sandstone or mudrock generally characterized by its dark color and poorly sorted angular grains including a mix of quartz, feldspar, dark mafic minerals, and tiny rock fragments cemented in a compact, clay-fine matrix. Generally, graywacke is a **featureless dirty**-looking, dark brown or gray sandstone or silty mudstone. Graywacke is common in active continental margin regions such as along coastal California (Figures 6-49 and **6-50**).

Figure 6.49. Graywacke is a poorly sorted mix of sediments common in marine deposits along active continental margins.

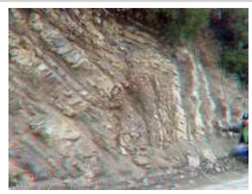


Figure 6.50. Graywacke is perhaps the most abundant sedimentary rock exposed mountainsides throughout coastal California.

6.13: Unique Characteristics of Lithogenous Deposits and Rounding of Sediment Grains

Unique characteristics of lithogenous deposits

Sediments preserve other characteristics that may tell information about the environment where they occur. Sediment particle shapes (**rounding**), degree of **sorting**, and **bedding** characteristics are typically unique to different geologic settings.

Rounding of sediment grains

When particles are moved by running water they become rounded ("**roundness**" is illustrated in Figure 6.51). The corners hit first and are worn down. The sharp edges are also pounded. The particles may become round boulders or pebbles. Bits of sand move with them. As the water slows the largest particles drop out first, making deposits of round boulders and pebbles called conglomerate. The smaller particles are swept away downstream (unless they are trapped between or beneath the large particles).

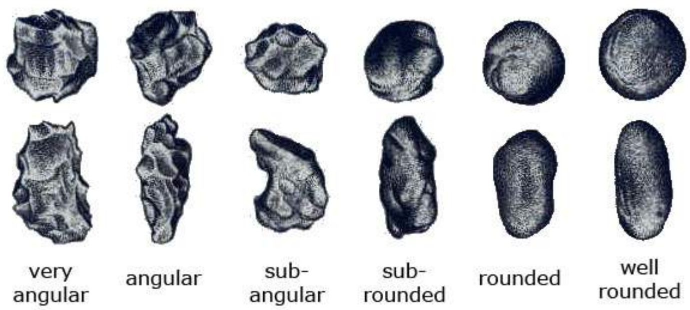


Figure 6.51. "Roundness" of sediment grains: The farther a particle is moved, the more rounded and spherical it should become. Angular particles tend to be deposited close to their source, they become more rounded the farther they travel downstream. Grains of beach sand are typically well rounded. Dune sand is typically even more rounded and better sorted (Image from Powers, 1959).

6.14: Sorting

Sorting

The ability of running water to move sediments also sorts particles by size and to a lesser degree by shape. This is called **sorting** (illustrated in Figure 6.52). Sediments exposed to longer transport or exposure to currents and waves tend to be more sorted by shape and size.

The amount of sorting depending on the energy conditions and amount of time at which the stream currents or ocean waves works on the particles. For instance, particles of the same mineral that are more rounded and more sorted have traveled farther.

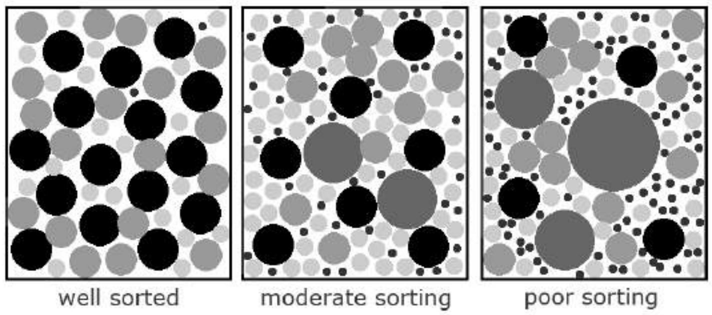


Figure 6.52. Sorting of sedimentary particles. Beach sands the to be very well sorted. River sands tend to be moderately sorted. Deep ocean turbidity current sediments tend to be very poorly sorted.

As **transportation distance increases**, sediment becomes more "**mature**" and:

• **Clay content decreases** (clays are carried away and deposited in other quiet water settings)

• **Sorting increases** (gravel and sand gets concentrated)

• **Non-quartz minerals decrease** (quartz is both an abundant and is harder than other common minerals)

• **Grains become more rounded** (sharp edge break off easier)

The sediments sorting, roundness, and sphericity could act as a clue to following either modern or ancient alluvial rocks to their ultimate source (such as for finding gold and diamonds). For example, very well sorted and rounded materials may suggest a source from an older sedimentary rock rather than from freshly exposed igneous rocks. Sand from rivers and stream are very different from sands associated with beach and sand-dune deposits (see Figures 6-53 to **6-56**).

			
Figure 6.53. **Sand from a mountain stream** may be rich in poorly sorted and angular grains of feldspars, quartz, and other minerals.	Figure 6.54. Beach sand is enriched in well rounded and consist mostly of well-sorted quartz grains. Fine materials are winnowed out.	Figure 6.55. Beach sand in many tropical settings may be enriched in shell material, including microfossils (such as shells of foraminifera).	Figure 6.56. **Wind-blown dune sand** is typically very well sorted and very well rounded, polished to frosted grains of mostly quartz.

6.15: Sedimentary Processes and Sedimentary Structures

Sedimentary Processes and Sedimentary Structures

Lamination and bedding

Sediments are deposited in layers ranging from paper-thin sheets to massive beds tens to hundreds of feet thick! A **laminae (or lamination)** is a layer of sediment or sedimentary rock layer only a small fraction of an inch (less than a centimeter) in thickness (see Figure 6.57). Thin lamination is typically associated with fine-grained sediments deposited in quiet or slack-water environments, such as in a lake basin or offshore below the influence of waves and strong currents. **Bedding** is the smallest division of a sedimentary rock formation or stratigraphic rock series marked by well-defined divisional planes (bedding planes) separating it from layers above and below (see Figure 6.58).

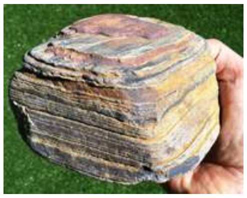


Figure 6.57. Lamination in shale. Each laminae may be an annual cycle of deposition or a seasonal storm flood event (scale is in mm to cm).	Figure 6.58. **Bedding** is layers of sediment deposited in an environmental setting on a scale of hundreds to many thousands of years.

6.16: Sedimentary Structures Preserved in Bedding

Sedimentary structures preserved in bedding

Sedimentary deposits (including sediments and sedimentary rocks) commonly preserve evidence of how they were deposited. Anyone who has been to the beach or a sand dune area have seen **ripple marks** created by the movement of sand under the influence of wind or water. Listed below are examples of sedimentary structures preserved in bedding of ancient sedimentary rocks. The processes that created them are the same that can be observed occurring today.

- **ripple marks**—a series of small ridges produced in sand by water currents or by wind (Figure 6.59).
- **cross bedding—**inclined sedimentary structures in a horizontal unit of rock. These tilted structures are deposits from bedforms such as ripples and dunes, and they indicate that the depositional environment contained a flowing fluid (typically, water or wind) (Figure 6.60 and **6-61**).
- **desiccation cracks**—mudcracks; irregular fracture formed by shrinkage of clay, silt, or mud under the drying effects of atmospheric conditions at the surface (Figure 6.58).
- **graded bedding**—bed is one characterized by a systematic change in grain or clast size from the base of the bed to the top. Large fragments tend to settle out fastest from a slowing turbulent flow.
- **biological structures—**many kinds of organisms burrow or bore into sediments creating holes for feeding or for shelter (or both). Most marine sedimentary beds preserve **bioturbation** features - bioturbation means "churning of the sediments" as organisms, typically worms, shrimp, and other invertebrates work through the sediments to eat decaying organic mater (or other organisms feeding there). They also use the burrows as shelter or nesting site. Very often the traces are preserved as structures in the sediment. Trackways, burrows, or resting sites are also common structures preserved in marine sediments.

Figure 6.59. Ripple marks on sand dune sand in water deposits form from current flow (air or water)

Figure 6.60. **Cross bedding** in ancient sand dune deposits Zion National Park, Utah

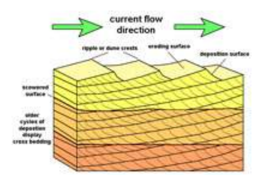


Figure 6.61. Formation of cross bedding caused by the migration of ripples or dunes

Figure 6.62. Desiccation mud cracks in Precambrian rocks, Grand Canyon, Arizona

Turbidity Currents and Development of Submarine Canyons and Fans

A turbidity flows is a turbid, dense current of sediments in suspension moving along downslope and along the bottom of a ocean or lake. In the ocean, turbidity currents can be massive episodic events. They typically form and flow down through a submarine canyon (carved by previous turbidity flows) and accumulate near the base of the continental slope on **deep-sea fans**. Turbidity flows produces deposits showing **graded bedding** (Figure 6.63 and 6-64). Slowing turbid currents drop their coarser fractions first (gravel and sand) and the finer silt and clay fractions settle out last.

Figure 6.63. Appearance and example of graded bedding in sedimentary deposits. Graded beds will "fine-upward" as currents slow down. They may "coarsen upward" if the energy of the depositing flow (current) increases.

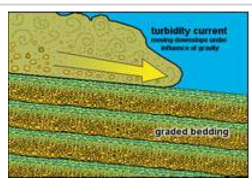


Figure 6.64. **Turbidity currents** flow down slope under water under the influence of gravity. At peak flow, turbidity currents will scour the seabed, but as flow slows and stops, coarse sediments are deposited first, and finer material last.

6.17: Deep Sea Fan, Turbidite Deposits, and Abyssal Clays

Deep Sea Fan, Turbidite Deposits, and Abyssal Clays

A **deep-sea fan** is a fan- or delta-shaped sedimentary deposit found along the base of the continental slopes, commonly at the mouth of submarine canyons. Deep sea fans form from sediments carried by turbidity flows (density currents) that pour into the deep ocean basin from the continental shelf and slope regions and then gradually settle to form graded beds of sediment on the sea floor. Deep-sea fans can extend for many tens to hundreds of miles away from the base of the continental slope and an coalesce into a broad, gently sloping region called a **continental rise**.

Graywacke is a fine-to-coarse-grained sedimentary rock consisting of a mix of angular fragments of quartz, feldspar, and mafic minerals set in a muddy base (commonly called a "dirty sandstone or mudstone" because of its mixed size fractions). Graywacke is the general term applied to sediments deposited by turbidity flows, and they commonly show **graded bedding**. Graywacke is a common rock-type in the Coast Ranges of California and other active continental margin regions around the world. It is exposed on land where tectonic forces push up rocks that originally formed in the deep ocean (examples in Figures 6-65 and to **6-66**).

Turbidites are sedimentary deposits associated with turbidity flows—they commonly appear as interbedded layers of sandstone and shale. Conglomerate typically occurs in thicker beds and were originally deposited as gravel and mud on ancient submarine fans closer to the mouths of submarine canyons or in channels carved into the seabed.

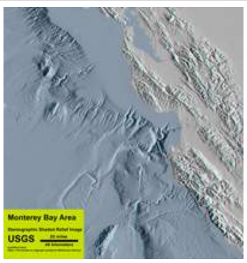


Figure 6.65. **Turbidity currents** scour submarine canyons in the deep offshore environment and deposit sediments in the deep ocean. **Deep-sea fans** build up the continental rise region at the base of the continental slope and spread for hundreds of miles seaward, sometimes extending onto abyssal plains.

Figure 6.66. Cretaceous-age **turbidites** (turbidity current deposits) at Bean Hollow State Beach, California. Each layer represents an undersea "storm" (turbidity flow) that spread across a deep sea fan on a continental rise. They were pushed up by tectonic uplift along the coast.

Abyssal Clays

Abyssal clays are very fine-grained sediments, mostly **clay minerals and iron-rich mineral dust** that are mostly blow in by the wind from distant terrestrial sources. Much of the abyssal clay components are derived from dust storms in the world's desert regions and from explosive volcanic eruptions that can blow fine particles high into the atmosphere. Abyssal clays are also fine-grained material carried and redistributed by ocean currents such as tail end of far-turbidity currents that can travel hundreds to even thousands of miles away from continental margins. Abyssal clays in the deep ocean basins accumulate very slowly relative to other ocean sediments. Some of the fine-grained material can possibly be from cosmogenous sources in some locations. Abyssal clays dominate sediments on the seafloor in the northern Pacific Ocean basin (see discussion on ***volume and distribution of marine sediments*** (in **Figure 6.18** above).

6.18: Biogenous Sediments in the Marine Environment and Carbonate Reefs

Biogenous Sediments in the Marine Environment

Biogenous sediments include sediments formed by **accumulation of organic materials.** Biogenous sediments are mostly composed of the remains of organisms (including skeletal remains of microplankton (both plants and animals), plant remains (wood, roots, and leaves) and remains of larger animals including shells of invertebrates, such as shells, coral fragments, and fish and other vertebrate teeth, bone, and scales, and fecal material left behind by any type of organism**.** Biogenous sediments may be partly mixed with **lithogenous sediments** (continental-derived sediments) in coastal regions, particularly where streams and rivers contribute sediments.

Bioaccumulation is the **buildup of organic remains**, such as deposits associated with coral reefs, shell or bone beds, and algae and ooze (calcareous and siliceous). On land bioaccumulation in swampy environments produces peat beds (with burial and time, peat eventually can be converted to coal). In many passive margin regions in tropical regions, carbonate sediments form and accumulate forming massive deposits along continental margins.

Carbonate Reefs

A **reef** is a general name for a ridge of jagged rock, coral, or sand just above or below the surface of the sea. A **carbonate reef** is one that is made of skeletal material composed of coral, coralline algae, and other carbonate skeletal material. Carbonate reefs are commonly called **coral reefs** but not all organisms that look like corals are actually corals—other organisms that create solid structure (branching or not) include coralline algae, bryozoans, sponges, stromatoporoids, and many other types of invertebrates). Figure 6.67 illustrates the variety of settings and features associated with **carbonate depositional environments**.

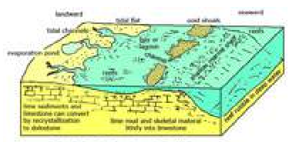
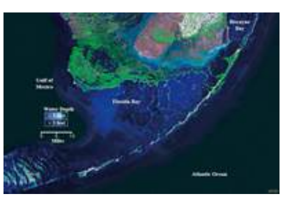


Figure 6.67. Carbonate depositional environments include coral reefs, keys, shoals, tidal flats, bays, and other coastal and offshore features.

Carbonate (coral) reefs form in clear shallow, warm, tropical marine waters.

Over time, **lime sediments** are produced by biological activity in and around carbonate reefs. **Carbonate reefs grow at rates of 10-30 feet per thousand years.** Wave action and currents will erode and redistribute lime sediments offshore where it may accumulate, slowly building up massive **carbonate platforms** (becoming regions underlain by **limestone**)**.** Examples of carbonate platform regions include the Bahamas, South Florida, and the Yucatan Peninsula (Figure 6.68 and **6-69**).

The world's largest reef system is the reef tracts, islands, and tidal shoals associated with the **Great Barrier Reef** located along the east coast of Australia (Figure 6.70)**.** The Great Barrier Reef is composed of over 2,900 individual carbonate reefs and about 900 islands stretching for over 1400 miles (2,300 km) along the northeast coast of Australia and encompassing about 133,000 square miles (344,400 km^2). It is the largest feature of biological origin on Earth. Similar reef tracts have formed throughout geologic history in other locations around the world.



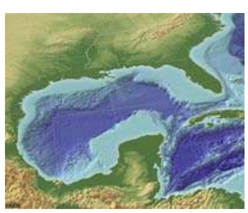


Figure 6.68. South Florida is part of a growing carbonate platform with the Keys consisting of an ancient and modern forming a barrier reef complex.	Figure 6.69. Carbonate platforms surround much of the Gulf of Mexico. They include continental shelf regions around the Yucatan Peninsula, South Florida, and islands of the Caribbean where Biogenous sediments form and accumulate.	Figure 6.70. Great Barrier Reef - The world's largest organic deposit. The growth of the great reef tract has kept pace with the global rise in sea level since the end of the Wisconsinian ice age.	Figure 6.71. **Atolls** are volcanic islands or seamounts covered or surrounded by **fringing carbonate reefs** that build up even long after the volcano stopped erupting.

6.19: Limey Sediments and Limestone

Limey Sediments and Limestone

Lime mud is sediment composed of **calcium carbonate** ($CaCO_3$) derived from the skeletal remains of shelled organisms, coral, and calcareous algae and plankton. Large amounts of lime mud is created by waves battering reefs and reef organisms (including dead corals and other calcareous skeletal material) being chewed up and **excreted** by reef-living organisms (Figures 6-72). With compaction and cementation (lithification) limey sediments become **limestone** (Figure 6.73).

Figure 6.72. Lime mud and sand accumulating around a living coral reef. Fine limey sediments are created mostly by organisms feeding on other reef organisms.

Figure 6.73. Skeletal remains of calcareous reef organisms erode and accumulate over time. **"Limey"** (shallow and warm) depositional environments are where lime sediments accumulate. Lime sediments turn to **limestone.**

Limestone is a sedimentary rock consisting predominantly of calcium carbonate ($CaCO_3$); the rock must have >50% calcium carbonate to be considered a limestone. Some limestones preserve large quantities of fossil material as crushed up shells or even old reef communities are sometimes preserved in nearly intact orientation of the corals and other calcareous organisms. These organic remains are made up of tiny crystals of two mineral forms of $CaCO_3$—**calcite** and **aragonite**. Aragonite is more soluble and is chemically less stable, and will usually convert to calcite with time.

Most limestone exposed throughout the United States formed in ancient shallow marine seaways that flooded portions of the continent in the geologic past. Large regions within the United States are underlain by thick sequences of limestone rock formations representing all geologic time periods from Precambrian age to the present (Figure 6.74). In many locations the limestone beds are many thousands of feet thick. Most **caverns** form in limestone. **Sinkholes** form in limestone regions (See Sinkholes [USGS])

Limestone is commonly used in the manufacture of lime for **cement**, used as building stone, and used to manufacture steel and many other products. Ancient carbonate deposits contain some of the **world's largest petroleum reserves**.

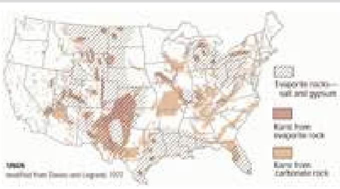


Figure 6.74. Map of the United States showing the location of carbonate rocks in the subsurface. Limestone rock formations occur under about 40% of the continental United States!

Figure 6.75. Fossiliferous limestone. This sample from Ohio is loaded with ancient **coral-like fossils** called **bryozoans** (not corals).

Figure 6.76. Fossiliferous limestone. This layer from Cincinnati, Ohio is loaded with ancient **brachiopod** shells that accumulated in an ancient inland seaway.

6.20: Oozes

Oozes

The oceans are full of many varieties of microscopic organisms, but only several varieties are responsible for generating vast quantities of biogenous sediments**.**

Ooze is slimy mud sediment (soft and mushy) on the bottom of an ocean or lakebed formed from the accumulation of skeletal and organic remains of microscopic organisms (**phytoplankton** and **zooplankton**).

- Oozes can be dominantly **calcareous** or **siliceous** in composition**.**
- To be considered an "ooze" sediment must consist of **>30% biogenous materia**l (Figure 6.77).
- **Oozes form slowly** - accumulating at a rate of 1/2 to 2 1/2 inch per 1000 yrs.
- Oozes form in **low energy environments** and are very fine grained (clay sized particles).

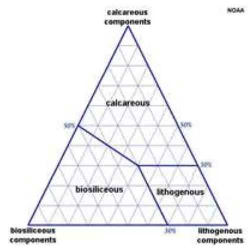


Figure 6.77. Components of oozes: calcareous, biosiliceous, and lithogenous materials

Calcareous oozes

Calcareous oozes are sediments dominantly composed dominantly of **calcium carbonate ($CaCO_3$)**. Two dominant groups of microorganisms that contribute carbonate remains: **Coccolithopores** (phytoplankton) and **Foraminifera** (zooplankton)

Coccolithopores

Coccolithopores are single-celled marine phytoplankton (microscopic plants) that live in large numbers throughout the upper layers of the ocean. Unlike any other plant in the ocean, coccolithopores secrete shells of microscopic plates made of calcite ($CaCO_3$). These scales, known as **coccoliths**, are shaped like hubcaps and are only three one-thousandths of a millimeter in diameter (Figure 6.78). Coccolithopores are part of base of the food chain and contribute vast quantities of coccoliths as sediment to large regions of the ocean basins. Coccoliths are concentrated in calcareous ooze.

Coccoliths first appear in the fossil record in Triassic time. Because they are composed of low-magnesium calcite (the most stable form) they are easily fossilized and preserved in sedimentary rocks. What is a Coccolithopores? (NASA)

Figure 6.78. A Coccolithopores is covered with calcareous plates called coccoliths.

Foraminifera (Forams)

Foraminifera (or forams) are a large group of single-celled zooplankton, most species have calcareous shells (or tests). Their shells are commonly divided into chambers which are added during growth and form patterns including spirals, open tubes, or hollow spheres (Figure 6.79). Depending on the species, the shell may be made of crystalline calcite, organic compounds, or sand grains and other particles cemented together. They are usually less than 1 mm in size, but some species grow much larger, reaching up to 20 cm. The majority of foraminifera species are benthic (meaning they live on or within the seafloor sediment) while typically smaller varieties are floaters (planktonic) in the water column at various depths. Foraminifera are found in all depths of the ocean, although deep ocean varieties do not have calcareous tests. They contribute a significant volume of sediments to carbonate reefs and a major component of carbonate oozes throughout ocean basins.

Over 10,000 species are recognized, both living and fossil. They first appeared in the fossil record in Cambrian time.

Figure 6.79. Examples of foraminifera tests.

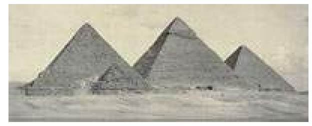


Figure 6.80. Pyramids of Giza, Egypt are constructed with foraminiferal limestone.

6.21: Calcium Carbonate Compensation Depth (CCD)

Calcium carbonate compensation depth (CCD)

Calcareous sediments are fairly evenly distributed in oceans, but their occurrence is influenced by the solubility of calcium carbonate. **Calcium carbonate forms and is stable in shallow, warm seawater, but it will dissolve in cold seawater.** Carbon dioxide dissolves easily in cold water, so $CaCO_3$ will dissolve in cold water. The **calcite compensation depth** (CCD) is the depth in the oceans where the rate of calcium carbonate material forming and sinking is equal with the rate the material is dissolving. Below the **CCD no calcium carbonate is preserved**—generally there is no $CaCO_3$ beneath about 15,000 feet (4500 meters) (Figure 6.81)**.**

Skeletal remains composed of calcium carbonate ($CaCO_3$) sinking into the deep ocean are mostly microscopic plankton. As carbonate materials settle or are moved by currents in to deep water, the smallest fragments dissolve before larger, denser fragments. The **lysocline** is the depth at which $CaCO_3$ begins to dissolve rapidly**.**

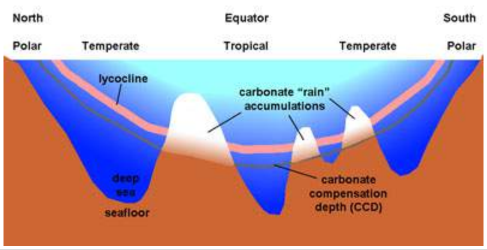


Figure 6.81. Relationship of the **lysocline** and the **carbonate compensation depth (CCD)** relative to depth of the ocean and latitude. The lysocline and CCD are at the surface near the poles where the water is cold. Calcareous oozes accumulate only above the CCD.

6.22: Chalk

Chalk

Chalk is a soft, fine-grained, white to grayish variety of limestone that is composed of the calcareous skeletal remains of microscopic marine organisms including coccoliths and foraminifera. Some of the purest varieties can have up to 99 percent calcium carbonate (see Figure 6.82). The White Cliffs of Dover, England are one of the most iconic landscape features in the United Kingdom. The White Cliffs consist of Cretaceous-age chalk deposited about 89 to 85 million years ago in more tropical conditions than exist in the region today. The layers of chalk reach nearly 500 meter thick. The sediment the chalk formed from was coccolithopore ooze.

Figure 6.82. The White Cliffs of Dover, England are chalk.

6.23: Siliceous Oozes

Siliceous oozes

Siliceous oozes are sediments dominantly composed dominantly of **SiO_2 (silica)**.
Two dominant groups of organisms that contribute siliceous remains: **diatoms** and **radiolarians.**

Diatoms

Diatoms are the most common plankton. Diatoms are **phytoplankton** (single-celled microscopic marine plants).
• Diatoms are most common in polar regions, but are also know from tropical and subtropical regions as well.
• Very important for **upwelling nutrients** (where deep water rich in .
• Diatoms have many economic uses including in beer filters, pool filters, and optical glass.

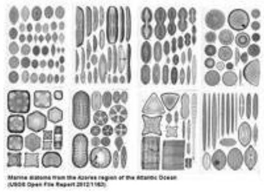


Figure 6.83. Example of **diatoms.** These are images taken with a microscope.

Radiolarians

A **radiolarian** is a single-celled aquatic animal (**zooplankton**) that has a spherical, amoeba-like body with a rigid spiny skeleton of silica. There are hundreds of known species of **radiolarians** (See a list on radiolaria.org website).
Figure 6.85 is a photomicrograph depicting the siliceous tests of ten species of marine radiolarians.

Upon death, their tests can accumulate on the seafloor and form siliceous marine sediments known as **radiolarian ooze** (a form of siliceous ooze). Radiolarians first appear in the geologic record in early Cambrian time and have experienced several periods of proliferation and extinctions as recorded in the geologic record.

Today, radiolarians are more common in equatorial regions.

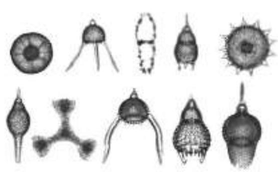


Figure 6.84. Example of **Radiolarian skeletons (tests).** These are images taken with a microscope.

6.24: Chert

Chert

Chert is a fine-grained siliceous sedimentary rock. It is a hard, dense, and consist chiefly of interlocking microscopic crystals of quartz and may contain opal. It has a conchoidal fracture and may occur in a variety of colors. Most chert forms from recrystallization of siliceous microplankton remains (siliceous ooze eventually looses its water content, recrystallizes and turns into chert.

Organic residues preserved as chert beds are known from rocks dating back to early Precambrian time. **Banded-iron formations (BIFs)** are composed of interbedded layers of iron-oxide minerals and chert, and are thought to be biogenous in origin. Younger marine cherts are mostly formed from diatoms and radiolarian oozes.

Figure 6.85. Layers of marine chert exposed in the Marin Headlands, California

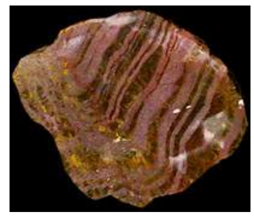


Figure 6.86. Banded-iron formation (with chert) from the Precambrian era.

6.25: Sedimentary Rock Formations

Sedimentary Rock Formations

A **rock formation** is the primary unit of **stratigraphy**, consisting of a succession of **strata** useful for mapping or description. A rock formation typical consists of a unique lithology (rock type) that has a relatively defined geologic age and is considered **mappable** (occurs throughout area or region, both on the surface and in the subsurface. Rock formations can be of igneous, sedimentary, or metamorphic origin. Sedimentary rock formations preserve information (including fossils and sedimentary structures) about the sedimentary environments they formed in. Figures 6-87 to **6-89** are examples of marine sedimentary rock formations.

Figure 6.87. Ancient beach, bay, and coastal dune deposits exposed in rock formations at the Del Mar Dog Beach, San Diego County, California

Figure 6.88. Ancient continental shelf deposits preserved in the Santa Cruz Mudstone Formation (Miocene-Pliocene age) in Santa Cruz, CA

Figure 6.89. Ancient deep ocean siliceous ooze deposits preserved as ribbon chert in the Franciscan Formation (Jurassic age), Santa Cruz Mountains, CA

6.26: Final Thoughts

Finally, food for thought...

Nuclear bomb testing and nuclear power-plant disasters has created a new identifiable sediment boundary preserved in Holocene sediments worldwide. This boundary is now associated with a proposed new epoch of the **Quaternary Period** called the **Anthropocene** — when human activities became plausibly the dominant force causing changes to Earth's global physical environment.

The United States conducted surface nuclear testing at Bikini Atoll in the South Pacific. Testing took place between 1946 and 1958. During that time, 23 nuclear devices were detonated at seven test sites on the reef itself, on the sea, in the air and underwater. So far, 8 nations in 2016 have successfully tested nuclear weapons. Whereas the last atmospheric nuclear test was in 1980, underground testing has continued.

Another proposed epoch name, not yet adopted, is perhaps.... **Weshouldhavecene**.

Figure 6.90. H-bomb test destroys Bikini Atoll

6.27: Quiz Questions - Chapter 6 - Marine Sediments

1. Manganese nodules are considered to be:
a. hydrogenous sediments.
b. lithogenous sediments.
c. biogenous sediments.
d. cosmogenous sediment.

2. Which is NOT a lithogenous sediment?
a. river sand
b. quartz-rich beach sand
c. lime mud
d. wind-blown dust

3. Which are NOT a biogenous sediment?
a. calcareous oozes
b. siliceous oozes
c. coral reef deposits
d. quartz-rich beach sand

4. Anhydrite is a “dry” (water free) variety of:
a. gypsum.
b. rock salt.
c. limestone.
d. quartz sand.

5. Where are the thickest accumulations of sediments mostly found around the world?
a. the outer margins of continental shelves
b. on continents
c. on ocean ridges
d. on abyssal plains

6. Which of these **best** describe weathering?
a. the transfer of rock material downslope by gravity
b. the mechanical and chemical disintegration of rock on or near the surface
c. the alteration of igneous rocks into sand and clay minerals
d. the removal of material by flowing water, air, or ice

7. The high level of salt in seawater comes from:
a. the weathering and erosion of rocks on the land surface or the seafloor.
b. salts dissolved in water flowing off of the continents or water flowing through sediments or rocks underground.
c. the concentration of water through evaporation of ocean water.
d. all of the above.

8. Regarding the size of **clastic sediment particles**, which selection below arranges particles from LARGEST to SMALLEST?
a. cobbles - boulders - gravel - sand - silt - clays
b. cobbles - boulders - gravel - silt - sand - clays
c. boulders - cobbles - gravel - silt - sand - clays
d. boulders - cobbles - gravel - sand - silt - clays

9. Which of the following would be considered a clastic sedimentary rock?
a. shale
b. conglomerate
c. sandstone
d. mudstone

e. all of the above

10. A sedimentary rock formed from the consolidation of gravel with a matrix of some sand, silt, and clay is called:
a. mudstone.
b. limestone.
c. conglomerate.
d. graywacke.

11. As sediments are transported by flowing water, over time, they tend to become:
a. more angular and poorly sorted.
b. more rounded and poorly sorted.
c. more angular and well sorted.
d. more rounded and well sorted.

12. A layer of sediment or sedimentary rock layer only a small fraction of an inch (less than a centimeter) in thickness, and is typically associated with fine-grained sediments is called:
a. a rock formation.
b. bedding.
c. lamination.
d. strata.

13. If you find a rock that was part of an ancient coral reef, you know that the rock must have formed in:
a. cold, deep water.
b. turbid waters, such as near a river delta.
c. cool, clear, shallow, polar water.
d. warm, clear, shallow, tropical water.

14. A **turbidite** is a kind of rock formed from:
a. sediments deposited by an underwater landslide on a deep-sea fan on a continental rise.
b. sediment deposited around a shallow water coral reef.
c. sediment deposited along a beach near a river delta.
d. sediment that accumulates from the underwater rain of pelagic biogenous sediments (such as the skeletal remains of dead plankton).

15. Which deposits are not likely found on a continental shelf?
a. delta sand and mud deposits.
b. siliceous oozes.
c. carbonate mud and reef deposits.
d. offshore bars and beach sand deposits.

16. Where are the thinnest sediments generally found in deep ocean basins?
a. on the mid-oceanic ridges.
b. in trenches.
c. on abyssal plains.
d. along a continental rise.

17. Coccolithopores are single-cell plants that grow in the warmer upper layers of the ocean. Their remain accumulate on the seabed forming:
a. siliceous ooze.
b. calcareous ooze.
c. turbidites.
d. mudstone.

18. What kind of sediment or rock are you likely NOT to find below the Carbonate Compensation Depth (CCD)?
a. lime mud
b. siliceous ooze

c. basalt
d. all of the above

18. Diatoms are the most abundant form of microplankton in the world oceans. Their remains accumulate on the seabed forming:
a. siliceous ooze.
b. calcareous ooze.
c. chalk.
d. limestone.

20. A siliceous rock that forms from the accumulation of the remains diatoms and radiolarians on the seafloor is called:
a. chalk.
b. chert.
c. graywacke.
d. quartz sandstone.

CHAPTER OVERVIEW

7: Properties of Seawater

7.1: Properties of Seawater

Properties of Seawater

Seawater is the most abundant resource on Earth! Seawater has evolved to what it is over the billions of years that oceans have existed on Earth. This chapter examines the physical and chemical properties of water and seawater.

Distribution of Water on Earth

97.2% in the world ocean
2.15% frozen in glaciers and ice caps
0.62% in groundwater and soil moisture
0.02% in streams and lakes
0.001% as water vapor in the atmosphere

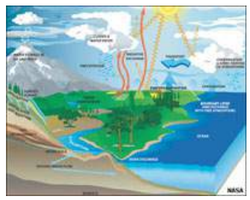


Figure 7.1. The water cycle.

Components of Seawater

Seawater is composed of**:**
- **Water**
- **Dissolved matter: solids and gas** (as **ions**)
- **Suspended matter** (dust and organic residues)

Ions in seawater
- Cl - 55%
- Na - 30.4%
- SO_4 - 7.6%
- Mg - 3.9%
- Ca - 1.2%
- K - 1.1%
- all other dissolved components - <1 %

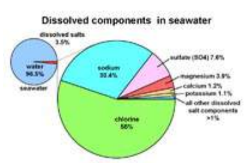


Figure 7.2. Components of seawater

Properties of Water

Water is a **polar substance**. Each molecule of water has a negative charge associated with its oxygen, and a positive charge with it hydrogen (Figure 7.3). This polar character is responsible for its properties cohesion and adhesion.

- **Cohesion:** water has high surface tension because water molecules stick together.
- **Adhesion:** water "sticks" to things.
- **High capillary action**: The cohesion and adhesion properties of water allow water to move upward against gravity in small confined spaces. The smaller the tube, the higher the water will rise. Capillary action helps plants to move water upward from their roots to their leaves.
- **Water is a powerful solvent**: A **solvent** is a substance that dissolves a **solute** (a chemically different liquid, solid or gas),

resulting in a **solution**. The polar character of the water molecule allows it to form weak bonds with other polar molecules. Substance held together with ionic bonds will readily dissolve in water. However, the solubility of chemical compounds in water is highly variable. The **solubility** of a chemical compound in water is defined as the maximum amount of the chemical that will dissolve in pure water at a specified temperature.

Seawater is a solution.

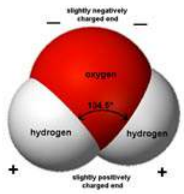


Figure 7.3. Water is a **polar molecule**.

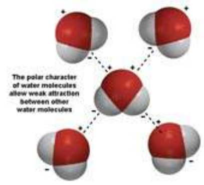


Figure 7.4. Water's polarity allows weak attraction between water molecules.

Figure 7.5. Water droplets illustrate water's high cohesive and adhesive properties.

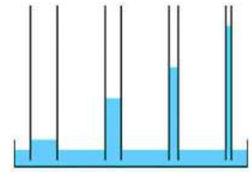


Figure 7.6. Capillary action works because water adheres to material. The smaller the tube the higher the water will rise.

Why don't oil and water mix?

Organic compound containing only carbon and hydrogen (hydrocarbon) are nonpolar and will dissolve in nonpolar solvents (like oil). However, many organic compounds have "functional groups with very electronegative elements" (i.e. oxygen), making the whole molecule polar, allowing them to dissolve in water (ex: sugar and starch can dissolve in water). **Soap** compounds (called **surfactants**) have molecules that are both; they have portions that behave as polar and non-polar ends. One end will stick to hydrocarbons and other non-polar substances whereas the other will stick to water and other polar molecules. This allows polar organic compounds to disperse in water.

Figure 7.7. **Oil** is a **non-polar** substance. **Water** is **polar**.

Figure 7.8. Ship cleaning up after an oil spill.

Properties of Water

pH (acidity and alkalinity)

pH is a measure of the acidity or alkalinity of a solution expressed on a logarithmic scale on which 7 is neutral, lower values are more acid, and higher values more alkaline. pH is an important measurement in seawater. Neutral water is a pH of 7.

Bicarbonate buffering of seawater

A natural buffering system with seawater's interaction with **carbon dioxide**. **Seawater is generally always within a range of pH of 7.5 to 8.5.** The interactions of dissolved components keep ocean water in a stable range. Organisms living in or near seawater have a limited tolerance for variations in pH and other factors. For instance, **calcite** (as in shell material) is stable within this range, but will dissolve if exposed to acidic conditions. **Carbonate buffering** keeps pH stable by precipitation (increase pH) or dissolution (decrease pH) of **calcium carbonate - $CaCO_3$**.

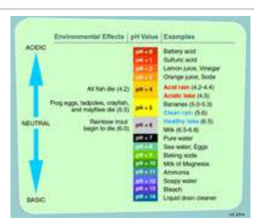


Figure 7.9. Salts can **dissolve** in water and then **precipitate** out again as water **evaporates** and concentrates salts in solution.	Figure 7.10. **pH** of common household substances compared with pure water (pH=7) and normal seawater (pH=8.2).

7.2: Specific Heat and Latent Heat Capacity of Water

Specific Heat and Latent Heat Capacity of Water

Specific Heat

Materials vary in their capacity to store thermal energy. For example, a material like copper will heat up much faster than water or wood. **Specific Heat** is a measure of the energy required to heat **1 gram** of substance **1° C**. Specific heat is recorded in "**calories"** for "**mass in grams**" (and "Joules for kg").

Figure 7.11 compares the specific heat of various metals to the specific heat of ice, water, and steam. It takes significantly more energy to warm water than other materials, including both ice and steam. Because of water's high specific heat capacity, the oceans are capable of storing vast quantities of energy from solar heating. Heat absorbed in equatorial regions can be carried long distances and carried by ocean currents before being released in polar regions.

Material	Specific Heat, c C/g*C°	Specific Heat, c, J/kgC°
Silver	0.06	251
Copper	0.09	377
Iron	0.11	461
Steel	0.12	502
Brass	0.22	921
Ice	0.50	2093
Steam	0.50	2093
Water	1.00	4187

Figure 7.11. Comparison of the specific heat of various substances with ice, steam, and liquid water.

High Latent Heat Capacity of Water

When any material is heated to the temperature where it **changes state** (converting from solid to liquid, or liquid to gas), the temperature will remain the same until all the material changes state. Because it takes more energy to convert a substance from one physical state to another (solid to liquid, or liquid to gas), those transitions require a larger amount of energy. **Latent heat** is the heat required (measured in calories burned) to convert a solid into a liquid or vapor, or a liquid into a vapor, **without a change of temperature**. For instance a pot filled with water on the stove will gradually warm up until the water temperature approaches **212° F (or 100° C)**—it will stay at that temperature until all the water has boiled away. The same is true as water freezes. As water cools it will reach **32°F (or 0° C)** is will stay at that temperature until all the water freezes (Figure 7.12).

To convert **1 gram** of **ice** at **0° C** to **1 gram** of **water** at **0° C** requires **80 calories.**
To convert **1 gram** of **water** at **100° C** to **1 gram** of **steam** at **100° C** requires **540 calories**.

When any material is heated to the temperature where it changes state, the temperature will remain the same until all the material changes state. That means ice water will remain at **0° C** (**32° F**) until **all** the ice is melted. The same thing applies when cooling the materials. The reason is that energy must be expended to change the state from solid to liquid or from liquid to gas. Likewise, energy must be withdrawn to change the state when cooling the material. The amount of energy required is call the latent heat of freezing or boiling.

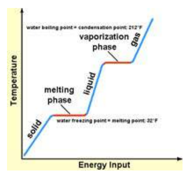


Figure 7.12. Diagram showing heat required to heat water from solid ice to liquid water and to vapor (steam). It take both specific heat and latent heat, released in stages, to convert ice to steam!

Specific Heat and Latent Heat Capacity of Ice, Water, and Steam Illustrated: (using charts listed above**)**

Example: How much energy would it require to heat **100 grams** of **ice** at **-10° C** to **steam** at **120° C**?

Calculation process:	**Energy required:**
To raise 100 grams of ice at -10° C to 0° C requires: (0.5 cal/g [specific heat of ice] x 10° C x 100 grams)	**500 calories**
To convert 100 grams of ice to water at -0° C requires: (80 cal/g [latent heat conversion] x 100 grams)	**8,000 calories**
To raise 100 grams of water from 0° C to 100° C requires: (1.0 cal/g [specific heat of water] x 100° C x 100 grams)	**10,000 calories**
To convert 100 grams of water to steam at 100° C requires: (540 cal/g [latent heat conversion] x 100 grams)	**54,000 calories**
To raise 100 grams of steam at 100° C to 120° C requires: (0.5 cal/g [specific heat of steam] x 20° C x 100 grams)	**1,000 calories**
Total energy required:	**73, 500 calories**

7.3: Energy Associated With Evaporation and Condensation of Water In the Air

Energy Associated With Evaporation and Condensation of Water In the Air

• **Evaporation/vaporization** takes a large amount of energy (to break hydrogen bonds). For example, water absorbs energy as it evaporates on your skin. Evaporation on the surface of a swimming pool will cool the water.
• **Condensation** releases a large amount of energy. For example, steam will burn you as it releases energy on your skin.

When water vapor in the air condenses to form water droplets in clouds it releases large amounts of energy.

As water evaporates into in air it cools the air and increases its **humidity**. Air at surface conditions can hold up to about 4% water before it becomes **saturated** and can not absorb more water. As humid air rises it expands and cools and if it reaches the saturation point clouds form as water is forced to condense. The condensation of water releases a lot of energy, heating the air and causing clouds to rise into larger thunderstorms clouds. The water released falls as precipitation.

Heat is absorbed as ice melts and it is released as it freezes. The latent heat of water is an important factor in weather systems and the stability of climates around the world.

Figure 7.13. Cloud formation releases heat into the air.

Figure 7.14. Melting ice absorbs heat from air and water

7.4: Salinity

Salinity

Salinity is a measure of the total amount of solid material (salts) dissolved in water, defined as:

Weight (mass) of salt
——————————— = Salinity
Weight (mass) of water

Units are described as:
- **%** is part per hundred (pph)
- **‰** is parts per thousand (ppt)

- Open ocean seawater ranges is 33 to 37 **‰** ppt. Average is about **35 ‰ (ppt)**.

Figure 7.15. Evaporation ponds constructed near the Dead Sea in Jordan are developed to manufacture salt.

Salinity is Measured by:
- electrical conductance (higher salinity = higher conductivity)
- density (higher salinity = higher density)

At room temperature, water can dissolve about 30% of its weight in salt (NaCl). Hot water can hold about 40%. A brine is water that is concentrated with high levels of salt. When evaporation concentrates salty water to it saturation point, salt crystals will precipitate.

Note that difference substances have different saturation levels in water.

Examples:
- Spring 0.3 **‰** ppt (**fresh**)
- Tap water 0.7 **‰** ppt (**fresh**)
- Limit on agriculture irrigation - 2 **‰** ppt
- Baltic Sea 10 **‰** ppt (**brackish**)
- Black Sea - 18 **‰** ppt (**brackish**)
- Average Ocean -35 **‰** ppt
- Mediterranean Sea - 38 **‰** ppt
- Red Sea 42 **‰** ppt (**hypersaline**)
- Great Salt Lake 280 **‰** ppt (**hypersaline**)
- Dead Sea 330 **‰** ppt (**hypersaline**)

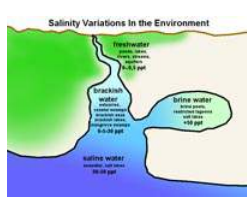


Figure 7.17. Variations in salinity in the natural environment.

Evaporation of Seawater Results In Precipitation Of Mineral Salts

As seawater evaporates in a restricted basin seawater is concentrated becoming a brine. As evaporation proceeds various mineral salts will precipitate out in the reverse order of their solubility. Salty sedimentary deposits produced by evaporation are called **evaporites**. The first to precipitate is **calcite** (if not consumed by organisms first). Next come **$CaSO_4$** (gypsum and anhydrite varieties). This is followed by salt (**NaCl**) (mineral name: **halite**; rock name: **rock salt**). By volume, NaCl is the most abundant salt from seawater. The last to precipitate are potassium salts (**sylvite**: KCl and others) and magnesium salts (**epson salt**: MgSO4 and others). Various other trace salt compounds are concentrated in the last of the brine to evaporate. About 80 different salt minerals have been reportedly found in evaporite deposits.

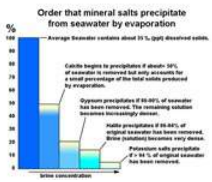


Figure 7.17. Order that salts precipitate from seawater as evaporation proceeds.

Figure 7.18. Salts forming from evaporation in Death Valley, California.

7.5: Formation of Sea Ice

Formation of Sea Ice

Fresh water freezes at **32° Fahrenheit (0° Celsius)**. **Seawater** freezes at about **28.4° F (-2 ° C)** because of the salt content. However, when seawater freezes, the ice that forms contains very little salt. Only the water part freezes, the remaining salt is concentrated as **brine** that separates from the sea ice. This process is very important for deep-sea circulation.

7.6: Relationship of Salinity, Density and Temperature

Relationship of Salinity, Density and Temperature

Assuming a closed system...
• **Temperature and Density**: **Inverse** (as temperature increases, density decreases)
• **Salinity and Density: Proportional** (as salinity increases, density increases)
• **Temperature and Salinity: None** (as temperature changes, salinity remains the same)

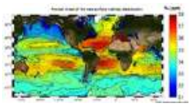
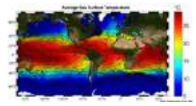
	

Figure 7.19. Sea Surface Salinity Average 2005	Figure 7.20. Sea Surface Temperature Average 2005

Animations of Satellite and Surface Oceans Data

These websites provide animations that provide stunning views of the Earth created from satellite sensor data. These data are the combined efforts of ocean and atmosphere scientists from many organizations.

NASA animations: **Average Sea Surface Temperature, Salinity and Density**
(This website has links to animations on a globe and a mercator map.) Animations include:
* Average Sea Surface Temperature (SST)
* Average Sea Surface Salinity (SSS)
* Average Sea Surface Density (SSD)

NASA Animations: (mercator) 1 year: December 2011 through December 2012 showing:
Global Sea Surface Salinity
Salinity and ocean circulation
Salinity and global seawater migration

NOAA animations: **Sea Surface Temperature** (World mercator map, last 6 months)
Monthly Isopycnal & Mixed-layer Ocean Climatology (MIMOC): Animations show pycnocline (temperature and salinity) data of different parts of the world.

The NASA animations provide views of how salinity, temperature, and density change over the course of a year.

		
Figure 7.21. Sea Surface Salinity Average 2009	Figure 7.22. Sea Surface Temperature Average 2009	Figure 7.23. Sea Surface Density Average 2009

7.7: Salinity and Latitude

Salinity and Latitude

Figure 7.24 is a map of the globe comparing the rates of evaporation and precipitation. The map is a compilation of **evaporation minus precipitation (E-P)** values. The data basically shows the regions where there is a net gain of salinity created in surface waters by high evaporation rates. There is also a net loss of salinity where precipitation is higher than evaporation rates (Figure 7.25). In general:

• The **tropics** (equatorial region) is humid and cloudy, and receives much more rain than evaporates.
• The **temperate regions** receive less precipitation, so evaporation dominates.
• The **polar regions** have low evaporation rates relative to the amount of precipitation they receive.

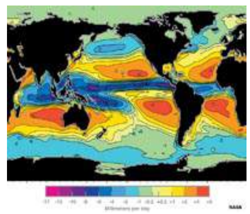


Figure 7.24. Map of net **evaporation minus precipitation (E-P)** on oceans.

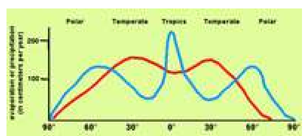


Figure 7.25. Evaporation and precipitation curves compared with latitude.

Variability of ocean salinity: Ocean salinity is stable at depth but can be highly variable at the surface. The upper surface layers of the ocean impacted by wave energy is a mixing zone. Simply this: the more waves, the more mixing. Freshwater is less dense than seawater and without mixing freshwater will float (stratify) on top of seawater.

Factors that decrease salinity:	**Factors that increase salinity**:
• **Precipitation** • **Runoff** • **Melting icebergs/sea ice**	• **Evaporation** • **Freezing sea ice**

7.8: "Cline Curves" and Mixing (Surface) Zone

The "Cline Curves" - changes in temperature, salinity, and density with depth

- **Thermocline** - a steep **temperature** gradient in a body of water marked by a layer above and below which the water is at different temperatures.
- **Halocline** - a vertical zone in the oceanic water column in which **salinity** changes rapidly with depth.
- **Pycnocline** - a layer in an ocean or other body of water in which water **density** increases rapidly with depth.

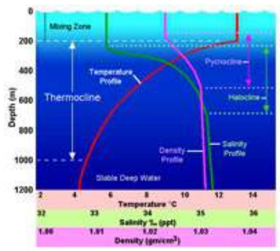


Figure 7.26. The "cline curves"

NOAA Animation: **Annual changes of pychnocline depth**

Mixing (Surface) Zone

Uppermost water where mixing from currents make temperature, salinity, and density mostly constant.

Vertical changes in temperature with latitude:
• **Polar regions** have almost **no thermocline**.
• **Temperate regions** have **weak thermoclines** (moderate in summer, less in winter).
• **Tropical regions** have a **strong thermocline.**

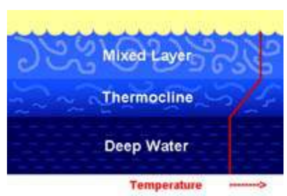


Figure 7.27. Mixing Zone

7.9: Gases Dissolved In Seawater

Gases Dissolved In Seawater

Oxygen concentrations (O_2) in air is about 21% oxygen, in water it is a tiny fraction of 1%. This large difference in oxygen concentrations forces oxygen to dissolve into water along the boundary between air and water. When wind blows creating waves, it increases the surface area, allowing more diffusion to occur.

Carbon dioxide (CO_2) is much more soluble in water than oxygen, but concentrations in the atmosphere are comparatively very low. When dissolved in water it becomes a **bicarbonate ion ($^-HCO_3$)**, so carbon dioxide readily diffuses into the atmosphere if it is not consumed in the production of **calcium carbonate ($CaCO_3$)**. Biological respiration releases $^-HCO_3$ which combines with available dissolved calcium which the organism either excretes or incorporates into its skeletal structure if environmental conditions are warm enough for $CaCO_3$ to persist. One of the gravest concerns about the burning of fossil fuels is that it is increasing the concentration of carbon dioxide in seawater, so organisms that produce carbonate shells and skeletons are negatively impacted.

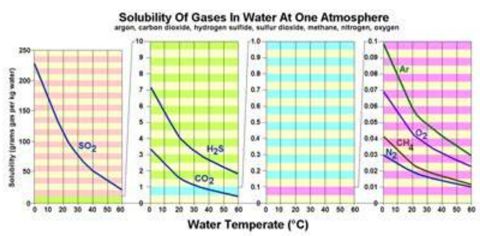


Figure 7.28. Solubility of gases in water is affected by temperature. Gases are much more soluble in cold water than warm water. In contrast, most solid materials (organic and inorganic; examples salt and sugar) are more soluble in hot water. The solubility of elements in seawater is complex and depends on many factors including pH (acid-base), eH (oxidation-reduction), temperature, pressure, and interactions between other compounds dissolved in seawater.

Methane (CH_4) has very low solubility in seawater, however, it is very abundant in sediments rich in organic mater. In cold settings, methane, carbon dioxide, and water form an unusual form of **ice** called a **methane hydrate (Figures 7-29** and **7-30)**.

A **clathrate** is a compound in which molecules of one component are physically trapped within the crystal structure of another, in this case CO_2 and CH_4 are trapped in the crystal structure of ice under certain pressure and temperature condition that exist on the seafloor in cold water, mostly on the outer continental shelves and slopes in polar regions. Global warming of the oceans can cause the release of tremendous amounts of CO_2 and CH_4 from the seafloor, contributing to anoxia conditions, with possible catastrophic consequences. Read about the "Clathrate Gun Hypothesis" (Wikipedia).

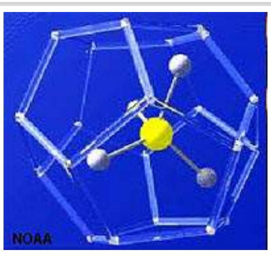


Figure 7.29. Methane-ice clathrate structure

Figure 7.30. Methane-ice clathrates will burn!

Sulfur dioxide (**SO_2**) is extremely soluble in water. Sulfur dioxide is a gas that **smells like rotten eggs**. It is released in large quantities by volcanic eruptions, forest fires, and by burning coal and petroleum. SO_2 is extremely soluble in water where it combines with water molecules to form **sulfate ions** ($-HSO_4$). When concentrated (when water is removed), the solution becomes **sulfuric acid** (**H_2SO_4**). When concentrated by **evaporation of seawater** (where **dissolved calcium** and other metallic ions are present) sulfate ions precipitates as the salts **gypsum** (**$CaSO_4·2H_2O$**), **anhydrite** (**$CaSO_4$**), **epson salt** (**$MgSO_4·7H_2O$**), and other salt minerals.

Figure 7.31. Gypsum

7.10: Local Conditions in the San Diego Region

Local Conditions in San Diego region

- In San Diego, we have a **temperate thermocline**, which is weak in the winter and fairly strong in the summer.
- During El Niño years we may get a strong thermocline all year.
- California's weather patterns are cyclical on multi-year periods of rain and drought.

Figure 7.32 shows California's annual precipitation 1895 to 2014. As of fall, 2015, California has currently experienced the worst drought in the period records have been recorded.

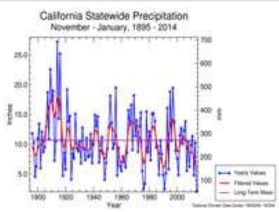


Figure 7.32. California's precipitation history.

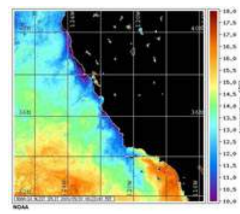


Figure 7.33. SoCal ocean temperatures (5/30/2000).

7.11: Quiz Questions - Chapter 7 - Properties of Seawater

1. It is currently estimated that 97.2% of water resources on Earth is in the world ocean. **Most** of the remainder is:
a. frozen in glaciers and ice caps.
b. trapped as groundwater and soil moisture.
c. stored in lakes, streams and reservoirs.
d. trapped as water vapor in the atmosphere.

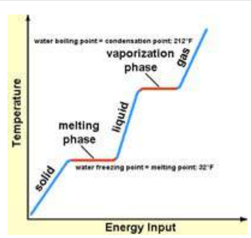
2. Seawater is composed of water, dissolved matter (including solids and gas [as ions], and suspended matter (dust and organic residues). Of the ions in seawater (besides hydrogen and oxygen), the **two** most abundant elements are:
a. sodium and calcium
b. chlorine and sodium
c. calcium and sulphate (SO_4)
d. magnesium and potassium

3. Water is a polar substance. Each molecule of water has a negative charge associated with its oxygen, and a positive charge with it hydrogen. This polar character is responsible for its properties to have high surface tension because water molecules stick together. This property is called:
a. cohesion.
b. adhesion.
c. capillary action.
d. a solution.

4. Water is a powerful solvent: A solvent is a substance that dissolves a solute (a chemically different liquid, solid or gas), resulting in a solution. Not everything dissolves equally in water. However, substances that are most easily dissolved are held together by:
a. covalent bonds.
b. metallic bonds.
c. ionic bonds.
d. Van der Waals forces.

5. **pH** is a measure of acidity and alkalinity of a water solution. Because of the natural buffering system of dissolved bicarbonate (+HCO3) dissolve in seawater:
a. seawater is slightly acidic.
b. seawater has a neutral water pH of 7.0.
c. seawater is generally always within a range of pH of 7.5 to 8.5.
d. seawater is highly salty with a pH of about 9.0 or higher.

6. How much energy would it require to heat 20 grams of ice at -20° C to steam at 120° C? **Do the math!**

(Key info) **Specific heat**: ice = 0.5 cal/gm water = 1.0 cal/gm steam = 0.5 cal/gm **Latent heat**: ice to water: 80 cal/gm water to steam: 540 cal/gm	

a. 3,400 calories
b. 7,350 calories
c. 12,980 calories
d. 29,600 calories

7. Lots of energy is released when:
a. water is converted to steam.
b. water evaporates on your skin.
c. ice melts to form water.

d. water vapor condenses in the air to form rain droplets.

8. As water evaporates into in air it cools the air and increases its **humidity**. As humid air rises it expands and cools and if it reaches the saturation point clouds form as water is forced to condense. The condensation of water releases a lot of energy, heating the air and causing clouds to rise into larger thunderstorms clouds. The water released falls as precipitation. How much water can the air hold to at at surface conditions before before it becomes **saturated** and can not absorb more water?

a. 2%

b. 4%

c. 8%

d. 12%

9. The salinity of seawater varies slightly from one part of the ocean to another, however, the average salinity of the oceans is about:

a. 4% (pph).

b. 17‰ (ppt).

c. 35‰ (ppt).

d. 40‰ (ppt).

10. Which of the relationships of temperature, salinity, and density of seawater is NOT true?

a. As temperature increases, density decreases.

b. As salinity increases, density increases.

c. As temperature changes, salinity remains the same.

d. As density increases, temperature increases.

11. Global data measurements of precipitation and evaporation show patterns of all EXCEPT which of the following.

a. The temperate regions receive more precipitation than tropical regions.

b. The polar regions have receive more precipitation than evaporates.

c. The temperate regions receive less precipitation than evaporates.

d. The tropics (equatorial region) receives much more rain than evaporates.

12. A thermocline is a layer of water at the ocean surface that prevents the upwelling and mixing of cool nutrient-rich water to ocean surface waters, reducing the production of primary plankton (food and nutrients for marine life). What is the best description of thermoclines based on latitude?

a. Polar regions have well-developed thermoclines in winter months.

b. Temperate regions have strong thermoclines in the winter months.

c. Tropical region have no thermocline in winter months.

d. Temperate regions have weak thermoclines (moderate in summer, less in winter).

13. Comparing oxygen carbon dioxide concentrations in the air compared with seawater, what of the following choices are true?

a. Seawater has higher concentrations of oxygen than the air.

b. Carbon dioxide (CO_2) is much more soluble in water than oxygen, but concentrations of CO_2 in the atmosphere are comparatively very low.

c. Wind and wave action reduces the exchange of oxygen and carbon dioxide (CO_2) with seawater.

d. All of the above are true.

14. Sulfur dioxide (SO_2) smells like rotten eggs. SO_2 is released in large quantities by volcanic eruptions and by burning coal and petroleum. SO_2 is extremely soluble in water where it combines with water molecules to form sulfate ions ($-HSO_4$). When concentrated by evaporation in seawater, what happens?

a. It becomes sulfuric acid ($H2SO_4$).

b. It precipitates as gypsum ($CaSO_4$-2H2O) and anhydrite ($CaSO_4$).

c. It is released back into the air as concentrated SO_2.

d. All of the above.

15. Methane (CH_4) has very low solubility in seawater, however, it is very abundant in sediments rich in organic mater. In cold settings, methane, carbon dioxide, and water form an unusual form of "flammable" ice called:

a. a clathrate.

b. sea ice.

c. permafrost.
d. all of the above.

CHAPTER OVERVIEW

8: Atmospheric Circulation

8.1: Atmospheric Circulation

Atmospheric Circulation

Our **atmosphere** is the gaseous mass or envelope surrounding the Earth, and retained by the Earth's gravitational field. Other planets and moons in the Solar System have atmospheres. The atmosphere plays many important roles in moving water in the world's ocean basins, and for supporting life on Earth!

Earth's atmosphere is:

- **Density stratified** - air is compressed and most dense near the surface and grows increasingly ***rarefied*** skyward.
- About **100 kilometers thick** between the ocean/land surface and the vacuum of space.
- **Composed mostly of gases,** mostly nitrogen (as N_2) and oxygen (as O_2), and trace amounts of other gases (including CO_2, argon, water vapor); **and traces of liquids and solids in suspension or falling as precipitation**: suspended water (clouds, water droplets and ice crystals), traces of organic compounds, and suspended particles of dust from a variety of sources.

Figure 8.1. Layers of the Earth's atmosphere as seen from space.

Structure of the Atmosphere

The Earth's atmosphere is subdivided into levels (Figure 8.2):

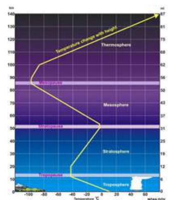


Figure 8.2. **Structure of Earth's atmosphere.**

* The **troposphere** is the lowest portion (**up to about 6-8 miles** [10-13 km]) where all weather takes place and contains about 80% of the air's mass and **99% of water vapor**.
* The overlying **stratosphere** contains an abundance of ozone which absorbs ultraviolet radiation, protecting life on land and in the shallow ocean extends **up to about 31 miles** (50 km).
*The **mesosphere** is the part of the earth's upper atmosphere above the stratosphere in which temperature decreases with altitude to the atmosphere's absolute minimum.
* The **thermosphere** the region of the atmosphere above the mesosphere and below the height at which the atmosphere ceases to have the properties of a continuous medium (about 60 miles [100 km]). The thermosphere is characterize temperature with height, where the charged atomic particles of the solar wind begins to interact with atmospheric gases.

Energy Transfer Through the Atmosphere

The amount of energy coming into the Earth from the Sun **is equal to** the energy **reflected** and **radiated** back into space. The atmosphere, oceans, and land **absorb and release energy**. Living things also absorb and release energy. Some of the energy stored in organic matter is preserved when it is buried in sediments. **Geothermal energy** is also a trace of the energy radiated into space. The rate of energy transfer also varies due to cloud cover and ice and snow coverage.

Incoming solar radiation involves all wavelengths of the **electromagnetic spectrum**. **Figure 8.3** shows the wavelengths and intensity of solar energy striking the top of the atmosphere and the energy reaching the surface. The atmosphere is transparent to most wavelengths, but part of the solar spectrum are absorbed by certain **greenhouse gases** in the atmosphere including water vapor, carbon dioxide, ozone, methane, and other gases. Shorter wavelengths (UV and blue light) is diffused in the air—making the sky blue. Longer wavelengths are less diffused—making sunsets and sunrises red (Figure 8.4).

Energy that is not reflected back into space is radiated back into space in wavelengths longer than visible light (mostly in the the**rmal infrared** portion of the electromagnetic spectrum).

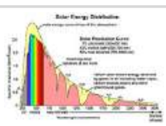
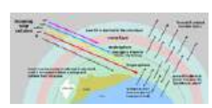
	

Figure 8.3. Wavelengths of solar energy transmitted and absorbed by the atmosphere.	Figure 8.4. Energy transfer through the atmosphere

Composition of the Atmosphere

• **Nitrogen (N_2)** - 78%
• **Oxygen (O_2)** - 21%
• **Argon** - 0.9%
• **Carbon Dioxide (CO_2)** - 0.036%
• **Others** < 1 % - Neon, Helium, Methane (CH_4), Krypton, Hydrogen (H_2), traces of other compounds

Other trace gases in variable amounts include nitrogen oxides, ozone (O_3), sulfur dioxide, hydrocarbons, and more. These gases are released by volcanic eruptions, lightning, wildfires, erosion, and pollutants of many kinds from human activity. Major sources of air pollutants included gases and smoke released by fossil-fuel energy consumption, industrial releases, agriculture, and leaks of refrigerator and air conditioner coolant compounds.

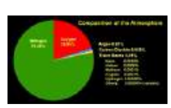


Figure 8.5. Chemical composition of the atmosphere (major and trace gases)

8.2: Water Moisture in the Air

Water Moisture in the Air (Humidity)

The amount of **water vapor** in the air can range from trace amounts up to about **4% by volume**. **Humidity** is a term used to describe the relative amount of water vapor dissolved in the air. In general terms, **humid** refers to moist air and **arid** refers to dry air conditions.

Warm air can hold more moisture than cold air. As warm, moist air cools, the **relative humidity** increases. When air has reached the maximum amount or water it can hold it is called **saturated** - this occurs when clouds form and moisture **condenses** to for water droplets. As the air continues to cool, microscopic water droplets grow in size and it may start raining! The atmospheric temperature below which water droplets begin to **condense** is called the **dew point**. The dew point is the temperature at which moist air reaches 100% saturation. **Dew** can form on objects and consists of tiny drops of water that form on cool surfaces at night when the atmospheric vapor condenses (such as on grass) (Figure 8.6).

Weather reports frequently report the **relative humidity. Relative humidity of 100%** indicates that the dew point is equal to the current temperature when the air is holding the maximum amount of water vapor (it is saturated), and water vapor will begin to condense into water droplets, forming fog (clouds). **Moist air is less dense than dry air.** This explains why moist are rises to form clouds.

The amount water moisture that air can hold depends on factors including **air temperature**, **air pressure**, and the amount and kinds of **particulate matter** dispersed in the air (see **cloud condensing nuclei [CCNs]** discussed below). For example, warm, humid air near sea level may be clear clear during warm daylight hours, but as the air temperature drops at night the relative humidity will increase until it reaches the dew point and f**og** begins to form. **Fog** is a thick cloud of tiny water droplets suspended in the atmosphere at or near the earth's surface (restricting visibility) (Figure 8.7). As the air continues to cool, the condensing droplets water form mist. When the mist droplets grow large enough to be influenced by gravity, it will fall as **precipitation**.

The dew point is called the **frost point** when the temperature is below the temperature that water freezes. Below freezing, water moisture in the air will **sublimate** directly into ice, forming frost, snow, or hail (Figure 8.8).

A **hygrometer** is a device that can measure the humidity in the air. There are many kinds of hygrometers and different ways to measure humidity in the air. Modern hygrometers use sensors that can directly measure the electrical, optical, thermal, and other means to accurately measure water content in the air. Hygrometers are part of any meteorological station, and can be measured with regional radar and satellite sensor data. Hygrometers are important devices for measure moisture in soil.

National Weather Service (NOAA) - Relative Humidity Calculator (enter data for current temperature and dew point to determine relative humidity).

		
Figure 8.6. As the atmosphere cools, the moisture content dissolved in the air will condense to form water droplets, such as illustrated by dew on leaves. As the air continues to cool, more and more moisture will be released and water droplets	Figure 8.7. **A Fog Bank Fog** under the Golden Gate Bridge, CA. where water moisture **condenses** in the air near the cool ocean surface. The warm moist air above the bridge remains clear because it is above the **dew point**.	Figure 8.8. **Frost** forms when air moisture directly **sublimates** from the air onto cold surfaces. These spectacular frost ice crystals formed on frozen ground in South Dakota on a day when the high temperature only reached -11° Fahrenheit.

The Water Cycle

The **water cycle** involves all processes by which water circulates between the Earth's oceans, atmosphere, and land. It involving precipitation as rain, snow, hail, drainage in streams and rivers, and return to the atmosphere by evaporation and transpiration. The weight of the atmosphere provides the pressure needed to keep water liquid on the surface of the planet. Planets and moons with thin or no atmosphere may have water as ice, but there will be no permanent bodies of liquid water. Ice will **sublimate** directly to water vapor in a vacuum.

The Water Cycle is also called the **Hydrologic Cycle** (USGS)

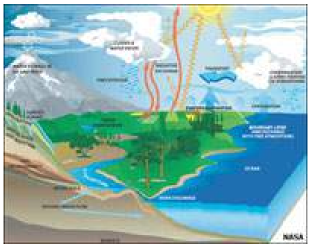


Figure 8.9. The Water Cycle

8.3: Atmospheric Pressure

Atmospheric (Barometric) Pressure

A **barometer** is an instrument measuring atmospheric pressure, used especially in forecasting the weather and determining altitude (Figure 8.10).
Air pressure on the planet is directly related to the mass of the air column above at any location under the influence of gravity: **Pressure = Force/Area**.

Atmospheric air pressure is reported as **average air pressure** measured at **standard sea level.** Reported barometric air pressure at elevations above sea level ***are adjusted*** to be equivalent to air pressure measured at sea level at locations closest to where measurements are taken.

Figure 8.10. Barometers

How Air Pressure Is Reported

Barometric units most used to describe atmospheric pressure includes **atmospheres**, **millibars**, and PSI (pound-per-square-inch).
The weight of **ONE ATMOSPHERE** (Earth's atmosphere above us) is equal to the weight of the **Earth's *average air pressure*** at ***standard sea level***.

One atmosphere (on Earth, on average) is equivalent to:

• **14.7 pounds-per-square-inch (psi)** - this might mean something when you add air to you car's tires.
• **29.92 *inches of mercury*** (a historic measure of air pressure that is still widely used).
• **406.8 inches of water (33.9 feet)** - how deep you'd need to dive in a freshwater lake to double the weight of the atmosphere.
• **seawater (33.4 feet)** - seawater is slightly denser than freshwater.
• **1.01325 bars** (**one bar** was supposed to be equivalent to the weight of **one average Earth atmosphere**; the slight number above **1.0000 bars** is from adjustments from atmospheric-pressured data that was later compiled from locations measured around the world. It was determined that the average weight of the Earth's atmosphere was slightly higher than the standard **one bar** was originally established between the year's 1793 and 1795 by the European science community as an attempt to add an air pressure standard to metric system. When analytical devices are calibrated, they use the revised metric unit: **millibars**.

The **average weight of one Earth atmosphere** is now commonly reported as **1013.25 millibars (mb)**.

Atmospheric Pressure Drops With Increasing Altitude (Elevation)

Elevation and air pressure have an inverse relationship - air pressure decreases with increasing elevation (Figure 8.11). At an elevation of about **18,000 feet** you would be above about **half of the atmosphere**. That, of course, depends on changing weather conditions! An common **altimeter** is a type of barometer that measures air pressure to report elevation, but altimeters must be adjusted to match local weather conditions.

What is the difference between altitude and elevation?

If you are flying an airplane, you need to know this! Technically, **altitude** is the vertical distance from the Earth surface (land or water) to an object (such as an airplane). **Elevation** is a the vertical distance between a location on the ground and global sea level.

Can you feel changes in Atmospheric Pressure?

The answer is a most definite **yes**! As you go up in elevation, air pressure trapped within your ears is not equalized with the air pressure outside, so your ears tend to occasionally **pop** as you climb in altitude, as your ear ducts release air when you swallow. Older people commonly complain about bone and joint pain when a storm is approaching and air pressure starts falling.

The opposite is true when you go down in elevation, such as on an airplane descending from high altitude. Anyone who has frequently flown can tell you about crying children complaining ear aches because their ears have not readjusted to air pressures at low elevations.

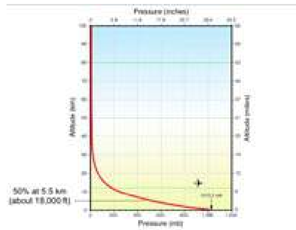


Figure 8.11. Atmospheric pressure decreases with altitude on a curve.

8.4: Density of Air

Density of Warm Air vs. Cool Air

As air is heated it expands (moving atoms apart). This reduces the density of air in unconfined space. As a result warm air rises. Conversely, as air cools, it condenses (moving atoms together) and increases it's density in unconfined space. As a result cold air sinks. Because the atmosphere is unconfined, dense cool air will sink and flow to displace warm air in another location (Figure 8.12).

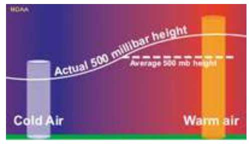


Figure 8.12. Differences in air pressure at different levels in the atmosphere drive the movement of air.

Density of Moist Air vs. Dry Air

Air saturated with water vapor is less dense than dry air. As a result, moist air will rise relative to dry air if air temperatures and pressures are the same.

8.5: Atmospheric Convection and Air Pressure Gradients/Systems

Atmospheric Convection

Convection is the circulation of fluid due to density differences. Atmospheric convection works like a pot of boiling soup, warm fluid rising (in middle) and cool fluid falling (on sides). A rising storm thunderhead is an example of atmospheric convection. Warm moist air rises, expands, releases energy as clouds form. After releasing its heat and moisture, the cooled air sinks, displacing warm air below (Figure 8.13).

Figure 8.13. Atmospheric convection.

Air Pressure Gradients and Air Pressure Systems

• Surface winds blow from high to low pressure - this is called a **pressure gradient—**displayed as lines of equal barometric pressure on a **weather map** (Figure 8.14). An **air mass** is a body of air with a relative horizontally uniform temperature, humidity, and pressure:

• **High pressure systems** have dry conditions with sinking air masses.
• **Low pressure systems** have wetter conditions with rising air masses.

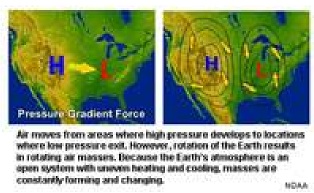


Figure 8.14. Air pressure gradients and air pressure systems.

8.6: Types of Air Masses and How They Form

Types of Air Masses and How They Form

An air mass is a large body of air with relatively uniform temperature, humidity, and pressure. Air masses move with the global atmospheric system and can change as the move over landmasses and oceans, picking up or loosing warmth and moisture as they move.

Types of air mass are classed by where they form:	**Maritime**	**Continental**
• **Polar** - source regions above 60° north and south:	Polar Maritime (cold and moist)	Polar Continental (cold and dry)
• **Temperate** - between 25° and 60°N/S:	Temperate Maritime (cool and wet)	Temperate Continental (warm and dry)
• **Tropical** - source regions within about 25° of the equator:	Tropical Maritime (warm and wet)	Tropical Continental (hot and dry)

As air masses move they change to match the attributes of the next region. For instance, if a polar (or Arctic) air mass moves south over the North American continent it will become warmer and dryer (becoming a **temperate-continental air mass**; see example in Figure 8.15). If it moves east over the Atlantic Ocean it may become warmer and pick up moisture and become a **temperate-maritime air mass**. When a maritime air mass moves over a large landmass it can loose its moisture, heat up, and become a continental air mass.

Air masses can move rapidly (if air pressure gradients are high). Air masses can control the weather for a relatively long periods ranging from days to months. They can also stagnate in one region causing long periods or rain or drought. **Tropical storms and hurricanes** can form in association with **tropical-maritime air masses**. Most weather occurs along around air masses at boundaries called **fronts** (discussed below).

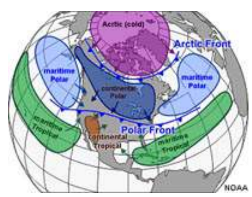


Figure 8.15. Origin of air masses affecting North America's weather. Air masses move as air pressure gradients change over time.

A Year in Weather (2013)

NASA YouTube animation- a global mercator map showing storm systems around the world for a year starting in January, 2013. Note the tropical cyclones (typhoons) in the Eastern Pacific, the weather patterns in the Intertropical Convergence Zone, and the Antarctic circumpolar region.

8.7: Dust, Aerosols, and Cloud Condensation Nuclei (CCNs)

Dust, Aerosols, and Cloud Condensation Nuclei (CCNs)

Cloud condensation nuclei (also known as **cloud seeds**) are small particles typically 0.2 µm, or 1/100th the size of a cloud droplet on which water vapor condenses. CCNs are **aerosols,** an aerosol is a colloidal suspension of microscopic particles dispersed in air or gas. The aerosols can be a combination of solid particles and liquid compounds (liquid water or organic residues).

Examples of CCNs include:
- dust particles (clays) - most are from wind storms in desert regions (see NASA video with Figure 8.16)
- soot from fires
- volcanic ash
- salts from sea spray
- sulfate compounds released by phytoplankton in the oceans
- pollen and organic aerosol compounds released by land plants (Figure 8.17)
- pollution (smog) (Figure 8.18).

CCNS are abundant in the air. The adhesion properties of water, allows water droplets (or ice) to form and grow on CCNs, until gravity is strong enough for droplets to fall as rain or snow. However, too many CCNs in the air can prevent water droplets or ice crystals from growing large enough to fall as precipitation (rain or snow), contributing to often thick **haze** or **smog**).

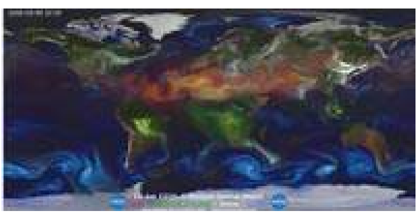


Figure 8.16. Dust from desert regions is a major source of CCNs. See Atmospheric aerosol/dust video (NASA) Globe version (NASA)

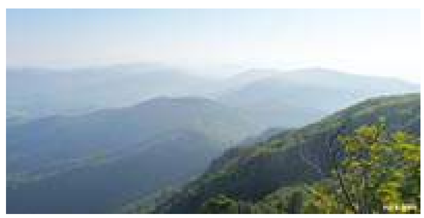


Figure 8.17. Natural CCN aerosols released by plants produce the haze of the **Smoky Mountains** region of the Appalachian Mountains.

Figure 8.18. Smog in NYC in the 1970s. Air pollution from human activity is an increasing source of CCNs in the atmosphere. Smoke from manufacturing, vehicles (particularly diesel-burning trucks), coal-burning power plants, and construction dust are significant sources. Efforts to regulate CCNs have helped reduce smog in the US, but what about China?

NASA Atmospheric Aerosols on a globe (YouTube animation)

8.8: How Does Air Pressure Relate to Weather?

How does air pressure relate to weather?

Increasing high pressure (above 1000 millibars) corresponds with ***clear, sunny weather***.
Decreasing pressure (below 1000 millibars) corresponds with ***cloudy, rainy weather***.

Highest barometric pressure (record): **1084 millibars** (32.01 inches of mercury) Agata, northern Siberia, on December 31, 1968. The weather was clear and very cold at the time, with temperatures between -40° and -58°
Lowest barometric pressure (record): **870 millibars** (25.69 inches of mercury) West of Guam (Pacific Ocean) on October 12, 1979 In the eye of Super Typhoon Tip which involved wind speeds of 165 knots (305 km/h; 190 mph).
Why does San Diego have the best weather in the US? **Highest air pressure:** 1033 millibars (February, 1883) **Lowest air pressure**: 987 millibars (January, 2010) This is the **lowest range** in the United States! (46 mb)!

8.9: Weather

Weather is the state of the atmosphere at any place and time in regards to **conditions**: sunshine, heat, dryness, cloud cover, wind, precipitation (rain, sleet, snow, hail), etc.

Clouds

Clouds form when the invisible water vapor in the air condenses into visible water droplets or ice crystals.
The **dew point** is when the **relative humidity** reaches **100%**. The base of a cloud marks the boundary where relative humidity has reached saturation. Cloud tops can rise until they encounter warmer air in the stratosphere. There they stop rising and spread out forming anvil-shaped thunderheads shapes (Figure 8.19).

4 general types of clouds (there are many sub-types)
Cirro-form: high level, ***wispy - fair weather*** clouds if ice crystals, typically above 20,000 ft (6000 m)
Cumulo-form: low to high level ***cotton-like puffy*** clouds with flat base at 100% humidity level, can rise to 60,000 feet.
Nimbo-form: ***rain clouds*** (low to mid level) - clouds typical thicken and lower as precipitation begins.
Strato-form. uniform flat cloud layer at any level, forms fog at the surface (coastal ***marine layer*** an example)

Names of clouds can include combinations of forms as they change. For instance, a small, puffy white **cumulus** cloud can build up and become an **altocumulus** cloud, before rising even further to become a **cumulonimbus** (thunderstorm) that can develop a high avil-shaped top as the rising moist air at top the cloud encounters the stratosphere and can't rise any higher.

Figure 8.20 illustrates **common forms of clouds**. Also see Types of Clouds (NOAA National Weather Services - Image gallery of clouds and cloud-related phenomena).

Figure 8.19. Cloud base and tops of a thunderstorm (a **cumulonimbus** cloud).

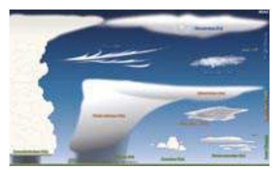


Figure 8.20. Common types of clouds.

Lightning and Thunder

Lightning is giant spark, or series of sparks (electrical discharges), that leap through the air.

Lighting occurs as mostly as **intra-cloud lightning** (leaping between different parts of a thunderstorm, Figure 8.21) or **cloud-to-ground lightning (Figure 8.22)**. Lightning is caused by the buildup of between positive and negative electrostatic charges within the clouds or between the clouds and the ground. The air acts as an insulator between the buildup of charges until they become great enough to overpower the insulating capacity of the air.

Figure 8.21. Intra-cloud lightning.

Figure 8.22. Sky-to-ground lightning with leader bands.

The passage of lightning has jagged path. Lightning probably follows the interconnect paths created by ionizing radiation particles passing through the atmosphere from outer space. These particle create very short-lived ***plasma passages*** through the atmosphere that allow electricity to propagate through the insulating air, creating the rapid electrified flashes we see as lightning. The discharge of lightning temporarily equalizes the charged regions in the atmosphere or the ground, until opposite charges can build up again.

Lightning tends to strike high places (closest to the cloud), such as the tops of building, telephone poles, trees, antennas, but this is not always the case. Lightning will strike any place where the electrical charges build up and where a ***stepped leader*** (an initiating passage of electrical discharge) arrive first. Typically, a negatively stepped leader leaving a cloud will arrive at the ground followed by a more powerful, brighter return stroke or multiple strokes moving in the opposite direction (sometimes the inverse of this occurs). A lightning bolt can be a complicate mix of stringers and leader besides the passage of the main bolt of lightning. In many cases lightning may strike water or a low lying area even if nearby trees are present. Lightning will often appear as a rapid series of strokes as discharges from different parts of the cloud utilize the previously ionized air passage created by an initial discharge giving the appearance of multiple strokes following the same path. In sky-to-ground lighting, the bright return stroke to the sky is estimated to travel about 60,000 miles per hour. In contrast, when conditions are right **spider lightning** is an unusual slow spread of lightning though lower stratus clouds at the base of a thunderstorm that appears to propagate in all directions away from an initial sky-to-ground stroke.

What causes lightning is complicated, and various theories apply. Areas of positive and negative charges can build up within the same thunderstorm cloud (Figure 8.23). The formation of precipitation (starting with cloud-condensing nuclei [CCNs] to the growing droplets that become rain drops, snow, sleet, and hail) all have surface area that are growing or diminishing as they move upward or downward through a cloud. Changes in surface area of droplets and ice crystals, and the frictional interaction of particles create the negative or positive charges and as condensation or evaporation takes place. Some researchers suggest that heavier, growing precipitation particles carry negative charges to the lower part of clouds as they descend with down-drafts. Updrafts may transport positive charges from near the ground upward through the cloud.

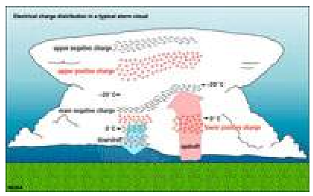


Figure 8.23. Lightning charges (positive and negative) can build up in different parts of a cloud relating to updrafts and down-drafts, and the changing character of precipitation within a cloud.

Lightning is associated with thunderstorms, but they are also known to occur in association with the clouds associated with volcanic eruptions, hurricanes, tornadoes, forest fires, snow storms, and even discharges from the ground during earthquakes.

The power or intensity of lightning varies with the volume of atmosphere hosting electrostatic charges and the distance lightning travels. A typical lightning stroke only lasts about 0.2 seconds. However, a typical lightning bolt can generate up to **one billion volts**, and they average between **5,000 to 20,000 amps** of **electrical current** (as much as 200,000 amps have been measured - enough to briefly power a small city!). Lighting can heat the air to temperatures around **15,000 to 60,000 degrees Fahrenheit** (or much higher). This causes the air to rapidly expand, creating shock waves we hear as thunder. Up close, thunder form a nearby lightning strike sounds as a sharp ***clap-like*** high frequency crackle and initial boom, followed by an extended low-frequency rumble as sound wave arrive at different times from farther distant parts of the lightning's path (higher frequency sounds are absorbed as they travel over longer distances through the air). Thunder can be heard for distances of 25 miles or more under the right conditions.

Estimates vary, but as many as 10,000 fires are started each year by lightning, and lightning kills between 6,000 and 24,000 people and lightning injures as many as 240,000 people each year.

How far away was that lightning strike?

After you see a flash of lightning start counting seconds. **For every 5 seconds the lightning bolt is one mile away.** It is advised to take shelter immediately if the sound is less than 5 seconds!

Weather Fronts

A weather **front** is a boundary separating two masses of air of different densities (Figure 8.24). Fronts are classified as to which type of air mass (cold or warm) is replacing the other.

A **cold front** forms along the leading edge of a cold air mass displacing a warmer (less dense) air mass. Cold fronts are typically narrow bands of showers and thunderstorm and are most commonly associated with severe weather condition.

A **warm front** is the leading edge of a warmer air mass replacing (riding up and over) a colder air mass. If the front is essentially not moving (i.e. the air masses are not moving) it is called a **stationary front**. Warm fronts typically have a gentle slope so the air rising along the frontal surface is gradual. This configurations results in widespread ***stratus*** (strato-form) cloud layers with precipitation near the rear of the frontal boundary. Warm fronts typically quite extensive, and can create typically gray skies and dismal weather—an all too common occurrence in parts of the Midwest and Northeastern United States as slow-moving warm fronts stall over the regions. This can happen any time of year. It reflects that warm, moist air is flowing above cooler air down below, creating the gray stratus cloud layer in-between.

Colliding air masses can have both warm fronts. For instance, when a warm, moist air mass (such a ***maritime-tropical air mass***) encounters a cold, dry air mass (such a ***polar continental air mass***), both warm fronts and cold fronts can form as air rotates around a center of low pressure (as illustrated in the lower graphic of Figure 8.24). This rotation is driven by the **Coriolis effect** (discussed below).

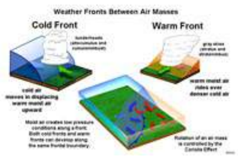


Figure 8.24. Weather fronts between air masses: cold fronts and warm fronts.

How do you say which way is the wind blowing?

We name wind direction based on which direction it is coming from (from high pressure to low pressure). For instance, if the wind is moving off the Pacific Ocean directly onto the land in California we call it a **west wind**, or to clarify, ***out of the west***. The direction of wind is named for the direction it is coming from, not in the direction that it is moving towards.

8.10: Weather and Climates

Weather and Climates

Weather is localized atmospheric conditions in the ***short term*** **(**described in terms of minute, hours, or possibly weeks)**.**
Climate is the prevailing weather conditions in an area in general or over a ***long period*** (years, decades, etc.).

Weather is typically constantly changing as air masses move across a region. A most common question on a long-distance phone call is: "How is the weather out there?" The answer can typically be "it's sunny," "it's cold," "it's snowing," "or "it's raining cats and dogs," or any other description of the prevailing atmospheric at any time in a location.

Climates are controlled by both geographic factors and ***regional weather patterns***. Different regions (climates) typically have seasonal cycles. For instance, the Eastern United States typically has 4 seasons and have frequent weather fronts between polar air masses from Canada and tropical air masses from the Gulf and Atlantic regions. In contrast, California typically has 2 seasons, summers are dry and winters have short rainy periods. Patterns in weather repeat each year and are typically consistent and predictable with **seasons** of the year. Examples include **monsoons** in India and the US Desert Southwest, Hurricane season in the tropics, etc. Figure 8.25 illustrates how California's weather and climate is influenced by regional geography and prevailing weather conditions.

History shows that climates change. The time spans for changes can range in cycles ranging from years and decades to centuries, or thousands of years. Droughts can start an last for years. Desertification (such as what is happening in Africa) has been progressing for centuries. Parts of the world experienced ***Mini-Ice Age*** conditions between the 13th and 19th centuries. Climate change has impacted civilizations throughout recorded history. A classic example is illustrated in the history of the Chaco Culture in the US Desert Southwest (Figure 8.26). See more climate cycle times and events in history on NOAA's Paleoclimatology website).

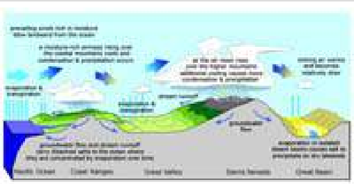


Figure 8.25. California's weather and climate is influenced by regional geography and prevailing weather conditions.

Figure 8.26. Chaco Canyon in New Mexico was at the center of a regional 13th century society impacted by climate change.

See **NOAA's Climate Change Impacts** website - time lines with many links and animations.

Climate Variability

California's history of droughts illustrates climate variability (Figure 8.27). Climate not only vary on a seasonal and annual basis, but there are larger scale fluctuations that impact different regions of the world. One is the **El Niño/Southern Oscillation (ENSO)** (discussed in **Chapter 9**). Because the atmosphere is an open system, changes in one region can affect other surrounding regions. Regions that may experience dry conditions for decades may suddenly have a severe rain period, or regions that are typically wet can sustain drought. Likewise, regional temperature average can swing through cyclic periods. Some of these changes can be progressive and represent long term changes. For instance, during the last ice age, Southern California was very wet, and large lakes filled many of the basins between mountain ranges. By about 5,000 years ago, the lakes dried up as the climate changed, then they returned as wet conditions returned for periods of time. The last major drying period was about 500 years ago, as recorded by the evidence of Indian village sites associated with fishing on the shores of SoCal lakes that now are mostly barren desert. See a website on **Climate Variability** (NASA).

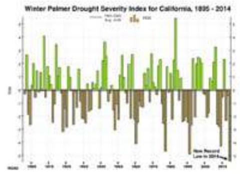


Figure 8.27. California's cycles of drought and wet periods is an example of climate variability.

Effects Of Uneven Heating Of Earth By the Sun

The amount of energy Earth receives from the Sun is not evenly distributed (Figure 8.28). More solar energy (per unit area) is delivered to the equator than near the poles.

- The equatorial regions are warmer than the poles because direct sunlight is concentrated and little is reflected.
- In polar regions, light strikes the earth at an angle; it is diffuse and much of it is reflected back into space.
- The seasonal variations (winter and summer) also affect the distribution of heating of the planet.

This imbalance between the solar heating in the tropics and at the polar regions is a major factor in atmospheric movement on Earth and other planets with atmospheres.

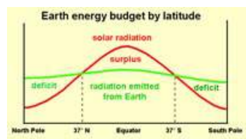


Figure 8.28. Solar energy budget by latitude

8.11: The Coriolis Effect on Atmospheric and Ocean Circulation Systems

The Coriolis Effect on Atmospheric and Ocean Circulation Systems

Heat from **insolation** (short for **IN**coming **SOL**ar radi**ATION**) is the driving force behind the fluid motion of the atmosphere and the oceans. However, the patterns of motion are also influenced by the forces created by the ***rotation of the Earth on its axis***. Any mass moving in a rotating system experiences a force (the ***Coriolis force***) the acts perpendicular to the direction of motion and to the axis of rotation. Because air has mass, air currents maintain ***momentum*** when moving from a location of high pressure to low pressure. However, because the Earth is rotating, the rotation causes a right-turn deflection in the Northern Hemisphere and a left-turn deflection in the Southern Hemisphere (Figure 8.29).

Figure 8.29. The **Coriolis effect** is cause by the rotation of the Earth on its axis. This rotation causes air masses moving from high to low pressure to deflect.

The Coriolis effect influences all moving objects, especially ones moving over large distances (such as intercontinental ballistic missiles). The Coriolis effect causes objects or moving masses of air to:

• Change direction—not speed.
• Maximum Coriolis effect occurs at poles.
• No Coriolis effect occurs at equator.

Rotation of pressure systems due to the Coriolis effect:

Northern Hemisphere:

• High pressure turns clockwise
• Low pressure turns counter-clockwise

Southern Hemisphere: opposite of N.H.

• High pressure turns counter-clockwise
• Low pressure turns clockwise

Coriolis effect video (NOVA PBS)

So... which way does the water spin in a toilet in the northern hemisphere, southern hemisphere, and on the equator?

8.12: Earth's Atmospheric Circulation System

Earth's Atmospheric Circulation System

The **global atmospheric circulation system** influences the movement of air masses in general **wind belts** that move air in rotating masses within zones around the planet. These wind belts seem relatively stable when viewed in a long-term view (decades). However, fluctuations may occur on seasonal or annual basis. The wind belts are influenced by the Coriolis effect and large-scale convection patterns in the atmosphere (Figure 8.30).

These relatively stationary wind belts impact the surface of the oceans, creating currents that circulate waters in the oceans. Studies of the atmosphere have show that their are 3 major atmospheric systems called **circulation cells** (Figures 8-30 and **8-31**).

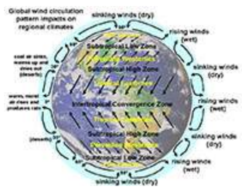


Figure 8.30. Global wind circulation patterns impact regional climates and drive the large current systems in the global ocean circulation system.

Circulation Cells in Earth's Atmosphere

Three major **circulation cells** move air, heat, and moisture through the atmosphere between the equatorial regions to the polar regions. These cells are constantly changing due to regional air pressure changes under the influence of the Coriolis effect.

Hadley cells (0° to 30° N and S of equator)
• Responsible for the **Trade Winds**: They blow NE in N. Hemisphere and SE in S. Hemisphere.

Ferrel cells (30° to 60° N and S of equator)
• Responsible for the **Prevailing Westerlies** in both hemispheres.

Polar cells (60° to 90° N and S)
• Responsible for the **Polar Easterlies** in both hemispheres.

What is the Jet Stream?

A **jet stream** is a narrow, variable band of very strong winds in the upper troposphere. They are predominantly **westerly air currents** encircling the globe several miles above the Earth. There are typically two or three jet streams in each of the northern and southern hemispheres. These high-speed wind currents often move at speeds exceeding 250 miles (400 km) per hour at altitudes of 6 to 9 miles (10 to 15 km). Jet streams are influenced by moving air masses and the Coriolis effect causing them to meander and sometime split. See the location of the jet streams in Figures 8-31 and **8-32**.

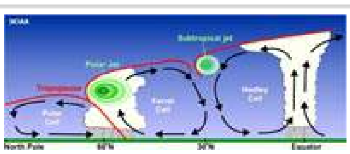


Figure 8.31. Hadley, Ferrel, and Polar circulation cells in Earth's atmosphere redistribute convectional heat.

Figure 8.32. Polar and Subtropical jet streams

Equatorial Doldrums and Inter-Tropical Convergence Zone (ITCZ)

The **equatorial doldrums** are associated with the **inter-tropical convergence zone (ITCZ)** the region that circles the Earth near the equator, where the trade winds of the Northern and Southern Hemispheres converge (Figure 8.33).

The **doldrums** are:

• Area of low atmospheric pressure with lots of rain.
• Located on equator where there is least influence of the Coriolis effect.
• Low wind area with calms, sudden storms, and light unpredictable winds

Seasonal shifts in the location of the ITCZ affects rainfall in many equatorial regions, resulting in the wet and dry seasons of the tropics rather than the cold and warm seasons of higher latitudes. The ITCZ moves north during winter in the northern hemisphere and south in the summer.

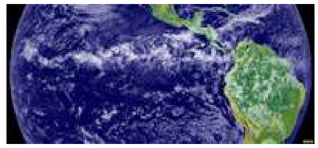


Figure 8.33. The **doldrums** are the belt of clouds along **inter-tropical convergence zone**. This belt of clouds (with lots of rain) migrates north and south across the equator with the seasons.

The Tropical Easterlies (Trade Winds)

During the age of sailing ships, ship captains learned take advantage of the prevailing wind belts to cross the oceans. Two belts of **trade winds** encircle the Earth, blowing from the tropical high-pressure belts (Hadley Cells) to the low-pressure zone of the equatorial inter-tropical convergence zone. The **tropical easterly wind belts** near the equatorial region are also called the **Trade Winds**. Trade winds blow steadily toward the equator from the northeast in the Northern Hemisphere, or the southeast in the Southern Hemisphere (see Figures 8-30 and **8-31**).

Horse Latitudes

The **horse latitudes** are belts of calm air and sea occurring in both the northern and southern hemispheres between the trade winds and the westerlies (roughly 30-38 degrees north and south of the equator). Horse latitudes separate the Hadley and Ferrel Cells. It is a region also called the **subtropical high**—a belt of very dry because of high pressure, little rain. Horse latitudes roughly correspond with major desert regions of the world. The horse latitudes got it name from historic legends describe ships becoming becalmed when crossing the horse latitudes and running out of water and unable to re supply. Sailors would throw horses on the ships overboard.

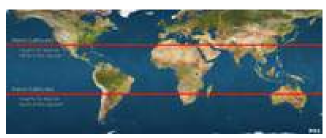


Figure 8.34. Location of the **horse latitudes** (subtropical highs).

Weather data animations:

Global atmospheric circulation video - High Speed Weather—Satellite Infrared of the entire globe (NASA data)
See animations current data from NASA Global Geostationary Weather Satellite (GOES weather satellite).
Current San Diego Weather Radar (accuweather.com) - this website provides current weather radar conditions for local, state, regional, and national scales with looping animations.

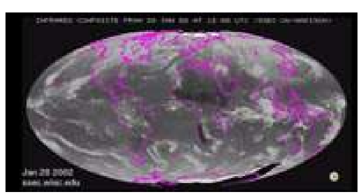


Figure 8.35. Weather satellite data animation.

8.13: The Coriolis Effect Influences Superstorms

The Coriolis Effect Influences Superstorms

Large rotating storms are called **hurricanes** (near North America), **typhoons** (near Southeast Asia) and **cyclones** (in the Indian Ocean). All are the same, caused by warm moist winds being drawn to the center of low pressure near the center of the storm (called the **eye** in well developed storms). North of the equator the Coriolis effect causes low-atmospheric pressure to rotate counterclockwise, but south of the equator they rotate in a clockwise direction. The lower the air pressure in the eye of the storm, the greater the wind speed and rotation. Note on the map in Figure 8.36 that there are no hurricanes along the equator or near the poles. These are regions where the Coriolis effect is not a significant force in deflecting storm winds to cause rotation.

Superstorms not only can cause major wind damage and flooding, but can erode and redeposit vast quantities of sediments, both offshore and onshore, heavily impacting impacting both communities and ecosystems.

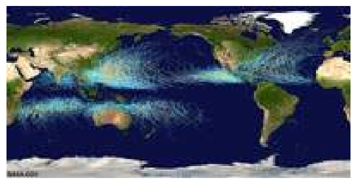


Fig.5-36. World map showing historic paths of hurricanes, typhoons, and cyclones. The large storms are the same (different names for different regions); storm rotation is influenced by the **Coriolis effect**.

Tropical Cyclones, Hurricanes, and Typhoons

Tropical cyclones are large rotating air masses with low atmospheric pressure (Figures 8-37 and **8-38**).

T**ropical cyclones** are called **hurricanes** in the Atlantic Ocean or in the Pacific near North or South America, and Hawaii). **Tropical cyclones are called typhoons** in the Western Pacific Ocean region. They are simply called cyclones in the Indian Ocean region.

Northern Hemisphere Example:

- Storms Intensify over warm water (>77 degrees F); warm water provides water vapor.
- Water vapor provides fuel for storm in the form of **latent heat** energy as water vapor condenses.
- Storms die over land and cool water.
- High winds, tornadoes occur near storm center and along **feeder bands**.
- Sea level can rise in front of storm called a **storm surge**.
- Classified by maximum sustained wind speed (see **rating storms** below).
- Hurricanes and other storms **rotate counterclockwise** in the Northern Hemisphere because of the Coriolis effect.

Figure 8.37. **Hurricane Andrew** (1992) was for a time a **Category 5 hurricane** with sustained winds of 175 mph (280 km/hr).

Figure 8.38. The eye of a hurricane is the center of low pressure. Hurricane Katrina (2005) shown here, was the most costly and destructive hurricane disaster in US history, killing more than 1,800 people.

Ratings Storms (By Maximum Sustained Wind Speed)

- **Tropical depression** (<38 mph)
- **Tropical storm** (between 38 and 74 mph)

• **Tropical cyclone** (>74 mph)

Saffir-Simpson Scale: 5 categories of hurricane intensity based upon wind speed (see **NOAA** website)
• Category 1 is from 74 to 96 mph.
• Category 2 is from 96 to 110 mph.
• Category 3 is from 111 to 130 mph - level considered a "superstorm" (Katrina, 2005).
• Category 4 is from 130 to 155 mph (examples: Andrew, 1992, Hugo, 1989).
• Category 5 is >155 mph (Camille, 1969).

Naming storms: Alphabetical lists of names are assigned each year to storms that develop in each of the ocean basins. Names of notoriously damaging storms are **retired** to remind people of their impacts and legacy.

The term **superstorm** is used to describe any powerful and destructive storm that affects a large area or region. Tropical storms and cyclones can be superstorms, but other massive storms in temperate and polar regions can be become superstorms. **Nor'easters** are ***extra-tropical*** superstorms that typically impact the Northeastern United States in the fall and winter season, causing massive amounts of snowfall and coastal flooding.

8.14: Severe Weather

Severe Weather

Severe weather conditions can occur anywhere, but some area are more susceptible to severe weather than others due to regional geography and climate factors. Severe weather includes strong convective thunderstorms, winter storms (severe cold, blizzards, and ice storms), damaging wind storms and tornadoes, flooding, dust storms, extreme heat, and firestorms.

Atmospheric scientists are constantly monitoring weather conditions to make predictions of potential severe weather conditions (and potential disasters), using ground-based weather observations combined with remote sensing data (satellite, airplane, Doppler radar, etc.). These are combined with historic weather data in order to make weather predictions.

The Federal government has been recording statistics of deaths and property damage due to weather-related activity for many decades. Floods and droughts (with associated famines) have remained the most deadly disasters worldwide. In the United States, extreme heat events and floods remain the numbers 1 and 2 killers (Figure 8.39). Tornadoes are number 3, but they are perhaps the most terrifying because of their unpredictable occurrence and suddenly destructive behavior.

Figure 8.39. NOAA severe weather statistics averages for the United States.

Tornadoes

Tornadoes are mobile funnel-shaped rotating vortexes of wind that form and advance beneath large storm systems (Figure 8.40). Tornadoes vary considerably in their destructive power—how strong their winds are, how long they are in contact with the land surface, and the distance they travel. Storm systems can often produce multiple tornadoes (called a tornado outbreak). A single storm cell can sometimes produce multiple tornadoes simultaneously. The 2011 Super Outbreak (April 25-28) produced 392 "confirmed" tornado in 21 states (between Texas and New York) with four rated as F5 tornado on the **Fugita tornado intensity scale** (see table below).

Fugita Tornado Intensity Scale

F-Scale #	Wind Speed	Intensity Phrase
F0	40-72 mph	light damage - branches off trees, minor damage to roofs
F1	73-112 mph	moderate damage - roof and window damage, mobile homes overturned, cars pushed off roads
F2	113-157 mph	significant damage - roofs off homes, mobile homes destroyed, large trees down/uprooted, cars push off roads
F3	158-206 mph	severe damage - roofs and walls torn from well constructed homes, most trees uprooted, heavy cars lifted off ground and thrown
F4	207-260 mph	devastating damage - well-constructed homes leveled, cars thrown and large object moved like battering missiles
F5	261-318 mph	incredible damage - homes lifted off foundations and ripped apart, trees debarked, concrete structures damaged, skyscrapers topple

Figure 8.40. this F3 tornado occurred on May 3, 1993 in Oklahoma.

Figure 8.41. Tornado probability map of the United States showing the likelihood of a tornado occur based on historic data for June 23 of any year.

Figure 8.41 shows a tornado probability map of a typical day (June 23) in the United States based of historical tornado data; data for each day of the year shows that tornado activity in the country varies significantly from season to season and from one region to another. The central Great Plains region is commonly called **Tornado Alley** because it statistically experiences the greatest number of tornadoes in any given year, but weather and climate data show that trends are changing (as well as better recording of data). The Great Plains and Midwest typically experience clashing air masses—cool and dry air masses that move east from the Rocky Mountains and Canada collide with warm, moist air masses moving north from the Gulf of Mexico and Atlantic regions. When conditions are right, large thunderstorms that display intense convection and rotation can generate vortexes that descend as funnel clouds—these become tornadoes when the start to impact the surface.

Drought

Drought is a prolonged period of abnormally low rainfall. Drought conditions commonly lead to other disastrous weather conditions including dust storms, heat waves, and firestorms, all of which can be catastrophic. The worst droughts in US history occurred in the 1930s and 1950s, resulting in **Dust Bowl** conditions throughout the Great Plains and Midwest that lead to severe economic damage and social upheaval and migrations. Drought periods have alternated with serious flooding in intervening years. Figure 8.27 (above) shows the cyclic nature of droughts and flooding periods for the State of California. During recent droughts, devastating **firestorms** have ravaged communities throughout the regions around San Diego, Los Angeles, Santa Barbara, San Francisco, and throughout the Sierra Nevada region—as urban development has spread into areas where vegetation is naturally apt to burn on a frequent basis during drought conditions (Figure 8.42). Conversely, flood conditions during wet **El Niño** years can potentially be more catastrophic to California than drought. Recent investigations into the impact of a California **mega-flood** event that happened in California in the winter of 1871-1872 suggest that if were a similar event were to happen today it could potentially be the most destructive natural disaster to impact the United States—possibly causing nearly three times as much damage than a great earthquake in the region.

Figure 8.42. A flame front of a **firestorm** near Santa Barbara in 2007.

Figure 8.43. Massive snow accumulation can be anticipated in places like Crater Lake, OR. However, giant winter storms can have long lasting effects, not just the cold and ice, but the shutting down of regional infrastructure and economies.

To see information about **current and forecasts of regional storm activity** see:
NOAA/National Weather Service Storm Prediction Center

8.15: The Greenhouse Effect and Global Warming

What is the Greenhouse Effect?

The **greenhouse effect** is the trapping of the sun's warmth in a Earth's lower atmosphere. This happens because lower atmosphere due to the greater transparency of the atmosphere to visible radiation from the Sun than to thermal infrared radiation emitted from the surface (Figure 8.44). A glass green house will let sunlight in, but captures some of the thermal energy within the enclosed interior. A **greenhouse gas** is any gas that absorbs and emits energy in the **Thermal infrared range**. Primary greenhouse gases in earth's atmosphere include: water vapor (H_2O), carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3).

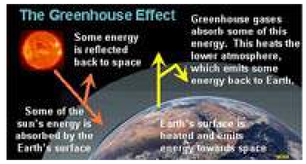


Figure 8.44. The greenhouse effect is enhanced by the presence of greenhouse gazes in the atmosphere**.**

Global Warming and Earth's Greenhouse

Earth is currently growing warmer at an alarming rate! The weather records compiled from around the world indicated that there has been a significant rise in global temperatures over the past century. This rise in temperature is linked to the increasing amount of carbon dioxide and other greenhouse gases accumulating in the atmosphere (Figure 8.45). The rise in carbon dioxide and other greenhouse gases is a result of consumption of fossil fuels, deforestation, and other human impacts since the start of the Industrial Revolution in the 19th century.

Figure 8.46 compares the rise in atmospheric CO_2 to the decrease in the ratio of **stable carbon isotopes $^{13}C/^{12}C$**.
The cyclic patterns in the graph is a result of the annual growth of plants in the northern hemisphere. During the summer months plant growth consumes CO_2, reducing CO_2 concentrations in the air. In the winter months the decay of organic matter increases CO_2 concentrations. The overall trend shows that atmospheric concentrations of CO_2 is increasing. The cyclic pattern in the $^{13}C/^{12}C$ also reflects the plant-growth cycles, but also shows the dilution of ^{13}C concentrations by the influx of carbon from fossil fuels. Carbon in fossil fuels (coal and oil) are enriched in^{12}C.

There are many ***knowns*** and ***unknowns*** about the future of **global warming**. Highlights include sea-level rise, climate changes, changes in storm intensity and regional precipitation, changes in air and ocean chemistry (acidification), and other impacts on humanity and natural ecosystems.

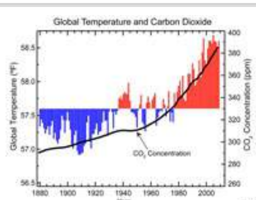


Figure 8.45. Changes in global temperature with the rise in atmospheric CO_2.

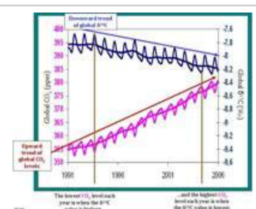


Figure 8.46. Changes in atmospheric $^{13}C/^{12}C$ concentrations.

Select resources about Carbon's role in the global environment:
Atmospheric Carbon Tracker Animation (NOAA)
The Carbon Cycle (NASA)
Environmental consequences of ocean acidification (United Nations)
Ocean acification: Issue briefs (United Nations)

8.16: Atmospheres on Other Planets

Atmospheres on Other Planets

The processes affecting Earth's atmosphere can also be seen on other planets. For instance, Jupiter, a planet about 318 times more massive than Earth has similar atmospheric circulation **zones** and **bands** (Figure 8.47). On Jupiter, the ***bright zones*** are regions of rising cloud tops, and the ***dark zones*** are regions of sinking air. Bright spots on Jupiter are massive cyclones (some are larger than planet Earth!). Jupiter's upper atmosphere is composed of hydrogen, helium, and has clouds composed of ammonia ice crystals (NH_3).

Figure 8.47. **Wind belts on Jupiter.**

8.17: Quiz Questions - Chapter 8 - Atmospheric Circulation

1. Nearly 80 percent of the air's mass and 99 percent of the water vapor in the air occurs within:
a. the stratosphere.
b. the troposphere.
c. the upper atmosphere.
d. outer space.

2. Incoming solar radiation involves all wavelengths of the electromagnetic spectrum. The atmosphere is transparent to most wavelengths, but part of the solar spectrum are absorbed by certain greenhouse gases in the atmosphere. Which of the following is NOT considered a **greenhouse gas**?
a. water vapor (H_2O)
b. oxygen (O_2)
c. carbon dioxide (CO_2)
d. methane (CH_4)

3. The amount of water vapor in the air can range from trace amounts up to about 4% by volume. Which of the following statements is NOT true?
a. Warm air can hold more moisture than cold air.
b. The amount water moisture that air can hold depends on factors including temperature, air pressure, and the amount and kinds of particulate matter dispersed in the air.
c. When air has reached the maximum amount or water it can hold it is called saturated.
d. Moist air is heavier than dry air.

4. At sea level, the pressure of the atmosphere:
a. averages about 1000 millibars.
b. increases in pressure when stormy weather is taking place.
c. decreases in pressure when cold, clear air masses moves into an area.
d. all the choices are correct.

5. Regarding atmospheric pressure systems moving into a region:
a. surface winds blow from high to low pressure.
b. high pressure systems have dry conditions with sinking air masses.
c. low pressure systems have wetter conditions with rising air masses.
d. all the choices are correct.

6. When a warm, moist air mass (a ***maritime-tropical air mass***) encounters a cold, dry air mass (a ***polar continental air mass***), what happens?
a. cold air moves in over the warm air, causing precipitation.
b. both warm fronts and cold fronts can form, possibly resulting in precipitation.
c. cold air rises, forming clouds, resulting in snow.
d. warm air sinks, forming clouds, resulting in rain.

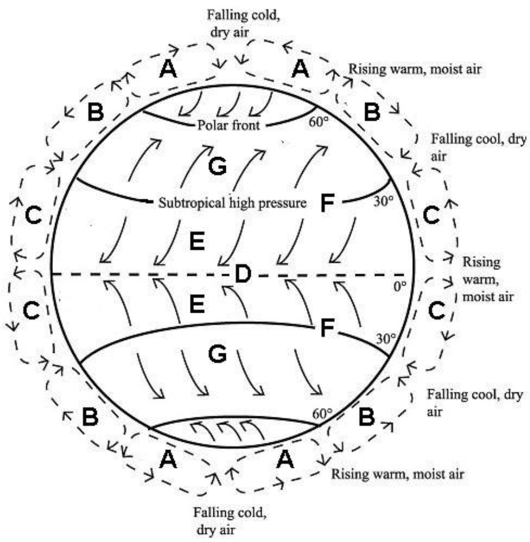
7. Tiny (very microscopic) dust particles and aerosols can become cloud condensation nuclei (CCNs). CCNs come from many sources: dust storms, fires, volcanoes, sea spray, plants, and pollution. If there are **too many CCNs in the air**, what happens?
a. It rains more intensely.
b. Smog turns to fog.
c. Rain droplets (or ice crystals) don't get big enough to fall as rain (or snow).
d. All of the choices are correct.

8. The fog often called the **marine layer** in coastal California is generally most often what kind of cloud?
a. Cirro-form
b. Cumulo-form
c. Nimbo-form
d. Strato-form

9. The Coriolis effect is caused by the rotation of the Earth. As a result:
a. low pressure systems (like hurricanes) turn counter-clockwise in the Northern Hemisphere.
b. high pressure systems turn clockwise in the Southern Hemisphere.
c. maximum Coriolis effect is at the equator and does not occur at the poles.
d. All of choices are correct.

10. A tropical cyclone is caused by ***spinning air currents above low pressure systems***. A tropical storm becomes a cyclone (a hurricane or a typhoon) when:
a. tropical depressions move north across the equator.
b. average wind speeds in the heart of the storm rise above 38 mph.
c. average wind speeds in the heart of the storm rise above 74 mph.
d. average wind speeds in the heart of the storm rise above 155 mph.

Questions 11-14 refer to the Global Atmospheric Circulation diagram below.



The **polar circulation cells** (60° to 90° N and S) are shown as letters **A**. The **Ferrel circulation cells** (30° to 60° N and S of equator) are letters B. The **Hadley circulation cells** (0° to 30° N and S of equator) are letters **C**.

11. Which letter represents the **Inter-tropical convergence zone (ITCZ)**?

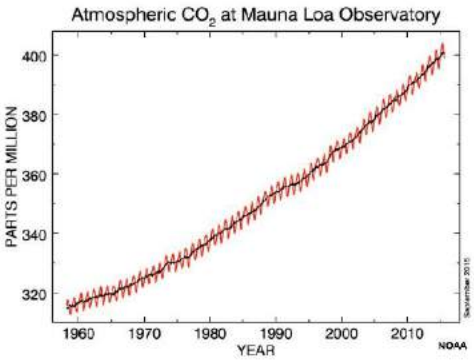
12. The **NE and SE Trade Winds** are represented by which letter?

13. The zone of potentially dangerous winds of the **horse latitudes** are represented by which letter?

14. **Doldrums** where sailing ships can be trapped without winds for extended periods of time are most common in the zone represented by which letter?

15. The figure below shows the record of changing carbon-dioxide concentrations in the atmosphere as recorded by NOAA at it's atmospheric research lab on Mauna Loa in Hawaii. The graph shows that:
a. carbon-dioxide concentrations have been steadily increasing for the last 50 years.
b. seasonal growth and decay of plant leaves in the northern hemisphere cause minor but measurable fluctuations in carbon-dioxide concentrations.
c. carbon-dioxide created by the burning of fossil fuels is being produced faster than the oceans can absorb and consume the gases.

d. all the choices are correct.



CHAPTER OVERVIEW

9: Ocean Circulation

9.1: The Atmosphere and Ocean Circulation Systems Are Linked

The Atmosphere and Ocean Circulation Systems Are Linked

The **global atmospheric circulation system** influences the movement of air masses in general "belts" that move air in rotating masses within zones around the planet (Figure 9.1). These relatively stationary wind belts impact the surface of the oceans, creating currents that circulate waters in the oceans under the influence of **Coriolis effect**, creating **five large subtropical gyres** encircling the major oceans basins (Figure 9.2).

Currents in the oceans include **surface currents** and **deep currents**:
• **surface currents** are driven **horizontally** by effects of the **wind**.
• **deep currents** are driven horizontally and vertically by differences in **density**
(density changes typically start near the surface).

Ocean circulation is also influenced by seawater **temperature** and **density**.
• **Warm water** in the tropics flows in currents to polar regions where it cools and the formation of sea ice concentrates the salt in seawater, increasing its density so that it sinks.
• **Cold and salty water** (concentrated by surface evaporation) sinks. Elsewhere seawater rises where it is displaced by colder and saltier water.

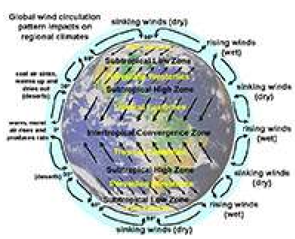


Figure 9.1. Global wind circulation patterns impact regional climates and drive the large **surface currents** in the global ocean circulation system.

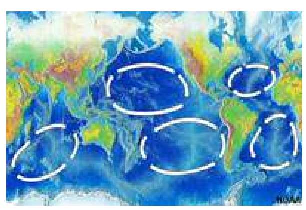


Figure 9.2. Five large **gyres** circulate surface waters in the global oceans. These rotating **subtropical gyres** are influenced by the patterns of atmospheric winds and the Coriolis effect.

9.2: Deep-Ocean Thermohaline Circulation

Deep-Ocean Thermohaline Circulation

Ocean circulation is also influenced by seawater **temperature** and **density**. Cold and salty water (concentrated by surface evaporation) sinks. Elsewhere seawater rises where it is displaced by colder and saltier (denser) water (Figure 15.20). Warm water in the tropics flows in currents to polar regions where it cools. In the Arctic region, the formation of sea ice concentrates the salt in seawater, increasing its density so that it sinks. Cold, salty water sinks both in the Arctic and Antarctic regions, feeding deep ocean circulation. The differences in temperature and salinity (or overall density) is the driving force behind deep-ocean thermohaline circulation (Figure 15.21). The coldest and densest (saltiest) water form around Antarctica where massive amount of **sea ice forms**. When seawater freezes, the sea ice is salt free (expelling the salt). The expelled salt adds to the saltiness (and density) of the coastal waters around Antarctica, causing them to sink in a slow current into the deep ocean basins. Lesser amounts of sea ice form in the northern Arctic region and around Greenland.

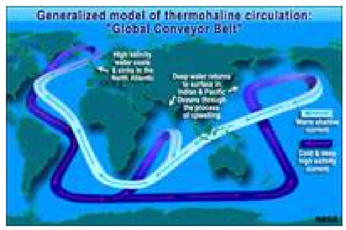


Figure 9.3. **Thermohaline Circulation**: cold and salty ocean water is dense and sinks. Warm water stays at the surface. Evaporation increasing salinity (and increasing density) before it can sink. Formation of sea ice also increases salinity.

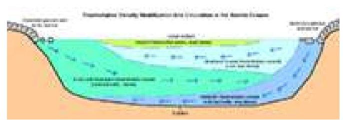


Figure 9.4. Thermohaline density stratification and currents of the world's oceans.

The deep ocean basins have slow moving currents (compared with the surface waters exposed to atmospheric winds. As currents move about the globe, evaporation increases salinity. Increased salinity combined with cooling increases seawater density, allowing affected seawater to sink into the deep ocean. The movement of surface waters downward supplies oxygen to the seabed, assisting in the decay of organic matter. The deep, slow-moving water picks up nutrients from the seafloor and from decaying organic particles sinking through the water column. In locations where deep-water upwells to the surface, these nutrients supply the ingredients for **phytoplankton blooms**, providing food for the food chain.

Animations: global perspectives of ocean currents based on salinity and temperature
Surface Salinity (annual) (NASA)
Perpetual Ocean (2005-2007) [NASA] global ocean circulation time lapse - YouTube video.
22 Years Sea Surface Temperature 1985-2007 [NOAA Polar satellite data] YouTube video
Worldwide Sea Surface Temperature simulation 2008 YouTube video

9.3: Sea Ice and Thermohaline Circulation

Sea Ice and Thermohaline Circulation

Glaciers flowing into the ocean contribute large amounts of iceberg and sea ice to the polar ocean regions. However, sea ice also forms where very cold air is in contact with the ocean surface. Currents in the upper sea (mixing zone) can inhibit the formation of sea ice. Water is most dense slightly above the freezing point and tends to sink whereas ice floats. Once sea ice starts to form the salt is either expelled back into the seawater and some is concentrated in microscopic pockets trapped in the sea ice. Antarctic sea ice is typically 1 to 2 meters (3 to 6 feet) whereas most of sea ice in the Arctic is 2 to 3 meters (6 to 9 feet) thick. However, in some Arctic regions sea ice can grow to 4 to 5 meters (12 to 15 feet) thick. The formation of sea increases the salinity of the seawater, and the combination of the increased salinity and cold water results in the formation of dense water that sinks into the deep ocean, driving the thermohaline circulation through the world's deep ocean basins.

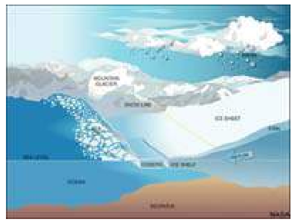


Fig 9-5. Origin of glaciers, icebergs, and sea ice. Sheets of sea ice form and melt back with the seasons.

Arctic Sea Ice time lapse from 1987-2009 (NOAA/NSIDC satellite data YouTube video)

9.4: Surface Currents

Surface Currents

Surface Currents involve large masses of water moving **horizontally** on the surface.

• **The transfer of wind energy to water is not very efficient**
(only about 2% energy transfer of "friction" between water and air).
• Wind produces both waves and currents (more on waves in Chapter 10).
• Surface currents occur in the **mixing zone** within and above the **pycnocline** (layer of rapidly changing density).
• **Effects of surface currents** is to redistribute heat from equatorial to polar regions.

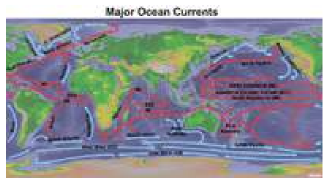


Figure 9.6. Major **surface currents** of the oceans. **See Oceans Currents Map** (NOAA-NWS)

Mechanisms moving surface currents include:
• **Wind**: **major** mechanism (result of atmospheric circulation patterns).
• **Solar heating**: (direct heating by the sun) - a **minor** mechanism (influences surface waters but not water at depth).
• **Tides**: (affect currents in coastal regions - tidal currents are discussed in **Chapter 10**).
• **Geography**: locations of continents (and islands) influence direction and flow currents (acting as barriers to flow).

Subtropical gyres are large system of rotating ocean surface currents driven by **global wind currents** with the **influence of Ekman Transport** (see below) and **continental geography** (land masses restrict and deflect the flow of water currents).

Movement of Surface Currents

Moving water (like wind) are influenced by the **Coriolis effect** (Figure 9.7):
• Moving water is deflected to the **RIGHT** in the **Northern Hemisphere**.
• Moving water is deflected to the **LEFT** in the **Southern Hemisphere.**

The Coriolis effect has a large influence on the movement of both surface water and deeper water. However, wind-driven currents move fastest near the ocean surface and diminish with depth. The difference in rate of movement results in a rotational process called **Ekman transport**.

Figure 9.7. Coriolis effect.

9.5: Ekman Spiral and Ekman Transport

Ekman Spiral and Ekman Transport

Early sailors traveling in regions where icebergs are common noticed that the icebergs moved in a different direction than the wind (causing alarm as the icebergs were cutting across the paths of ships moving down wind).

Figure 9.8. Sailors of ships noticed that icebergs move in a different direction than the wind.

Walfrid Ekman (1874-1954, a Swedish physicist) resolved the problem of why wind currents and water currents were not the same. The force of wind affect surface water molecules, which in turn, **drag** deeper layers of water molecules below them (drag is caused by **friction** between water molecules). The deeper below the surface, the slower the water moves compared to the water layer above it.

Surface movement ceases at a depth of about 100 meters (330 feet).

As noted above, both surface water and deeper water is deflected by the Coriolis effect.
—90° to the **right** in the **Northern Hemisphere**
—90° to the **left** in the **Southern Hemisphere**.

Depth is important: Each successively deeper layer of water moves more slowly to the right (or left), creating a **spiral effect** (called the Ekman Spiral). Because the deeper layers of water move more slowly than the shallower layers, they tend to ***twist around*** and flow opposite to the surface current. **Net result is that net transport in surface currents is 90° from wind (Figure 9.9).**

This twisting character of ocean surface waters is called the **Ekman spiral**. The impact of the Ekman Spiral is enhanced where geographic features create barriers to the movement of water. **Ekman transport** is the net motion of a fluid (seawater) as the result of a balance between the Coriolis effect and turbulent drag forces (within surface waters and geographic features (shoreline and seabed).

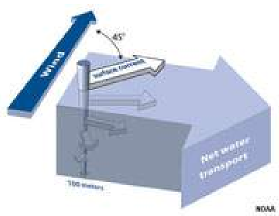


Figure 9.9. The **Ekman spiral**

9.6: Boundary Currents

Boundary Currents

Boundary currents: currents associated with gyres **flow around the periphery of an ocean basin**. Boundary currents are ocean currents with dynamics determined by the presence of a coastline.

Two distinct categories of boundary currents:
• western boundary currents
• eastern boundary currents

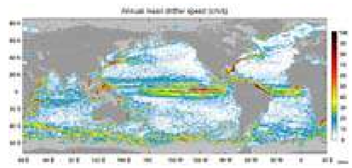


Figure 9.10. Speed of currents measured by drifting devices (annual average in cm/sec)

Western Intensification of Boundary Currents

Wind blows westward along the inter tropical convergence zone at the equator, causing **western intensification.**
• Wind blowing across the oceans ***mounds*** water on the western side of ocean basins-up to 2 meters.
• The mounding of water is caused by converging equatorial flow and surface winds.
• The Coriolis effect is most intense in polar regions, so current flowing eastward near the poles is more dissipated than currents flowing westward at the equator.
• The higher side of a ***mound*** is on the western side of the ocean basins, having a steeper ***slope*** and therefore faster moving.

Eastern boundary currents (EBC) are **slow** (a few miles or km per day), **wide** (less than 600 miles [1000 km]), and **shallow** (less than .3 miles [.51 km])
Examples: Canary, **California**, Benguela, Peru
EBCs form along the ***cool and dry east side*** of ocean basins.

Western boundary currents (WBC) are **fast** (many miles or km per day), **narrow** (less than 60 miles [100 km] wide), and **deep** (up to 1.3 miles [2 km])
Examples: Gulf Stream, Brazil, Kuroshio, E. Australian, Agulhas.
WBCs form along the ***warm and wet west side*** of ocean basins.

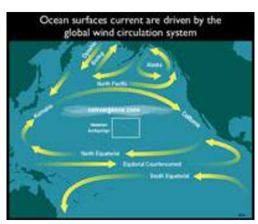


Figure 9.11. The **California Current** is an **eastern boundary current**; part of the **Northern Pacific Gyre**. The **Kuroshio Current** near Japan is a **western boundary current**.

Gyres and boundary currents are large scale, but are also complex. Boundary currents change constantly (called **meandering**) producing spinning cone-shaped masses of water - spinning off of larger boundary currents.

Eddy Currents

Satellite temperature data of the ocean surface reveals the spreading and mixing of surface waters as currents move from one region to another, gaining intensity and dispersing energy as they move. The temperature data reveals large spinning eddies in portions of the ocean basins along the margins of major currents.

Figure 9.12 illustrates large eddy currents forming in the surface waters of the southern Atlantic Ocean west of southern Africa as revealed by satellite ocean surface temperature data. The eddy currents form as a part of the meandering processes that dissipate energy in the ocean waters. This meandering creates warm- and cold-core rings of swirling currents (Figure 9.13).

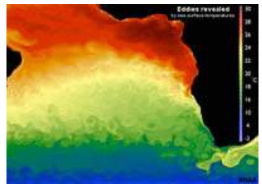


Figure 9.12. Large **eddy currents** in the South Atlantic Ocean revealed by surface temperature data.

9.7: Warm- and Cold-Core Rings

Warm- and Cold-Core Rings

• **Warm-core rings** are rotating warm masses of water surrounded by colder water. Example: Warm water areas in the Sargasso Sea water surrounded by cool water (Figure 9.14).

• **Cold-core rings** are cold masses of water surrounded by warmer water.

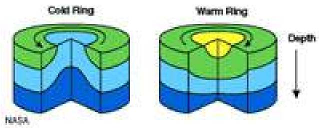


Figure 9.13. Warm- and cold- core rings are created by eddies in ocean currents (Northern Hemisphere).

These spinning rings can last for years and serve as refuges for sea life (warm and cold water) and can influence storm development (such as intensifying or reducing hurricane intensity). Core rings typically have **unique biological populations**.

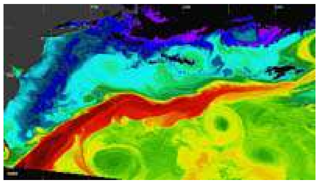


Figure 9.14. Cold-core rings in the North Atlantic associated with the Gulf Stream current.

9.8: The Gulf Stream and the Antarctic Circumpolar Currents

The Gulf Stream Current

The **Gulf Stream** is a fast moving ocean current (Figure 9.15).
• The **North Equatorial Current** moves east across the Atlantic Ocean in the Northern Hemisphere.
• This flow splits into the **Antilles Current** (east of the West Indies) and the **Caribbean Current** (around the Gulf of Mexico).
• These currents merge into the **Florida Current**. (about 30-50 miles [50-80 km] wide, moving 2-6 mph [3-10 km], and about a mile deep).
• Along the East Coast, the Gulf Stream experiences ***western intensification***.
• North of Cape Hatteras (NC) the current moves away from the coast and gradually looses much of its intensity (by **meandering**) producing numerous warm and cold core rings.
• The Gulf Stream gradually merges eastward with the water of the **Sargasso Sea**, the rotating center of the North Atlantic Gyre (named for floating marine alga (seaweed) called ***Sargassum*** that accumulates in the stagnant waters.
• For comparison, the volume of water moved by the Gulf Stream is about 100 times all the world's rivers combined!

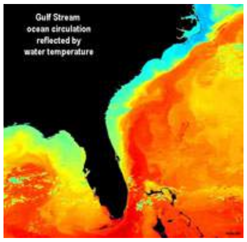


Figure 9.15. The **Gulf Stream** is the world's largest ocean current (revealed here by water temperature patterns).

Antarctic Circumpolar Current

• The **Antarctic Circumpolar Current** is the only current to completely encircle Earth (Figure 9.16).
• The current moves more water than any other current.
• The current is in a region of the world with intense winds and wave action.
• The region has lots of upwelling - very "rich" ocean basin (nutrients for plankton; food for higher-level feeders)

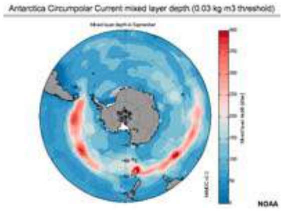


Figure 9.16. **Antarctic circumpolar current** revealed by mixing zone depths.

Antarctic Circumpolar Current (NOAA website); also see an animation of the changes in the mixing zone by seasons: **Antarctic Circumpolar Current** (NOAA)

Climate Effects Of Ocean Currents

• Cold water offshore results in dry condition on land (example: California).
• Warm water offshore results in more humid condition on land (example: Florida).
• Depends on seasonal wind patterns and water temperatures.
• Depends also on regional geography along coastal regions.

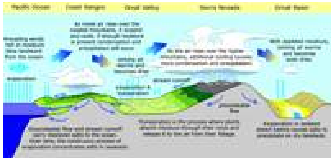


Figure 9.17. California's climate and geographic factors.

9.9: Upwelling and Downwelling

Upwelling and Downwelling

Upwelling is the vertical movement of cold, nutrient-rich water from deep water to the surface, resulting in ***high productivity*** (plankton growth).
• Can bring cold, nutrient-rich water to the surface (photic zone) unless thermocline is strong and prevents it.
• **Nutrients** are not food but act like a fertilizer.
• Upwelling water rich in nutrients feeds phytoplankton, the base of the food chain.

Downwelling is the vertical movement of surface water downward in water column. Regions where downwelling is occurring typically have low biological productivity.
• Downwelling takes dissolved oxygen down where it is consumed by the decay organic matter.

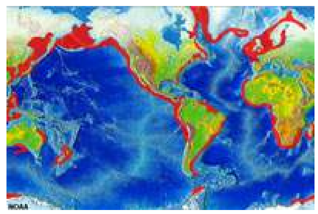


Figure 9.18. Regions of the world where coastal upwelling occurs.

Where Upwelling Occurs

Diverging surface waters occur where surface waters are moving away from an area on the ocean surface.
• **Equatorial upwelling** occurs where SE trade wind blow across the equator (Figure 9.19); Ekman transport forces surface water movement to the south (south of the Equator), and to the north (north of the Equator). Upwelling of deep ocean waters is most intense in equatorial regions.
• **Coastal upwelling** occurs where wind blowing along a coastline is influenced by Ekman current moving surface waters offshore, or winds blowing off the land pull surface waters away from the coast, pulling deeper water up to replace surface waters. See Figure 9.18 for locations where coastal upwelling most commonly occurs.
• Other locations where upwelling occurs include around **underwater obstructions (guyots)** or **sharp bends in coastlines**.

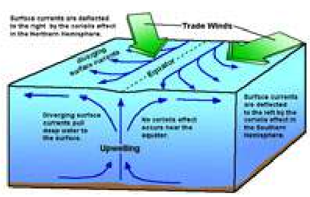


Figure 9.19. **Equatorial upwelling** involves the Trade Winds blowing across the equator and the Coriolis effect taking over as diverging currents move away from the equator.

NOAA animation: Coastal Upwelling

Coastal Upwelling and Downwelling

The continental margins of the world are places where coastal upwelling and downwelling are taking place (Figure 9.18). Coastal upwelling is influenced by coastal geometry, wind directions, and the influence of the Coriolis effect (Ekman transport). Figures 9-20 and **9-21** illustrate how the direction of wind movement determines how coastal upwelling and downwelling takes place in the Northern Hemisphere (such as in California). Figure 9.22 shows regions of coastal upwelling along the California continental margin—revealed ocean-surface temperature imagery. Upwelling water along the coastline is colder than waters farther offshore.

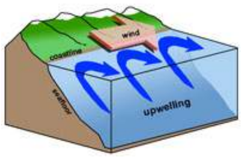


Figure 9.20. Coastal upwelling (example of California)

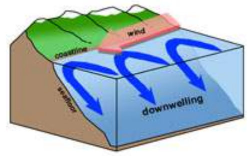


Figure 9.21. Coastal downwelling (wind reversed)

9.10: Large Cycles in Ocean Climate Variability

Large Cycles in Ocean Climate Variability

The ocean/atmosphere systems display cyclic changes beyond annual seasonal changes. Longer-term cycles are also taking place. Changes happening in one region can gradually impact other regions on multi-year to decade cycles (example: cycles in coastal upwelling on North America's West Coast, **Figure 9.23**). Even longer-term cycles are influenced by extraterrestrial pattern changes in the orbit and rotation of the Earth relative to the Sun over time. These changes impact the distribution of precipitation and influence the warming or cooling of climates over multi-year periods, and changes in sea level over time linked to the accumulation and melting of continental glaciers.

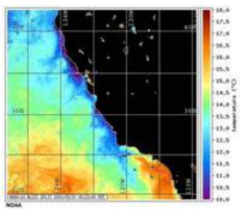


Figure 9.22. Upwelling offshore of California revealed by ocean surface temperatures.

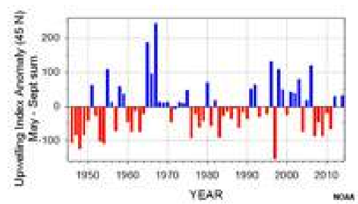


Figure 9.23. Cycles of upwelling on North America's West Coast influenced by ENSO.

9.11: El Niño/Southern Oscillation (ENSO)

El Niño/Southern Oscillation (ENSO)

El Niño/Southern Oscillation (**ENSO**) in the Pacific Ocean [also called **El Niño-La Niña Cycles**] is associated with a band of warm ocean water that develops in the central and east-central equatorial Pacific. El Niño/Southern Oscillation (ENSO) is perhaps the most important ocean-atmosphere interaction phenomenon to cause cyclic global climate variability. Here's how the ENSO cycle works: **ENSO involves the interactions of ocean currents, ocean temperatures, and atmospheric effects, over time**.

Pacific Ocean Currents Involved With ENSO

- West moving winds at the Equator help to drive the two **Pacific Subtropical Gyres** (**northern** and **southern gyres**)(see Figures 9-6).
- In the **North Pacific Subtropical Gyre**, the western-intensified **Kuroshio Current** moves up the Asian seaboard (warming China, Japan), flows east with the **North Pacific Current**, then south as the **California Current** along the west coast of North America.
- In the **South Pacific Subtropical Gyre**, the western intensified **East Australian Current** moves south and merges with the Antarctic Circumpolar Current, the completes the gyre as the Peru Current (flowing northward along the west coast of South America).

ENSO Ocean Temperature Effects

ENSO Cycles are influenced by ocean surface temperatures throughout the Equatorial Pacific Ocean region. During the **El Niño** periods, ocean surface temperatures are much warmer than the **La Niña** periods. This is a reflection of the amount of cloud cover (deflecting incoming solar radiation) and winds driving cold upwelling currents to the ocean surface in the equatorial region. During **El Niño** periods, the **Pacific Warm Pool** grows larger and more intense in the Eastern Pacific region near Australia and Indonesia (Figure 9.24).

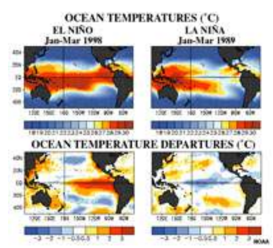


Figure 9.24. Ocean surface temperatures reveal the changing patterns and regional extent of the **Pacific warm pool** associated with **El Niño-La Niña Cycles.**

ENSO Weather Effects And the Walker Cell

• The rising warm-moist air in the western Pacific contrasts with the cool sinking air along South America, resulting in the **Walker Cell** (an unstable equatorial air circulation pattern region in the Pacific Ocean)(Figure 9.25). The **Walker Cell** operates ***perpendicular*** (**east to west**, ***not north to south*** like the **Hadley**, **Farrell**, and **Polar circulation cells** [see Figure 15.15]). the intensity Walker Cell weather pattern is controlled by temperature contrasts on opposite sides of the Pacific Basin along the equator.

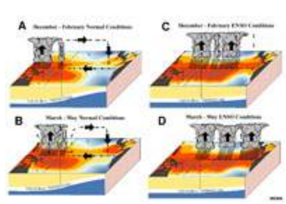


Figure 9.25. El Niño-La Niña Cycles changes in the **Walker Cell** wind currents affect ocean surface temperatures which impact the thickness and extent of the thermocline (which impacts upwelling).

Under *normal year* ENSO conditions (which is actually rare) cool water conditions persist along the west coast of South America (Peru) (Figure 9.26):

• Trade winds blow to the west allow waters to upwell along the west coast of South America (some of the most productive waters in the world).

• West-moving winds drive surface currents westward across the Pacific Ocean where they heat up creating the **Pacific Warm Pool** - a thick thermocline in the western Pacific Ocean.

Under El Niño (the warm phase of ENSO) wind intensity of the Walker Cell circulation is diminished (Figure 9.27). El Niño is associated with high air pressure in the western Pacific and low air pressure in the eastern Pacific.

La Niña (the cool phase of ENSO) is associated with below average surface water temperatures and high air pressures in the eastern Pacific and low air pressures in western Pacific (Figure 9.28). Air circulation in the Walker Cell is intensified.

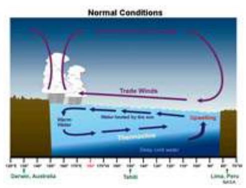


Figure 9.26. A **normal year** thermocline and weather pattern under somewhat rare ***normal*** conditions in the equatorial Pacific region.

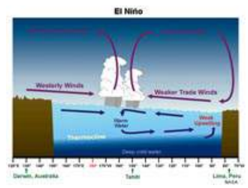


Figure 9.27. **El Niño** thermocline and weather during strong El Niño conditions in the equatorial Pacific region; coastal upwelling near South America is diminished.

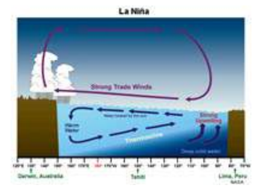


Figure 9.28. La Niña thermocline and weather during La Niña conditions in the equatorial Pacific region; coastal upwelling near South America is strengthened.

El Niño/La Niña Global Climate Impacts—NOAA videos, websites, animations

Warm El Niño Southern Oscillation (ENSO)- Episodes in the Tropical Pacific
El Niño/La Niña Explained (YouTube video).
NOAA's **El Niño** website.
El Niño/La Niña 1997-1998 (NOAA) - Shows sea surface temperature time lapse.
Global Sea Surface Temperature time lapse showing **El Niño/La Niña** (NOAA)

9.12: Impacts of ENSO Cycles

Impacts of ENSO Cycles

ENSO cycles [**El Niño-La Niña Cycles**] consist of shifting weather and oceanographic conditions in the tropical Pacific region (refer to Figures 9-24 and **9-25**).

During El Niño:

• **High and low atmospheric pressures systems** reverse across the equatorial Pacific region. As a result the **Walker Cell** circulation pattern is very weak.
• Winds become slack or blow against the west-moving **Equatorial Current**.
• The west-moving Equatorial Current **mounds** warm water on eastern side of Pacific Basin. near Australia and Indonesia.
• Along the coast of South America, a normally thin **temperate thermocline** replaced with a thick **tropical thermocline**.
• This thick thermocline prevents mixing of deep cold nutrient rich water because of the buoyancy of extra warm surface water.
• The tropical thermocline shuts down upwelling currents that would otherwise provide nutrients to the base of the food chain in shallow ocean waters, resulting in a **collapse of marine fisheries** offshore (often resulting in economic and ecological catastrophe along South America's west coast).
• During El Niño, the warm conditions typically arrive around Christmas, so **El Niño** refers to the ***Christ Child*** in Peruvian weather — El Niño conditions offshore results in both warm and wet conditions on land.

During La Niña:

• The **Walker Cell circulation** intensifies across the equatorial Pacific region.
• This increase in windy weather condition pulls the thick warm waters away from the coast of South America.
• As a result, there is increased cooling and more upwelling along the coast, enhancing ocean productivity.
• Cool conditions offshore results in persisting drought conditions on land in South America.

Global significance of ENSO cycles:

These fluctuating cycles of ocean surface water temperatures influence climate factors (warm/wet or cool/dry) conditions around the entire Pacific Basin, if not the entire world. **Monitoring for El Niño** is conducted by:
• studies of wind speed and direction on the Equatorial regions.
• monitoring high and low pressure systems on the Equatorial regions.
• monitoring water temperature changes on Equatorial regions, mainly warming on east side of Pacific Basin.
• measuring water heights (mounding) above average sea level along the Equator.

ENSO Impacts on Coastal California

During **El Niño** periods, California's coastal ocean waters are warmer, and a more well-developed thermocline hinders coastal upwelling. This reduces the nutrient supply for sea life, so marine specie either adapt and migrate elsewhere, or in many cases, loose populations due to competition for limited food resources. Southern California typically gets heavier winter rainy periods because the southern tropical jet stream move north from the Central America region. As a result, Southern California gets more tropical moisture which can translate to increased rainfall if conditions are right.

During **La Niña** periods, California's coastal ocean waters are cooler, only a weak thermocline can develop. As a result, there is stronger and well developed coastal upwelling. As a result, more food is available, and marine life flourishes in coastal waters. Colder waters offshore translate to drier conditions on land.

9.13: Sea Level Changes Caused by Continental Glaciation Cycles

Sea Level Changes Caused by Continental Glaciation Cycles

Sea level changes caused by the melting of continental glaciers (Antarctica and Greenland) are some of the gravest concerns associated with global warming. Why we know that sea level is changing because vast amounts of data are now available. The observable effects of sea level changes are preserved everywhere around the world's ocean basins. The study of sedimentary deposits of all geologic ages has revealed that sea level has risen and fallen many times, sometimes in the range of hundreds of meters (Figure 9.29).

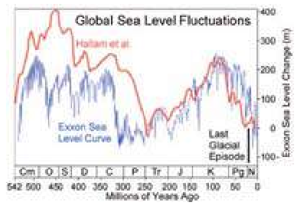


Figure 9.29. Sea level changes through Earth history.

9.14: Ice Ages of the Pleistocene Epoch

Ice Ages of the Pleistocene Epoch

The Pleistocene Epoch began about 2.56 million years ago. This Pleistocene ice ages are linked to climate changes cause by many factors resulted in the cyclic expansion of continental glaciers in the polar regions of both hemispheres. Important factors that may have helped initiate the ice ages may be related to plate tectonics.

Studies of ice cores from Antarctica, Greenland, cores samples derived from ocean sediments, and studies of glacial deposits found on land indicate that there may have been as many as 20 glaciation periods starting during the late Pliocene through the Pleistocene Epochs (during the last 3 million years). Figure 9.30 shows evidence of glaciation cycles for the last 650,000 years based on studies of greenhouse gases preserved in ice core taken from the Greenland Ice Sheet.

Glacial periods

Figure 9.30. Glaciations of the late Pleistocene Epoch

The rise and fall in sea level is preserved in sediments deposited in restricted coastal and marine sediments. These sediments are well exposed in many places allowing paleoclimate scientist to evaluate the sedimentary record in many locations (such as at Ft. Funston sea cliffs near San Francisco, CA, Figure 9.31). Some of these cycles were more intense than others, and they impacted regions around the world differently. Each of the glaciation cycles was followed by an interglacial warming period in which the continental glaciers ***retreated*** (or melted back). We are currently in one of the interglacial warm periods (although it wouldn't feel like that in Greenland or Antarctica where glaciation is still occurring).

Figure 9.31. The ***sedimentary record*** preserves evidence of numerous glaciation cycles. A famous, well-studied location where a record of sea level changes during the ice ages are well preserved and well in Quaternary-age sediments exposed is in the sea cliffs at Ft. Funston Beach near San Francisco, California.

Plausible Causes Of the Onset of Continental Glaciation Of the Ice Ages

• Prior to the ice ages, the passages between the Arctic Ocean and the Pacific and Atlantic Oceans was more open, allowing unhindered ocean circulation between the regions.
• Before about 3 million years ago there was open circulation between the Pacific and Atlantic ocean basins. Plate convergence caused the formation and rise of the Isthmus of Panama, shutting off open tropical ocean circulation between North America and South America.
• The plate convergence of the Indian subcontinent with Asia caused the rise of the high and extensive Himalayas and Tibetan Plateau, causing significant defection of the Earth's atmospheric circulation patterns.
• The interactions of global plant cover, global cloud cover (and precipitation), polar sea ice, and impacts of massive volcanic eruptions may all have possible influence on glaciation cycles.
• Other changes in regional and global atmospheric and oceanographic circulation patterns may have been factors. The rise in CO_2 concentrations in the atmosphere over the past century add to the complexity of interpreting the causes of the current rise in global temperatures.

The total number, extent, and duration of Pleistocene glaciation cycles is unclear. This is because erosion subsequent glaciation cycles largely destroyed evidence of previous glaciations. In addition, glaciation in one region was not exactly synchronous with other regions. This is illustrated by the fact that the last major glaciation cycle ended about about 11,000 years ago, yet both Antarctica and Greenland are both still experiencing ice-age conditions. Current data suggests that there may have been as many as 20 glaciation cycles in the last 2 million years or so. At least 4 of them were ***major glaciation cycles*** that are well preserved in continental glacial sediment deposits exposed in parts of central North America (more cycles are recorded in ocean sediments).

9.15: Sea Level Changes Caused By Glaciation Cycles

The most recent ice age is called the **Wisconsin Stage** or **Wisconsin Glaciation**—it began about 85,000 years ago and ended about 11,000 years ago. The peak of the last ice age, about 26,500 years ago when massive continental ice sheets, ice caps, and alpine glaciers cover much of northern Europe and North America, more extensive glaciers in Antarctica (Figure 9.32). This displaced nearly 10 million cubic miles of ocean water onto the land to be stored as ice. At the peak of the last ice age, glaciers covered about one-third of the land surface. Modern Greenland and Antarctica ice sheet were more extensive than they are today. With water trapped as ice on land, sea level fell around the world by as much as **400 feet below current sea level**, exposing all the regions that are now submerged on continental shelves. The location of **shelf breaks** around the world shows that sea level where coastlines existed at the peak of the last ice age. Research shows that onset of deglaciation began about 20,000 years ago in the Northern Hemisphere with a massive rise in sea level starting starting about 14-15,000 years ago with deglaciation of the West Antarctic Ice Sheet.

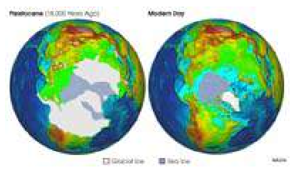


Figure 9.32. Extent of glaciers and sea ice during the peak of the last ice age and today in the Northern Hemisphere.

According to a USGS source, the glaciers currently store about 69% of the world's **freshwater** (preserved as ice). If all land ice melted the seas would rise about 70 meters (about 230 feet). During the last warm period (an interglacial ***stade***) about 125,000 years ago, sea level rose about 18 feet higher than the current level. About three million years ago, before the major continental glaciation cycle began, sea level was as much as about 165 feet higher than today.

Glacial Cycles Interpreted From Ice Cores and Ocean Sediments

Drilling programs have collected ice cores from the Antarctic and Greenland ice sheets, and many more cores have been collected from marine sediments from around the world. Using geochemical methods and isotopic dating techniques the history of the chemistry of the oceans and atmosphere, and sea level changes through time are well documented (Figure 9.33). For instance, ice has tiny bubbles trapped in them that preserve the chemistry of the air and ice at the time it formed. Sea sediments are loaded with many organic and inorganic materials that can be studied and dated. Shell material of foraminifera contain stable isotopes of carbon and other elements that match the chemistry of seawater at the time that they lived. When glaciers form, the water that forms as ice in polar regions is enriched in light isotopes of oxygen and carbon (light isotopes evaporate from seawater faster than heavy isotopes). As a result, sea water at the peak of glaciation cycles are enriched in the heavy isotopes of carbon and oxygen. The ratios of these isotopes are preserved in microfossil shell material. As a result, scientists have been able to clearly reconstruct a "sea level curve" compared with atmospheric greenhouse gases.

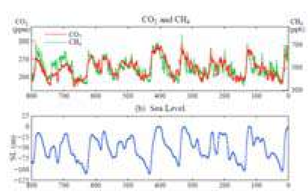


Figure 9.33. Comparison of concentrations of ***greenhouse gases*** with the sea level curve for the last 600,000 years.

9.16: The Astronomical Connection- Milankovitch Theory

The Astronomical Connection: Milankovitch Theory

Early in the 20th century, a Serbian geophysicist and astronomer name **Milutin Milankovitch** worked out mathematically the subtle changes in Earth's orbital cycles, involving cyclic changes in its rotational axis and its revolution around the Sun changes. Three **orbital forcing cycles** include the **eccentricity** of Earth's orbit, Earth's **axial precession** (41,000 years), **precession of equinoxes** (21,000 years)(illustrated in Figure 9.34). **Eccentricity** refers to the change of earth's orbit from being round to more elliptical in shape this cycle repeats every 95,000 years. When it is more elliptical the Earth has shorter, warmer summers and longer, colder winters. **Axial precession** refers to the ***wobble*** in the tilt of Earth's axis. The tilt of the axis changes from about 21.5 to 24.5 degrees on a cycle lasting about 41,000 years. The **precession of equinoxes** refers to which hemisphere is facing the sun when it is closest to the sun. Right now, the earth is closest to the sun during the winter in the Northern Hemisphere. These cycles impact how much incoming solar radiation that the regions of the earth receive over time, most important being where land is exposed in high latitude regions (where continental glaciation has taken place repeatedly). Milankovitch showed that these cycles combine or interfere with each other in the amount of energy the polar regions receive through time. Climate investigations in the last century have shown that Milankovitch Cycles closely correspond with the record of global temperature changes retrieved from ice cores, marine sediments, and other sources.

However, **Milankovitch Cycles** alone don't explain the onset of the ice ages.

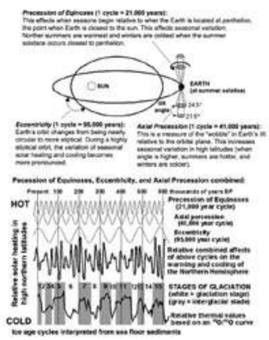


Figure 9.34. **Milankovitch cycles**

9.17: World Oceans and Landmasses During the Ice Ages

World Oceans and Landmasses During the Ice Ages

Sea level change since the end of the last glaciation has had major impacts on humans and all "remaining" species alike. A major mass extinction has been on-going since the last ice age. Many will argue that it is because of ***human over-consumption***, but climate change and sea-level-rise have also been major contributing factors (the two factors are linked). When sea level was low, humans (and other species) were able to migrate throughout the world when what are today's ***continental shelves were coastal plains*** (Figure 9.35 and **9-36**).

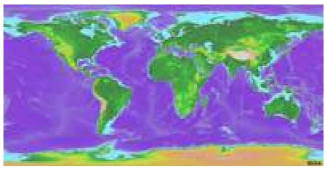


Figure 9.35. Map of the world with continental shelves shown in light blue. During the peak of the last ice age continental shelves were exposed as extensive coastal plains (allowing humans to migrate).

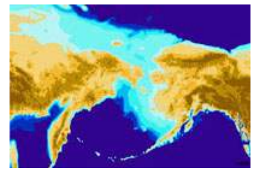


Figure 9.36. The **continental shelf** in the Bering Straits region between Siberia and Alaska was exposed during the last ice age, allowing many species (including humans) to migrate between continents.

At the peak of the last ice age sea level about 400 feet (120 m) lower than today. What are now continental shelves were exposed land (coastal plains) that extended out to near the shelf break around continental landmasses. Rivers and streams carved canyons that have flooded as sea level rose, creating **fjords**, **estuaries** and **bays** we see around the world today. Most of the record of human prehistory is now submerged.

9.18: Increasing CO2 Concentrations, Hypoxia, and Eutrophication

Increasing CO_2 Concentrations in the Atmosphere and Oceans

CO_2 concentrations and temperature have tracked closely of the last 300,000 years (Figure 9.37).

The recent (if not alarming) increase in CO_2 concentrations in the atmosphere is a result of human consumption of fossil fuel, burning forests, and other land use changes. How the Earth's ecosystems are responding to these changes is measurable, and many things are changing. Continental glaciers are melting faster (causing serious concerns about coastal flooding), and the chemistry of ocean water is slowly growing more acidic (endangering ocean species that secrete $CaCO_3$ skeletal material).

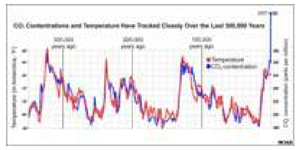


Figure 9.37. Global temperature and CO_2 concentrations over the last 300,000 years.

Hypoxia and Eutrophication

Hypoxia is oxygen deficiency in a biotic environment. **Eutrophication** is caused by excessive amounts of nutrients in a body of water (lake, sea, or parts of an ocean) which causes a dense growth of plant life and death of animal life from lack of oxygen (hypoxia). Excessive amount of nutrients come from runoff from land, with agriculture and sewage being primary contributors. Hypoxia has become a major problem in many parts of the world where whole regions of the seabed are dead or dying because of lack of oxygen. Eutrophication is a serious problem in the northern Gulf of Mexico around the mouth of the Mississippi River delta (Figures 9-38 and **9-39**). Density stratification in isolated ocean basins can lead to depletion of oxygen at depth at as microbial decay consumes free oxygen and then starts to break down sulfate ions ($^{-}HSO_4$) to hydrogen sulfide (H_2S). The Black Sea is an example where thermohaline density stratification has lead to anoxic conditions at depth (Figure 9.36).

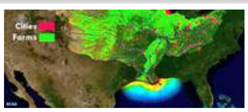


Figure 9.38. Region impacted by eutrophication in the northern Gulf of Mexico caused by high-nutrient runoff in the Mississippi River system.	Figure 9.39. Example of a fish kill caused by hypoxia in a coastal marine environment. Hypoxia increases in the Gulf as water warms up during the summer season.

See **Hypoxia and Eutrophication** (NOAA)

9.19: Could the Oceans Become Anoxic?

Could the Oceans Become Anoxic?

Anoxia it the chemical state of bodies of water losing its free oxygen. This is largely due to density stratification between less dense surface waters and colder, saltier waters at depth. This stratification can cut of upwelling and downwelling, preventing the movement of oxygen into deeper waters. Large portions of the world's ocean basins have become anoxic in the geologic past. During a million year interval of the Late Cretaceous Period the world's ocean basins became density stratified. This period is called the **Cenomanian-Turonian Oceanic Anoxic Event** (OAE). This happened between about 90.5 and 91.5 million years ago (the Cenomanian and Turonian are named epochs of the Cretaceous Period). The world was much warmer in the Cretaceous Period, and there were no continental glaciers. The oceans were warmer, and a thick thermocline and intense pycnocline blocked oxygen-rich surface waters from penetrating deep water. Organic-rich deposits preserved in ocean sediments of the OAE show that there is no bioturbation, suggesting that plankton in the grew in the shallow mixing zone was not consumed if their remains sank into the anoxic condition that existed at the seabed.

Density stratification can cut of oxygen supply to deep water in restricted basins (including isolated lake basins and inland sea basins). The Black Sea is an inland sea that has anoxic conditions. Marine surface waters flow into the Black Sea from the Aegean Sea through the shallow **Bosphorus Straight** (Figure 9.40). Denser saline water trapped in the basin are unable to circulate out of the basin. A strong pycnocline prevents oxygen from reaching depths below about 100 meters.

Figure 9.40. Thermohaline density stratification cuts off oxygen supply to deep water in the Black Sea, causing anoxic conditions below ~100 meters. Normal seawater exists above a halocline in the basin.

9.20: Ocean Acidification

Ocean Acidification

Ocean acidification is the reduction in the pH of the ocean over an extended period, typically taking decades or longer. The primarily cause is the uptake of carbon dioxide from the atmosphere into seawater, but can also be caused by other chemical additions or subtractions from the ocean. Examples of ocean acidification are recorded in the geologic record associated with major periods of geologic eruptions and massive extraterrestrial impacts (such as the event that wiped out the dinosaurs along with many groups of marine organisms with shells about 66 million years ago).

Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity. In the last 250 years, the concentration of CO_2 in the atmosphere has increased from 280 parts per million to over 394 parts per million. Most of this is due to the burning of fossil fuels (coal, gas, and oil) and also by CO_2 and other acid-forming compounds released by land use changes (such as burning off forests to be replaced by agriculture). Ocean acidification has potentially devastating ramifications for all forms of ocean life, from microscopic plankton to the largest animals at the top of the food chain. See **Environmental consequences of ocean acidification** (United Nations).

Ocean acidification, increased temperatures, and changing oxygen level are all related, all of which can have catastrophic impacts of marine ecosystems (example in Figure 9.41).

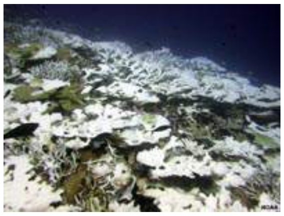


Figure 9.41. Bleaching of coral results death of symbiotic algae living within the corals. This also kills the coral, and is resulting in the collapse of local ecosystems. Elevated water temperatures and acidification are contributing factors.

9.21: What is a Garbage Patch?

What is a Garbage Patch?

A **garbage patch** is a popular name for concentrations of marine debris (mostly small pieces of floating plastic) that accumulate across the more stagnant central parts of the large gyres in the ocean basins. The central regions of ocean basins are areas of convergence and downwelling, so trash from sources on land and sea are carried long distances by currents, much of it ending up in a convergence zone garbage patch. The largest garbage patch is in the north Pacific Ocean (Figure 9.42). Garbage is generally quite hazardous to sea life.

Figure 9.42. Garbage patches in the Pacific Ocean basin.

(See NOAA's **Great Pacific Garbage Patch** website.)

9.22: Quiz Questions - Chapter 9 - Ocean Circulation

1. What **primarily** drives the surface ocean currents?
a. density differences between water bodies
b. rotation of the Earth on its axis
c. Coriolis forces
d. regional winds patterns

2. In ocean basins, the Coriolis effect helps creates large, circular ocean currents called:
a. gyres.
b. cyclones.
c. typhoons.
d. anticyclones.

3. What drives deep ocean currents?
a. Equatorial waters are more dense, causing seawater to sink into deep ocean basins.
b. Formation of sea ice, increases salinity and the density of seawater, which then sinks into deep ocean basins.
c. Equatorial waters are less dense and warmer, displacing cold water in deep ocean basins.
d. The oceans are stratified by temperature, so surface waters do not sink into deep ocean basins.

4. What consequence does the Coriolis effect have on ocean water currents that are changing latitude?
a. Moving water is deflected to the left in the Northern Hemisphere and to the right in the Southern Hemisphere.
b. Moving water is deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere.
c. Moving water is deflected to the right in both hemispheres.
d. Moving water is deflected to the left in both hemispheres.

5. Surface currents involve large masses of water moving horizontally on the surface. Which of the choices below are NOT true?
a. Wind produces both waves and currents.
b. Surface currents occur within the mixing zone.
c. Most ocean current waters move below the pycnocline (the layer of rapidly changing density).
d. Effects of surface currents is to redistribute heat from equatorial to polar regions.

6. Because of the phenomena called Ekman Transport (and Ekman Spiral), which is true about wind and water movement in the Northern Hemisphere?
a. Ocean currents always move in the same direction as the wind is blowing.
b. Ocean currents are deflected 90° to the right.
c. Ocean currents are deflected 90° to the left.
d. Ocean currents move in the opposite direction that the wind is blowing.

7. The current that flows along the East Coast of North America until it is deflected to the right by westerly winds is called the:
a. Gulf Stream.
b. North Atlantic Drift.
c. North Equatorial Current.
d. Florida Current.

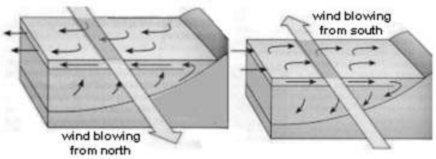
8. Only one ocean current flows unimpeded (without obstruction or barriers) around Earth. It is named the:
a. Gulf Stream Current.

b. California Current.
c. Antarctic Circumpolar Current.
d. Aghulas Current.

9. The large central area of the North Atlantic that has no well-defined currents, and has one of the large, floating ***garbage patches*** of the modern world. This part of the ocean is known as the:
a. Red Sea.
b. Dead Sea.
c. Sargasso Sea.
d. North Sea.

10. Where does most deep ocean upwelling usually occur?
a. In the middle of the oceans.
b. Near continents.
c. Near the equator where diverging currents occur.
d. Near the poles where converging currents occur.

11. Under what conditions does coastal upwelling commonly occur?
a. Only where biotic productivity is high enough to sustain it.
b. Only on the eastern coasts of continents.
c. Where winds blow toward shore or Ekman flow carries surface water toward shore.
d. Where winds blow away from shore or Ekman flow carries surface water away from shore.



12. The Coriolis Effect (Ekman Transport) can affect near-shore currents as well as those in the deep ocean. From these graphics, we can see or infer each of the following EXCEPT:
a. winds from the south will bring cold, nutrient-rich waters to the surface.
b. surface currents are deflected to the right of the direction the wind blows.
c. winds from the north create surface currents directed away from the shore.
d. erosion of the shoreline is likely greatest when winds blow from the south because of onshore flow of surface currents and wave action.

13. Based on historical data, how does **El Niño** conditions generally impact Southern California?
a. Ocean water temperatures are higher (impacting sea life), and there is typically increased rainfall in the rainy season.
b. Ocean water temperatures are lower (impacting sea life), and there is typically increased rainfall in the rainy season.
c. Ocean water temperatures are higher (impacting sea life), and there is typically less rainfall in the rainy season.
d. Ocean water temperatures are lower (impacting sea life), and there is typically less rainfall in the rainy season.

14. Why is the Black Sea experiencing **anoxia**?
a. The Bosphorus Straight prevents fresh ocean water from entering the Black Sea.
b. There is no mixing zone in the Black Sea.
c. Density stratification of heavier high saline waters prevents oxygen from reaching the seabed.
d. There is no marine life in the Black Sea.

15. Discussed in oceanographic terms, what is a **garbage patch**?
a. A place where lots of people hang out and garbage is dumped on the beach.
b. Locations in the center of ocean gyres where floating garbage (mostly floating plastic items) accumulates.
c. Places where seagulls flock to feed on garbage.
d. Locations where ocean currents carry trash to the seafloor.

CHAPTER OVERVIEW

10: Waves

10.1: Waves

Waves

This chapter focuses on the phenomena associated waves on bodies of water (oceans, lakes, etc.)
In oceanography, waves are:

• Short-term changes in sea level.
• A wave is energy moving through water.

Waves are generated by a **disturbing force** - something that transmits energy into a fluid medium (such as wind blowing on water). A pebble hitting a puddle generates a splash that creates ripples (tiny waves) that propagate away from the source (Figure 10.2). The ripples grow smaller as they move away from the splash (source) until they diffuse away with increasing distance, or when it encounters the edge of the puddle.

Figure 10.1. A wave crashing onshore releases energy.

Wind is the disturbing force for waves in the ocean and large bodies of water. Waves are also generated by earthquakes, landslides, and volcanic eruptions (producing **tsunamis**), and **tides** are produced by gravitational interactions between the Earth, Moon and Sun.

Figure 10.2. A splash is an example of a **disturbing force** creating waves. The ripples radiate away from the splash site, dispersing the energy transmitted to the surface of the water.

Types of waves

Wind Waves	**Tsunamis**	**Gravity Tides**
• Height = range from small ripples up to 60 feet (sometimes higher) • Speed = 10 – 75 mph • Periods = 5 – 25 sec.	• Height = open ocean less than 2 feet; -- onshore up to 300 feet • Speed = jetliner speeds 400-500 mph • Wavelength = 100's of kilometers • Periods = minutes	Height = up to 50 feet plus Period 12 ½ to 25 hours (discussed in Chapter 10)

See: BIGGEST WAVE in the World surfed 100ft at Carlos Burle Portugal (YouTube video)

Terms Used To Describe Waves

- **Crest** - the highest part of a passing linear wave
- **Trough** - the lowest part of a passing linear wave

- **Wavelength** (L)	= Distance between waves
- **Period** (T)	= Time between passing waves
- **Height** (h)	= Height from crest to trough (same meaning as ***amplitude***)
- **Water depth** (d)	= Average water depth - determines wave behavior

Characteristics of Waves

Ocean waves are created by wind blowing over water. The distance between two **wave crests** or two **wave troughs** is called the **wavelength**. Wave **height** is the vertical distance between the highest (crest) and lowest (trough) parts of a wave. (Figure 10.3). Wave **period** is the time interval between passing wave crests (completing one cycle) and are measured as wave crests pass a stationary point (such as waves passing a buoy or pole on a pier)(Figure 10.4).

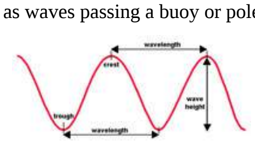


Figure 10.3. **Wavelength** and **wave height** of wave cycles.

Figure 10.4. Waves approaching a shoreline arrive at cyclic intervals called a **period**.

10.2: Wave Speed and Energy and Wave Base

Wave Speed and Wave Energy

Wave speed is a function of wavelength and wave period, and is related to the wind velocity where the waves form.

Wave speed (c) is the distance the wave travels divided by the time it takes to travel that distance. Wave speed is determined by dividing the **wavelength (L)** by the **wave period (T)**. [c = L/T]. Wave period is the average of how many seconds pass between a series of wave crests moving past a stationary object in the water, such as a post on a pier or a buoy.

What is important is the combination of the wave height and wave period. **Wave period** is directly related to the speed the wave is traveling. The longer the period, the faster the wave, and the more energy in contains.
The greater the period the faster the wave moves (Figure 10.5). Also, the greater the period, typically the higher the wave breaks as it approaches the shore.

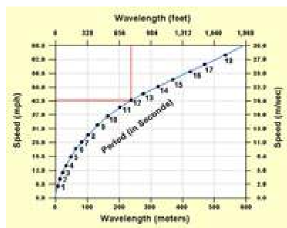


Figure 10.5. Comparison of **wavelength** to **wave speed** and wave **period**.

Wave Base

Wave base is the depth of influence of a passing water wave—it is about half the wavelength of passing water waves (Figure 10.16). At depths greater than half the wavelength wave motion dies out—the water motion is less than 4% of its value at the water surface and is generally insignificant.

10.3: Wave Orbits and Orbital Depth

Wave Orbits and Orbital Depth

Passing waves create a circular current in the water. This is revealed by the orbit-like motion of particles in the water. The orbital motion of a wave is greatest at the surface and diminishes with depth. **Orbital depth** is the depth to which the orbital motion of the wave energy can be felt. **Orbital depth is equal to half of the wavelength**. At the sea surface, **orbital diameter** is equal to wave height. As depth increases, less wave energy can be felt. The orbital depth is the depth where zero wave energy remains. For example, if a wave at the surface has a height of 4 meters and a wavelength of 48 m, then the depth where no motion from the wave exists is 48/2 or 24 meters.

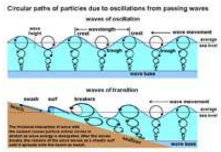


Figure 10.6. Orbital oscillations in deep and shallow waves.

Deep-Water Waves and Shallow-Water Waves

The depth of the water determines the character of wave behaviors.

- **Deep-water waves** are waves passing through water **greater than half of its wavelength**. Deep-water waves are **waves of oscillation**. A wave of oscillation is a wave in the open ocean where movement in the water below a passing wave is in a vertical circular motion.
- **Shallow-water waves** are waves that are interacting with the seabed in depths **less than half it wavelength.** Shallow-water waves are called **waves of transition** because they change character as the move shoreward and dissipate their energy interacting with the seabed onto the shore.

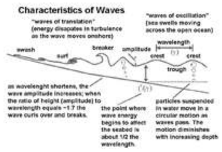


Figure 10.7. Waves of oscillation, breakers, and waves of transition moving onto the beach.

Type of wave	Define	Orbit	Speed
Deep water wave (wave of oscillation)	d > L/2	Circle	L/T
Shallow water wave (wave of transition)	d < L/20	Elliptical	√gd
Where... • L/2 to L/20 is a **transitional wave** • Speed of a shallow water wave is dependent on water depth • G = gravitational constant 9.8 m/s^2			

Wind waves change as they approach the shore:

- As a wave approaches shallow water its begins to transform when it's orbital depth comes in contact with the seabed (when d < L/2).
- The friction caused by waves interacting with the seabed causes waves to slow down as the move onshore.
- The friction of the seabed begins to slow the bottom of the wave; whereas the top of the wave does not slow as quickly..
- Circular motion within the wave becomes interrupted and becomes elliptical.
- As waves approach the beach, their wavelengths (L) and velocity decrease. However the period (T) stays the same. The shortening of the wavelength results in an increase in wave height as it moves into shallow water.
- A wave **breaks** when the water depth (d) is about the same as the wave height (h). Where a wave curls over on itself is called a **breaker**.
- **Breakers** then turn into a turbulent front called **surf** that moves onto the beach.
- When the dying wave runs up on the beach and then retreats it is called **swash**.

Figure 10.8. **Waves of transition** build up, **break**, and become **surf** before ending on the beach as **swash**.

Figure 10.9. A breaking wave (with surfer in Puerto Rico)

10.4: Breakers and Wave Trains

Breakers

When a wave approaches shore, the base of the wave encounters the bottom—the front of the wave slows down and the back overtakes the front. This forces the water into a peak where the top (crest) curves forward. This peak will eventually fall forward in a tumbling rush of foam and water called a **breaker**. Waves break on or near shore, they also crash over reefs or offshore sandbars if water depths are shallow.

Wave steepness is the ratio of height to wavelength. When **wave steepness exceeds a ratio of 1:7**, **breakers** form.

Example: If a moving wave has a height of one foot and a length from crest to crest of 8 feet, then the ratio is 1:8 and this wave is not going to break. However, if the height is 1 foot and the length decreases to 6 feet, then the ratio is 1:6, then the wave has now become steep enough that the crest topples over and the wave breaks.

Slope of the seabed/beach creates different kinds of breakers

There are three types of breaking waves: **spilling breakers**, **plunging breakers**, and **surging breakers**. Breakers may be one or a combination of these types.

Gentle slopes produce **spilling breakers**. Spilling breakers begin far from shore and take a relatively longer time to reach the beach. The breaking crest slides down the front of the wave in a flurry of foam as the wave moves shoreward. Spilling breakers give surfers a long slow ride.

Moderate slopes produce **plunging breakers**. Plunging breakers build up rapidly into a steeply leaning crest. The crest curls further forward of the rest of the wave before crashing down in the surf zone. Plunging breakers are dangerous because the crash into shallow water.

Steep slopes produce **surging breakers**. Surging breakers occur where waves slam directly on the shoreline. With no gentle slope the waves surge onto a steep beach, producing no tumbling surf. Surging breakers also create huge splashes on a rocky cliff shoreline.

Figure 10.10. Spilling breakers at Torrey Pines Beach, CA.

Figure 10.11. Plunging breaker (threatens a boat).

Figure 10.12. Surging breaker on a narrow Hawaii beach.

Figure 10.13. Surging wave crashing on seacliffs

Wave Trains

A **wave train** is a group of waves of equal or similar wavelengths traveling in the same direction. Individual waves move from the back to the front of a wave train, gradually building up, peaking, then declining as it moves to the front of the wave train (Figure 10.14). The result is that individual waves within a wave train are moving about twice as the wave train itself. Surfers watching advancing waves may notice that the first waves to arrive decline in intensity as they arrive as the following waves build higher. After the highest crest passes, the trailing waves decline in intensity as the wave train passes.

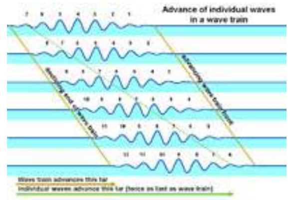


Figure 10.14. Waves moving through a wave train.

10.5: Origin of Wind Waves

Origin of Wind Waves

Wind waves form from wind blowing on the ocean surface. The key factors influencing wave intensity include **fetch**, wind **duration**, wind **strength**, and **proximity** to wind source area. Wind energy is gradually transferred to the waves forming on a body of water, causing waves to absorb energy and grow in amplitude and period over distance and time (Figure 10.15). The transfer of wind energy to wave energy is not very efficient (only about 2% of the energy is actually transferred) but it is the size of the area that the wind is impacting, as well as how strong the wind is blowing that matters.

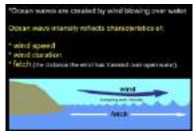


Figure 10.15. **Waves energy** depends on **wind speed**, **wind duration**, and **fetch**.

Wind-Wave Input Factors:
• **Fetch** is the length (distance) wind blows over open water. This is the uninterrupted distance over which the wind blows without significant change in direction.
• **Duration** is how long the wind blows. Strong wind that does not blow for a long period will not generate large waves.
• **Wind strength**: The stronger the wind, the bigger the waves. The wind must be moving faster than the wave crests for energy to be transferred.
• **Proximity**: Separation of wave trains by period. Long-period waves move faster than shorter-period waves and will separate and advance before wave trains with shorter periods.

Wind-Wave Output Factors: (Waves!)
• **Wave height** increases.
• **Wavelength** increases.
• **Wave period** increases.
• Direction - wave travel in the direction that the wind blows.

Wave Equation: Large **Fetch** + Long **Duration** + Strong Winds (**wind speed**) = Large, Long Period Waves

Fetch is important because the interrelationship between wind speed and duration, both functions of fetch, is predictive of wave conditions.

Figure 10.16. Sea and Swells illustrated. A storm generates winds that impact a region over open water. The area impacted by the wind is called a **sea**. The waves generated by the storm will move out and away from sea are called **swell**.

10.6: Sea and Swell

Sea and Swell

• **Sea**: Area where wind waves are generated, mixed period and wavelengths. Seas are typically a chaotic jumble of waves of many different sizes (wave heights, wavelengths, and periods) (Figure 10.16).
• **Fully Developed Sea**: Max size waves can grow given a certain fetch, wind speed and duration.

Ocean swell refers to series of ocean surface waves that were not generated by the local wind. **Swell** refers to an increase in wave height due to a distant storm. Ocean swell waves often have a long wavelength. Swell can develop on lakes and bays, but their size varies with the size of the water body and wave intensity. As waves move out and away from the storm center, they sort themselves out into groups of similar speeds and wavelengths. This produces the smooth undulating ocean surface called a swell. Swells may travel thousands of kilometers from the storm center until they strike shore. Swells are generated by storms over the open ocean, but many ocean swells originate in the oceans around Antarctica where there is high winds with nearly infinite duration and fetch (Figure 10.17).

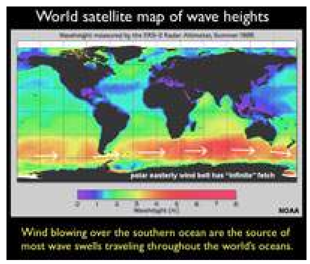


Figure 10.17. Most ocean swells originate in the southern oceans where strong winds combine with unlimited fetch.

10.7: How Waves Form

How Waves Form

When the wind starts to blow, the surface of a water body will go through a progression as waves form and intensify. When the wind starts to blow, the ocean surface will change from **calm** (mirror-like) conditions to form **capillary waves** (**ripples**), **chop**, **wavelets**, to **waves** (each with increasing wavelengths, wave heights, and wave periods). Smaller wave features can form on existing larger wave features, adding to the complexity of the water's surface.

Ripples (Capillary Waves)

Capillary waves are very small waves with wavelengths less than 1.7 cm or 0.68 inches (Figure 10.18). The formation of capillary waves is influenced by both the effects of **surface tension** and **gravity**. The ruffling of the water's surface due to pressure variations of the wind on the water. This creates stress on the water and results in tiny short wavelength waves called ripples. Ripples are often called capillary waves. The motion of a ripple is governed by surface tension. They are the first waves to form when the wind blows over the surface of the water and are created by the friction of wind and the surface tension of the water. These tiny little waves increase the surface area of the sea surface and if the wind continues to blow, the size of the wave will increase in size and become a wind wave.

Figure 10.18. Capillary wave (ripples) forming next to a calm area (Lake Hodges, CA)

Chop

Chop refers to small waves causing the ocean surface to be rough. Ripples and small wavelets form and move independently of large waves moving through an area, creating rough and irregular wave patterns (Figure 10.19).

Figure 10.19. With increasing fetch, ripples merge to become wavelets in choppy surface water conditions.

10.8: Cat's Paws

Cat's Paws

A **cat's paw** is the imprint that a light breeze that ruffles small areas of a water surface. When generated by light wind in open water, a nautical name for them is cat's paw waves, since they may resemble paw prints (Figure 10.20). Light breezes which stir up such small ripples are also sometimes referred to as cat's paws. On the open ocean, much larger ocean surface waves (seas and swells) may result from coalescence of smaller wind-caused ripple-waves.

A **squall** is a sudden violent gust of wind or a localized storm. A squall line is a line of thunderstorms that can form along or ahead of a cold front. It contains heavy precipitation, hail, frequent lightning, strong straight-line winds, and possibly tornadoes and waterspouts. At sea, a squall is used to describe a relatively rapid change in weather from calm or mild weather to sudden strong winds and intense precipitation, usually associated with passing a cold front.

Figure 10.20. Wind gusts creating **cat paws** capillary ripple patterns on the lake surface.

10.9: Beaufort Wind Force Scale and Wave Interference Patterns

Beaufort Wind Force Scale (Wind Velocity, Wave Height, and Sea Conditions)

The Beaufort wind force scale relates wind speed (velocity) to observed conditions at sea (including wave height) or impact of features on land. It is a numbered scale from 0 to 12 to describe sea conditions and wave size. The Beaufort Scale was developed by Rear Admiral Sir Francis Beaufort 1774-1857, an officer in Britain's Royal Navy). Zero 0 on the Beaufort scale represents the calmest of seas (the water is so smooth that it looks like glass). A 12 on the Beaufort scale represents hurricane force waves (Figure 10.21).

Beaufort scale

Figure 10.21. **Beaufort Wind Force Scale** for sea conditions (and on land).

Wave Interference Patterns

Wave interference occurs where waves from different sources collide **(Figures 10-22** and **10-23**).

- **Constructive wave interference** occurs where waves come together in phase or crest meets another crest (or trough meets another trough).
- **Destructive wave interference**: Waves come together out of phase or crest meets a trough.

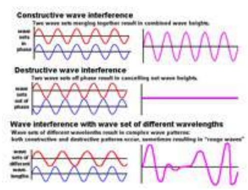


Figure 10.22. Examples of constructive and destructive wave interference patterns.

Figure 10.23. Interference patterns created by winds gusts blowing from different directions.

10.10: Rogue Waves

Rogue Waves

Rogue waves are large, unpredictable, and dangerous. Rogue waves (also called 'extreme storm waves') are those waves which are greater than twice the size of surrounding waves. They often come unexpectedly from directions other than prevailing wind and waves. Many reports of extreme storm waves describe them sudden "walls of water." They are often steep-sided and associated with unusually deep troughs. Some rogue waves are a result of constructive interference of swells traveling at different speeds and directions. As these swells pass through one another, their crests, troughs, and wavelengths sometimes coincide and reinforce each other. This process produces large, towering waves that quickly form and disappear. If the swells are traveling roughly in the same direction, these massive waves may last for several minutes before subsiding. Rogue waves can also form when storm swells move against a strong current, resulting in a shortening of the wavelength and increasing it's amplitude. Large rouge wave of this kind are frequently experienced in the Gulf Stream and Agulhas currents (Figure 10.24).

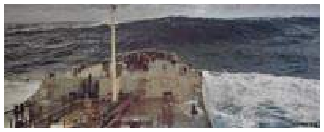


Figure 10.24. This 60 foot rouge wave threatened a ship in the Gulf Stream near Charleston, South Carolina. Rogue wave have sunk ships, destroyed drilling rigs, and are responsible for many deaths and injuries along coastlines.

10.11: Behavior of Waves

Behavior of Waves

Waves can bend when they encounter obstacles or changes on the sea floor.

- **Refraction** involves bending. Wave refraction starts when wave base starts to interact with the sea bed and slow the waves down, causing them to bend toward shore. Refraction occurs when wave swells approach the beach at an angle (Figure 10.25).
- **Diffraction** involves spreading (or dispersion) of wave energy. **Wave diffraction** refers to various phenomena which occur when a wave encounters an obstacle or change in geometry of the seabed. For example waves are diffracted when they when they pass an island, or when they pass a point or other structure, such as a jetty at the mouth of a harbor (Figure 10.26).
- **Reflection** (bouncing) involves crashing into a solid surface (such as a seawall or cliff) and reflecting back to sea. Reflection can result in standing waves—waves that move back and forth (oscillate) in a vertical position waves strike an obstruction head-on and then are reflected backwards in the direction they came from.

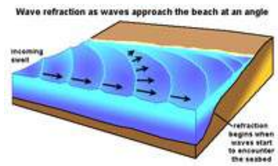


Figure 10.25. Wave refraction as waves approach the beach at an angle.

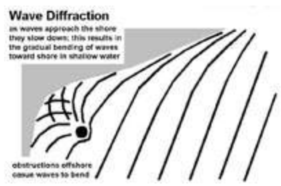


Figure 10.26. Wave diffraction around offshore obstruction on waves nearshore

10.12: Surfer's Guide to Wave Forecasting for San Diego County

Surfer's Guide to Wave Forecasting for San Diego County

San Diego County Swell Window

• The compass bearing window that we can receive swell from is between 180° and 340° **(Figure 10.27**). Waves are weak on the "edges" of this window. The best part of our window is really between 200° and 300° degrees because the waves simply have to bend too much to be received on our coastline if they are outside of that range.

• North San Diego County is better for S + SW Swells
• South San Diego County is better for N + NW Swells
• Everyone loves a West Swell!

Figure 10.27. The **swell window** for San Diego County is roughly between 180° and 340° (with North being 360°).

Getting Swell Information Data Real-Time

Casual surfers in San Diego County can get forecasts of waves from a number of surfing and weather websites. However, professional surfers (and swell wave forecasters for navigation and other purposes) use real-time buoy information available from the **National Data Buoy Center (NOAA)** network to evaluate swell period and height in different parts of the Pacific Ocean basin and around the world. Data from this system is incorporated into many government weather and commercial shipping navigation websites and several surfing organization websites.

For example: check this **maximum wave energy** animation: **http://www.surf-forecast.com**/

Surfers check at distant buoy locations to look for increases in wave period, but not so much in wave height. (Why?)

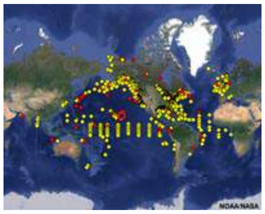


Figure 10.28. Location of buoys associated with the **National Data Buoy Center** (NOAA)

Summer Swells Affecting San Diego County

• Swell generated between Antarctica and New Zealand dominates the world oceans much of the year because it is a region with large storms (largest on Earth), and there is constant wind (infinite duration) and unhindered passage over open waters (infinite fetch)(Figure 10.29).
• In the northern Pacific Ocean, storm track is always west to east.
• Initial angle is 210 degrees (west-southwest), then moves towards 180 degrees (south) and out of our swell window.
• The largest summer surf is in northern San Diego County comes from the south.

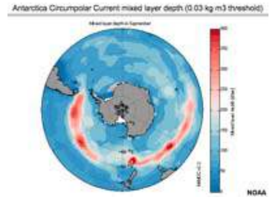


Figure 10.29. The Antarctic Circumpolar wind belt is the source of most swells. Why?

Winter Swells Affecting San Diego County

• Winter swells are largest swells on average in San Diego County
• San Diego's winter swell is mostly generated in the Gulf of Alaska, most begin off of the Kuril Islands
• Storm track is generally from west to east
• Early season swell is usually more northerly (N or NNW direction or about 320 to 340 degrees).
• Later season storms drop farther south and give us a more westerly swell direction from about 280 to 300 degrees. We also get more rain from these storms.
• Partial swell blockage occurs in the Southern California Bight from wave shadows created from the Channel Islands.
• During the winter the largest surf is in southern San Diego County and northern Baja. We also can get colder water and upwelling conditions.

Locally Generated Swell In San Diego Region

We have a number of locally generated swells that come from smaller storms in the Pacific Northwest.
• These storms produce surf that has a shorter period (between 6 and 10 seconds) because the storms are not very large.
• The swell angle is very steep from the north-northwest around 320 to 340 degrees.
• We often get upwelling associated with these storms as well.

Hurricane Swell In San Diego Region

During the late summer and early fall we can get swell from hurricanes that form off of the coast of mainland Mexico.
• The wave periods generated from these storms is usually between 10 and 14 seconds.
• The key identifying waves from these storms is the angle. The swell angle begins from the S or SSE between 160 and 180 degrees. The angle increases with time as the storm moves up the coast and either onshore or out to sea towards Hawaii.

Figure 10.30. A southwest swell coming in at Beacons Beach, Encinitas, San Diego County, California.

10.13: Tsunamis

Tsunamis

A tsunami is a very long and/or high sea wave or coastal serge of water caused by an earthquake or other disturbance. **Tsunamis get their name from Japan (where they are fairly common): "Tsu"[*harbor*], "nami" [wave].**

Tsunamis are caused by displacement of the earth's crust under an ocean or body of water of any size. They can also be generated by earthquakes, volcanic explosions, underwater landslides, even asteroid impacts. When the solid earth moves, the water above it also moves with it (Figures 10-32 and **10-33**). Tsunamis are the result of both the initial shock waves and the following motion of the water readjusting to a stable pool (sea level). Tsunamis can travel great distances throughout the world's ocean. Their energy is dissipated when they approach shorelines where they come onshore as a great surge of water, with or without massive waves crashing onshore. Although most tsunamis are small (barely detectable), some modern tsunamis have reached inland elevations many hundreds of feet above sea level.

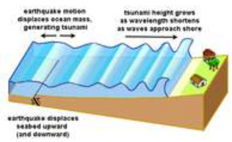


Figure 10.32. How a tsunami is generated by an earthquake.

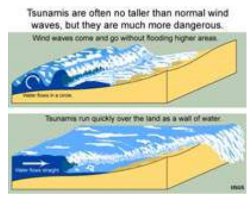


Figure 10.33. Tsunamis move onshore more as a surge than just a wave.

Tsunami Characteristics:
• Tsunamis are usually less than 2 feet in the open ocean.
• In deep ocean, tsunami wavelengths are long, commonly 100’s of miles.
• Tsunamis always behave like shallow water waves (d < L/20) because no ocean deep enough!
• Undetectable by ships in open ocean because wavelengths are so long (slow rise and fall as wave passes).
• Open ocean tsunami velocity is 400 – 500 mph. So about 4 – 5 hours from Alaska to San Diego (or Hawaii).
• Wave stacks up on continental shelf, about ½ of the time a trough arrives first (sea recedes from shore).
• Waves 30 – 100 ft are common – locally run-up can be higher.
• Highest is thought to be +300 ft., 66 million years ago from asteroid collision in the Gulf of Mexico.

10.14: Impact of Tsunamis in Modern World History

Impact of Tsunamis in Modern World History

Major Tsunami Events	Cause and Effects	Damages
Sumatra, Indonesia, 26 December 2004	The 9.1 magnitude earthquake offshore of Sumatra. The fault zone that caused the tsunami was roughly 800 miles (1300 km) long, vertically displacing the sea floor by several meters.	Tsunami was as tall as 50 m, reaching about 3 miles (5 km) inland. Many l 230,000 people killed.
North Pacific Coast, Japan, 11 March 2011	Tsunami was spawned by an 9.0 magnitude earthquake. Many coastal communities were destroyed and the Fukushima Daiichi nuclear power plant was damaged, releasing radiation	10 m-high waves swept over the east coast of Japan, killing more than 18, **disaster in history**: ~$235 billion.
Lisbon, Portugal, 1 November 1755	A magnitude 8.5 earthquake produced a series of three huge waves that struck various towns along the west coast of Portugal and Spain. Tsunami was up to 30 m high in some places	The earthquake and tsunami killed an estimated 60,000 people in the Portu
Krakatoa, Indonesia, 27 August 1883	This tsunami event was caused by explosive eruptions of the Krakatoa caldera volcano in the Sunda Strait between the islands of Java and Sumatra. Multiple waves as high as 37 m.	The event killed about 40,000 people in total; however, about 2,000 deaths
Enshunada Sea, Japan, 20 September 1498	An earthquake estimated about magnitude 8.3, caused tsunami waves along the coasts of Izu, Kii, Mikawa, Sagami, and Surugu (Japan).	Coastal communities were washed away; estimated 31,000 people were ki
Nankaido, Japan, 28 October 1707	A magnitude 8.4 earthquake caused tsunamis as high as 25 m that swept onto the Pacific coasts of Kyushyu, Shikoku and Honshin.	About 30,000 buildings were damaged and about 30,000 people were kille
Sanriku, Japan, 15 June 1896	An estimated magnitude 7.6 earthquake off the coast of Sanriku, Japan generated a tsunami reported to have reached a height of 38.2 m.	11,000 homes destroyed and 22,000 people killed in Japan; 4,000 also kill
Northern Chile, 13 August 1868	Earthquakes estimated at magnitude 8.5, off the coast of Africa, Peru (now Chile). Tsunamis affected entire Pacific Rim; waves reported up to 21 m high over two and three days.	Estimated 25,000 deaths and an $300 million in damages caused by the tsu Peru-Chile coasts.
Ryuku Islands, Japan, 24 April 1771	A magnitude 7.4 earthquake produced a tsunami that damaged coastal communities on Ishigaki and Miyako Islands and others in the region. Tsunamis were 11 to 15 m high.	Tsunami destroyed 3,137 homes and about12,000 people were killed.
Ise Bay, Japan, 18 January 1586	An earthquake that caused a tsunami estimated to be about magnitude 8.2. The tsunamis rose to a height of 6 m.	Earthquake and following fired destroyed most of a city. 8000 people were

Simple tsunami origin animation (NOAA) - How tsunamis form from an earthquake.
Three Chile Tsunamis animation (PTWC) - Breakout animations of tsunamis of different intensities.

Figure 10.34. Drawback from tsunami in Sri Lanka exposed about 150 meters before the tsunamis arrived from 2004 earthquake.

Figure 10.35. Tsunamis arriving on coast of Thailand, 2004

Figure 10.36. Giant whirlpool caused by the Japan, 2011 tsunamis (note the boat for scale).

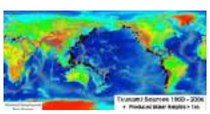


Figure 10.37. Map showing locations of tsunami-generating earthquakes

Tsunami travel time from 1960 earthquake in Chili

Figure 10.38. Map of tsunami travel times generated by magnitude 9.5 earthquake Chili, 22 May, 1960.

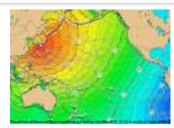


Figure 10.39. Map of tsunami travel time from magnitude 9.0 earthquake in northern Japan, 11 March 2011

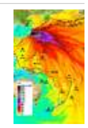


Figure 10.40. Maximum wave northern Japan, 11 March 2011

Tsunami Damage from the 2004 Sumatra tsunami

Figure 10.41. Banda Aceh, Indonesia before 2004 tsunami

Figure 10.42. Banda Aceh, Indonesia after 2004 tsunami

Only a brick mosque survived tsunami damage in Banda Aceh, 2004 tsunami

Figure 10.43. Mosque survived 2004 tsunami in Banda Aceh, Sumatra

Figure 10.44. Vegetation strip Aceh, Sumatra tsunami 2004

Examples of Tsunami Damage

Figure 10.45. The Sumatra 2004 earthquake caused damage in Sri Lanka 2,000 miles away.

Figure 10.46. Damage from the Tsunami of July 12, 1993, a magnitude 7.6 in the Sea of Japan near Hokkaido. The tsunami was 32 meters high on Okishuri, Island.

Figure 10.47. Tsunami damage in Kodiak, Alaska from the March 27,1964 earthquake (magnitude 9.2)

Figure 10.48. March 11, 2011 tsunami

Tsunami Warning System

Tsunami Dart Alert System

Figure 10.49 & 50. DART Buoy and DART tsunami warning system (left).

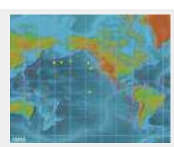


Figure 10.51. Location of tsunami warning system buoys around Pacific and Atlantic basins.

Everything you ever wanted t

Pacific Tsunami Warning C

Learn about: **Tsunami Paleog**

Tsunami videos (as of July, 2019)

Indonesia Tsunami 2004 (NOAA): Tsunami waves ***move out*** animation of Indian Ocean

Japanese 2011 Tsunami caught on CCTV: YouTube video

Incredible TSUNAMI in Kamaishi City - Complete Edition (Japan)
https://www.youtube.com/watch?v=uRyM1ujSwrM

Thailand Tsunamis 2004, raw footage: https://www.youtube.com/watch?v=a7WyJ4S1Pdc

Helicopter view of Japan 2011 tsunamis: YouTube video

Scale of the TSUNAMI Power - Educating Document: https://www.youtube.com/watch?v=_eh5aq_GeUY

Figure 10.52. Surfing a tsunami wave? (Not recommended!)

10.15: Quiz Questions - Chapter 10 - Waves

1. The time it takes for one full wave to pass a fixed position, such as a pole on a pier, is called:
a. wave period.
b. wave height.
c. wave fetch.
d. wavelength.

2. The vertical distance between the trough of a wave and the crest of a wave is called:
a. wave height.
b. wave period.
c. wave velocity.
d. wavelength.

3. As waves move along the surface of the water, what do water particles do?
a. They move back and forth in a direction parallel to wave motion.
b. They move back and forth in a direction perpendicular to wave motion.
c. They move along the crests of waves and can travel thousands of miles.
d. They oscillate in circles parallel to wave motion and the circle diameters decrease with depth.

4. In deep water in the open ocean, how deep in water can surface waves cause particle motion?
a. Half the wave height
b. Exactly twice the wave height
c. Twice the wavelength
d. About half the wavelength

5. What determines wave speed in the open oceans?
a. Wave period
b. Wavelength
c. Wind velocity
d. All of the above.

6. What is **surf**?
a. Surf is fully-developed waves generated by strong winds.
b. Surf is waves moving out of the generating sea area.
c. Surf is where waves steepen and build up near shore.
d. Surf is the waves moving into shallow water as turbulent front that moves onto the beach.

7. What happens to ocean waves when they reach shallow water?
a. They become waves of oscillation.
b. They slow down and become waves of transition and waves of translation.
c. They speed up.
d. They veer to the right.

8. Wave base is:
a. the depth of influence of a passing water wave.
b. about 1/2 of the wavelength of passing water waves.
c. the depth at which the wave motion dies out.
d. all of the above.

9. Where do waves of transition generally start to form?
a. In conditions where the fetch is 50% of the wind speed.
b. In conditions where there is a decrease in water depth to about 1/2 of wavelength between passing wave crests.
c. In deep bays.
d. In the deep water of the open ocean.

10. Waves typically break when:
a. the base of the wave starts to impact the sea floor.
b. when a wave reflected from the beach passes through incoming waves.
c. the slope of the wave reaches a ratio of about 7:1 (7 long to 1 high).
d. all of the above.

11. The region where storm winds blowing over the ocean surface generating waves is called a:
a. swell.
b. sea.
c. cyclone.
d. tsunami.

12. Groups of waves that move out of area where waves are generated by strong storm winds and travel long distances across ocean basins are called:
a. seas.
b. cyclones.
c. swells.
d. tsunamis.

13. Waves that have the longest wavelengths and most wave energy form from situations where there is:
a. long fetch exposure to the wind.
b. long duration of exposure to the wind.
c. exposure to strong winds (high wind speed).
d. all of the above.

14. The bending of waves so that they are more parallel to the shore is called:
a. diffraction.
b. reflection.
c. refraction.
d. translation.

15. Which of the following waves generally have the longest wavelength?
a. capillary wave
b. swell
c. chop
d. tsunamis

CHAPTER OVERVIEW

11: Tides

11.1: Tides

Tides are one of the most reliable and predictable phenomena in the world.

What are tides and how they are created?

Tides are cause by the gravitation pull of extraterrestrial objects, the Sun and Moon being the most significant tidal forces on planet Earth. Tidal forces can affect crustal rocks and especially water (oceans and great lakes). Water will flow in the direction of gravitational pull. However, because the earth is rotating, this gravitational pull is constantly changing causing daily tide cycles.

Tides are **very long-period waves** that move through the oceans in response to gravitational forces exerted on the oceans by the Moon and Sun. Both the solid Earth and the oceans are impacted by **tidal forces**, but oceans can move because they are fluid. Tidal forces create **bulges** on the ocean surface (Figure 11.1). The **largest tidal effect** is from the **Moon** due to its proximity to Earth; a **smaller tidal effect** is from the **Sun**. The sun's gravitational pull on the Earth is **about half (~44%)** of the moon's gravitational pull.

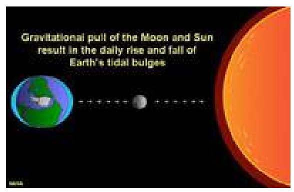


Figure 11.1. Tidal bulge from the gravitational attraction of Earth, Moon, and Sun

Tides are consistently predictable because the rotation of the Earth is a consistent **24 hours** (a **solar day**). Tides are influenced by a **lunar day** (a consistent **24 hours 50 minutes**). Tides advance 50 minutes each day. This is because the Moon rises **50 minutes later each day**.

Tides arise in the oceans and move toward the coastlines where they appear as the daily rise and fall of the ocean surface. Large lakes can have tides, but they are small because of the comparatively small volume of water.

A **tidal range** is the difference in height between the **highest high water (HHW)** and the **lowest low water (LLW)** (Figure 11.2). Tidal ranges vary from region to region, influenced by the geography of coastlines.

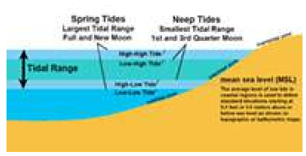


Figure 11.2. Tidal range is the distance between average highest and lowest tides.

A **tidal current** is a horizontal flow of water that accompanies the rising and falling of the tides. Tidal currents can be strong on shallow continental shelves and coastlines with restricting geography (such as in bays, inlets, narrow straits, lagoons, and estuaries). Tidal currents are relatively weak in the open ocean.

Tidal Currents

An incoming tide along a coast is called a **flood current**; an outgoing tide is called an **ebb current**. The strongest currents usually occur near the time of the highest and lowest tides. The tidal currents are typically weakest midway between the flood and ebb currents and are called **slack tides**.

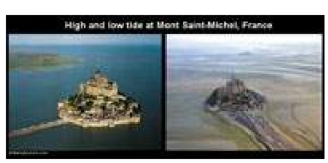


Figure 11.3. Tides and tidal flats at Mont Saint-Michel, France, a region with a high tidal range.

Daily tides move vast quantities of water along coastlines, filling in and emptying coastal bays and estuaries, flushing out stagnant waters, and moving nutrients in and out. The ebb and flood tides cause rivers in delta regions to reverse their flow directions and bring in seawater to mix with freshwater (creating brackish waters).

The speed of tidal currents can reach up to several miles per hour.

11.2: Phases of the Moon and Tides

Tides are periodic short term changes in the elevation of the ocean surface caused to the gravitational attraction of the Moon and Sun, AND the rotational motion (**inertia**) of the of the Earth. The gravitational pull of the Moon is slightly stronger than the Sun. However, sometimes the gravitational forces of the Sun and Moon join together to make higher tides (Figure 11.4).

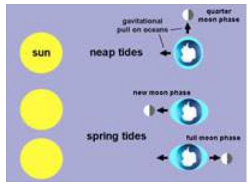


Figure 11.4. Spring and neap tides are related to the orientation of the Earth, Moon, and Sun (note polar orientation in this view).

Spring Tides and Neap Tides

- During **full moon** or **new moon phases**, the gravitational forces of the Sun and Moon are maximized, producing very large ranges of tidal highs and lows called **spring tides (Figure 11.5)**. During a full moon, the Earth and the Sun and Moon are approximately aligned, producing very large ranges of tidal highs and lows (spring tides).

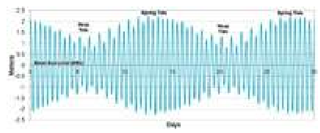


Figure 11.5. Monthly tidal cycle showing **spring tides** and **neap tides**.

- During the **quarter moon phases**, the gravitational forces of the Sun and Moon are at their minimum, producing very small ranges of tidal highs and lows (neap tides). A **neap tide** is the lowest level of high tide; a tide that occurs when the difference between high and low tide is least. Neap tide comes twice a month, in the first and third quarters of the moon. During the quarter moon phase, the gravitational forces of the Sun and Moon are at their minimum, producing very small ranges of tidal highs and lows (neap tides).

Neap and Spring Tides illustrated (NOAA animation)

11.3: The Effects of Elliptical Orbits of Earth and Moon On Tides

It take the Earth **365.242 days** for the Earth to orbit the Sun. The Moon completes one orbit around the Earth in **27.3 days** (called the **sidereal month**). However, due to the Earth's motion around the Sun it has not finished a full cycle until it reaches the point in its orbit where the Sun is in the same position (***29.53 days***) - this is the time from **one full moon to the next**.

However, both the Earth and the Moon have orbits that are slightly **elliptical** (not circular). This has an influence on the intensity of tide cycles (Figure 11.6).

- **Perigee** is when the Moon is closest to the Earth.
- **Apogee** the Moon the farthest from the Earth.
- **Perihelion** is when Earth is closest to the Sun (in early January).
- **Aphelion** Earth is farthest from the Sun it is called (in early July).

Because the Moon has a greater influence on tides, the highest tides happen at perigee when there is a full or new moon. This happens a couple times a year and are called **king tides**. King tides occur when the Earth, Moon and Sun are aligned at perigee and perihelion, resulting in the largest tidal ranges seen over the course of a year.

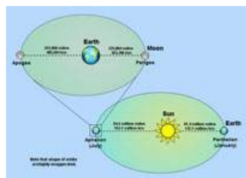


Figure 11.6. Effects of elliptical orbits.

11.4: Types of Tidal Cycles and Regional Tidal Variations

Types of Tidal Cycles

If the Earth were a perfect sphere with no continents, all parts of the planet would have two equally proportioned low and high tides every **lunar day** as the Earth rotates. However, the large continental land masses block the westward movement of the tidal bulges. This blocking of the tidal bulges results in the development of complex tidal patterns within each ocean basin. As a result, different parts of ocean basins have different types of tides (Figures 10-7 and **10-8)**.

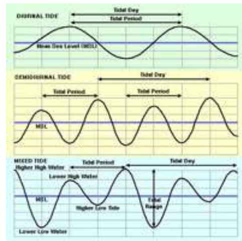


Figure 11.7. Tidal curves for diurnal, semi-diurnal, and mixed tides.

- **Diurnal Tides**—a region where there is only one high tide and one low tide each lunar day. For example, the Gulf of Mexico has diurnal tides.
- **Semidiurnal Tides**—a region that experience 2 high tides and two low tides of approximately equal size each lunar day. For example, the Atlantic Coast of North America has semidiurnal tides.
- **Mixed Semidiurnal Tides**—a region where the two high tides and two low tides differ in height. For example, West Coast of the North America (including here in San Diego) has mixed semidiurnal tides.

Regional Tidal Variations

Tidal ranges vary considerably around the world and are influenced by factors including shoreline and continental shelf geometries, latitude, size of the body of water, and other factors (Figure 11.8). For instance, the equatorial regions have very minimal tides compared with higher latitudes. Like all ocean currents, tidal currents are influenced the influence of the **Coriolis effect**. Ebb and flood currents influenced by the Coriolis effect create circular flow patterns in large bays.

Figure 11.8. Map of the world showing the regions affected by semidiurnal, diurnal, and mixed tides.

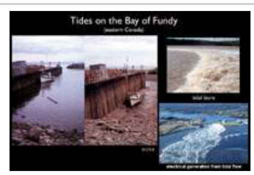


Figure 11.9. Tides at the Bay of Fundy, Maine and Canada, are the largest in the world with spring tide ranges more than 50 feet!

The **Bay of Fundy** has the **highest tidal range in the world**! Check out:
Bay of Fundy Tides, New Brunswick and Nova Scotia YouTube video
Fall and rise of the tide in the Bay of Fundy - Time Lapse YouTube video
Bay of Fundy Tide, Time-lapse, Fundy National Park YouTube video

11.5: Sea Level

What is Sea Level?

"Sea level" is generally used to refer to **mean sea level (MSL)**. A common accepted definition of mean sea-level standard is the midpoint between **a mean low and mean high tide** at a particular location.

Sea level is an average level for the surface of one or more of Earth's oceans from which heights such as elevations may be measured. However, sea level varies for place to place due to gravitational differences in the solid earth, and variations in sea water characteristics (water density) and atmospheric pressure effects. For instance, Figure 11.10 shows topography of the ocean surface one specific day, however, it is constantly changing day by day, season to season. MSL is a standardized geodetic reference point for geographic locations.

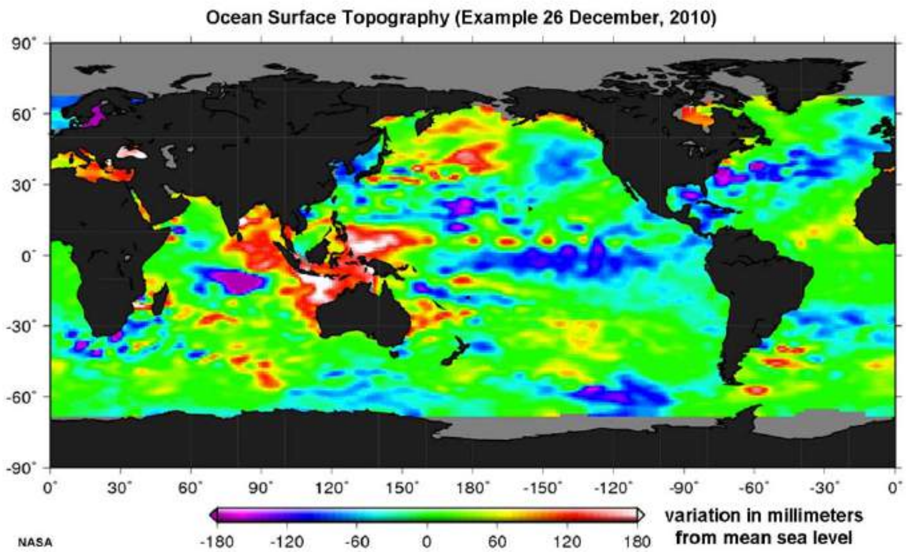


Figure 11.10. Sea level height map on a particular day (departure from mean sea level).

Mean Sea Level (MSL) is not really level...

- Sea levels are different for each ocean basin. Sea level is about 20 cm higher on the Pacific side of North America than the Atlantic due to the water being less dense (on average) than on the Pacific side. Variations in sea level are due to the prevailing weather and ocean conditions.
- Differences in MSL are also related to the gravity variation cause by different densities rocks in the lithosphere and depth of the ocean basins (Figure 11.11). For instance mid-ocean ridges (MORs) tend to be low gravity areas.

Sea level is influenced gravitational acceleration. A boat on sea level region near the North Pole in the Arctic Ocean has the highest gravitational acceleration of the planet: 9.8337 m/s^2. The lowest is on Mount Huascaran in Peru on the equator where the gravitational acceleration is only 9.7639 m/s^2 (a difference of 0.7% - which you would not feel).

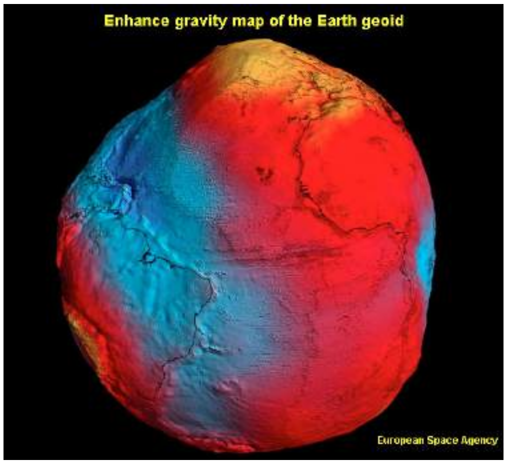


Figure 11.11. Gravity map of the Earth exaggerated: highs are red, lows are blue.

11.6: Changes of the Sea Level

Sea levels are constantly changing around the globe. Long-term trends in sea-level rise are linked to global climate change. Sea level changes are primarily due to the melting and freezing of the icecaps due to global temperature changes. Sea level change is also due to the expansion and contraction of the total water mass due to global temperature changes. Figure 11.12 illustrates the dramatic rise in sea level over the past 20,000 years—estimated at about 120 meters (400 feet)! Figure 11.13 shows how much sea level has risen since detailed global record have been kept (starting around 1900).

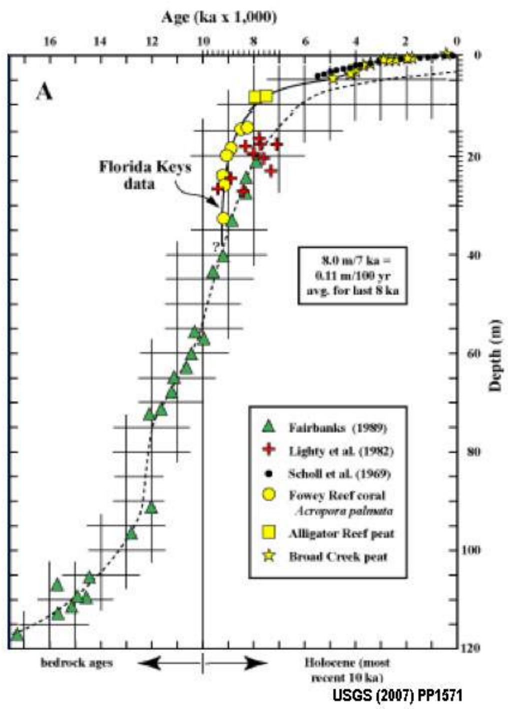


Figure 11.12. Sea level changes of the past 20,000 years (Late Pleistocene and Holocene)

Figure 11.13 show that in most places around the coastline of North America sea level is rising, however, in some places sea level is falling. In northeastern North America the land is rising due to glacial rebound (an isostatic adjustment caused by the melting of the great Laurentide continental glacier). In Alaska and other part of the West Coast, tectonic forces are pushing up coastal regions, some of these were rapid adjustments associated with massive earthquakes.

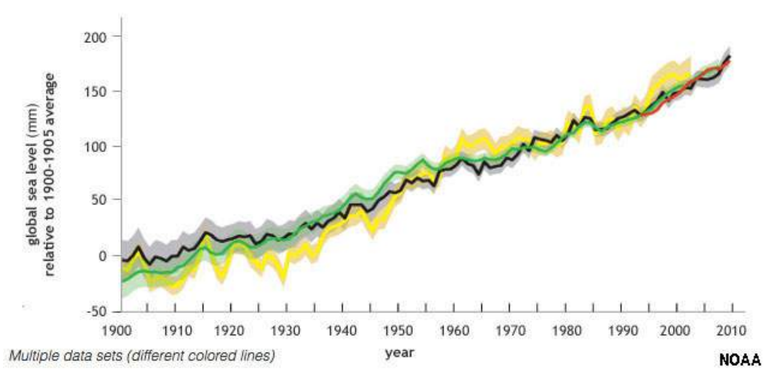


Figure 11.13. Average global sea-level rise 1900 to 2010.

What is Sea Level? YouTube video explaining the geodesy of defining sea level.
Sea Level Trends (NOAA website linked to data used in Figure 11.14).

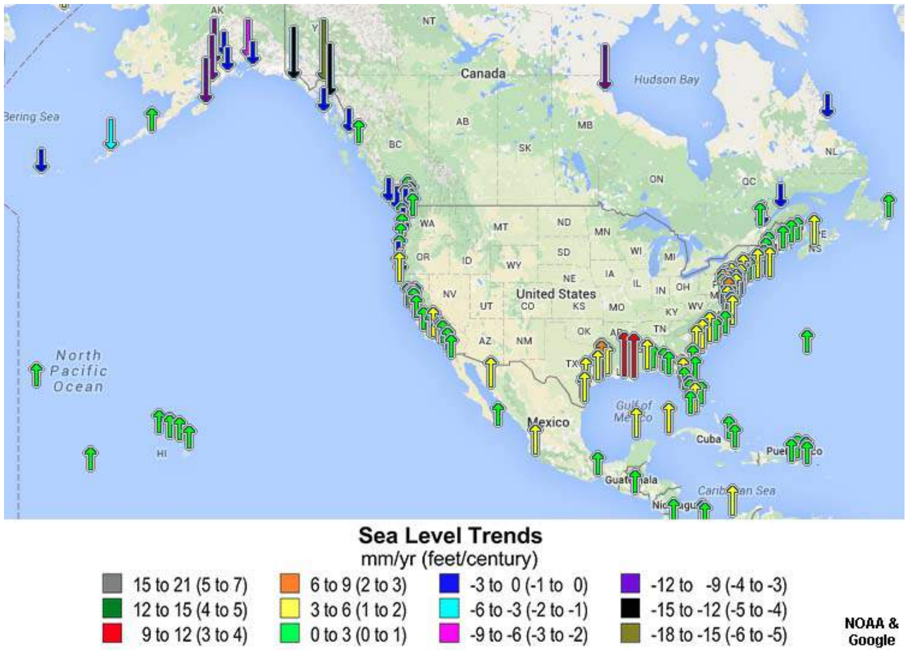


Figure 11.14. Sea level changes around North America.

11.7: Amphidromic Points and Co-tidal Lines

Amphidromic points are locations where there are little or no tide in the ocean. (This is also related to influence of continental land masses interfering with the westward movement of tidal bulges and the influence of the Coriolis effect.)

- The closer to the amphidromic the lower the tidal range.
- There are about 1 dozen amphidromic points in the oceans (Figure 11.15).
- About five in the Pacific Ocean.
- One near Hawaii - there is little tide change there, so beaches tend to be narrow.

A **cotidal line** is a line on a map connecting points at which a tidal level, especially high tide, occurs simultaneously.

- Cotidal lines are hypothetical tidal crest rotating around an amphidromic point (Figure 11.15).
- Cotidal lines rotate around amphidromic points about every 12 hours.
- They rotate **left** in Northern Hemisphere, and rotate **right** in Southern Hemisphere.

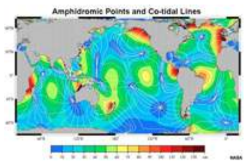


Figure 11.15. World map showing locations of **amphidromic points** and **cotidal lines**. Note: this map also shows where the highest tides occur around the world.

11.8: What is a Tidal Wave?

What is a Tidal Wave?

Tidal wave is a term often confused with the term **tsunami**. They are different.
Tsunamis are seismic sea wave formed by rapid displacement of the seafloor, such as by earthquakes, volcanic explosions, landslides, etc.). Tsunamis are not related to tides. Tsunamis are generally **unpredictable**, especially close to the source of the disturbance, with only minutes to hours to warn large coastal populations.

A **tidal wave** is a large wave associated with a tidal bore. A **tidal bore** is a surging flow of a large about of water moving with the incoming tide that funnels a large amount of water into a river mouth or a narrow bay (Figure 11.16). Tidal bore can produces sizable waves that move inland along rivers and estuaries (they are surges of water that can behave like a tsunami). Tidal bore characteristics are **often predictable**, but can be influenced by storm surges and high sea waves causing potentially hazardous conditions.

	
Figure 11.16. A **tidal bore** moving up a tidal estuary near Truro, Nova Scotia on the Bay of Fundy. A tidal bore is associated with the surge of an incoming ebb tide.	Figure 11.17. High tide combined with storm waves can cause intense erosion at the base of sea cliffs, such as illustrated here at the Del Mar Dog Beach, CA.

Check out these tidal bore videos:
Tidal bore surfing on the Bono waves, Kampar River, Indonesia (YouTube video)
Tidal bores surge in Qiantang River(YouTube video)
Tidal Bore Surfing Seven Ghosts in Indonesia (YouTube video)

11.9: Storm Surge and Tides and Subdivisions of the Intertidal Zone

Storm Surge and Storm Tides

A **storm surge** is a wind-driven current of water that piles water into shallow coastal areas and onshore areas with low coastal elevation. A storm surge is a buildup of water created by winds associated with large storms where wind moves water into coastal areas that have no place to drain away.

Storm surges are typically associated with large low pressure tropical cyclones (hurricanes and typhoons) and strong extra-tropical storms that move into shallow neritic zone environments, and often have enhanced effects where coastal geography, such as a shallow bay or estuary, that cause water to accumulate. Storm surge effect are most catastrophic when they occur in association with high tide, and are often the cause of the greatest death & destruction associated with large storms.

A **storm tide** is when a storm surge coincides with a regular high tide. The effects of storm tides adds to the catastrophic effects of storms associated with cyclones on coastal settings (Figures 11-18 and **11-19**).

Fortunately, storm tides can be **predicted** in association with large storms.

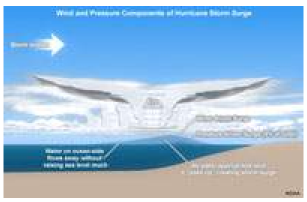


Figure 11.18. Storm surge associated with a cyclone.

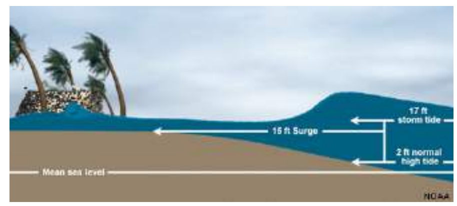


Figure 11.19. Additive effects of storm surge with high tide.

Subdivisions of the Intertidal Zone

The **intertidal zone** is the region where land surface is intermittently exposed between the lowest-low water and the highest-high water. The intertidal zone is between the subtidal and supratidal zones (Figure 11.20). Tidal ranges influence the distribution of sediments and the habitats occupied by plants and animals.

The **subtidal zone** is the submerged region lying below the low-tide mark but still shallow and close to shore.
The **supratidal zone** is the typically vegetation-free splash or spray zone above the high water line where back-beach dunes accumulate.

A **wrackline** is an accumulation of shell material and debris that typically marks the location of the last high tide cycle on a beach or after a storm surge (Figure 11.21).

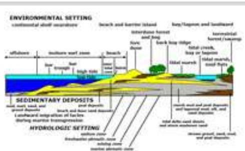


Figure 11.20. Coastal environments within the intertidal zone extend from offshore bars to inland estuaries and bays.

Figure 11.21. A wrackline consisting of most shell material, pebbles, and flotsam along Plumb Beach, Jamaica Bay, Brooklyn, NY

11.10: Tidal Forces In Other Planet Systems

Tidal Forces In Other Planet Systems

Tidal features have been observed in other planet systems. For instance, Jupiter’s moon, **Europa**, is covered with large cracks that are attributed to Jupiter’s enormous gravity pulling on the moon, causing the thick ice crust to fracture (Figure 11.22). Tidal forces release heat, enough to melt large quantities of ice below its surface, allowing the Solar System’s largest oceans to remain liquid.

Figure 11.22. Tidal ice cracks on Jupiter's moon Europa

Jupiter's moon, **Io**, is perhaps the most geologically active moon in the Solar System (Figure 11.23). Tidal forces between Jupiter and its other moons are generating heat within the moon that are driving volcanic activity, recycling the planets crust every few million years. Tidal forces also play a role in the heat generated within planet Earth, and may have a significant influence on plate-tectonics and magnetic reversals associated with the core.

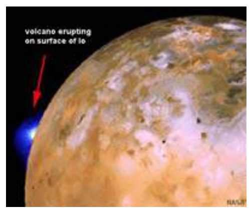


Figure 11.23. A volcanic eruption on Jupiter's moon Io

11.11: A Rare King Tide Experience In San Diego

A Rare King Tide Experience In San Diego

Opportunity to see the effects of Perigee and Perihelion happening on a full moon on the same day!

On January 1, 2018, the Moon was both full and at perigee, and on January 2 the Earth was at perihelion. In other words, the best conditions for creating maximum tides. The tide chart showed that the tidal ranges are 9.5 feet on those days—the largest in seen in many years in San Diego!

Figure 11.24 compares the view in the early morning and afternoon high tides on the beach near Encinitas in northern San Diego on January 2. The upper picture shows waves crashing on the upper beach looking south near near the D Street Stairs to the beach. The ocean was fairly calm this day, but wave were crashing against the base of the sea cliff farther south along the beach. The second image shows the same beach view at the extreme low tide level of the day. The water level has dropped to the point the offshore sand bars are exposed (that are rarely visible). The dark wrackline at the upper beach is mostly composed of black magnetite sand sorted by the wave action at high tide.

Figure 11.24. A rare **king tide** as experienced in San Diego (high tide and low tide, same day in Encinitas).

Students! Be Prepared to understand our local tides! Check out:
Oceanside Harbor Tides (Surf-Forecast.com website).
Del Mar Tides
San Diego (NOAA Tides website)

NOAA's Long Term tide prediction calculator for La Jolla, California (Scripps Institute of Oceanography)

11.12: Quiz Questions - Chapter 11 - Tides

1. The force primarily responsible for tides is:
a) gravity.
b) friction.
c) the Coriolis effect.
d) wind pressure.

2. What is the relative tidal forces of the Sun and Moon as they impact the Earth?
a) The Sun and Moon exert equal tidal forces on the Earth.
b) The Sun exerts about twice the tidal force of the Moon.
c) The Sun exerts three times the tidal force of the Moon.
d) The Moon exerts about twice the tidal force of the Sun.

3. When water currents flows out to sea as tide levels fall is called a:
a) ebb tide.
b) spring tide.
c) flood tide.
d) neap tide.

4. When the Moon is closest to the Earth is called:
a) apogee.
b) perigee.
c) aphelion.
d) perihelion.

5. When do spring tides occur?
a) during new moon & full moon phases
b) during first quarter & third quarter moon phases
c) in March and April in the Northern Hemisphere
d) all of the above.

6. How many high tides occur per day in most coastal areas (on most days, including in San Diego)?
a) 1
b) 2
c) 3
d) 4

7. Where are the greatest tidal ranges on Earth found?
a) In large lakes like Lake Ontario.
b) In narrow bays like the Bay of Fundy in Canada.
c) In polar oceans like the Arctic Ocean.
d) In the largest oceans, particularly the Pacific.

8. The intertidal zone is:
a) the area between the high tide mark and dunes, a sea cliff, or permanent vegetation.
b) the area between the low and high tide marks.
c) a platform formed by depositional processes along the beach.
d) the area between the beach and a barrier island.

9. Which is NOT true about sea level?
a) Sea level is a equal everywhere.
b) Sea level is influenced by variations in the gravitational field of the lithosphere.
c) Sea level is about 20 cm higher on the Pacific side of North America than the Atlantic.
d) Sea level is influenced by the regional density of seawater.

10. The zone that is the typically vegetation free, splash or spray zone above the high water line where back-beach dunes accumulate is called:

a) the subtidal zone.
b) the intertidal zone.
c) the supratidal zone.
d) the wrackline.

CHAPTER OVERVIEW

12: Coasts

12.1: Coasts

Coasts

Coastlines are a dynamic interface between land and sea. Coastlines preserve evidence of many process from the past, going back hundreds, thousands, even millions of years. Coastlines are shaped by an ongoing series of processes involving daily wind and wave action, tides, occasional storms and superstorms, earthquakes, and massive tsunamis. Coastlines reflect process of their origin including erosion of bedrock features, and are influenced by regional geology, geography, and climate.

Understanding coastline dynamics is important considering that about 75% of the worlds megacities are on coastlines. According to the United Nations. presently about 40% of the world's population lives within 100 kilometers of the coast, with hundreds of millions living in low-lying coastal areas (below about 10 meters elevation).

Wave erosion is persistent and intense, especially when storm waves combine with high tides. As a result, coastal landforms are generally delicate, and short-lived features. The **sediment supply** to coasts are offset by **erosion rates** along shorelines. Sediment supply is influenced by climate factors and geography, and can vary significantly from place to place, season to season, and by isolated events, such as changes caused by a massive superstorm (Figure 12.2).

Figure 12.1. New York, the largest coastal city in North America. More than 12 million people in the US live in regions within 3 meters above current sea level.

12.2: Classifications of Coastlines and Shoreline Features

Classifications of Coastlines and Shoreline Features

Three different classification schemes of coastlines include:
a. **Primary or Secondary Coastlines**
b. **Active or Passive Margins**
c. Emergent or Submergent Coasts

Note below that characteristics of each classification scheme overlap and complement each other.

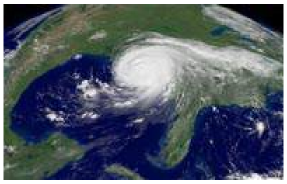


Figure 12.2. Hurricane Katrina, North America's most expensive disaster, wiped out an estimated 328 square miles of coastal land along the Gulf of Mexico.

Primary and Secondary Coastlines

Primary: Young coasts formed by **terrestrial influences**, not significantly altered by marine processes.
Secondary: Coasts that have been significantly changed by **marine processes** after sea level has stabilized.

Figure 12.3. Jade Beach, CA

Primary Coasts - 5 Types

Ria Coasts: Drowned river valleys caused by a rise in sea level.
Examples: Chesapeake Bay (Figure 12.4).

Glacial Coasts: Coastlines influenced by recent glacial activity such as glacial cut **"U shaped" valleys** called "**fjords**." Examples: Norway, British Columbia, Alaska, Hudson Valley, New England region, Long Island (Figure 12.5).

Deltaic Coasts: Coastlines associated with active river and delta systems.
Examples: Mississippi and Nile Rivers (Figure 12.6).

Volcanic Coasts: Coastlines associated with recent or active volcanoes (mostly basaltic or andesitic volcanoes).
Examples: Hawaii, Aleutian Islands, Japan, Philippines, Indonesia (Figure 12.7).

Fault/tectonic Coasts: Coastlines associated with major active fault systems along continental margins
Example: San Andreas fault going off shore at San Francisco (Figure 12.8).

Figure 12.4. Ria Coast: Chesapeake and Delaware Bays (**estuaries**), and the Delmarva Peninsula. Sea-level rise has back filled river valleys draining into the Atlantic Ocean. Ridges on land became **peninsulas**.	Figure 12.5. **Glacial Coast**: Kenai Fjords NP, Alaska	Figure 12.6. Deltaic Coast: Nile River Delta	Figure 12.7. Volcanic Coast: Hawaii Volcanoes NP	Figure 12.8. Tectonic Coast: Thornton SP, San Francisco

Secondary Coasts

Secondary coasts are coastlines that have been significantly changed by **marine processes** after sea level has stabilized allowing **erosional** and/or **depositional processes** to dominate shaping of the landscape. However, to explain this better, we need to examine the other classifications of coastlines first.

Both primary and secondary coasts are influenced by whether they are **active or passive continental margins** (the second method of coast classification).

Both primary and secondary coasts are influenced by whether they are **emergent or submergent coastlines** (the third method of coast classification - discussed below). Passive margins tend to be submergent due to the ongoing rise in sea level (Figure 12.10). In contrast, active margins can be both emergent or submergent depending on local tectonic forces, such as caused by faulting.

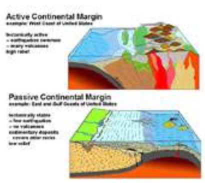


Figure 12.9. **Active** versus **passive** continental margins.

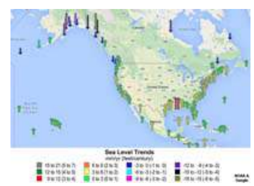


Figure 12.10. Changing sea level trends around North America.

12.3: Coastlines on Active and Passive Continental Margins

Coastlines on Active and Passive Continental Margins

In North America, the Pacific Coast is an **active continental margin**, whereas the Atlantic Coast is a **passive continental margin** (Figures 12-11 and **12-12**).

An **active continental margin** is a coastal region that is characterized by mountain-building activity including earthquakes, volcanic activity, and tectonic motion resulting from movement of tectonic plates. Active margins typically have a narrower and steeper continental shelf and slope. They can also be subsiding or uplifting. Active continental margins are also associated with subduction zones, often include a deep offshore trench. The Pacific Coast is an active margin that is characterized by narrow beach, steep cliffs, rugged coastlines with headlands and sea stacks (see features discussed below).

Passive continental margins occur where the transition between oceanic and continental crust which is not an active plate boundary. Passive margins are characterized by wide beaches, barrier islands, broad coastal plains. Offshore passive margins typically have a wider and flatter continental shelf and slope. They are usually subsiding. Examples of passive margins are the Atlantic and Gulf coastal regions which represent setting where thick accumulations of sedimentary materials have buried ancient rifted continental boundaries formed by the opening of the Atlantic Ocean basin.

Figure 12.11. **Passive margin:** North Carolina's Outer Banks region showing coastal plain, rivers, tidal estuaries, lagoon, barrier islands, and shallow Atlantic continental shelf.

Figure 12.12. Active margin: San Francisco Bay and Monterey Bay region has actively rising coastal range mountains and sinking coastal basins.

12.4: Erosional Coastal Landforms (on Secondary Coastlines)

Erosional Coastal Landforms or Features (on Secondary Coastlines)

Emergent coastlines typically have **sea cliffs** carved by wave and current action along the shoreline. The geometry of a coastline is largely a reflection of how some rocks along a coastline are **more resistant to erosion**.

Sea Cliffs and **Wave-Cut Platforms**

- **Sea cliffs** form where persistent wave erosion carves into elevated coastlines.
- Waves erode the base of cliff, causing it to subside or fail (Figure 12.13).
- Waves carve a flat surface where they scour the seabed leading up to the beach creating a **wave-cut platform**.
- When sea level locally falls falls (such as from uplift of a regional earthquake) wave action scours out a **new wave-cut platform**, leaving remnants of the old seabed surfaces exposed as expose **wave-cut bench** (Figure 12.14). A **wave-cut bench** is a flat bench-like platform of rock typically preserved in the upper surf zone associated with an actively eroding sea cliff on an emergent coastline **(Figures 12-14** and **12-17**, also see **marine terraces** below**).**

Figure 12.13. **Sea cliff** rise above the wave-cut platform (with beach) at Del Mar Dog Beach, CA

Figure 12.14. Wave-cut platform, **wave-cut bench**, and **sea cliffs** on Point Reyes National Seashore, CA

Headlands are rocky shorelines that have resisted wave erosion more than surrounding areas, forming points or small peninsulas that jut seaward. Small sandy beaches typically occur in **bays** between headlands (Figure 12.15).

Figure 12.15. **Headlands** and **bays** at Point Reyes National Seashore.

Sea stacks are large rocky outcrops that have resisted wave erosion and stand offshore as the beach and sea cliff continues to erode landward

- Mound of rock and debris that eventually is taken to sea by waves.
- The product of a sea arch caving in (Figure 12.16).

Figure 12.16. **Sea stacks** along the coast at Olympic National Park, WA

A **sea cave** is an underground passage or enclosed overhang carved into a sea cliff carved by focused wave action (Figure 12.17). A **sea arch** is a natural rock arch caved by wave action. Sea arches form where two caves join together or where a cave cuts through a narrow fin of rock (Figure 12.18).

Figure 12.17. A **sea cave** and wave-cut benches at Wilder Ranch State Park, Santa Cruz, CA.

Figure 12.18. A **sea arch** at Natural Bridges State Park, Santa Cruz, CA.

Marine terraces are elevated step-like benches formed by the combined effects of long-term wave erosion during the rise and fall of sea level on an emergent coastline (Figures 12-19 to **11-22**). Marine terraces are old wave-cut platforms and benches that have been elevated by the land rising relative to the ocean surface.

Elevated marine terraces on the California coastline (examples in northern and southern California are illustrated in **Figures 12-19** and **12-20).**

California preserves much evidence of geologic, geographic, and climatic changes caused by ice ages. During the last ice age, alpine glaciers and ice caps covered upland regions in the Sierra Nevada Range and Cascades volcanoes, but lower elevations were ice free (Figure 12.21). The formation of continental glaciers in North America and Europe caused sea level to fall almost 400 feet, causing the shoreline to migrate seaward as much as 10 to 70 miles (16 to 110 km) westward of the current coastline in some locations. This rise and fall of sea level happened with each glaciation cycle (of which there were many through the ice ages of the Pleistocene Epoch). In places where the California coastline is slowly rising, each of the major glaciation cycles is preserved as a step-like bench, called a **marine terrace**. The formation of marine terraces is illustrated in Figure 12.22.

Figure 12.19. Marine terraces at Davenport, California

Figure 12.20. Step-like marine terraces on San Clement Island located offshore in southern California

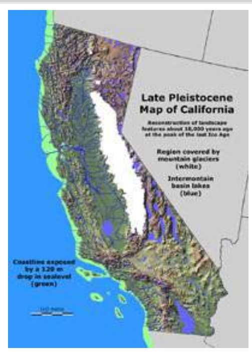


Figure 12.21. California at the peak of the last ice age. Glaciers covered the higher mountains, lakes filled inland valleys, and a coastal plain was extended offshore.

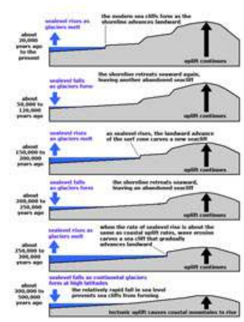


Figure 12.22. Formation of marine terraces. This example shows the formation of two terraces. At least seven major terrace levels are preserved in some areas along the California coast.

12.5: Depositional Coastal Landforms

Depositional Coastal Landforms or Features

Spits are ridges of sand projected from land into the bay (Figure 12.23).
A **bay-mouth bar** is a sandbar that stretches across a bay, separating it from the ocean (Figure 12.24).

Barrier islands are ridges of sand islands that run parallel to the coast **(Figure 12.25).** In locations where **inlets** occur cutting across bay-mouth bars or barrier islands, **tidal deltas** can accumulate sediments on both ends of an inlet. **Ebb tidal deltas** form as the outgoing tidal current erode and move and deposit sand on the seaward side of an inlet. **Flood-tide deltas** form where incoming tidal currents carry sediments eroded from the ocean-beach side of a barrier-island inlet and deposit them in the lagoon or bay side of an inlet.

Figure 12.23. **Spits**: Rockaway Spit (on Long Island, NY) and Sandy Hook Spit (New Jersey project into outer New York Harbor and Raritan Bay.

Figure 12.24. Bay-mouth bar: Bolinas lagoon has a baymouth bar. The bar is composed of sand eroded and transported along shore from the Point Reyes Peninsula (in the distance).

Barrier islands along Cape Cod's south shore, Massachusetts

Figure 12.25. Nauset-Monomoy barrier islands along Cape Cod's south shore, Massachusetts, with tidal deltas visible in the shallow waters on the landward side of the inlets.

12.6: Emergent and Submergent Coasts

Emergent and Submergent Coasts

Another important factor in understanding shorelines is tectonic activity and the rise and fall of sea level.

Submergent coastlines display characteristics caused when sea level rises or the land sinks down. Submergent coastlines:
* Contain **estuaries** and **barrier bars**, and **barrier island** systems.
* Ridges that separate valleys that propel into the sea.
Example: East Coast (see Figure 12.4).

Emergent coastlines display characteristics caused when sea level drops or the land rises (from tectonic uplift).
* Wave cut platforms and elevated marine terraces.

Example: West Coast California **(Figure 12.26**).

Figure 12.26. San Diego's coastline displays characteristics of both emergent and submergent coastlines, having both seacliffs, headlands and marine terraces (**emergent**), and bays and estuaries filling flooded river valleys (**submergent**). View south along the Coast Highway at Torrey Pines Nature Preserve.

In some regions around the world, tectonic forces are pushing rocks up along coastal regions, mostly in regions associated with active continental margins. There areas are called **emergent coasts** and display features including sea cliffs and marine terraces (see below). Where sea level is rising faster than land is rising, or where coastal areas are sinking, it is called a **submergent coast**. Submergent coasts are associated with passive continental margins with wide coastal plains and continental shelves. Estuaries are associated with submergent coastlines formed when sea level rises and floods existing river valleys. Active margins can have both emergent and submergent coastlines in close proximity to each other.

12.7: Common Shoreline Features of Beaches and Barrier Islands

Common Shoreline Features of Beaches and Barrier Islands

Figure 12.27 illustrates common shoreline features associated with beaches and barrier islands.

A **beach** is an accumulation of mostly sand (and some gravel) along a shoreline where wave action winnows away finer sediment. Beaches occur in the **intertidal zone** (the zone between highest and lowest tides). Above the high tide line the upper **supratidal** part of the beach is mostly impacted by wind (forming dunes) and storm surges (Figure 12.28).

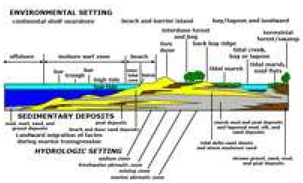


Figure 12.27. Coastal environments extend from offshore to inland estuaries and bays.

Figure 12.28. Beach and coastal dunes at Point Reyes National Seashore, California

A **barrier island** is a long and typically narrow island, running parallel to the mainland, composed of sandy sediments, built up by the action of waves and currents (Figure 12.29). Barrier islands serve to protect the mainland coast from erosion by surf and tidal surges. Examples include the Outer Banks in North Carolina and Padre Island in Texas. Barrier islands are most common on submergent coastlines associated with low-relief regions such as is present along the Atlantic Coast and Gulf Coast of the eastern United States. They form where the sea floor remains shallow for a long distance offshore.

An **estuary** is the mouth of a river or stream where the tide-driven flow allows the mixing of freshwater and ocean saltwater (Figure 12.30). A **lagoon** is a saltwater-filled **bay** or **estuary** located between a barrier island and the mainland.

A **tidal flat** is a nearly flat coastal area (at or near sea level) that is alternately covered and exposed by the tides, and consisting of unconsolidated sediments.

Figure 12.29. Fire Island, NY, is a barrier island on the south shore of Long Island, NY.

Figure 12.30. Tidal marshes and tidal flats along an estuary, Elkhorn Slough, CA.

12.8: Coral Reefs, Keys, and Atolls

Coral Reefs, Keys, and Atolls

Biogenous carbonate sediments can accumulate faster than sea level is rising. **Skeletal reefs** (including **coral reefs**) thrive in the surf zone, and are able to weather wave action, although they can be heavily damaged by superstorm wave energy. The sediments generated by wave erosion and **bioerosion** (critters eating critters) contribute to the buildup of carbonate islands (**keys**) and **atolls** associated with **fringing reefs** forming around extinct and eroding volcanic islands (Figures 12-31 to **11-33**). Keys and reefs of the world experience exposure and erosion during low sea levels during the ice ages.

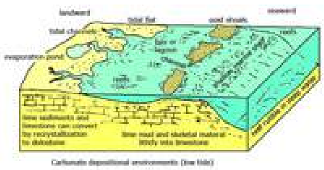
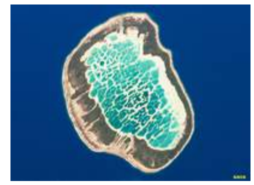
		

Figure 12.31. Landforms associated with carbonate depositional environments.	Figure 12.32. Coral reefs and keys, Kwajalein Atoll, Marshall Islands, South Pacific Ocean	Figure 12.33. Mataiva Atoll, Tuamotu Archipelago, South Pacific Ocean

12.9: Shoreline Erosion

Shoreline Erosion

Shoreline erosion depends on several factors:
1) **Amount of sediment to buffer land**: If the sand supplied to a beach is less than the amount removed by shoreline erosion processes, the beach will retreat landward.
2) **Amount of tectonic activity**: Uplift along the coastline allows erosion to provide sediments to a coastline. If the coast is not rising, then shoreline will retreat landward.
3) **Topography**: Coastal uplands provide more sediments to beaches than flat coastal plain regions.
4) **Composition of land**: Hard bedrock (such as granite) is harder to erode than softer unconsolidated deposits.
5) **Waves and weather**: The greater the waves and storm-generated currents, the more material can be eroded.
6) **Coastline configuration**: Coasts facing prevailing storm waves are eroded faster than isolated bays and down-wind protected shorelines (Figure 12.34).

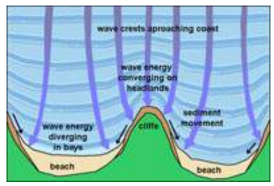


Figure 12.34. Wave refraction focuses wave energy on headlands and deposits sand in quieter bay settings.

Seasonal Erosional Changes to a Beach Profile

During the winter, storm-wave energy is most intense. Waves wash up on the beach and erode sand, and transport it offshore to where wave-driven currents aren't so strong and the sand accumulates on offshore bars. Heavier materials (gravel and boulders) are concentrated on the beach (Figure 12.35).

During the summer, lower wave energy prevails, and the sand gradually migrates back onshore, gradually expanding the beach seaward (Figure 12.36).

Figure 12.35. Cove Beach at Año Nuevo State Park (CA) in winter.

Figure 12.36. Cove Beach at Año Nuevo State Park (CA) in summer.

12.10: Longshore Currents and Longshore Drift

Longshore Currents and Longshore Drift

A **longshore current** is a current that flows parallel to the shore within the zone of breaking waves. Longshore currents develop when waves approach a beach at an angle (Figure 12.37). Longshore currents cause sediment transport called longshore drift. **Longshore drift** is the movement of sediments along a coast by waves that approach at an angle to the shore but then the swash recedes directly away from it. The water in a longshore current flows up onto the beach, and then back into the ocean in a "sheet-like" formation. As this sheet of water moves on and off the beach, it can transport beach sediment back out to sea. Objects floating in the longshore current move in a zigzag pattern up and down the beach as it moves down current.

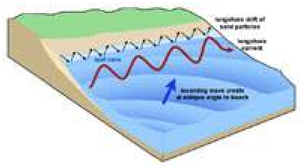


Figure 12.37. Longshore currents and longshore drift are caused by waves approaching the beach at an oblique angle.

12.11: Rip Currents and Rip Tides

Rip Currents and Rip Tides

A **rip current** (or just “rip”) is a current that flows away from the coast. Rip currents form when wave break strongly in one direction, but weakly in another. In the surf zone, breaking waves produce currents that flow both along the shore and out to sea. Rip currents typical form on beaches with a sand bar and channel system in the nearshore area. A rip current forms as a narrow fast-moving current of water moving in an offshore direction. Obstructions in the water can also deflect current offshore. Rip current vary in size and speed (up to 6 miles per hour [10 km/hr], or faster than an Olympic swimmer). Rip currents move offshore and dissipate beyond the breaker zone. If caught in a rip current, swim parallel to shore to leave the current before heading for shore.

A rip current is different than a **rip tide**, which is current associated with the swift movement of tidal water through **inlets** and the mouths of estuaries, embayments, and harbors caused by the rise and fall of tides.

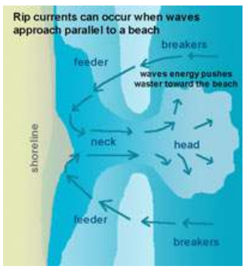


Figure 12.38. Rip currents are wave-generated currents that move in an offshore direction.

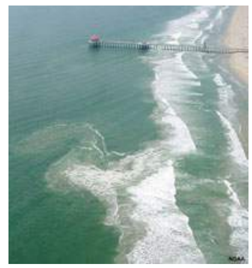


Figure 12.39. Rip current can vary with size and intensity depending of waves and shore geometry.

Tidal currents (including rip tides) are strong erosional forces where they are restricted at the mouths of inlets and straights between bodies of water. One example include the narrow straights of the Verrazano Narrows (between Staten Island and Brooklyn on Long Island, NY) (Figures 12-40 and 12-**41**). Another example is the Golden Gate Narrows between San Francisco and Marin County in northern California (Figure 12.42). In both cases, the seabed has been scoured deeply by the daily tidal flows. Tidal flows redistribute sediments building submerged **tidal deltas** at opposite ends of the channel that need to be dredged frequently to mitigate hazards to shipping.

Figure 12.40. Dominant winds, waves, and currents of the New York City region.

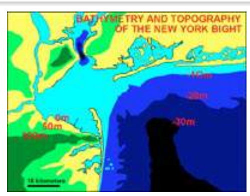


Figure 12.41. Bathymetry shows tidal current scour in the Verrazano Narrows.

Figure 12.42. Bathymetry shows tidal current scour in near the Golden Gate Bridge.

12.12: Coastal Littoral Cells

Coastal Littoral Cells

A **coastal cell** is a relatively self-contained **compartment** within which sediments circulate. A coastal cell contains a complete cycle of sedimentation including sources, transport paths, and sinks. In the San Diego area, the **Oceanside Coastal Cell extends** from Dana Point to La Jolla Canyon; some of the sand is lost to Carlsbad Canyon as well (Figure 12.43). Streams and cliff erosion provide sediments to the shore zone. The arrow on the map indicates the predominant longshore current direction (and the direction of the migration of beach sand along the coast). Most of the sand moves down the coast and eventually drains down La Jolla Canyon and is deposited as turbidity flow deposits on the La Jolla Canyon deep-sea fan in the San Diego Trough (Figure 12.44).

Figure 12.43. Map of the **Oceanside littoral cell** and **Carlsbad and La Jolla Canyons** offshore.

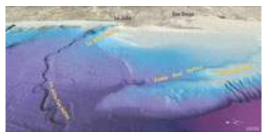


Figure 12.44. Sediments move from shore down La Jolla Canyon to the San Diego Trough.

San Diego's Coastal Erosion Problems Related To the Oceanside Coast Cell

The dominant swell direction in northern San Diego County is from the northwest. This creates longshore currents that move sediments (longshore drift) from north to south along area beaches. The sand on northern San Diego County beaches are mostly derived from sediments derived from coastal erosion in the shallow nearshore, beach, and sea cliffs along the coast between Dana Point and Oceanside (much of it from along the undeveloped coast within Camp Pendleton north of Oceanside). In addition, large quantities of sandy sediments are contributed to beaches from streams (small rivers) that, during episodic floods, dump large amounts of fresh sediment into the nearshore environment, contributing about half of the sand supply to area beaches over time. The amount of sand from river sources is highly variable with the seasonal weather, year to year.

Large waves (swell) especially during high tides in stormy conditions can erode, transport, and deposit large quantities of sediments.

12.13: Shoreline Erosion Problems

Shoreline Erosion Problems

Shoreline changes quickly with natural forces; they are not a stable landforms. Coastlines, especially on the East Coast and Gulf regions, are constantly changing, especially from the impacts of **superstorms**. These coastal regions are underlain by unconsolidated sediments that are easily eroded by strong currents. They remain relatively stable, as long as there is a new supply of sediment to replace materials eroded by longshore currents, tides, and storm waves. Figure 12.45 illustrates how much shorelines can change. In less than two centuries, Fire Island's eastern spit has grown about 5 miles (8 km) longer. The sediments creating this new land came at the expense of coastal lands father east on Fire Island, making the island increasing narrower. Barrier Islands are prone to be breached by storm erosion, creating new inlets, and filling in others.

Many attempts have been made, often at great expense, to try to prevent the effects of erosion and deposition along coastlines. Common construction efforts include jetties, groins, and seawalls to protect harbors, infrastructure, and communities.

Figure 12.45. Fire Island (on Long Island, NY) has steadily grown about 5 miles (8 km) longer since 1825 by longshore drift (see Figure 12.40). Fire Island Inlet at the west end of Fire Island is scoured by rip tides, adding sediments to the tidal delta in Great South Bay.

12.14: Structures Used to Protect Properties from the Destruction by the Sea

Jetties and Groins

Jetties are built at entrances to rivers and harbors. Their purpose is to protect properties from storm and wave damage, and to keep sand out of channels (so that there is no beach). Jetties require high maintenance costs to manage because they impede longshore drift (which is continues relentlessly). Most the costs are for dredging sand from one side, and moving it down current to replenish sand to community beaches. Loss of the sand supply makes down current areas susceptible to beach loss and coastal erosion (a major problem for Southern California's coastal communities, Figures 12-46 and **12-47**).

Figure 12.46. Dana Point Harbor and Jetty (Orange County, CA)

Figure 12.47. Oceanside Harbor and Jetty (Northern San Diego County, CA)

Groins are built as barriers perpendicular to the beach in an attempt to stabilize shorelines. Their purpose is to trap sand migrating along the shore by longshore drift (Figure 12.48). Figure 12.9A is an aerial view of a wash-over fan created by a breach in **Sandy Hook Spit** (on the New Jersey side of New York City's Outer Harbor (see Figure 12.40).The inlet formed when coastal storm waves and currents cut an inlet across the spit. Note the sand trapped on the left side of the groins (longshore drift is moving left to right). Figure 12.49B shows an accretionary prism of sand building up at the end of Sandy Hook Spit. Figure 12.50 shows the growth of **Rockaway Spit** on the north east side of New York's Outer Harbor. It has grown nearly 2 miles (3 km)since the end of the Civil War (1866). The area has been heavily modified by construction of groins and a jetty to keep the inlet to Jamaica Bay accessible to boat navigation.

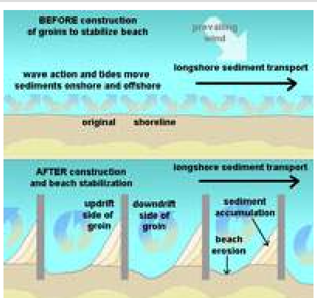


Figure 12.48. Groins are designed to trap migrating sand by impeding the flow of longshore drift.

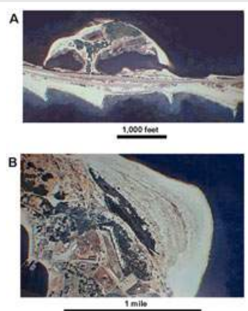


Figure 12.49 (A&B). Groins, a washover fan, and accretionary prism on Sandy Hook, New Jersey.

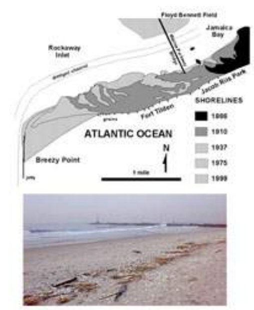


Figure 12.50. Map showing the growth of Rockaway Spit impacted by construction of groins and a jetty.

Other structures used to protect properties from the destruction by the sea

- **Breakwaters** are structures used to protect boats from large waves (jetties and groins are forms of breakwaters).
- **Seawalls** are walls built to protect land structures from large waves and coastal erosion (Figure 12.52 show an example of some seawalls used to stop cliff erosion).
- **Rip Rap** are piles of large boulders put on the beach or shoreline. They are cheap but take up beach space and are not as permanent as a seawall, and are unsightly and dangerous. However, they do create habitat for sea life that needs a hard substrate to live (Figure 12.52).
- **Beach nourishment** adds large amounts of sand to the beach to keep water away from land structures. Sand is dredged form harbor areas or mined from sand bars offshore and pumped onshore in slurries. The process is quite expensive.

Figure 12.51. Seawalls built in Encinitas, CA are an attempt to stop sea cliff erosion.

Figure 12.52. Rip-rap was used in the construction of the breakwater (Oceanside Harbor).

12.15: The Dam Problem

The Dam Problem

Dams have been constructed on most of the small rivers and streams throughout upland regions of San Diego County. The intentions of dam construction were to store water (reservoirs) and to reduce flood damage in low-lying communities. The problem is that dams have largely shut off the supply of sand from rivers and streams to the shore. One of the largest dams is for Lake Hodges on the San Dieguito River near Escondido, California (Figure 12.53). Construction of highway and railroad bridges, dikes, and causeways also restrict the flow of sediment-bearing water, preventing the migration of sediment to the coast. As a result, less sand is finding its way to the shore, resulting in **narrower beaches**. Without the protection of well-developed beaches, erosion of the sea cliffs are progressively endangering homes and infrastructure along the coast.

Figure 12.53. Lake Hodges Dam.

Dam construction: The easy way to kill a coastal community.

Dams on rivers trap sediments that would otherwise find their way to ocean beaches. A classic example was the construction of a dam on Matilija Creek in Ventura County. The dam is currently being demolished in order to return the sediment flow to sensitive habitats along the river downstream, but also to return a sediment supply to the Ventura County coastline (Figure 12.54). Many other dams constructed in the 19th and 20th century are being removed for the same reasons.

Coastal Dynamics—The Unending Saga

Sea-level rise due to global warming is a highly political topic of our times. The world's Scientific Community has been studying the changes happening around the world for many decades. Real-time observations show that the atmospheric temperatures are steadily rising along with the concentrations of greenhouse gases in the atmosphere. What is perhaps most alarming is that the rate of **sea-level rise is accelerating** as the ice caps melt and the oceans expand from increased warmth (there are many NASA and NOAA websites on these matters). However, the threat doesn't seem to fit within the interest span of politicians and corporations keen on making high profits from the extraction of coal, oil, and gas. Sea-level rise will likely continue unabated until either we either consume all the economically available carbon-based resources, or human populations collaborate to change the fate we, collectively, are facing.

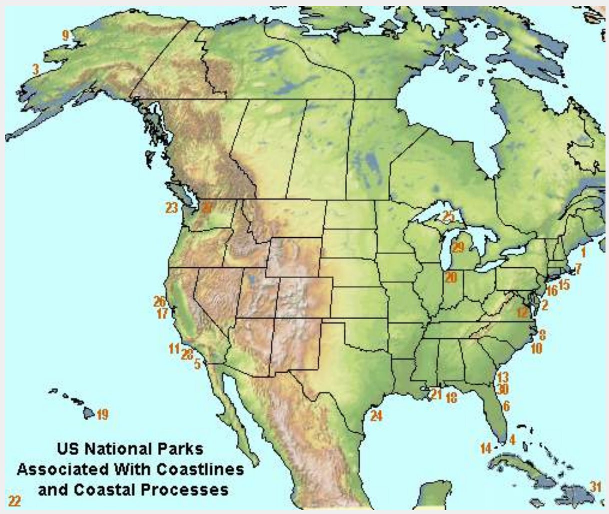
Figure 12.54. The Ventura River (left) supplies massive amounts of sediments to the coast during infrequent floods, then persistent coastal erosion processes take over the action. Construction of the Matilija shut of much of the sediment supply to the coast. The dam is now being removed.

12.16: National Parks Associated With Coastlines and Coastal Processes

National Parks Associated With Coastlines and Coastal Processes

Acadia National Park, ME - 1
Assateague Island National Seashore, MD, VA - 2
Bering Land Bridge National Preserve, AK - 3
Biscayne National Park, FL - 4
Cabrillo National Monument, CA - 5
Canaveral National Seashore, FL - 6
Cape Cod National Seashore, MA - 7
Cape Hatteras National Seashore, NC - 8
Cape Krusentern National Monument, AK - 9
Cape Lookout National Seashore, NC - 10
Channel Islands National Park, CA - 11
Chesapeake Bay, DC, DE, MD, PA, VA, WV - 12
Cumberland Island National Seashore, GA - 13
Dry Tortugas National Park, FL - 14
Fire Island National Seashore, NY - 15
Gateway National Recreation Area, NY, NJ - 16
Golden Gate National Recreation Area, CA - 17
Gulf Island National Seashore, FL, MS - 18
Hawaii Volcanoes National Park, HI - 19
Indiana Dunes National Park, IN - 20
Mississippi Gulf National Heritage Area, MS - 21
National Park of American Samoa - 22
Olympic National Park, WA - 23
Padre Island National Seashore, TX - 24
Pictured Rocks National Lakeshore, MI - 25
Point Reyes National Seashore, CA - 26
San Juan Island National Historical Park, WA - 27
Santa Monica Mountains National Recreation Area, CA - 28
Sleeping Bear Dunes National Lakeshore, MI - 29
Timucuan Ecological & Historical Preserve, FL - 30
Virgin Island National Park, VI - 31
Virgin Islands Coral Reef National Monument, VI - 31

The coastline of United States has an abundance of national parks. The West Coast is an active plate margin with cliffs and mountain fronts extending to the shoreline (and partly responsible for the incredible scenery of these parks). The parks along East Coast and Gulf Coast are host to sandy beaches and barrier islands and coastal bays, lagoons, and estuaries that are important wildlife habitats. These coastline are also at risk of hurricanes and storms (East and Gulf Coasts). The West Coast has the risk of damaging storms and tsunamis.



12.17: Quiz Questions - Chapter 12 - Coasts

1. The region on the East Coast (including the Delmarva Peninsula, Chesapeake Bay, and Delaware Bay) is what kind of Coast?
a. Ria coast
b. Deltaic coast
c. Glacial coast
d. Fault/tectonic coast

2. Exposed wave-cut cliffs and platforms, and marine terraces are most frequently found along:
a. submergent (sinking) coasts.
b. static coasts (stationary) coasts.
c. emergent (rising) coasts.
d. all of the above.

3. Large rocky outcrops that have resisted wave erosion and remain as small isolated islands offshore as the beach and sea cliff continues to erode landward are called:
a. headlands.
b. wave-cut benches.
c. sea stacks.
d. sea arches.

4. Over time, sea level has risen and fallen many times in the past during the ice ages. Along emergent coastlines, such as along many parts of California's coastline, the interactions of these gradual sea level changes and a slowly rising coastline has resulted in the formation of:
a. elevated marine terraces.
b. spits.
c. bay mouth bars.
d. barrier islands.

5. Low ridges of sand that parallel coastlines and rise above sea level are called:
a. barrier islands.
b. marine terraces.
c. wave-cut platforms.
d. tidal deltas.

6. Which of the following is NOT a depositional coastal landform?
a. spit
b. baymouth bar
c. beach
d. sea cliff

7. A depositional coastal feature that form where incoming tidal currents carry sediments eroded from the ocean-beach side of a barrier-island inlet and deposit them in the lagoon or bay side of an inlet is called:
a. a spit.
b. a bay-mouth bar.
c. an eb tide delta.
d. a flood-tide delta.

8. Barrier islands are most common in regions where there are:
a. emergent active continental margins.
b. submergent passive continental margins.
c. volcanic island chains along coastlines.
d. subduction zones along coastlines.

9. Barrier island beaches generally develop where:

a. the coast is composed of hard rock.
b. the nearby land has a rugged topography of hills and mountains.
c. the sea floor deepens rapidly offshore.
d. the sea floor remains shallow for a long distance offshore.

10. When incoming waves reach an irregular coastline, how is their energy distributed?
a. It is equally distributed between bays and headlands.
b. It is focused on bays and cuts them deeper.
c. It is focused on headlands and erodes them back.
d. It is reflected back out to sea.

11. During stormy periods in winter, what happens to beaches?
a. There is a higher percentage of fine-grained sand on beaches.
b. More erosion occurs in bays than on headlands.
c. Beaches are eroded and the sand moves to offshore bars.
d. Offshore sand bars are eroded and beaches are built up.

12. How are longshore currents and longshore drift best described?
a. They involve movement of water and sediment perpendicular to the shoreline.
b. They involve movement of water and sediment toward the shoreline.
c. They involve movement of water and sediment parallel to the shoreline.
d. They involve movement of water and sediment away from the shoreline.

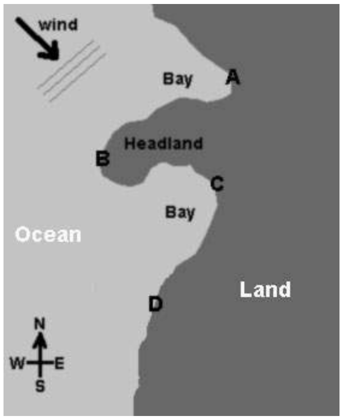
13. What is significant about longshore currents?
a. They are agents of erosion along shorelines.
b. They are agents of deposition along shorelines.
c. They move in directions dependent on the direction of the dominant incoming swell.
d. All of the above.

14. A strong current associated with the swift movement of water through inlets and the mouths of estuaries, embayments, and harbors is called a:
a. longshore drift.
b. longshore current.
c. rip current.
d. rip tide.

15. Construction of dams upstream on rivers may lead to which of the following?
a. Narrower beaches
b. Wider beaches
c. The filling in of bays with sediment
d. The building of a barrier island

16. An artificial barrier built at a right angle to the beach to trap sand that is moving parallel to the shore is known as a:
a. groin.
b. stack.
c. seawall.
d. breakwater.

17. On which side of a groin would sand collect if it was put into a south-flowing longshore current?
a. on the north side.
b.on the south side.
c. on both the north and south sides.
d. on neither side.



Examine the diagram above showing an irregular coastline (common on many portions of the California Coast). The arrow shows the wind direction; lines show incoming swell. Use the diagram to answer questions 18 and 19 below.

18. Longshore currents are likely to travel along the coast from:
a. mostly north to south.
b. mostly south to north.
c. mostly east to west.
d. mostly in a northeast direction.

19. Examine the diagram above. Which part of the coast would likely receive the maximum amount of wave energy?
a. Location A
b. Location B
c. Location C
d. Location D

20. Which of the following choices is a significant cause of coastal erosion, requiring expensive efforts to restore beaches along coastal California?
a. Dams trap sandy sediments that would otherwise be carried by floodwaters to be deposited on coastline beaches.
b. Lack of a supply of sand to a beach allows wave energy to erode sea cliffs, endangering coastal homes and infrastructure.
c. Construction of jetties to protect harbors end up trapping sediments that would otherwise migrate along the coast by longshore drift.
d. all of the above.

CHAPTER OVERVIEW

13: Primary Production

13.1: Primary Production

Primary Production

Primary productivity is the rate at which energy is converted to organic substances in a region or ecosystem. Energy is converted through **autotrophic** (self-feeding) organisms, converting solar or chemical energy into biomass. Basically, primary production is **generation of food** by *making organic matter from inorganic matter*.

Primary process is **photosynthesis** (in shallow surface waters), and small amount from **chemosynthesis** (at deep sea vents and underground). **Solar energy** is the primary source of energy in the production of biomass in the global oceans, with comparatively trace amount coming from chemosynthetic sources.

Figure 13.1. Solar energy is the main source of energy in ocean primary production.

13.2: Trophic Pyramids

Trophic Pyramids

A **trophic pyramid** exemplifies **feeding levels within an ecosystem**.

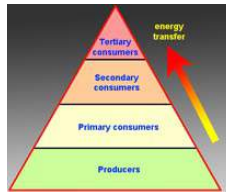


Figure 13.2. Trophic pyramid

There are three major categories of living organisms in an ecosystem and each has a special role: **producers** (plants), **consumers** (animals), and **decomposers** (and detritus feeders).

Tropic Levels	**Organisms**
Tertiary consumers	carnivores (larger animals, i.e. tuna, sharks, birds, sea mammals, etc.)
Secondary consumers	carnivores and detritus feeders (i.e., small fish, crustaceans)
Primary consumers	herbivores (zooplankton)
Primary producers	photosynthetic bacterial - plankton - plants (**focus of this chapter**)

A “**food chain**” is a hierarchical series of organisms each dependent on the next as a source of food.
A “**food web**” is a system of interlocking and interdependent food chains.

Note: food chains range from simple to complex! For instance, larvae of some organisms may start as primary consumers but rise to secondary levels as they mature

Figure 13.3. Food chains and food webs in the oceans.

All living things rely on the continual uptake of organic compounds from their environment. These compounds are used to provide energy both for **biosynthesis** (the production of a chemical compounds by a living organism) and **metabolism** (the processes that drives cellular activity and to generate carbonate skeletons).

The first organisms on the primitive Earth had access to an abundance of the organic compounds in the young oceans and continents. However, most of these original compounds were used up billions of years ago. Through evolution over time, today, the vast majority of the organic materials required by living cells are produced by photosynthetic organisms, including many types of **photosynthetic bacteria**, **green algae**, and **plants**.

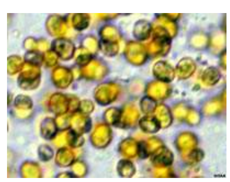


Figure 13.3. Green algae cells.

13.3: Photosynthesis

Photosynthesis

Green plants, algae, and some bacteria use sunlight to synthesize foods from carbon dioxide and water. These organisms thrive with sunlight with minimal nutrient requirements. They use water and the energy of sunlight to convert atmospheric CO_2 into organic compounds—a process called **carbon fixation**. A bi-product is oxygen (O_2) released into water, and eventually, the atmosphere**.**

Photosynthesis in plants generally involves the green pigment **chlorophyll** (but also other colors and compounds) and generates oxygen as a byproduct. The process is:

$6\ H_2O + 6\ CO_2 = C_6H_{12}O_6$ (glucose) + $6O_2$

In the oceans, photosynthesis is completed by **microscopic** and **macroscopic plants**.

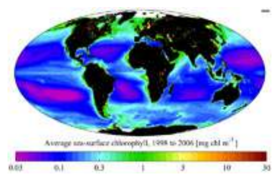


Figure 13.4. Average sea-surface chlorophyll concentrations around the world (1998-2006). Most productivity is near coasts.

13.4: Microscopic Plants- Phytoplankton

Microscopic Plants: Phytoplankton

Phytoplankton means “**floating plants.**” **Over 90% of the worlds food (carbohydrates)** come from phytoplankton. It is the single most important process for life and the production of food on Earth.

Types of phytoplankton include bacteria, protists, and single-celled plants. Primitive photosynthetic bacterial appear in the fossil record about 3 billion years ago. Their oxygen production is what made life possible for aerobic organisms (particularly animals) to evolve.

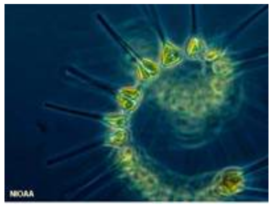


Figure 13.5. Phytoplankton.

13.5: Photosynthetic Bacteria

Photosynthetic Bacteria

Bacteria are very small in size, and many varieties. Some have evolved to be capable of photosynthesis (called photosynthetic bacteria). They contribute a large amount to primary production in certain parts of the oceans, and may contribute up to 50% of the world's biomass.

Cyanobacteria (commonly called called blue-green algae) are photosynthetic algae common in marine and freshwater environments. Cyanobacteria contain **chlorophyll** while other forms of bacteria contain **bacteriochlorophyll**. Although bacteriochlorophyll resembles chlorophyll, it absorbs light of a longer wavelength than chlorophyll. Common kinds are cyanobacteria in the marine environment include **golden algae** and **green algae**.

Figure 13.6. Cyanobacteria

13.6: Golden and Green Algae

Golden Algae

Golden algae are characterized by the presence of the pigments chlorophyll, carotene, and xanthophyll, which impart yellow-brown to golden colors**.** the name golden algae encompasses nearly three dozen genera, and over a thousand species in oceans and bodies of water worldwide. The dominant types of golden algae in the marine environment include **diatoms**, **coccoliths**, and **dinoflagellates**.

Diatoms: (from Greek *diatomos* meaning "cut in two") **Diatoms are the most productive in the oceans**. They have skeletal cell walls (**tests**) composed of silica and thrive mostly cooler waters. Their tests come in a variety of shapes but has a top and bottom that fit together like a shoe box and a single cell in the "box" (Figure 13.7). Nutrients and waste are pushed through the test perforations. Diatoms are the chief component of **siliceous ooze** throughout ocean basins. Diatomaceous earth (or diatomite) is a naturally occurring, soft, siliceous sedimentary rock that is easily crumbled into a fine white to off-white powder used in filters and manufacture of glass and ceramic products.

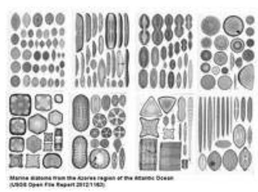


Figure 13.7. Diatoms have siliceous tests and prefer colder water settings.

Coccoliths (*coccus*-berry, *lithos*-stone)(also called *coccolithopores*): These produce less than the diatoms. They have a calcareous shell that is made up of a number small individual round plates (Figure 13.8). Coccoliths have calcareous tests prefer warmer waters. Coccoliths are the prime component of **calcareous ooze** which becomes the sedimentary rock: chalk.

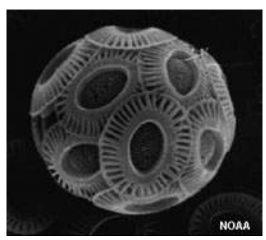


Figure 13.8. Coccoliths have calcareous tests and prefer warmer water settings.

Dinoflagellates (dino-whirling flagellum-whip) (Figure 13.9): These have cellulose tests which are biodegradable (typically not preserved in marine sediments).
They also have a small whip-like tail which provides a small means of locomotion.
These are the critters that produce **red-tides** or **harmful algae blooms (HAB)**.

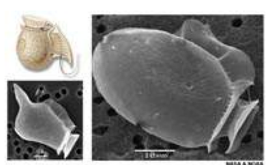


Figure 13.9. Dinoflagellates have whip-like appendages that help propel them through the water.

Figure 13.10. A **red tide** or better, a harmful algae bloom (HAB) are caused by a bloom in dinoflagellates.

Green Algae

Green algae (and plants, which share ancestral roots) developed much later, and utilize **chloroplasts**—internal organelles that use "chlorophyll" (photosynthetic compounds) that produce sugars for metabolism. Chloroplasts are thought to have evolved by through symbiosis between primitive (and ancient) cyanobacteria and other eukaryotic cells. For instance, lichens are a combination of a symbiotic algae and a fungus. Mitochondria in cells are also an example of ancient symbiosis of ancient bacteria. Photosynthesis is the mechanism for organisms to first thrive in the oceans, and eventually on land.

13.7: Macroscopic Marine Algae (Seaweeds)

Macroscopic Marine Algae (Seaweeds)

Although in terms of ocean biomass, they are relatively insignificant compared to microscopic planktonic forms, however, they fill important niches is marine ecosystems, often found attached to the seabed offshore or extending up into the intertidal zone.

Brown algae: Occur in temperate or cooler waters.
Kelp and **Sargassum** are examples.
Can be attached to bottom like kelp or encrusting mostly in the intertidal zone.
The Sargasso Sea in the North Atlantic gets its names for large patches of sargassum floating in the open ocean.

Green algae: Mostly attached to bottom.
Sea lettuce, sea grass, and dead mans fingers are examples.

Red algae: These are encrusting or sometimes branching in the near-shore environment. Very hardy.

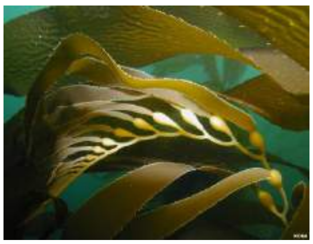


Figure 13.12. Kelp

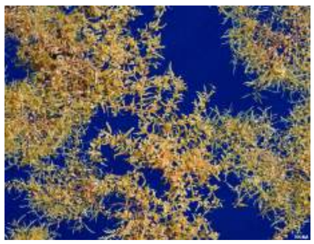


Figure 13.13. Sargassum

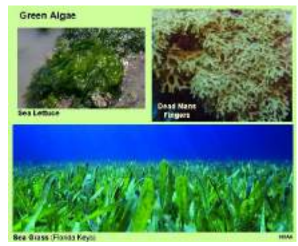


Figure 13.14. Green algae

Figure 13.15. Red algae

13.8: Marine Plants

Marine Plants

Some plants have adapted to transitional marine environments (being salt tolerant). Examples include eel grass, prickleweed, and mangroves.

Eel grass is common in protected lagoons and estuaries.

Pickleweed is abundant here in California covering tidal flats in protected bays and lagoons.

Mangroves are common in tropical regions.

Figure 13.16. **Eel grass**

Figure 13.17. Pickleweed

Figure 13.18. **Mangroves**

13.9: Factors Influencing Primary Production

Factors influencing Primary Production

Sunlight and Nutrient Availability

Sunlight penetration decrease with depth; it is impacted by water clarity (**turbidity**).

The **Epipelagic Zone** is also called the **Euphotic Zone** (where sunlight penetrates, Figure 13.19).
The **Euphotic zone** extends downward around 200 meters in the open ocean, but varies with seasonal changes in turbidity. This zone is also called the neritic zone on continental shelves and the epipelagic zone in open ocean settings. The euphotic zone where all photosynthesis takes place. It is also the part of the ocean most likely to have a thermocline is mostly above the **oxygen minimal zone** (OMZ).

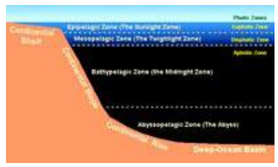


Figure 13.19. Pelagic zones in the oceans

Compensation Depth: where respiration (consumption) equals photosynthesis production. The compensation depth is depth at which the light intensity is just sufficient to balance between the amount of oxygen produced and consumed by algae (typically a depth where only 0.1-1% of solar radiation penetrates). The compensation depth varies with latitude, water clarity, and nutrient availability.

Nutrients: These are not like food, they are more like a **fertilizer**. Major nutrients in need for biological activity include nitrogen, phosphorus, and silicon, iron, zinc, and copper. Organic compounds including vitamins are also essential. However, some nutrients can become toxic if concentrations become too high.

Sources of nutrients include:
* **Upwelling from deep ocean** (particularly nitrates and phosphates)
* **Rock weathering** (minerals provide iron, silica, and other element)
* **Decaying organic matter** (releases elements and vitamins back into seawater)

Human activities are also creating artificial sources of nutrients: **Agriculture** (fertilizers) and **pollution** (sewers, etc.)

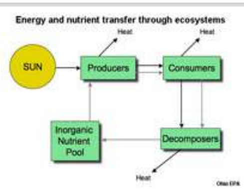


Figure 13.20. Energy and nutrient transfer through ecosystems.

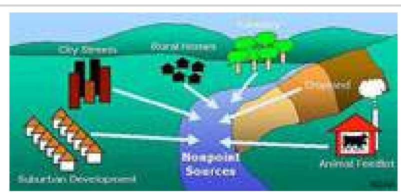


Figure 13.21. Sources of ocean pollution.

Measuring Primary Productivity

Primary Productivity is measured in biomass or in gC/m^2 day (or grams of carbon per square meter per day). Ocean biomass is measured by pulling fine nets to catch plankton and weighing/examining catch (however, smallest organisms pass through nets). Ocean biomass is also measured by **satellite**: 2 dimensions (i.e.: square meters per day). Satellites can detect levels of chlorophyll in seawater, but not far below the surface.

Question: How could this be a source of error in measuring biomass?

13.10: Global and Seasonal Distribution of Plankton Biomass

Global and Seasonal Distribution of Plankton Biomass

Figure 13.22 shows the net productivity of the oceans observed from satellite data. Figure 13.23 compares ocean productivity to regions on vegetation cover on land. In general, plants on land have access to more concentrated light, but the availability of water and nutrients are a factor of climate and geology. Although tropical forests account for a large volume of biomass, the volume is a fraction of the amount of biomass in the oceans because of the differences in surface area. Productivity in the oceans are influenced by atmospheric and oceanographic factors:

- **Tropics**: Reliable sunlight but the strong tropical thermocline prevents mixing of cold deep nutrient rich water. The warm water on top is too buoyant. The exception to this are coral reef areas.
- **Temperate:** Reliable sunlight and weak thermocline. Most productive zone. In California we get lots of production in the winter as that's when we get upwelling from our coastal winds.
- **Polar regions:** Lots of nutrients little or no thermocline. Sunlight limited only in the few months of summer, but is highly productive.

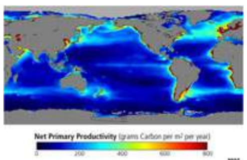


Figure 13.22. Net productivity in the oceans as observed from satellite data. Net primary productivity is measured in kilograms of carbon per meter^2 per year.

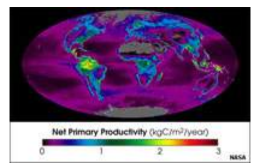


Figure 13.23. Net productivity is much greater on land (in tropical forested regions) than in the oceans, but the oceans cover a vastly larger area.

13.11: Examples of Satellite Evaluations of Ocean Productivity

Examples of Satellite Evaluations of Ocean Productivity

Figure 13.25 is a satellite composite image showing the Gulf of Mexico and East Coast of the United States. Warm water at the surface creates a strong thermocline preventing nutrient upwelling in the open ocean. However, nutrients from rivers and stream are abundant along coastal waters, allowing phytoplankton to proliferate.

Figure 13.26 compares sea-surface temperatures to chlorophyll productivity, revealing regions of upwelling along coastal California.

Figure 13.27 shows an image generated from data captured by NASA's Aqua satellite used a Moderate Resolution Imaging Spectroradiometer (MODIS). It shows a massive phytoplankton bloom off of the Atlantic coast of Patagonia (Argentina). Seven different spectral bands (visible light and infrared) were used to accent the differences in the plankton communities in the ocean (this is a false-color composite image).

These green and blue shades indicate phytoplankton blooms developed on the continental shelf off of Patagonia. This is where warmer, saltier coastal waters and currents from the subtropics meet the colder, fresher waters flowing up from the south. Where these currents collide turbulent eddies form, allowing nutrients to well up from the deep ocean. In addition, the nearby Rio de la Plata supplies nitrogen and iron-laden sediment into the sea just north of the area shown in the image.

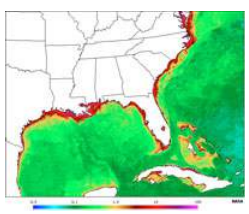


Figure 13.25.Productivity along the East Coast.

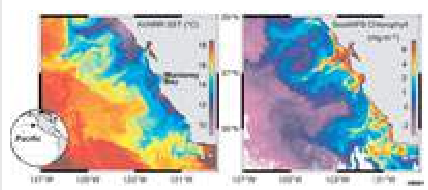


Figure 13.26. Productivity along coastal California

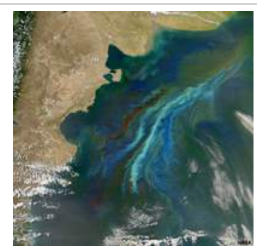


Figure 13.27. Phytoplankton blooms off of Patagonia (Argentina).

13.12: Quiz Questions - Chapter 13 - Primary Production of Life in the Oceans

1. This form of primary productivity that uses solar radiation. 99.9% of the ocean's biomass relies directly or indirectly on this process for food:
a. photosynthesis.
b. biosynthesis.
c. chemosynthesis.
d. metabolism.

2. A form of primary productivity that uses chemical reactions (involving mostly sulfur compounds) to generate food that do not involve energy from sunlight.
a. photosynthesis.
b. biosynthesis.
c. chemosynthesis.
d. metabolism.

3. A trophic pyramid exemplifies ***feeding levels within an ecosystem***. Planktonic herbivores would be considered:
a. Tertiary consumers.
b. Secondary consumers.
c. Primary consumers.
d. Primary producers.

4. Which of the following would NOT be considered a golden algae?
a. diatoms
b. coccolithopores
c. dinoflagulates
d. kelp

5. There are many species of seaweeds (macroscopic plants that can tolerate marine water), some of which are edible by humans. Seaweeds include types of:
a. Brown algae.
b. Green algae.
c. Red algae.
d. all of the above.

6. The top layer of the ocean (down to about 200 meters) is called the **neritic zone** on continental shelves and the **pelagic zone** in deeper open ocean settings. The top 200 meters of the ocean is:
a. part of the euphotic zone where all photosynthesis takes place.
b. the part of the ocean most likely to have a thermocline.
c. is mostly above the oxygen minimal zone (OMZ).
d. all of the above.

7. The bottom parts of the ocean that totally dark even during daylight hours is called:
a. the littoral zone.
b. the aphotic zone.
c. the epipelagic zone.
d. the benthic zone.

8. The depth in the oceans where respiration (consumption) equals photosynthesis production is called:
a. the CCD.
b. compensation depth.
c. Euphotic Zone.
d. Epipelagic Zone.

9. The region of the world oceans that has a strong thermocline that mostly prevents mixing of cold deep nutrient rich water with surface water is:
a. the tropical regions.
b. the temperate regions.
c. the polar regions.
d. The euphotic zone.

10. Nutrients are not like food, they are more like a ***fertilizer***. Major nutrients in need for biological activity include nitrogen, phosphorus, silicon, iron, zinc, and copper. Sources of nutrients include all EXCEPT which of the following?
a. Upwelling of waters from deep ocean
b. Rock weathering and erosion on land and the seafloor
c. Decaying organic matter floating in the ocean or sinking to the seafloor
d. Sunlight in the euphotic zone

CHAPTER OVERVIEW

14: Marine Environments

14.1: Marine Environments

Marine Environments

This chapter focuses on the physical, chemical, and biological factors affecting marine communities in the oceans and coastal waters.

What is a Marine Community?

A **marine community** is an **area** where a group of marine organisms live and interact with each other. An **ecosystem** is defined as a community involving the **interactions** or **interrelationships** of living and nonliving things in an **area**. Marine ecosystems have distinct groups of organisms and have characteristics that result from unique combinations of physical factors that create them. A **habitat** is the natural home of an organism. Some species can adapt to a variety of environmental settings. **Ecology** is the branch of biological sciences that deals with their relationships of organisms with one another and to the physical environments where they are observed.

Figure 14.1. A reef community in Hawaii.

Marine communities include different feeding (trophic) levels:

Tropic Levels	Organisms
Primary producers	include photosynthetic bacterial - plankton - plants **(discussed in Chapter 13)**
Primary consumers	**herbivores** (zooplankton)
Secondary consumers	**carnivores** and **detritus feeders** (i.e., small fish, crustaceans)
Tertiary consumers	**carnivores** (larger animals, i.e. tuna, sharks, birds, sea mammals, etc)

The term **food chain** is defined the hierarchical series of organisms that are each dependent on the next as a source of food. However, nature provides complexity that is better explained as a **food web**. A food web may have a variety of food chains that move energy and nutrients through an ecosystem. For instance, small or microscopic offspring may start as primary or secondary consumers when they are small, but they may become tertiary consumers if they survive to become large adult forms.

Figure 14.2. Food chains and food webs can be complex.

14.2: Definitions

Definitions

- **Planktonic:** applies to organisms that **float or drift** with flowing currents (zooplankton are animals, phytoplankton are plants.)
- **Nektonic:** applies to organism that actively move **swim** by their own means.
- **Pelagic**: means *relating to the open sea, chiefly shallow layers*. Planktonic and nektonic organisms live in **open water** (more in chapter 16).
- **Benthic:** means *relating to, or occurring at the bottom of a body of water* (oceans, lakes), relates to bottom-dwelling organism (more in chapter 15).

The term **benthic** applies to:
• **shoreline and nearshore environments** (**littoral** and **estuarine**)
• **littoral** (pertaining to the shore and very near shore of ocean or lake)
• **estuarine** (pertaining to transition from river to ocean settings)
• **neritic** (pertaining to the seabed in shallow ocean and deep water settings)
• **limnetic** (pertaining to lakes)

- **Terrestrial** refers to **land** environments (desert, mountain, rivers, etc) - some marine predators live in terrestrial environments.

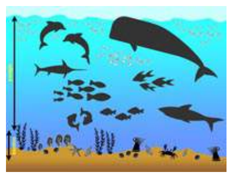


Figure 14.3. Benthic and pelagic zones.

Figure 14.4. Elkhorn slough, a tidal estuary in central California, has littoral, estuarine, neritic, and limnetic sub environments.

Feeding behaviors

* **Autotrophic:** Produce their own food (primary producers)
* **Heterotrophic:** Eat other things (living or dead) (consumers - primary, secondary, and tertiary).

Feeding strategies of heterotrophic marine organisms:
* **Filter feeding:** ex: shellfish
* **Deposit feeding:** Eat deposits of dead or decaying matter
* **Carnivorous feeding:** Capture and eat it!

Figure 14.5. Humpback whales and birds joining in on a feeding frenzy on smaller fish who were feeding on zooplankton.

14.3: Natural Factors Influencing Marine Life-

Physical factors:

a) **Temperature** (very significant!)

b) **Salinity** (also very significant!)

c) **Tides, Waves, Currents** (generally relates to the release of **energy** in the environment)

d) **Water Transparency**

e) **Nutrients**

f) **pH** (acidity and alkalinity)

g) **Pressure** (depth)

h) **Dissolved Gases**

i) **Environmental Stability**

Biological factors:

i) **Competition** for mates, food, and space

j) **Predators**

14.4: Physical Factors - Temperature

Temperature

Temperature governs the rate chemical and metabolic rates especially in cold-blooded organisms.
Many organisms are sensitive to changes in temperature and this results in **species zonation.**

Example—Different species of sharks: Sharks can be classified as tropical, temperate, or polar, depending on the surface temperature of the ocean region they inhabit.

Tropical sharks live year round in warm temperature waters (21° - 30° C, 69.8° - 86° F). Examples include nurse shark, the tiger shark, and the bull shark. They are only comfortable in warm waters where food is plentiful, so they remain there year-round without migrating.
Sharks in Temperate regions tolerate temperatures within a range (10°-21°C, 50-69.8° F). Sharks in temperate regions tend to migrate south in the winter and north in the summer and as their food sources move up and down the coast.
Sharks in Polar regions always stay in colder waters (below 5° C, 41° F). For example, Greenland sleeper shark is adapted to living under ice floes and will not migrate.

Figure 14.6. Hammerhead sharks live in tropical waters

Figure 14.7. Great white sharks live in temperate regions.

Temperature controls an organism's metabolism
For poikilothermic (or **cold blooded**) organisms: every 10° C rise in temperature doubles their metabolism. Most fish, reptiles, and invertebrates are cold blooded.
For homeothermic (or **warm blooded**) organisms: metabolism increases with decreasing temperature to stay warm. Only mammals and birds are warm blooded.
Some species have various degrees of **thermo regulation** - ability to raise or lower their body temperature. An example in fish is Opah an Blue Fin Tuna.

Figure 14.8. Polar bears are homeothermic and adapted to living on arctic ice flows.

14.5: Physical Factors - Salinity

Salinity

Salinity in the open ocean is typically in a tolerable range for most marine creatures living in **normal seawater** (about 3.5‰ [ppt]). However, salinity is variable near landmasses (i.e.: tide pools, river outlets and with depth).

Different organisms have different tolerances to salinity changes. For examples, some **bull sharks** can tolerate both freshwater and marine water settings. **Oysters** can't tolerate normal seawater because of predation and food supply. If drought shuts down the supply of freshwater, the water where the oysters are attached to the seabed may get too salty.

Many of the predators that feed on oysters can only tolerate normal seawater, and will only move in to feed on oysters when highest tides or storm surges flood oyster beds with normal seawater conditions.

	
Figure 14.9. Bull shark	Figure 14.10. Oysters

14.6: Physical Factors - Water Transparency

Water Transparency

Water has a high transparency. So many organisms use different strategies to survive predation.

Counter shading or **camouflaging** help organisms hide from predators.
• Animals that display counter shading are typically dark colored on top and light colored underneath.
• Animals that use camouflaging typically have skin or scales that match the habitat where they live and feed.

Migration into **darker areas during the day** and **lighter areas at dawn and dusk** is another means of survival.

Another consideration is clarity for photosynthesis.
• **Photic zone**: The upper part of the ocean where sunlight penetrates (down to ~3,300 feet in very clear water!).
• **Euphotic Zone**: upper ½ of photic zone where most primary production occurs.

Figure 14.11. Trout displaying counter shading.

Figure 14.12. Goosefish displaying camouflaging.

14.7: Physical Factors - Nutrients

Nutrients

Nutrients: are not "food," but are more like vitamins and minerals (fertilizer) essential to life functions.

• Aids in the production of food (primary production).
• Nutrients are essential to support photosynthesis—the process that provides sugars (energy) to support all other life processes.
• There are many more intermediate processes requiring nutrients to produce other complex organic compounds (proteins, carbohydrates, fats, etc).

Sources of Nutrients: Upwelling and continental weathering & erosion
Primary nutrients = nitrates and phosphates
Secondary = minerals: calcium, iron, zinc, sodium, and many others.

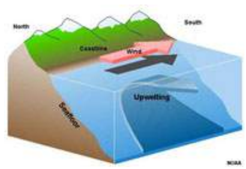


Figure 14.13. Upwelling brings nutrients to the surface where they are utilized in **primary production**.

14.8: Physical Factors - pH (acidity and alkalinity)

pH (acidity and alkalinity)

Seawater averages about 8.1 on a scale from 1 – 14 (1 is acidic, 14 is basic and 7 is neutral).
Seawater is a **buffered system** meaning it is controlled in a range.
If it gets too acidic it dissolves $CaCO_3$, if its too basic it precipitates $CaCO_3$

Seawater becomes slightly more acidic near the **CCD (carbonate compensation depth)**. Animals with carbonate shells and tests need slightly basic (alkaline) water in order to precipitate and maintain their shells. This is a potentially HUGE problems for the oceans with the increasing accumulation of CO_2 in the atmosphere and oceans.

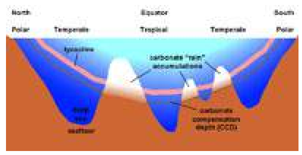


Figure 14.14. Carbonate compensation depth (CCD)

14.9: Physical Factors - Pressure

Pressure

Pressure is the same inside an organism as outside.
Organisms at great depths must be able to withstand great internal pressures.
Many species of fish have gas-filled bladders in order to maintain buoyancy.

Sperm whales hold the deep diving record for cetaceans at 3050m (10,000 ft). They can dive for over one hour in search of their main prey—squid and some fish.

Humans get the bends if they rise to the surface too quickly (causing nitrogen to boil out of the blood). The same happens to deep water fish when they are brought to the surface.

Figure 14.15. Sperm whales can dive to great depths in search of food.

Figure 14.16. Nautilus controls pressure in it shell and changes its buoyancy.

14.10: Physical Factors - Dissolved Gases

Dissolved Gases

There must be sufficient CO_2 for plants and O_2 for animals or they must: move, adapt or die.
Most ocean pollutants remove the waters ability to hold CO_2 or O_2.

Hypoxia and **eutrophification** are discussed in chapter 8.

Figure 14.17. Fish killed by hypoxia (lack of O_2).

14.11: Physical Factors - Environmental Stability

Environmental Stability

The open ocean is generally a very stable environment compared to shallow and nearshore environments where the factors listed above may vary wildly with weather changes and other natural and artificial causes, both physical or biological in nature. Destabilizing forces include the impacts of superstorms, undersea landslides (causing turbidity flows), and hypoxia. Reefs and coastal ecosystems can be destroyed by the effects of hurricanes, but like wildfire on land, sea life can and will re-establish itself if the physical factors (described above) normalize. Coastal communities

(ecosystems) can be heavily damaged by superstorms, but many species have evolved means to adapt to occasional events, and even take advantage of the aftermath.

Figure 14.18. Hurricane Katrina

14.12: Biological Factors

Biological factors:

Competition for mates, food, and space

Competition may be between members of a species or between species

Predators

Too many predators can wipe out a community; not enough predators cause population explosions, resource exhaustion, and collapse.

Figure 14.19. Predator and prey (seal with fish meal).

14.13: Seasonal Impacts of Food Resources in the Marine Environment

Seasonal Impacts of Food Resources in the Marine Environment

Primary productivity is a primarily function of sunlight an available nutrients. Figure 14.20 shows the primary productivity of the three zones: tropical, temperate, and polar.

Primary productivity in the **tropical zone** is limited not by sunlight it receives, but because a thick thermocline prevents nutrients from moving up in to the surface in the photic zone. Primary productivity in the **polar zones** are most intense in the summer months when both sunlight and nutrients are available.

Primary productivity in the **temperate zones** have two peaks in the spring and fall. Productivity is limited in the summer months because a thermocline builds up, shutting down the nutrient supply to the upper ocean. Primary productivity increases in the spring when sunlight increases and before a strong thermocline shuts down the supply of nutrients. Productivity also increases in the fall when cooler weather breaks up thermocline (allowing upwelling of nutrients) while ample sunlight is still available to support phytoplankton growth.

Impacts on Consumers

Primary, **secondary**, and **tertiary consumers** follow the cycles of primary productivity described above. A proliferation of **zooplankton (primary consumers)** occurs when their food (phytoplankton) becomes increasingly available. Zooplankton populations grow at the ultimate expense of the phytoplankton, and their populations peak, phytoplankton first, then zooplankton next. Secondary and tertiary consumer populations consume these recourses, and then migrate to search of other sources of food following the **blooms** in productivity northward in the spring and then returning south for the winter.

Figure 14.21 compares the **biomass** of phytoplankton and zooplankton for the tropical, temperate, and polar zones through the months of year. Figure 14.22 compares the availability of nutrients and sunlight with biomass of phytoplankton and zooplankton for the temperate zone through seasons of the year.

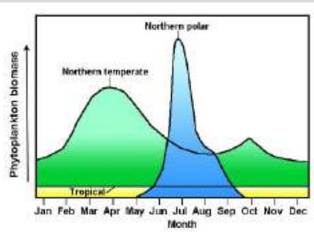


Figure 14.20. Primary productivity in 3 zones.

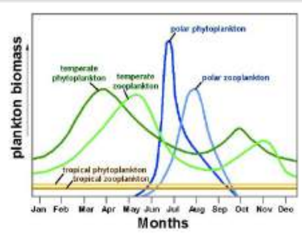


Figure 14.21. Plankton biomass by season in three zones.

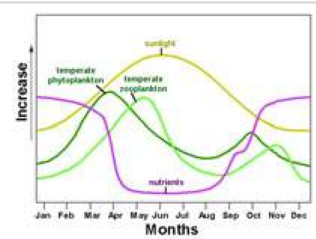


Figure 14.22. Temperate zone productivity by seasons.

14.14: Divisions in the Marine Environment

Divisions in the Marine Environment

The Pelagic (open sea) environment is divided into the **Neritic** and **Oceanic Provinces**.
Neritic (nearshore zone): Extends from shore with water less than 200 meters. It is subdivided into two zones:

- **Littoral (intertidal) zone**: Interval between high and low tides
- **Sub-littoral zone:** Below the littoral zone to a depth of 200 meters.

Figure 14.23. Coral reef in the neritic zone.

Oceanic Provinces (based on depth)

- **Epipelagic:** Water less than 200 meters
- **Mesopelagic:** Water between 200 and 1000meters
- **Bathypelagic:** Water between 1000 and 4000meters
- **Abyssopelagic**: Water deeper than 4000 meters
- **Hadal:** Depths below 6000 meters in deep sea trenches

Sunlight penetration has its own divisions (Figure 14.25):

- **Photic zone:** The upper part of the ocean where sunlight penetrates
- **Euphotic Zone:** upper ½ of photic zone (usually to about 100 meters)
- **Dysphotic Zone**: lower ½ of photic zone
- **Aphotic Zone**: No light penetrates

Figure 14.24. Depth zones

Figure 14.25. Photic Zones

14.15: Zoning and Extinction in Marine Communities

Both **physical and biological factors** result in **zoning** of organisms in a specific environment.

Each group of organisms are affected by **physica**l and **biological factors** (listed above). These conditions exist within geographically definable areas ranging from large (entire oceans) to micro environments (such as a rock outcrop on a beach).

Extinction results when all members of a species dies off. Die offs happen when a local community is disrupted by changes in physical and biological factors. A species will survive when those factors return to tolerable conditions, and a nearby population can supply offspring to repopulate a location. With climate change, many areas are loosing species, causing local extinctions. Another factor is the introduction of non-native species that either out-compete native species, or modify the environment that make a habitat intolerable for survival of native species.

Figure 14.26. A lone rock on a beach is an example of a micro environment.

14.16: Carrying Capacity in Marine Communities

Carrying capacity is the stable number of individuals in a community. Carrying capacity has limiting factors including living space, food availability, and the physical and biological factors (previously discussed). For example prey and predator populations have limits within a geographic area.

Example: Raise the temp 10 degrees C for a group of **poikilothermic** organisms with a limiting factor of food and hold other factors constant -- what is the most likely result?
Same problem but with **homeothermic** organisms?

Changes in physical and biological factors **create opportunity** and **misfortune/bad luck**, operating under **natural selection** (**Adapt, move, or die!**)

Local die-offs happen frequently. Die offs occur because of seasonal changes (warm vs. cold), changes on food supply, predation, major storms, or any of the other natural physical or biological factors that change in an environmental setting. Species that survive these events have adaptations that allow them to survive, such has having abilities such as migration, hibernation, or producing seeds or eggs that can survive and create a new generation of offspring even when all adult members of a species are wiped by a seasonal or catastrophic event. Many species will migrate from suitable birthing grounds in one region to another location with the capacity to feed a population in another. Examples include migrations of many birds, whales, and other animals that migrate from the tropical regions in the winter season, to polar regions when the receive the greatest sunlight (summer in the northern hemisphere; winter in the southern hemisphere).

Survival or Extinction (Past and Present)

When **all viable reproducing members** of a species or community of species die off, it is **extinction**. Extinction is a natural process. ***Most fossils preserved and recovered from past geologic time periods represent species that do not exist in the modern world.*** These ancient species have either undergone extinction, or through time (many generations), have produced offspring that have adapted and changed into new species with new characteristics. For example, members of a species may become geographically isolated from a greater population. Examples include:

- species that are trapped and then isolated islands in the oceans (such as Hawaiian Islands).
- species trapped near isolated sources of water when climates change from wet to desert conditions.
- species that become isolated on nearshore land masses by sea-level rise.
- species that survive on isolated mountain ranges that are separated from a large regional population when climate change occurs.
- species surviving patches of unglaciated land that were not destroyed advancing continental glaciers.
- streams river systems become blocked or change course, isolating or shifting a population.

In many cases, when ice ages occurred, some species survived in a refugia. A **refugia** is an area where special environmental circumstances have allowed a viable population of a species to survive after extinction occurred in the surrounding area.
Species that survive in refugia can become the only survivors where the rest of the species could be wiped out by disease, predation, or other environmental catastrophes.

Exotic and Invasive Species

The name **exotic species** applies to any plant or animal species introduced into an area where they do not occur naturally. Most plants and animals sold in plant and pet stores are exotic species. Humans have both intentionally and unknowingly introduced **exotic species** into environments that native species are unprepared to cope with. However, some of these species can become **invasive species** when they escape, reproduce successfully, and spread through a new environmental setting. These species can consume, threaten, and displace native species. Examples include introduction of species sold in pet and plant stores that have either escaped or have been intentionally turned loose into a natural setting. Many countries now have laws and enforcement are trying to cope with the sale and the prevention of the introduction invasive species. Note that not all all exotic species are considered invasive species; most exotic species would not survive without some human intervention. Examples of invasive species include the introduction of lionfish introduced into the Caribbean Sea (Figure 14.27), pythons and other snakes into south Florida's Everglades and other coastal areas, carp and other "sport fishing" species into lakes and rivers practically everywhere.

Everywhere humans have moved around the world, particularly in the last two centuries, humans have unintentionally brought **invasive species** with them. Examples include rats, feral cats and pigs, cockroaches, mosquitoes, snakes, grasses and other ***weeds***, and many other invasive species of plants and animals (both aquatic and terrestrial). In many places around the world invasive species are contributing to widespread habitat destruction and the displacement or annihilation many species, and including extinctions.

Figure 14.27. Lionfish, native to the tropical Pacific, were introduced the Caribbean by pet owners who purchased them and then decided to turn them loose when they didn't want them anymore. In the tropical parts of the Atlantic Ocean basin, these toxic beasts have no predators to control their population, and they are contributing to wiping out populations of some native species.

Unfortunately, human activities are now the ***primary cause of extinctions*** in many parts of the world. Global environmental changes, expansion of agricultural lands and urban development, and irresponsible exploitation are driving forces of extinction.

In our modern world, zoos, arboretums, and wilderness preserves are becoming the only **refugia** for many species.

Collectively, we must face the fact that in most places around the world, **without sustainability, *humans are both exotic and/or invasive species*!**

14.17: Distribution of Organisms

Distribution of Organisms: How are they distributed throughout an environmental setting?

i. **Random**: rare in marine environment
ii. **Uniform**: more common than random. Examples: eels in holes or penguins on nests
iii. **Clustered**: most common **schooling fish**. Examples clusters of barnacles and mussels on rocks.
iv. **Zoned**: species or community of species living together in a limited geographic range defined by physical and biological factors. Examples: oyster reef along an estuary with a limiting range in salinity.

Most organisms in marine environment are **ZONED** or **CLUSTERED**.

Figure 14.28. School of unicorn fish on a Hawaiian reef.

14.18: Symbiotic Relationships

Symbiotic Relationships

- **Mutualism**: benefits both host and symbiont.
  - Example: Anemone and the anemone fish; fish cleans and feeds anemone, stays with anemone for protection – fish can't be stung (clown fish) (Figure 14.29)
- **Commensalisms**: no effect on host, benefits symbiont.
  - Example: Shark and pilot fish (pilot fish eats leftovers). Or barnacles attached to a humpback whale (Figure 14.30).
- **Parasitism:** Harms host, benefits symbiont.
  - Examples: Parasites in tuna. Humans catching and eating tuna (with parasites).

	
Figure 14.29. Clown fish living in a mutual relationship with a sea anemone.	Figure 14.30. Barnacles attached to a humpback whale.

14.19: Evolution in Marine Environments

Evolution in Marine Environments

Physical, chemical, and biological factors drive evolution in marine communities in the oceans and coastal waters. **The life mission of any species is to eat, survive, and reproduce**(Figure 14.31). Every species is adapted to a limited range of physical, chemical, and biologic factors. When the conditions of the physical environment are ideal, a species, or community of species, can thrive and expand. However, if environmental changes occur that affect the range of factors they can tolerate, populations will decline from such factors of loss of body mass, reduced reproduction, diseases, and attrition from competition. Collapses in populations result in isolation of groups of individuals. These isolated groups, if they don't go extinct, become the nucleus of a subsequent population that may evolve into a new species over time, perhaps better adapted to expand their populations when environmental conditions become favorable. The ability to move or migrate in search of more favorable conditions is an important factor. Charles Darwin's famous synopsis, ***survival of the fittest*** basically means: if you can't compete, your options are "adapt, move, or die!"

Figure 14.31. How evolution works.

14.20: What is the Carrying Capacity for Humans on Earth?

What is the carrying capacity for Humans on Earth?

strong>Human consumption and interactions are the most influential driving force affecting species evolution and extinction in the world today. Humans have been extremely successful in their ability to adapt to new environments and to "eat, survive, and reproduce." Humans have essentially eliminated many **threats** (physical and biological) that have allowed the global human population to rise (through advances in agriculture, medicine, housing, transportation, technology, etc.). However, these eliminations of threats have often resulted in new threats. Consider that it took all of human history until about the year 1804 to reach a population of 1 billion. The next billion was added around 1927. Since then the global population is doubling with each generation. The amount of material and space consumed by humans have also been roughly doubling with each generation.

The problem is that Earth has limited resources. **Every human has an impact** related to both environmental changes and to competition (with other humans and with other species). The environmental effects of unmitigated human consumption of land and natural resources by the growing human populations around the world are becoming increasingly obvious. Can "we" (humanity) collectively adapt? What role do we have as individuals in facing global environmental problems? What are the roles of governments, corporations, and societal organizations? What defines "success" and "failure" (and by "who")?

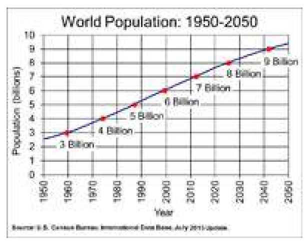


Figure 14.32. Past and projected future human population growth. Question: how many humans can the world sustain, and at what cost to the environment?

14.21: Quiz Questions - Chapter 14 - Marine Environments

1. The oceanographic term that means **floating** or **drifting** - relating to both microscopic and macroscopic organisms is:
a. plankton or planktonic.
b. nekton or nektonic.
c. benthos or benthic.
d. poikilothermic or homeothermic.

2. The oceanographic term that means **swimmers** - relating to organisms including fish, squids, and marine mammals is:
a. plankton or planktonic.
b. nekton or nektonic.
c. benthos or benthic.
d. littoral or limnetic.

3. The oceanographic term that means **open-water environment** - applies to organisms that live in open-water settings is:
a. pelagic.
b. planktonic.
c. estuarine.
d. limnetic.

4. The oceanographic term that means **lives on the seabed** - includes sessile or mobile organisms.
a. plankton or planktonic.
b. nekton or nektonic.
c. benthos or benthic.
d. littoral or limnetic.

5. The ability of an organisms to blend in (hide or disguise) in an environment using special coloration, patterns, or body shapes:
a. caumoflage.
b. pelagic.
c. homeothermic.
d. top shading.

6. A common method of hiding from predators and prey where the top of the organism is dark colored and the bottom is light colored:
a. caumoflage.
d. poikilothermic.
c. top shading.
d. homeothermic.

7. Animals that are cold blooded, matching the temperature of the environment are called:
a. neritic.
b. nektonic.
c. homeothermic.
d. poikilothermic.

8. Animals that are warm blooded, using food energy to raise the temperature of their bodies above the temperature of the environment are called:
a. homeothermic.
b. pelagic.
c. neritic.
d. poikilothermic.

9. Salinity is one of the factors the factors that many species have a tolerance range within which they can survive. Seawater has about 35 grams of salt per liter of water. pH is another factor. Many species can only tolerate ***normal*** seawater. What is the pH of normal seawater?
a. 6.5
b. 7.0
c. 8.1
d. 10.0

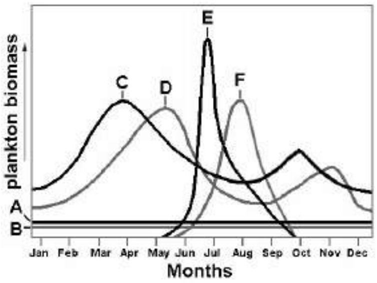
10.Seawater is a **buffered system** (meaning it's pH is naturally controlled in a range). If it gets too acidic then:
a. $CaCO_3$ dissolves.
b. $CaCO_3$ precipitates.
c. water pressure increases.
d. water temperature decreases.

11. Many species have symbiotic relationships with other organisms. When two or more species benefit each other it is called:
a. mutualism.
b. parasitism.
c. commensalism.
d. predation.

12. The bottom parts of the ocean that totally dark even during daylight hours is called the:
a. littoral zone.
b. aphotic zone.
c. epipelagic zone.
d. benthic zone.

13. The stable number of individuals in a community within a confined geographic region is called:
a. carrying capacity.
b. predator and prey relationship.
c. zoning.
d. the extinction boundary.

Questions 14 to 19 relate to the illustration below that illustrates primary production in the Pacific Ocean along the West Coast of North America. The six lines (3 pairs) show changes in plankton biomass in tropical, temperate, and polar regions during months of a yearly cycle.



14. Which lines represent phytoplankton production?
a. lines A and B
b. lines C and D
c. lines B, D, and F
d. lines A, C, and E

15. Which lines represent zooplankton production?

a. lines A and B
b. lines C and D
c. lines B, D, and F
d. lines A, C, and E

16. Which lines represent polar regional production?
a. lines A and B
b. lines E and F
c. lines B, D, and F
d. lines A, C, and E

17. What would explain the two **peaks** in biomass production represented by line C?
a. An increase in sunshine occurs during summer months.
b. Periods of coastal upwelling in the spring and fall cause blooms in phytoplankton production.
c. Periods of coastal upwelling in the summer and winter cause increases in zooplankton production.
d. Warm weather in the fall and spring seasons occur along coastal California.

18. What would explain the shape of lines A and B?
a. There is more zooplankton production in the oceans than phytoplankton.
b. Tropical regions have a thermocline year round that prevent upwelling of nutrient rich waters.
c. Polar regions are too cold to support primary production.
d. There is no primary production in the region of the ocean represented by lines A and B.

19. What would explain the pattern of biomass production for lines E and F?
a. Biomass production is greatest in tropical regions during the summer months.
b. In polar regions, there is a bloom of zooplankton proceeding an increase in phytoplankton.
c. In polar regions, there is a bloom of phytoplankton proceeding an increase in zooplankton.
d. Zooplankton and phytoplankton migrate north from California to Alaska in the summer months.

20. An area where special environmental circumstances have allowed a viable population of a species to survive after extinction occurred in the surrounding area is called:
a. acatastrophe.
b. a exotic species habitat.
c. an invasive species habitat.
d. a refugia.

CHAPTER OVERVIEW

15: Marine Communities (Invertebrates)

15.1: Marine Communities in Benthic Environments

Marine Communities in Benthic Environments

This chapter focuses on animals that are grouped as lower-level organisms in the **benthic environment**, specifically **invertebrates** —most of which are **benthic** animals that live attached on or near the seabed in the open ocean or coastal marine environments. The next Chapter 16 focuses on **vertebrates** and life in the **pelagic** environment.

Review: General classifications of Living Things

Taxonomy is the system of classifying and naming organisms (reviewed in Chapter 2). **Carolus Linnaeus** was first to development of a hierarchical system of classification of nature (biological organisms, present and past) .

Today, this system includes seven **taxa: kingdom, phylum, class, order, family, genus, and species**. (These are constantly being split into additional taxa levels as discoveries are made. Look at the example of humans.

Taxa							**Example: Taxonomy of Humans**
kingdom							**kingdom: Animalia**
	phylum						**phylum: Chordata** (subphylum: **vertebrata**)
		class					**class: Mammalia** (subclass: Theria) (Infraclass: Eutheria)
			order				**order: Primates** (suborder: Anthropoidea)
				family			(superfamily: Hominidae) **family: Hominidae**
					genus		***Homo***
						species	**sapiens**

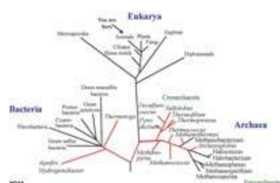


Figure 16.1. Bioscientists are constantly reclassifying life forms as discoveries and new information becomes available. The term **domain** has been added to apply to **super kingdoms** subdivision status based largely on modern discoveries in microbiology - still under debate!This figure shows one of the more complex diagrams showing all the current know domains and lineages of life forms on Earth.

Kingdoms of Life

KINGDOMS	Examples
Monera	Bacteria/algae (more complex classification of monera is illustrated in Figure 16.1)
Protista	Forams/amoebas
Fungi	Mushrooms, molds
Plantea	Ferns, mosses, flowering plants (all are **Autotrophs**, **photosynthetic)**
Animalia	includes **Invertebrates** and invertebrates (all are **Heterotrophs**)

What is a Benthic Community?

• A benthic community is an **area** where a group of marine organisms live and interact with each other on, near, or within the seafloor (or in any water setting including lakes and rivers).

Benthic or **benthos** means “relating to, or occurring at the bottom of a body of water (oceans, lakes).“

Benthic environments include:
• **littoral** (includes shore or nearshore)
• **neritic** (seabed in shallow ocean/continental shelf)

- **limnetic** (pertaining to lakes)
- **estuarine** (pertaining to transition from river to ocean settings)
- **sub-littoral** (Below the littoral zone to a depth of 200 meters)
- **sub-neritic** (below 200 meters, include continental slope, continental rise, abyssal plain and trench settings).

Figure 15.1. Shells collections from shorelines reveal information about benthic communities.

15.2: Marine Animals in Benthic Environments - Invertebrates

Invertebrates

Invertebrates are animals without backbones.

Invertebrates inhabit pelagic, benthic, and terrestrial environments. The majority of animal species that inhabit benthic environments are **invertebrates.** These organisms feed on other benthic organism (plants and animals), pelagic organisms (small fish and plankton forms), and decaying matter. These animals are, in turn, eaten by a host of pelagic animals (secondary and tertiary tropic feeders).

PHYLUMS	Examples
Protozoa	Single-celled animals (microbes): single-celled zooplankton, ciliates, flagellates, amoebas
Porifera	Sponges – filter feeders
Coelenterada	Coral, Jellyfish, Anemones
Annelida	Worms
Mollusca	Bivalves, squid, octopus, nautilus, gastropods (things with shells or large cavities), (extinct varieties: cephalopods, belemnites, ammonites)
Brachiopoda	Have two valves, but valves are on top and bottom
Arthropoda	Crabs, shrimp, scorpions, and spiders (trilobites, eurypterids)
Echinodermata	Sea Stars, urchins and sea cucumbers (spiny skin)

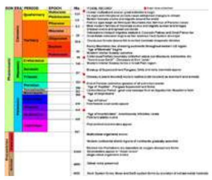


Figure 15.2. Geologic Time Scale with summary of major events and appearance of plant and animal groups in the geologic record.

15.3: Marine Animals in Benthic Environments - Protozoa

Protozoa

Protozoans are single-celled animals (microbes). In the ocean environment they have the role of primary consumers in the food chain (they are zooplankton).

Protozoa are a diverse group of unicellular eukaryotic organisms. Historically, protozoa have been defined as single-celled organisms with animal-like behaviors, including motility (able to move) and predation. Protozoan that are major contributors to the food chain and to marine sediments include foraminifera and radiolarians.

Figure 15.3. Many foraminifera have calcareous skeletons that accumulate as calcareous sediment.

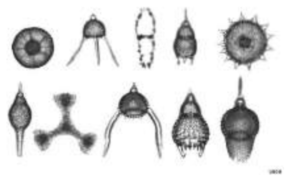
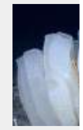


Figure 15.4. Radiolarians have siliceous tests that accumulate as siliceous sediment.

15.4: Marine Animals in Benthic Environments - Porifera

Porifera

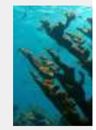
Poriferans are “**sponges**.” They are among the oldest known animal fossils, dating from the Late Precambrian. The fossil record exceeds 900 genera. There are about 5,000 living sponge species in three distinct groups: ***Demospongia*** (soft sponges), ***Hexactinellida*** (glass sponges), and ***Calcarea*** (calcareous sponges). **Sponges are filter feeders**. Sponges have tiny pores in their outer walls through which water is drawn in. Cells within sponge walls filter plankton from the water pumped through the body and out other larger openings.

Examples of Sponges			
			
Figure 15.5. Branching tube sponge (soft sponge)	Figure 15.6. Barrel sponge (soft sponge)	Figure 15.7. Calcareous sponge	Figure 15.8. Glass sponge

15.5: Marine Animals in Benthic Environments - Coelenterada

Coelenterada

Coelenterates include jellyfishes, sea anemones, corals, and hydra. They are among the most ancient multicellular organisms, appearing in Late Precambrian time. All coelenterates are aquatic, mostly marine. Coelenterates are animals that have very simple tissue organization, with only two layers of cells, external and internal. They are characterized by a single hollow internal cavity serving for digestion, excretion, and other functions and having tentacles on the oral end. radially symmetrical body arrangement. Coelenterates have a network of nerves is spread throughout the body. Many forms exhibit **polymorphism**, where individuals with different body arrangements are present in a colony for different functions. Coelenterates generally reproduce asexually by budding, though sexual reproduction does occur in some groups.

Examples of Coelenterates			
			
Figure 15.9. Anemone	Figure 15.10. Anemone	Figure 15.11. Coral polyps	Figure 15.12. Pink soft coral
			
Figure 15.13. Jellyfish	Figure 15.14. Jellyfish	Figure 15.15. Moon jellyfish	Figure 15.16. Elkhorn coral

15.6: Marine Animals in Benthic Environments - Annelida

Annelida

The annelids also known as **segmented worms**, are a large phylum, with over 17,000 species. They have soft bodies with no legs or hard skeleton. Annelid bodies are divided into many little ring-like segments. There are many other kinds of worms, but only annelids are segmented this way. Most marine species are polychaetes (two mostly terrestrial groups are earthworms and leaches). Annelids have bilaterally symmetrical, triploblastic (having three layers of flesh--ectoderm, mesoderm, and endoderm),; they have an internal body cavity with a mouth and anus), invertebrate organisms. They also have parapodia used for locomotion. Many species can reproduce sexually and asexually. Polychaetes produce planktonic larvae. Because they are soft-bodied, fossils are rare. Annelids are known from the Cambrian Period.

Examples of Annelid Worms			
			
Figure 15.17. Fireworm	Figure 15.18. Christmas Tree Worms	Figure 15.19. Tubeworms	Figure 15.20. Flatworm

![LibreTexts logo]

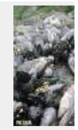
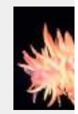
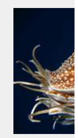
15.7: Marine Animals in Benthic Environments - Mollusca

Mollusca

Mollusca (or **mollusks**) are a very diverse groups of animal with at about 85,000 living species. Mollusks are the largest marine phylum, comprising about 23% of all known marine organisms. Mollusks include clams, scallops, oysters, mussels, limpets, chitons, and snails (snails are gastropods—the account for about 80% of invertebrate species). **Cephalopods** are mollusks and include octopuses, squid, cuttlefish, and nautilus.

• Mollusks all have unsegmented soft bodies with a "head" and a "foot" region (they may not look like a head or foot!).
• Often their bodies are covered by a hard exoskeleton, as in the shells of snails and clams or the plates of chitons.
• Many have shells, either calcareous, or made of proteins and chitin.
• Most mollusks have eyes.
• Mollusks have a mantle with a body cavity (used for breathing and excretion), and the presence of a radula (something tongue-like).
• All mollusks larvae nervous system, blood circulation system, and often complex digestive system.
• All produce eggs that emerge as larvae or miniature adults.

Mollusks appeared in the Cambrian Period and have diversified into their multiple forms. A large group called **ammonites** dominated the oceans during the Mesozoic era, but vanished with many other species at the K/T Boundary extinction event. Their distant relatives, **squids**, that do not have calcareous shells, survived the K/T extinction event. Another distant relative, the **nautilus**, also survived the K/T event.

Examples of Mollusks			
			
Figure 15.21. Clams	Figure 15.22. Scallop	Figure 15.23. Oysters	Figure 15.24. Mussels
			
Figure 15.25. Giant clams	Figure 15.26. Limpet	Figure 15.27. Chiton	Figure 15.28. Nudibrach
			
Figure 15.29. Gastropod	Figure 15.30. Conch	Figure 15.31. Cowrie	Figure 15.32. Nautilus
			
Figure 15.33. Octopus	Figure 15.34. Squid	Figure 15.35. Ammonite (extinct)	Figure 15.36. Belemnites (ext

15.8: Marine Animals in Benthic Environments - Brachiopoda

Brachiopoda

Brachiopods are marine animals that have hard **valves** (shells) on the upper and lower surfaces (different than bivalve mollusks that have a left and right shell arrangement). Brachiopod valves are hinged at the rear end so that the front can be opened for feeding or closed for protection. Brachiopod have a stalk-like pedicle that projects from an opening in one of the valves that attaches the animal to the seabed. Brachiopods appeared in the early Cambrian, and diversified in stages throughout the Paleozoic Era. One group, *Lingula*, has been around since the Early Cambrian (Figure 15.37). At their peak the brachiopods were among the most abundant filter-feeding and reef-building groups of organism, but their significance diminished after the great extinction at the end of the Permian Period.

			
Figure 15.37. Lingula	Figure 15.38. Brachiopod (Ordovician)	Figure 15.39. Brachiopod (Mississippian)	Figure 15.40. Brachiopod (Paleo

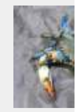
15.9: Marine Animals in Benthic Environments - Arthropoda

Arthropoda

Arthropods include **insects**, **arachnids** (spiders), **myriapods** (millipedes, centipedes), and **crustaceans** (lobsters, crabs, shrimp, and barnacles). **Only crustaceans are abundant in the marine environment.**

Arthropods have an exoskeleton (external skeleton), a segmented body, and jointed appendages (limbs) and cuticle made of chitin, often mineralized with calcium carbonate. The exoskeletons inhibits growth, so arthropods replace their rigid cuticle periodically by molting. Most species have compound eyes.

Arthropods appeared in the Cambrian period with **trilobites** a dominant group throughout the early Paleozoic Era. **Eurypterids** (sea scorpions) grew to over a meter in length in the Silurian Period. Most Paleozoic forms vanished at in the end of the Permian extinction event, but they have since successfully diversified into inhabit nearly all of Earth's environmental settings. All insects are arthropods, but not all arthropods are insects. Amazingly, biologists estimate there may be between 6 to 10 million species of insects, but there are none known that live in the marine environment.

Examples of Arthropods			
			
Figure 15.41. Crayfish	Figure 15.42. Horseshoe crabs	Figure 15.43. Blue crab	Figure 15.44. Dungeness crab
			
Figure 15.45. Krill	Figure 15.46. Tiger shrimp	Figure 15.47. Mantis shrimp	Figure 15.48. Blue Crab
			
Figure 15.49. Ghost crab	Figure 15.50. Spiny Lobster	Figure 15.51. Trilobite (Ordovician)	Figure 15.52. Eurypterid (Silu

15.10: Marine Animals in Benthic Environments - Echinodermata

Echinodermata

Echinoderms are marine animals recognizable by their (usually five-point) radial symmetry. Echinoderms include starfish, sea urchins, sand dollars, and sea cucumbers, and crinoids (sea lilies). Echinoderms are found at every ocean depth. The phylum contains about 7000 living species. There are no known freshwater or terrestrial species. They are one of the groups of organisms that successful proliferate in the deep-sea environment.

Crinoids have “flower-like” crowns that filter plankton. The crowns are connected to stocks attached to the solid sea floor (making them “sessile” organisms). Other echinoderms are mobile, capable of moving to avoid prey, seek prey, or adapt to changing conditions on the seafloor.

Most echinoderms appear to have a “five sided” or pentagonal or star-shaped appearance (it is really bilateral symmetry). Sand dollars and sea biscuits have small spicules similar to sea urchin spines. They use them to move and to work food toward their mouth-like openings.

Echinoderms first appear in abundance in the early Paleozoic Era. Echinoderms have **ossified** skeletons (composed of calcium carbonate), and contributed massive amounts of biogenous sediments to many of the world's ancient massive limestone deposits.

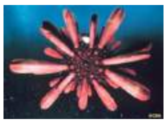
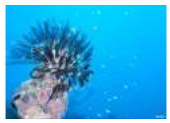
	

Figure 15.53. Urchin	Figure 15.54. Crinoid	Figure 15.55. Starfish	Figure 15.56. Brittle Star
			
Figure 15.57. Sea cucumber	Figure 15.58. Sand Dollars	Figure 15.59. Crinoids	Figure 15.60. Sea Biscuit

15.11: Rocky Intertidal Zonation

Rocky Intertidal Zonation

Species are either:
• Attached to bottom (e.g., anemones, corals)
• Move over seafloor (e.g., crabs, snails)

Rocky shores subdivisions include:

Spray and Upper Tide Zone • Harsh environment - few organisms • Experiences large temperature and salinity changes • Both Marine and Land Predators
Middle Tide Zone (Transition Zone) • More Species Diversity • More Organisms, most move with the tides • Seaweeds, limpets, chitons, mussels attached to rocks
Low tide zone • Life is easy here! • Stable temp/salinity • Lots of Species Diversity • Space is limited

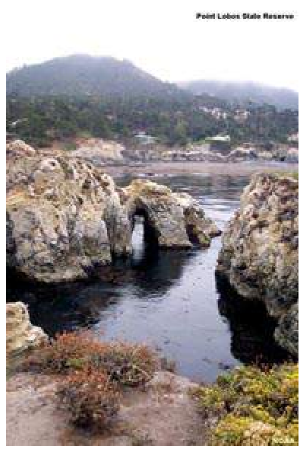


Figure 15.61. Rocky shore tide pool (Point Lobos, CA).

15.12: Communities on Sandy Beach Shores

Communities on Sandy Beach Shores

* **Sandy Beach Intertidal Zone**
• No stable, fixed surface
• Burrowing provides more stable environment
• Less risk of temperature extremes and drying out

Figure 15.62. Mussels on an isolated rock on a sandy beach.

Burrowing invertebrates include: **Mollusks** (with a soft body, hard shell—most, not all) (clams and mussels most common); **Worms** (annelids) and **Sand Crabs.**

Figure 15.63. Most sandy beaches appear deceivingly barren of marine life.

15.13: Shallow Offshore Benthic Communities

Shallow Offshore Benthic Communities

Shallow offshore benthic communities include:

- **offshore sand bars** (mostly inhabited by burrowing organisms)
- **rocky bottoms** (host many attached organisms)
- **coralline reefs** (complex, self-constructing communities).

Shallow offshore benthic communities are described as rich ecosystems because of the diversity and abundance of organisms in some of these environmental settings.

Figure 15.64. Northern Europe rocky bottom community

15.14: Kelp and Kelp Forests

Kelp and Kelp Forests

Kelp attaches to **rocky bottoms**.
Kelp grow up to 0.6 meters (2 feet) per day—one of the world's fastest growing species.
Kelp can live as solitary plants to forests several miles long.
Individual plants can grow up to 175 long.
Kelp provides shelter for other organisms.

Figure 15.65. Kelp "forest"

Figure 15.65. Offshore kelp bed along the California coast.

15.15: Coral Reefs

Coral Reefs

Coral reefs are located in tropical settings.
• Reefs require **warm, clear, and shallow water**.
• Reefs also provide sediments and food to deeper water settings.

Corals are animals (or communities of animals) consisting of **polyps –** each polyp is an individual coral animals.
Corals produce calcium carbonate skeletal structures.

Other reef-forming animals include coralline algae (plants), bryozoans, sponges, mollusks, and many others.
Animals feeding on reef-forming organisms produce large quantities of sediment (building up reefs).

Figure 15.66. Coral reef

Importance of Coral Reefs

Reefs are the largest structures created by living organisms.
• The **Great Barrier Reef** in Australia is more than 1250 miles (2,000 km) long and many miles wide.
• Coral reefs are found in the **Florida Keys, Bahamas**, many coastal **Caribbean** destinations. The land itself in these regions consist of ancient coral reef deposits.
• **Atolls** throughout the South Pacific and Indian Oceans are surrounded by coral reefs.
• Coastlines of Red Sea, Persian Gulf, and Africa are lined with coral reefs.

Coral reefs have great diversity of species. Reefs protect shorelines from storm erosion and protect inland freshwater supplies. Coral Reefs are in decline: 30% are healthy today, 41% were healthy in 2000.

Threats to coral reefs:
• Hurricanes
• Floods
• Coral bleaching
• Human encroachment and exploitation.

Figure 15.67. Atoll reef community

Figure 15.68. Hawaiian reef community

15.16: Deep-Ocean Floor Communities

Deep-Ocean Floor Communities

- The deep ocean is largely unexplored.
- Light is completely absent below 3300 feet.
- Temperature usually 28°F to 37°F.
- A very high pressure environment.
- Deep-ocean floor communities exist in oxygen depleted environments compared to the surface environment.

Figure 15.69. Deep-sea community

15.17: Hydrothermal Vents

Hydrothermal Vents

Hydrothermal vent communities on the deep sea have an abundance of "unusual" life forms (unlike anything in coastal environments). Life around deep-sea vents are supported by **chemosynthesis** (primary production not supported by photosynthesis). Microscopic organisms (base of local food chain) thrive on **hydrogen sulfide** from vents. Microbes manufacture sugar, carbon dioxide, and dissolved oxygen.

Hydrothermal vent species (secondary consumers and decomposers) include:

- Giant tubeworms
- Giant clams
- Giant mussels
- Crabs.

Hydrothermal vents may active for years or decades.
Animals species are similar at widely separated vents.
Larvae from vent communities drift from site to site.

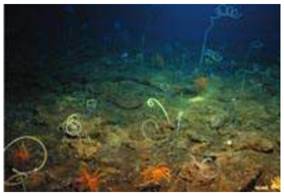


Figure 15.70. Hydrothermal vent community.

15.18: Quiz Questions - Chapter 15 - Marine Communities in Benthic Environments

1. ***Mollusca*** include:
a. crabs, shrimp and spiders.
b. sponges – filter feeders.
c. bivalves, squid, octopus, gastropods (things with shells or large cavities).
d. coral, jellyfish.

2. ***Echinodermata*** include:
a. sea stars, urchins and sea cucumbers (all with spiny skin).
b. single celled organisms: foraminifera, radiolarians, copepods.
c. bivalves, squid, octopus, gastropods (things with shells or large cavities).
d. squid, octopus, nautilus, cuttlefish.

3. ***Porifera*** include:
a. crabs, shrimp and spiders.
b. sponges – filter feeders.
c. bivalves, squid, octopus, gastropods (things with shells or large cavities).
d. squid, octopus, nautilus, cuttlefish.

4. ***Annelida*** include:
a. crabs, shrimp and spiders.
b. worms.
c. squid, octopus, nautilus, cuttlefish.
d. sponges – filter feeders.

5. ***Arthropoda*** include:
a. crabs, shrimp and spiders.
b. sponges – filter feeders.
c. worms.
d. coral, jellyfish.

6. ***Protozoa*** include:
d. coral, jellyfish.
b. foraminifera, radiolarians, copepods.
c. worms.
c. bivalves, squid, octopus, gastropods (things with shells or large cavities).

7. ***Coelenterates*** include:
a. crabs, shrimp and spiders.
b. sponges – filter feeders.
c. squid, octopus, cuttlefish, nautilus.
d. anemones, coral, jellyfish.

8. Deep-ocean floor communities live in under high pressure conditions around hydrothermal vents. These warm to hot water vents on the seafloor often host local communities that include an abundance of unusual life forms - including giant tube worms, giant clams, giant mussels, and crabs. These larger organisms derive their food from a microbial community in the water and sediments around the vents that make up the base of the local food chain. The life in this zone derives the energy they need to live from:
a. photosynthesis.
b. chemosynthesis.
c. consumers.

d. decomposers.

9. Coral reefs only occur and thrive in:
a. tropical settings.
b. shallow water conditions.
c. warm and clear water conditions.
d. all of the above.

10. The largest accumulation of biogenous sediments associated with coral reefs found in the world today are associated with:
a. the Great Barrier Reef of Australia.
b. the Caribbean inlands reef.
c. The Amazon rain forest.
d. The Amazon delta.

CHAPTER OVERVIEW

16: Marine Communities (Vertebrates)

16.1: Animals in the Pelagic Environment

Animals in the Pelagic Environment

This chapter focuses on higher-level organisms in the marine environment, specifically v**ertebrates**, all of which are **pelagic animals** that can swim (or fly) in the open ocean or coastal marine environments. (The previous Chapter 15 focuses on invertebrates - most of which are either attached or live on or with the seabed (the benthic environment).

Vertebrates

Vertebrates are a large group of animals distinguished by the **possession of a backbone or spinal column**. They belong in the taxa:

Kingdom	**Animalia**		
	Phylum	**Chordates**	
		Subphylum	**Vertebrata**

Figure 16.1. This Wyoming fish fossil displays a well preserved backbone (spinal column), common to all vertebrates.

Classes in Vertabrata in the Marine Environment

CLASS	Examples
Mammalia	Whales, seals, sea lions, otters, polar bears (mammals)
Amphibia	Frogs, salamanders (amphibians are rare in marine environments but a few species exist in near-marine settings)
Reptilia	Snakes, turtles, lizards (crocodillians, iguanas)
Aves	Birds
Osteichthyes	Fish with bony skeletons
Chondrichthyes	Fish with cartilage skeletons- sharks (very old fish with cartilage, some are up to 280 million years old)

Example of the Taxonomy of Whales

Taxa							**Example: Taxonomy of Whales**
kingdom							**kingdom: Animalia**
	phylum						**phylum: Chordata** (subphylum: **vertebrata**)
		class					**class: Mammalia**
			order				**order: Cetacea**
				family			**Mysteceti** (mustache whales) **Odontoceti** (toothed whales) **Archeoceti** (ancient whales - now extinct)
					genus		*one or several genus within families*
						species	*one or more species within a genus*

Characteristics of All Marine Mammals

	• **Land-dwelling ancestors**
	• **Warm-blooded**
	• **Breathe air**
	• **Hair/fur**
	• **Bear live young**
	• **Mammary glands for milk**

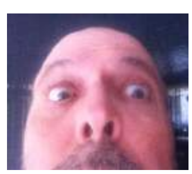
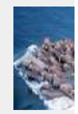
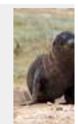


Figure 16.2. Are humans marine vertebrates?

16.2: Marine Vertebrates

Taxonomy of marine vertebrates include:

ORDER	Carnivora	**(have prominent canine teeth)**		
	FAMILY	**Mustelidea**	**• Sea otters**	Among the smallest of marine mammals, range member of the **weasel family**. Each carries a pe shells.
	FAMILY	**Ursus**	**• Polar bears**	Live in the arctic circle, primary diet of seals, li ocean.
	FAMILY	**Pinnipeds**		
		GENUS	**• Walruses**	Range is in the Arctic and subarctic in Northern continental shelves. Large tusks and whiskers u bivalves on seabed.
		GENUS	**• Seals**	Fin-footed (flippers), semi-aquatic marine mar worldwide.
		GENUS	**• Sea lions**	Sea lion have external ear flaps, long fore flippe all fours, and are voracious eaters. Six species v Atlantic.
		GENUS	**• Fur seals**	Similar to sea lions (smaller), 1 species in Nor Hemisphere; have external ear flaps, long fore on all fours.

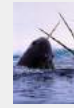
Examples of Marine Carnivores			
			
Figure 16.3. Sea otter	Figure 16.4. Polar bears	Figure 16.5. Walrus	Figure 16.6. Walruses on ice.
			
Figure 16.7. Monk seal	Figure 16.8. Steller sea lion	Figure 16.9. Steller sea lion colony	Figure 16.10. Fur seals

ORDER	Sirenia	**(Aquatic herbivores living in coastal areas)**
	FAMILY	**• Manatees (tropical Atlantic Ocean)**
	FAMILY	**• Dugongs (Indian and western Pacific Oceans)**

Examples of Sirenia	
	
Figure 16.11. Manatees	Figure 16.12. Dugong

ORDER	***Cetacea***		**Cetaceans** have elongated skull with **blowholes** on top, use **echolocation**: they emit click-like noises and get return—used to detect fish, and can be used to stun fish. Cetacea have large brains relative to body size; can communicate with each other, many are considered trainable.
	SUB ORDER	Odontocetes	**Toothed whales:**
		FAMILY	**• dolphins (*Delphinidae*)** - seven genera with about 40 species, worldwide
		FAMILY	**• porpoises (*Phocoenidae*)** - Compared with dolphins, porpoises have shorter beaks and flattened, spade-shaped teeth.
		FAMILY	**• killer whales** (technically a subfamily of dolphins, called "blackfish" or orcas - 6 species)
		FAMILY	**• beaked whales** (have prominent noses [or nose -like features] - 22 species)
		FAMILY	**• Sperm whales** - largest of the toothed whales, 3 species, (They use echolocation to hunt giant squid.)
	SUBORDER	Mysticeti	**Baleen whales (Baleen** is fibrous plates in whale mouths used to sieve prey items.**)**
		FAMILY	**• Right whales (*Balaenidae*):** 4 species live in northern oceans, mostly North Atlantic
		FAMILY (1species)	**• Rorquals whales** (9 species, worldwide), includes: *** Blue whale** - largest of all mammal species - up to 30 m (98 ft), 180 tons
		FAMILY	**• Humpback whales** (1 species) - found in all oceans
		FAMILY	**• Gray whales** (1 species) - live in coastal waters of the Northern Pacific only

Examples of Cetaceans

			
Figure 16.13. Dolphin	Figure 16.14. Porpoises	Figure 16.15. Killer whale	Figure 16.16. Narwhales
			
Figure 16.17. Sperm whale	Figure 16.18. Blue whale	Figure 16.29. Humpback whale	Figure 16.20. Atlantic right w

16.3: Migration of Gray Whales on the West Coast

Migration of Gray Whales on the West Coast

Gray whales are probably the most commonly sighted whales in the coastal waters of California. Gray whales have the longest migration of any mammal species, about 10,000 miles 16,000 km) every year. Gray Whales have a routine. They spend the winter months (December to April) in their **birthing and mating grounds** the shallow bays and lagoons in and around the southern Baja California and southern Gulf of California (Figure 16.23).

Gray Whales begin their northward migration in late February to May along the coastline, following the spring blooms of phytoplankton and zooplankton. They are frequently seen moving in small groups (pods) several hundred yards beyond the breaker zones to about 4 kilometers (2.5 miles [4 km]) from shore. Their destination is the rich summer feeding grounds along coastal Alaska and the Bering Sea, a distance of about 5,000-7,000 miles (8,000 to 11,000 km). Adult males and juveniles arrive in northern waters in June; females and young offspring leave and arrive a little later. They spend the summer (June to October) feasting. The first to head south are the pregnant females, followed by the others, some of whom don't make it as far south as Mexico if food resources are available farther north.

Figure 15.21. Gray whale

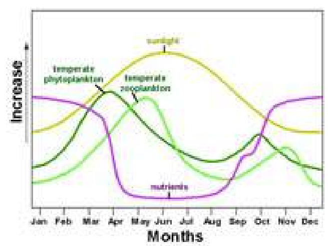


Figure 15.22. Temperate zone productivity by seasons.

Figure 16.23. Migration pattern of gray whales along the West Coast of North America.

16.4: Marine Reptiles

Marine Reptiles

Compared with the number of reptiles groups and species on Earth, relatively few are adapted to marine environments. The earliest marine reptiles appear in the Permian Period. Many groups emerged in the Mesozoic Era including more familiar varieties including **ichthyosaurs**, **plesiosaurs**, and **mosasaurs**. Many varieties of the Mesozoic Era vanish at the K/T Boundary extinction.

CLASS	Reptilians	
	ORDER	**Crocodiles**
	ORDER	**Lizards**
	ORDER	**Sea Turtles**
	ORDER	**Sea Snakes**

Crocodiles

There are 23 living crocodilian species in both terrestrial aquatic and coastal marine environments. Crocodilians are found in the tropical to subtropical regions on all continents (not Antarctica); they're found in over 90 countries and islands. They are unable to survive and reproduce successfully in cold climates.

What's the difference between an alligator and a crocodile?	
American Alligator	American Crocodile
Habit: feisty	**Habit:** more feisty, but shy and reclusive
Habitat: freshwater to brackish water	**Habitat:** brackish to salt water
Color: gray to black	**Color:** greenish gray
Encounters with humans: common	**Encounters with humans:** not so common
Diet: most everything, fish, birds, pets	**Diet:** mostly fish
Maximum size: `12 feet	**Maximum size:** ~13 feet
Characteristics: Alligators snout is blunt and shovel like (used like a shovel too)	**Characteristics:** Crocodile snout is pointed with more teeth sticking out (better for catching fish)
Range in US: Gulf & Atlantic coasts (TX to SC)	**Range in US:** South Florida only
Example: Figure 16.25	**Example: Figure 16.26**

	
Figure 16.24. Alligator	Figure 16.25. Crocodile

Marine Lizards

The only marine lizard is the **Galápagos marine iguana** (*Amblyrhynchus cristatus*)—found only on the Galápagos Islands. This iguana lives along rocky island shorelines and can dive over 9 m (30 ft) into the water to forage for its main diet of red and green algae (Figure 16.27).

Figure 16.26. Galápagos marine iguana

Extinct Large Marine Reptiles

Aquatic reptiles first noted from the Permian Period. There were many varieties of large marine reptiles during the Mesozoic Era. All vanished at the end of the Cretaceous Period (about 65 million years ago).

Ichthyosaurs: Triassic to Late Cretaceous
Plesiosaurs: Early Jurassic - Late Cretaceous
Mosasaurs: Late Cretaceous

The ancient marine reptiles illustrated convergent evolution - they had terrestrial ancestors like dolphins and whales.

Figure 16.27. A fossil ichthyosaur from Berlin-Itchtyosaur State Park, Nevada

Sea Turtles

There are seven species of sea turtles worldwide. Sea turtles sea turtles can be found in all oceans except for the polar regions, along the continents shelves and islands. They are known to nest in more than 80 countries. Sea turtles first appear in the geologic record in early Cretaceous time (land proto-turtles appeared in Permian time).

Unlike land turtles, sea turtles are unable to pull their heads or appendages into their shells. Sea turtle shells are lighter and more hydrodynamic than terrestrial turtle shells. There flippers enable them to swim long distances. Male sea turtles spend their entire lives at sea. Females return to the same beaches they were born on about every two years to lay eggs.

All adult **green sea turtles** are herbivores, feeding on algae, sea grasses, and other vegetation. Juvenile are carnivorous, feeding on jellies and other invertebrates. Large adult green sea turtles can weigh upward of 400 pound and over 1 meter.

Leatherback turtles are carnivorous, migrating thousands of miles each year to feed on jellyfish.
Leatherback Turtles can weigh as much as 1500 pounds and reach lengths of over 2 meters.

Sea Turtles Green sea turtle Leatherback sea turtle Loggerhead sea turtle	 Figure 16.28. Green sea turtle	 Figure 16.29. Leatherback sea turtle	 Figure 16.30. Loggerhead sea turtle.

Sea Snakes

There are about 50 species. They live in tropical waters of the west Pacific Ocean, around Australia, and in the Indian Ocean. Sea snakes inhabit marine environments for most or all their lives. Sea snakes are generally non aggressive, brightly colored, with small mouth and fangs. Sea snakes have very powerful venom. An average of about 20 deaths per year happen from fishermen trying to remove them from nets.

Figure 16.31. Sea snake.

16.5: Seabirds

Seabirds

There are many varieties of seabird (too many to discuss here!). Here are characteristics of seabirds:

• Seabirds are found on all continents and islands around the world.

• Seabirds can be highly pelagic, coastal, or partly terrestrial.

• Most species nest in colonies (dozens to millions of birds)

• Seabirds live longer, breed later, and have fewer young.

• Many species undertaking long annual migrations, crossing the equator or even circumnavigating the Earth.

• Seabirds feed both at the ocean's surface,below it, and even on each other.

• All seabirds share feed in saltwater (some may feed in both sea and terrestrial sources).

• Wing morphology and body shape depends the niche a species or family has evolved.
-- Longer wings and low wing loading are typical of more pelagic species,
-- Diving species have shorter wings.
-- Seabirds like albatross and pelicans use dynamic soaring to take advantage of wind deflected by waves to provides lift.

• Seabirds also almost always have webbed feet.

• Salt glands in their nasal cavities are used to excrete the salt they ingest by drinking and feeding.

• Birds appear in the Mesozoic Era, but **modern seabirds** proliferated in the Paleogene (after the K/T extinction).

Figure 16.32. Seagull

Figure 16.33. Arctic tern

Figure 16.34. Pelican

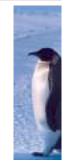


Figure 16.35. Penguins

16.6: Fish

Fish

There are many varieties of fish (too many to discuss here!). Here are important facts about fish.
Fish are found in nearly all aquatic environments (land & sea), and all depths of the oceans.
Fish are all aquatic, gill-bearing, craniate (head-bearing) animals that lack limbs with digits.
Fish groups account for **more than half of all vertebrate species**.
At 32,000 species, fish exhibit greater species diversity than any other group of vertebrates. * almost 28,000 known extant (not yet extinct) species, ~27,000 are bony fish, ~970 sharks, rays, and chimeras. * over 100 hagfish and lampreys. * many extinct varieties.
Most fish are **ectothermic** (cold-blooded), allowing their body temperatures to vary as ambient temperatures change some of the large active swimmers (examples white shark and tuna can hold a higher core temperature).
Fish are abundant in most bodies of water, all parts (depths) of the oceans.

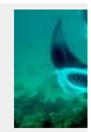
Fish Evolution

Amphibians, reptiles, birds and mammals) and fish share a common evolutionary ancestry.
The earliest fish-like organisms appeared during the Cambrian period. (However, they lacked a true spine, but possessed notochords.)
Fish evolve through the Paleozoic era, diversifying into a wide variety of forms.
Many Paleozoic fishes developed external armor that protected them from predators. The first fish with jaws appeared in the Silurian period, after which many (such as sharks) became formidable marine predators rather than just prey.

Osteichthyes	Fish with bony skeletons
Chondrichthyes	a class of fishes that have the cartilaginous skeletons, rather than bone—they have jaws, paired fins, scales, a heart with its chambers in series. Subclass *Elasmobranchii* (includes sharks, rays, skates, sawfish), and subclass *Holocephali* (include chimaeras). Some lineages are up to 280 million years old.

Examples of Osteichthyes (bony fish)

			
Figure 16.36. Oarfish (a species with ancient roots)	Figure 16.37. Anchovies	Figure 16.38. Marlin	Figure 16.39. Blue fin tuna

Examples of Chondrichthyes (Sharks and Rays)			
			
Figure 16.40. Great white shark	Figure 16.41. Hammerhead shark	Figure 16.42. Whale shark	Figure 16.43. Manta Rays

16.7: Adaptations to the Marine Environment

Adaptations to the Marine Environment

• **Ability to float** (**Zooplankton** – some produce fats or oils to stay afloat)
• **Ability to swim** (**Nekton** – larger fish and marine mammals)

Propulsion and movement of fish - the body plan of fish reflect adaptations to feeding on prey and fleeing predators.

Width/Length Ratio

Tuna - .28
Dolphin - .25
Swordfish - .24
Whale - .21

Most efficient is about.25, but there is a size-scale factor.
Ratio produced from natural selection "the fittest survive and produce offspring"

Figure 16.42. Swordfish

Compare with Surfboard Design!

Type	Width	Length	Ratio	Comments
Short Board	19 ¼"	6'4"	0.25	Small – medium waves
PT (Ebenizer Townsend, 1798)	19 ¼"	6'7"	0.24	Large waves
Average Long Board	22"	9'0"	0.20	Like a whale – scale factor
Average Surf Board	18 ¼"	6'2"	0.25	rapid turns, harder to control

Kinds of Zooplankton

Includes organisms described as **floaters** and **drifters**. **All forms are invertebrates.**
Microscopic Zooplankton include:
Radiolarians, Foraminifers, Copepods

Macroscopic Zooplankton:
• Krill (resemble mini shrimp or large copepods, critical in Antarctic food chains)

Figure 16.43. Copepods

Figure 16.44. Krill

Floating Macroscopic Zooplankton include:

• **Portuguese man-of-war** (have gas-filled float)
• **Jellyfish** (have soft, low-density bodies; there are hundreds of species)

Many species of portuguese man-of-war and jellyfish can sting or produce potent toxins.

Figure 16.45. Portuguese man-of-war	Figure 16.46. Jellyfish

Swimming (Nekton) Organisms

Includes all fish, squids, sea turtles and sea snakes, and marine mammals.

• Swim by trapping water and expelling it (squid, octopus)
• Swim by curving body from front to back (fish, etc.)

Figure 16.47. Squid

Adaptations for Finding Prey

• **Lungers** wait for prey and pounce (grouper).
• **Cruisers** actively seek prey (tuna).

	
Figure 16.48. Groupers are lungers	Figure 16.49. Tuna are cruisers

Adaptations to Avoid Predation
• **Speed**
• **Hiding**: includes **Transparency**, **Camouflage** and **Countershading**
• **Poison** (to touch or eat: examples: sea snakes, blowfish, lion fish)
• **Schooling** (safety in numbers, appear as a larger unit, maneuvers confuse predators)

Figure 16.50. Lionfish are highly poisonous.

Video: Schooling anchovies at Scripps Pier (Scripps Institute of Oceanography)

16.8: Protecting and Preserving Marine Life- A Most-Essential Goal For the 21st Century

Protecting and Preserving Marine Life: A Most-Essential Goal For the 21st Century

The efforts of human exploitation of ocean resources have had catastrophic effects on marine life. The large disasters of modern times have brought attention to some of the problems (i.e. The Alaska-Exxon Valdez oil spill (1989), the destruction of Kuwait's oil fields in the 1st Gulf Wa (1991)r, and the BP Deepwater Horizon Oil Spill in the Gulf of Mexico (2010) are high-profile examples of marine ecosystem disasters (each having long-term impacts). However, it is the small scale, daily exploitation impacts of a growing human population that is having catastrophic effects on marine ecosystems (and human communities that rely on marine resources).

* 80% of available fish stock are now fully exploited, overexploited, or depleted/recovering.
* Large predatory fish reduced are greatly reduced in populations.
* Global warming of ocean waters is causing havoc on marine ecosystems: warmer water increases metabolism needs of marine life, affecting their life and reproduction cycles. In addition, thicker thermoclines reduce upwelling of nutrient-rich waters, reducing primary production.

Many countries are now using **Fisheries Management**. Fisheries management involves **regulation, education, enforcement,** with an effort to **create self-sustaining ecosystems**.

Much work needs to be done!

Feeding Frenzies (YouTube videos)

Anchovies in Santa Cruz:
Sharks along North Carolina beach
Sardines, dolphins, birds, sharks, whales
Sei whale feeding

16.9: Quiz Questions - Chapter 16 - Animals in the Pelagic Environment

1. In the science of taxonomy (the classification of living things) the correct order from highest grouping level down to the to the single group of organisms capable of reproducing viable offspring is:
a. Class - Order - Family - Genus - Kingdom - Phylum - Species.
b. Kingdom - Phylum - Class - Order - Family - Genus - Species.
c. Phylum - Kingdom - Family - Class - Genus - Order - Species.
d. Kingdom - Family - Phylum - Order - Class - Genus - Species.

2. The large group of organisms that include all creatures that have a spinal column or a feature called a ***backbone*** are called:
a. Animalia.
b. carnivores.
c. vertebrates.
d. mammals.

3. Which choice is NOT characteristic of all marine mammals:
a. They all evolved from land-dwelling ancestors.
b. They are all warm-blooded and breath air.
c. They all bear live young and have mammary glands for milk.
d. They all live their entire lives in the ocean.

4. The group of marine carnivores that are called *Pinnipeds* include:
a. seals, sea lions, and walruses.
b. blue whales and green whales.
c. sea otters and polar bears.
d. sea snakes and sea turtles.

5. Of the order *Sirenia*, marine mammals that are herbivores that live in coastal waters of the tropical Atlantic are called:
a. manatees.
b. dugongs.
c. walrus.
d. fir seals.

6. All members of the Order Cetacea have elongated skulls with blowholes. Which is NOT a member of the order Cetacea?
a. dolphins.
b. porpoises.
c. killer whales.
d. sea lions.

7. The Suborder *Mysticeti* include blue, finback, humpback, gray, and right whales. These whales have fibrous plates in their mouths they use to sieve prey items from seawater or sandy sea bottoms. These fibrous plates are called:
a. polyps.
b. baleen.
c. countershading.
d. netting.

Use the diagram below to answer questions 8 and 9.

8. What would explain the shape of the northbound migration route of Gray Whales?
a. During the late spring and summer there is an abundance of food along the western coastline of North America due to coastal upwelling.
b. As spring transitions to summer there is more food production in the polar region than the tropical region.
c. Whale try to migrate through areas where zooplankton production is at their highest rate.
d. all of the above.

9. What would best explain the shape of the southbound route of gray whales?
a. There isn't as much food available for gray whales in coastal waters in the in the fall and winter.
b. Whales have stored up large amounts of fat stored up from eating all summer in polar waters.
c. Gray whale don’t eat as much during mating and birthing season is in the winter months in the waters around Baja.
d. all of the above.

10. The largest group of marine animals (including over half of all vertebrate species) are:
a. marine mammals.
b. marine reptiles.
c. birds.
d. fish.

11. A variety of macroscopic zooplankton (copepods) that are extremely abundant in the waters around Antarctica and are a major part of the food chain in that region of the world are called:
a. penguins.
b. krill.
c. anchovies.
d. sardines.

12. Examples of floating macroscopic zooplankton include:
a. jellyfish and Portuguese man-of-war.
b. foraminifera and coccoliths.
c. radiolarians and diatoms.
d. squid and octopus.

13. Fish have many adaptations for finding prey. Some varieties of fish wait and pounce (like groupers) when prey swim or crawl by. These kind of animals are called.
a. loungers.
b. lungers.
c. lurkers.
d. cruisers.

14. When sometimes large numbers of small fish swim closely together and maneuver in irregular patterns to avoid or confuse larger predators it is called:
a. transparency.
b. camouflage.
c. schooling.
d. countershading.

15. The goal of Fisheries Management is to:
a. provide regulation, education, enforcement, and create self-sustaining ecosystems.
b. reduce the number large predatory fish.
c. hunt and remove predatory sea mammals.
d. none of the above.

CHAPTER OVERVIEW

17: Marine Pollution

17.1: Human Impacts- Marine Resources and Pollution

Human Impacts: Marine Resources and Pollution

Humans have been exploiting ocean resources for as long as our ancestors have been living on its shores back into antiquity. The oceans provide a major means of subsistence for about a quarter of the world's population. The exponential growth of the human population in the last 3 centuries have significantly impacted the physical environment, both land and water. This chapter starts with an examination of natural resources the oceans provide and also examines the degradation of the quality of the marine environment due to the addition of anthropogenic (from humans) materials. The production and consumption of natural resources by the growing global human population is harming sea life throughout the world's oceans. Laws and regulations are helping to manage some of the sources of ocean pollution. But, perhaps most detrimental, and the hardest to control, are the impacts of the behavior of people in their daily lives. This chapter examines the types and causes of ocean pollution, and the effects on sea life, and provides suggestions for some ways to mitigate problems.

Coral on Cordell Banks, offshore California

Figure 17.1. A healthy reef on Cordell Banks, California

17.2: Ocean Resources

Ocean Resources

A **resource** simply defined means ***something useful***. Humans have been utilizing marine resources extending back into antiquity, but within the last couple centuries, exploitation of world marine resources have lead to increasing vulnerability to both resources of the natural environment and the communities who rely on them. Marine resources include exploitable **physical resources** (primarily petroleum, construction materials, and minerals) and **biological resources** (fish, shellfish, plants, and other wildlife utilized for fishing and aquaculture). A third category is **aesthetic resources** which include preservation of coastal scenery, wetlands and wildlife preserves, park lands and recreation, and applies to environmental quality of coastal communities. Unfortunately, economic and social factors with our growing human population lead to a myriad of conflicts relating to marine resources.

Petroleum resource map of the world

Figure 17.2. Petroleum resource map of the world. Most resources occur in sedimentary deposits in modern and ancient continental margin regions.

17.3: Petroleum (Oil and Gas) Resources in the Marine Environment

Petroleum (Oil and Gas) Resources in the Marine Environment

Without question, the petroleum and natural gas industry is the largest source of jobs and revenue in the world, involving seven out of top ten of the world's largest corporations and is the largest source of wealth for countries around the world. Oil and gas reserves in marine and coastal regions is the largest natural resource. Almost all oil and gas resources occur in sediment-filled basins along continental margins or in regions within continents that were ocean-margin basins in the geologic past (Figure 17.2). The Middle East region has the greatest amount of oil & gas resources (Saudi Arabia, Iraq, Iran, and other countries around the Persian Gulf). Venezuela, Canada, Russia also have significant reserves. About 1/3 of world's reserves occur on continental margins.

Sadly, petroleum consumption is at the heart of the environmental, economic, and social issues related to greenhouse gas/global warming**,** climate change, ocean acidification, and related issues.

What is the difference between a resource and a reserve?

The term **resource** applies to the total amount of material that occurs in a region. In the case of petroleum (oil and gas), this includes "fuel" that is both discovered and undiscovered, and may or may not be economically recoverable. In contrast, reserves are deposits of fossil fuels that are known to exist in a region with a reasonable level of certainty based on geologic and engineering research. **A reserve is only a portion of a resource that is economically recoverable based on technologies that already exist.** The value of an oil field is only based on the amount of petroleum that can be reasonably extracted over a period of time. The **reserves** of the world's oil resources are constantly changing. For instance, the new technology associated with ***fracking*** has nearly doubled the amount of petroleum reserves in the United State in the last decade, whereas the resource assessments have remained essentially unchanged.

Unfortunately the easiest to access reserves on land and in shallow coastal areas have already been exploited and depleted, forcing ongoing exploration for future reserves into deeper water.

17.4: Sand and Gravel Resources

Sand and Gravel Resources

Sand and gravel accumulates along shorelines and on continental shelf regions where waves and currents winnow away finer clay fractions allowing coarser sediments to accumulate (Figure 17.3). After petroleum, in economic terms, extraction of sand and gravel from the seabed is the next largest marine physical resource. Sand and gravel are increasingly being mined from continental shelf regions as sources on land in crowded coastal regions are being depleted or operations are restricted do to changes in land use. Sand and gravel are added to cement used in building foundations and is used in all forms of construction, including artificial island and levees (Figure 17.4).

Figure 17.3. Gravel deposit on South Carlsbad Beach, CA

Figure 17.4. Artificial islands in Dubai, United Arab Emirates

Sand is mined from offshore areas and pumped in slurry form to replenish beaches that loose sand to beach erosion. Offshore sand and gravel mining operations are expensive, but the impact is as visually obvious as land-base operations, but benthic communities can be impacted by offshore dredging activities.

Offshore dredging is currently used to replenish beach sand in San Diego County. It is the source of sand for artificial beaches like Miami Beach, Florida and massive coastal construction projects in many places including Dubai, Saudi Arabia, and the construction of artificial islands in the South China Sea.

17.5: Mineral Resources

Mineral Resources

Sea salts are generated from from seawater evaporated in ponds. About 1/3 of all table salt (NaCl) in the world comes from evaporation seawater. Other economically significant mineral derivative from seawater evaporation operations include gypsum and salts of potassium, magnesium, iodine, and bromine.

Iron-manganese nodules are hydrogenous rocks that precipitated from seawater. They form very slowing (taking millions of years to form fist-size nodules, Figure 17.5). However, large regions of abyssal plains in the deep ocean are covered with them, particularly in the southern Pacific Ocean.. Samples collected show that they are rich in iron, manganese, copper, nickel, and cobalt. Mining manganese nodules from the deep sea bed is not considered economically feasible at this time. Similarly, deposits around deep sea vents (**black smokers**) are also rich in valuable metals but mining them is not economically feasible. However, ancient back smoker and manganese nodule deposits have been discovered and mined on land.

Figure 17.5. Iron-manganese nodules on the seafloor on an abyssal plain in the South Pacific Ocean.

17.6: Biological Resources

Biological Resources

Seafood (fish, crustaceans, and mollusks) is perhaps the most valuable biological resource. An estimated 86.6 million tons/yr., or 170,000 million pounds, of seafood are harvested around the world each year. Most seafood is harvested from temperate latitudes.

Seafood consumption has been gradually increasing worldwide, meanwhile fish and other seafood supplies have been diminishing, largely due to overfishing in poor, developing regions of the world. China alone consumes about 1/3 of all seafood harvested each year.

Aquaculture is gradually replacing traditional "capture" deep sea fishing. In the early 1970s only about 1 percent of seafood came from **fish farms** (**aquaculture**). Today, many kinds of seafood are ***farm raised*** - most abundant are freshwater-trout, catfish, and crayfish, but marine aquaculture is increasing, primarily salmon, oysters, mussels, shrimp, crabs, lobster, and other crustaceans. Aquaculture now account for more than 80% of the seafood in China, and nearly about 30% consumed by the rest of the world (Figure 17.6). Most varieties of commercial fish are now farm raised or captured in a managed and (hopefully) sustainable manner (Figure 17.7). ***Capture*** fishing has become increasingly infeasible in many parts of the world where many ocean fish stocks have been depleted. Traditional hook-and-net style fishing has many environmental problems. Drag nets scour the seafloor, destroying benthic communities, and large nets capture and kill unintended sea creatures including sea turtles, marine mammals, and many other endangered species. Lost nets, fishing lines, and trash from fishing ships are a major source of trash in marine pollution. Many advances are being made in marine aquaculture, however, it too can have environmental consequences including generating large quantities of fish wastes, interfering with native species populations (including spreading diseases), and taking space away from natural benthic communities.

Aquaculture - fish farm.

Figure 17.6. Aquaculture (fish and shellfish farms) account for about 20 percent of the seafood sold in the United States.

Figure 17.7. Most sushi prepared in the United States are from farm-raise species.

Commercial whaling in the 19th and 20th centuries had a devastating impact on many marine mammal species. Whales were harvested for meat, oil, and for fertilizer. Whaling operations peaked in the 1950-60's with approximately 60,000 whales a year. As a result, whale populations crashed. 8 out of 11 species are now considered "commercially extinct." Whale population estimates are that 4.4 million ***commercial whales*** were in the world resource population in 1900, but only about 1 million are estimated to exist today. Large-scale commercial whaling operations ceased in 1987 worldwide with exception of small operations still being conducted by Japan, Norway, and some coastal North American tribes.

Marine plants are being farm raised for food and other purposes. For example, extracts from kelp is used as a clarifier in beer and to form emulsions in salad dressings, inks and paints.

17.7: Coastal Land Resources

Coastal Land Resources

Coastal lands are probably the most rapidly changing and economically significant part of the Earth's physical environment. According to United Nations reporting, presently about 40 percent of the world's population lives within 60 miles (100 kilometers) from a coast. The population density and development within the first mile of a coastline is typically both the most densely populated and also the highest value in terms of real estate value (Figure 17.8). However, this desire from humans to live along coastlines also comes at a great price to long-term sustainability of natural resources associated with coastlines. In many regions, features such as mangrove forests and wetlands are disappearing as development progresses. The predicted problems associated with sea-level and climate change rise will progressively cause catastrophic impacts. In 2017, the United Nations released a report that natural disasters are the greatest threat to humanity, and most of those disasters are associated with superstorms impacting coastal regions.

Figure 17.8. A night sky view of Europe showing city lights highlights the fact that the world's coastlines are among the most densely populated regions of the planet.

17.8: Marine Pollution

Marine Pollution

Major types of ocean pollution include:
* Petroleum
* Sewage
* Solid Waste
* Heavy metals and toxic chemical compounds.

Critical factors relating to ocean pollution:
*There are many ways these substance end up in the ocean ranging from intentional dumping, acts of ignorance, to impacts of disasters (natural and otherwise).
* The majority of pollutants come from land. According to NOAA studies, about **80 percent of marine pollution comes from sources on land** (Figure 17.9).
* Man-made products become pollution when exposed to natural processes that move them through the natural environment. Materials like paper and metals typically decay, but plastic and glass can survive indefinitely. Plastic bags, nets, and fishing lines can trap, injure, and strangle marine creatures. Small plastic objects are consumed and block digestion. Inks, dyes, metals, and toxins from cigarette butts can poison sea life on all tropic levels.

Garbage washed up on a Hawaii beach

Figure 17.9. Garbage that has washed up on a beach in Hawaii.

17.9: Pollution and Pollutants

Pollution and Pollutants

Pollutants comes in many forms and from many sources. The impact of pollutants depends on many factors: chemical properties, concentrations, what they react with, what they can convert into, and where and how they may become concentrated through both physical or biological processes. Some chemicals are purely toxic, poisoning organisms in small concentrations, loss of biomass, interfering with reproduction, growth, neurological and respiration function, and causing organ failure, and death. Some chemical pollutants make it more difficult for water to hold gases (such as O_2 and CO_2). Solids in silt or clay form can cover benthic animal, clog filter feeders, and block sunlight.

Some chemicals **bio-amplify**. Biologic amplification involves a toxin that does not metabolize and accumulates in an organism, and possibly increases in concentrations as it moves up the food chain. For example the banned insecticide DDT goes through biologic amplification as it is consumed in a contaminated ecosystem. DDT is an example of a chemical pollutant that goes through biologic amplification as it moves up the food chain (Figure 17.10).

Tropic Level in Food Chain	**DDT concentration in parts per million**
Phytoplankton	0.000003 ppm.
Zooplankton	0.04 ppm
Small fish	0.5 ppm
Large fish	2.0 ppm
Birds	25 ppm

Figure 17.10. **Biologic amplification** is illustrated by DDT. Through political action it was finally banned in 1972 by the United States Environmental Protection Agency. DDT is discussed more below.

Point and Non-Point Sources of Pollution

All pollution has a source of origin. Point sources are visibly obvious sources. The U.S. Environmental Protection Agency (EPA) defines **point source pollution** as "any single identifiable source of pollution from which pollutants are discharged, such as a sewage outfall, a ship, or a smokestack." Strict laws and regulations implemented in recent decades have helped reduce pollution from point sources in most developed countries (mostly because they are visibly obvious and can be linked directly to an original fiscally-responsible source). However, the major contributions to marine pollution come from **non-point sources** associated with runoff from land (Figures 17-11 and **17-12**). Some ocean pollution starts as air pollution. Non-point sources include small sources (cars, trucks, boats, septic tanks, chimney smoke), and larger sources including agricultural wastes (pesticides, herbicides, fertilizer, and animal wastes) from farms, ranches, and harvesting forest areas. Runoff from industrial and urban areas (roads, parking lots, roofs), faulty managed industrial operations, and poorly-designed waste-water treatment facilities contribute pollutants and garbage to marine settings.

Pollution, and the secondary effects of pollution (causing harmful bacterial and algal blooms), can be very harmful to both wildlife and humans. About a third of shell-fish growing coastal waters are adversely impacted by pollution. Coastal waters and beaches are often unsafe for swimming after storm runoff.

Non-point pollution illustrated by a Florida coastal community setting

Figure 17.11. Non-point source pollution illustrated in Florida.

Sources of non-point pollution

Figure 17.12. Sources of non-point pollution affection coastal waters.

Environmental Concerns with Petroleum Industry Activities

As discussed in previous chapters, most scientists point to fossil fuel consumption as a primary cause for global warming and associated climate change—a topic of greatest concern for the future fate of humanity and the quality and biodiversity of the world's physical environments. More discussion related to petroleum pollution is discussed below under Marine Pollution. The burning of fossil fuels (oil, gas, coal) are a primary factor impacting climate change. Although alternative energy sources are gradually reducing the demand for fossil fuels in the United States, the consumption worldwide is still gradually increasing (Figure 17.13).

Petroleum exploration, production, and consumption are the leading causes of pollution affecting the oceans. Petroleum includes crude oil, refined oil products, oil, gas, and tars (asphalt), petroleum derivatives (plastics, waxes, etc.), and greenhouse gases and toxins released by the production and burning of fossil fuels.

Fossil fuel energy consumption and carbon dioxide emission statistics for the United States and the World

Figure 17.13. Statistic of fossil fuel consumption and CO_2 emissions for the US and World.

Sources of Carbon Dioxide (CO_2) Emissions

Carbon dioxide entering Earth's atmosphere comes from the oceans, soil, plants, animals and volcanoes. Greenhouse gases and pollution from the consumption of fossil fuels is now considered a major cause of climate change and changes in ocean chemistry detrimental to sea life. Climate change investigations show that although human sources of carbon dioxide are much smaller than natural emissions. However, human-source CO_2 emission have been significantly increasing since the Industrial Revolution began in the 19th Century. Human activities are offsetting the balance between "sources" of emissions and "sinks" that remove CO_2 from the atmosphere. Currently carbon dioxide emissions from fuel combustion include about **43% from coal, 36% is produced by oil, and 20% from natural gas**. Destruction of natural "sinks" on land are cause by deforestation and degradation of organic-rich soils in developing agricultural regions which are also releasing large quantities of CO_2 into the atmosphere.

Crude oil is a natural resource. Petroleum (gas, oil, and tar) form naturally in the Earth's crust and are derived from sedimentary deposits, mostly from the continental margin regions of the world (both ancient and modern settings. Crude oil and gas forms from the slow biological and thermal decay of organic remains and residues buried in sediments. It typically takes many millions of years for organic-rich sediments deposited in coastal swamp regions, continental shelves, or the deep ocean to go through the processes to be converted to petroleum resources. The conversion involves: how much organic matter occurs in sediments, how much heat the sediments are exposed to, and for how long it is exposed. The more time organic matter is exposed to heat, the more it breaks down to by-products of gases, fluids (oil), and heavy carbon-rich residues (tar), (Figure 17.14). Most of these materials remained trapped in sediments, but gas and oil can migrate to underground reservoirs or escape to the surface.

Unrefined crude oil is generally biodegradable. Many microscopic organisms (chiefly bacteria) will consume crude oil, however, refine oil products are generally non-biodegradable and are more toxic to wildlife. Light, volatile components will gradually evaporate. Heavier, carbon-rich residues can take much longer. Crude oil breaks down faster with higher temperatures, so spills in cold-water settings take much longer to break down.

Tar balls are a common feature found on beaches around the world. It must be noted that roughly half of the tar balls found on beaches come from natural sources (oil seeps on the seafloor). The other half comes from human activity (pollution). Natural tar seeps are typically common in oil production regions. For instance, anyone visiting the beaches in and around Santa Barbara, California will note that their shoes will become covered with tar after walk on the beach. Although there is oil drilling and production operations both offshore and onshore in the region, the tar on the local beaches mostly comes from natural sources: seeps on the seafloor.

Organic maturation converts organic mater to oil, gas, and coal over time	Deepwater Horizon	Bathymetry of the Deepwater Horizon disaster area
Figure 17.14. Organic maturation converts organic matter into coal, oil, and gas with burial over time.	Figure 17.15. Deepwater Horizon submersible drilling platform before the disaster in 2010.	Figure 17.16. Location of the Deepwater Horizon disaster.

17.10: Impact of Large Petroleum-Related Disasters

Impact of Large Petroleum-Related Disasters

Large marine disasters involving petroleum spills have happened many times over the past century. The impact of these events depends on where and how they occur. Some are accidents, others include intentional acts of war, such as the destruction of Kuwait's oil fields in the First Gulf War. Oil spills can have a wide variety of impacts ranging from minimal (when far from coastal regions) to catastrophic when they impact shore regions. Two of the largest (most expensive) petroleum-related disasters affecting North American coastal waters are discussed below.

Deepwater Horizon on fire.

Figure 17.17. The Deepwater Horizon on fire in 2010.

The Deepwater Horizon Disaster, 2010

The Deepwater Horizon Disaster started on April 20, 2010 with an explosion and fire of a submersible drilling platform located in the Gulf of Mexico about 40 miles (64 km) offshore from the Louisiana coast (Figures 17-15 to **17-23**). The drilling operation involved tapping an oil reservoir deep in sedimentary deposits on the offshore region beyond the continental shelf. Problems with the drilling operation and failure of equipment to prevent a blowout that resulted in the explosion and fire, and the eventual sinking of the drilling platform two days later. 17 platform workers were killed and another 11 were injured by the explosion and fire. The open well, sheared of at the seabed, proceeded to spew large quantities of crude oil into Gulf waters until it was shut down in mid July when a 75 ton cap was put in place, sealing off the well. The disaster resulted in the largest oil spill in the history of the Petroleum Industry.

An estimated 200 million gallons (about 5 million barrels) of oil poured into ocean from the unconstrained well. Some of oil stayed on or near the seabed, much of it formed a large plum in layers within the ocean waters, and some migrated to the surface where wind and currents dispersed it. An extensive cleanup effort was undertaken to trap, degrade and disperse, or burn off much of the oil on the surface. Unfortunately, large amounts found its way onshore, impacting beaches and coastal wetlands, and severely impacting wildlife. The bad publicity wreaked economic havoc on coastal communities and businesses involved in fishing and recreation from Texas to Florida. As of 2015, BP (the company that operated the drilling program) agreed to pay $18.7 billion to settle all federal and state claims for the disaster - the biggest pollution penalty in U.S. history. Total settlement costs was in the range of $54 billion.

Settlement of all federal and state claims brings total costs to nearly $54 billion. BP PLC agreed to pay $18.7 billion to settle all federal and state claims arising from the 2010 Deepwater Horizon oil spill, including the biggest pollution penalty in U.S. history.

Because the spill happened in the warm open ocean waters, much of the crude oil from the spill eventually dispersed (evaporated or diluted) or was consumed by microbial activity.

Oil-soaled bathtub ring in coastal wetlands	Oil on a beach on the Gulf of Mexico	pom-poms used to soak up spill
Figure 17.20. An oil-soaked bathtub ring in wetlands.	Figure 17.21. Oil on a beach along the Gulf of Mexico.	Figure 17.22. Pompoms and booms used to trap oil.

	oil-soaked sargassum	Deepwater Horizon Impact Zone map
Figure 17.18. An oil slick spreads on the Gulf of Mexico from the Deep Horizon disaster.	Figure 17.19. Oil-soaked sargassum (seaweed) in the Gulf of Mexico.	Figure 17.23. Regional economic impact zone map of the Deepwater Horizon Disaster of 2010. The disaster impacted fishing, tourism, recreation, and the livelihoods of millions of Gulf Coast residents.

Exxon Valdez Oil Spill Disaster, 1989

Prior to the Deepwater Horizon disaster, the worst petroleum-related disaster affecting the US coastline was the Exxon Valdez oil spill (Figures 17-24 and **17-25**). The oil spill occurred in Prince William Sound in the Gulf of Alaska. The Exxon Valdez, a large oil tanker bound for refineries in Long Beach, California, veered off course and struck a submerged rock "reef" outcrop on March 24, 1989. The disaster was blamed on poor navigation by a drunken ship captain, poorly trained personnel, and faulty and unused navigation equipment.

Estimates by governmental and other sources suggest that at least 10 to 11 million gallons (about 250,000 barrels) of Alaskan crude oil spilled into the coastal waters. The spill, so close to shore, eventually impaction about 1,300 miles (2,000 km) of coastline in the Gulf of Alaska (closer to 9,000 miles [14,500 km] considering all the islands, headlands, and bays along the rugged coastline). Rough seas, and the rugged and remote coastline made clean-up efforts extremely difficult, and the cold-water setting hampered the rapid decay and dispersion of the oil. The spill devastated habitats for salmon, seals, seabirds, and sea otters, and had a catastrophic effect of coastal communities in the region. The cost of the disaster, spread over many years, was in the range of about $7 billion. Hard facts were learned from the disaster. It turns out that some of the beach areas were "cleaned" - basically cooked with 150 F water. These areas were actually harmed more by the cleaning processes used. It was determined that about 35% of the oil evaporated, 8% burned, 5% dispersed by surf , and only about 5% biodegraded; the rest formed slicks that dispersed into the greater ocean currents offshore.

An outcome of the disaster is that all new large petroleum-transport vessels are now being built with double hulls to hopefully prevent future transport-spill disasters.

Exxon Valdez

Figure 17.24. The Exxon Valdez leaking crude oil into the Gulf of Alaska in 1989.

Oil spill cleanup of a turtles from the Deepwater Horizon Disaster.

Figure 17.25. Clean-up effort on Alaskan beaches after the Exxon Valdez oil spill disaster.

Impact of Petroleum Pollution on Wildlife

Pollution from petroleum-source products is a major problem in parts of the worlds oceans and coastlines. In addition, tar-ball, waxes, and other petroleum-derivative products can now be found throughout the world's oceans. Evidence of the pollution is most abundant along developed (urban and industrial) coastlines where accidental spills occur most frequently. The risks of spills occur along all infrastructure systems associated with the petroleum production, refining, transportation, and consumption. Leaky oil from cars and trucks are a major non-point source of water pollution. Large oil spills and oil production disasters are some of the most costly, devastating both wildlife and the economic livelihoods of communities in regions where they occur (Figure 17.26).

Oil spills are particularly bad for homeothermic (warm blooded) organisms with fur of feathers. Saturation with oil causes these animals to loose insulation and they die from hypothermia. Oil slicks poison kill 150-450,000 sea birds killed each year. Organisms living in the intertidal zone most sensitive to oil contamination.

Refined oil and oil-derivative products tend to be non-biodegradable, and are more toxic to wildlife.

Turtle being rescued from oil spill

Figure 17.26. A turtle being rescued from an oil slick in the Gulf of Mexico after the Deepwater Horizon Disaster. Sea creatures that are rescue are cleaned with soap and released in oil-free waters.

17.11: Solid Wastes

Solid Wastes

Marine debris is a persistent pollution problem of global problem. Marine debris is a threat to wildlife, navigation safety, and is a factor affecting the economy and human health, particularly in poor countries in coastal regions. According to NOAA sources, approximately 1.4 billion pounds of trash per year ends up in the world's oceans. The major components involve floating consumer plastic objects (including plastic bottles and caps, cigarette butts and lighters, and plastic bags), and these materials decay very slowly, if at all. Other materials include metals, rubber, paper, textiles, construction materials, and glass. The entire world's oceans are impacted by solid wastes transported by currents. Large portions of the ocean in the center of the large gyres have become floating ***garbage patches*** where floating debris is accumulating.

Trash comes from many sources, mostly by careless acts that release trash into storm drains and eventually drain into coastal waterways. Some trash material blown into the by the wind. Much of it comes from coastal recreation and shoreline activities. In impoverished regions, garbage is intentionally dumped at sea. Fishing nets, hooks, lines, abandoned vessels are lost, drifting at sea. Trash washes up on beaches, accumulates on the seafloor, or drifts practically endlessly as sea. Trash is very harmful to wildlife. Small objects that are swallowed cannot be digested, often injuring or killing sea life. Bags, lines, and nets entangle animals, leading to starvation or strangulation.

Garbage patches are regions in the world's oceans where downwelling waters in the middle of ocean gyre region cause floating garbage to accumulate (discussed in **Ocean Circulation**, Chapter 9).

Video: 11 Things Found After Japanese Tsunami

17.12: Sewage

Sewage

In many regions of the world sewage from populated regions is a major source of pollution in coastal regions. Sewage is a major problem in poor and overpopulated communities that cannot afford the technology to treat and process sewage before it is released into rivers or coastal waters. Old, over-used, and poorly-designed waste treatment facilities often cannot handle the volume of both sewage and runoff created by storms. As a result raw sewage can find its way into coastal waters **(Figure 17.27**).

Sewage discharge from an industrial area on the

Figure 17.27. Sewage discharged from a point source on the Calumet River, Illinois.

Sewage from urban areas include human wastes, food wastes, and household and industrial chemical wastes of many kinds from any different sources.

In San Diego County, urban runoff through storm drains account most of the coastal pollution resulting in beach closures.
The *rule of thumb* is that for every rain greater that ¼ inch, it is advised to stay out of the ocean for **72 hours**.

Here's the variety of diseases you can get from swimming in contaminated water:
- Sinus infection
- Hepatitis A (bad)
- Gastrointestinal problems, including Cholera
- Staph infection
- Blood poisoning.

17.13: Heavy Metals and Toxic Compounds

Heavy Metals and Toxic Compounds

Heavy metals and other toxic contaminants can accumulate in seafood and make it harmful to eat. According to NOAA sources, more than a third of the shellfish-growing waters of the United States are adversely affected by coastal pollution.

Mercury, lead, chromium, copper, cadmium, and arsenic are perhaps most significant. Mercury and lead are released into the environment from burning coal and fossil fuels, and by mining operations. Consumer products that contain lead, mercury, and other toxic metals end up in landfills which can leak into waterways. Lead from improperly disposed of batteries is a major contributor to lead contamination. Starting in the 1920‘s lead was used as an “additive” to gasoline to increase engine performance, but was found to be a toxic addition to air and soil pollution. It has been banned in most countries, but the lead is still finding its way into ocean waters. Lead and many other toxic compounds were also used in paints before being banned.

Mercury was used in gold mining and extraction, and in light bulbs, and used in many other industrial purposes, now mostly banned. Large quantities of mercury was mined in the New Almaden mercury mining district near San Jose, California. Over 65 million pound of mercury were extracted from the mines in the, nearly all of it was consumed in the gold fields along the western Sierra Mountains of central California and is a major contaminant in the Sacramento River system feeding into San Francisco Bay. Mercury is problematic in that it is concentrated in organisms highest in the food chain. In many areas, fish, such as tuna, have unsafe levels of mercury that, if over-consumed, can lead to mercury poisoning in humans. After WWII, a chemical process used to manufacture plastics released large quantities of mercury compounds into Minamoto Bay, Japan. The bio-accumulated mercury in fish that was the primary source of protein in the fishing community populations around the bay, nearly the entire population was sickened, many displaying severe neurological disorders.

Cadmium is used in non-rechargeable nickel-cadmium batteries, and is a major toxin in landfill waste waters. Both cadmium and arsenic are released by runoff from poorly managed mining operations, both past and present throughout the world today. Arsenic in a common natural contaminant in groundwater in some coastal regions. Various cancers and other diseases are linked to consuming contaminated water and food with high levels of arsenic.

Heavy metal pollutant come from many sources including mining, smelting, abandoned lead batteries and garbage, chromium from tanneries, and other local industrial sources mostly in impoverished urbanized areas where there is little or no regulation oversight. Modern electronic gadgets are host to many toxic metals and organometallic compounds and should be recycled (not thrown into landfills that may leak toxins). Research by world health organizations report that at least **100 million people worldwide suffer health effects or die from heavy-metal pollution each year.**

17.14: Phosphorus, Nitrogen, and Other Nutrient Pollution

Phosphorus, Nitrogen, and Other Nutrient Pollution

The nutrients in fertilizer makes plants grow. Whereas using fertilizers may help crop yields (and profits) on land, their unintended release into waterway that lead to the ocean can have devastating impacts in the marine environment. Phosphorus and nitrogen compounds are essential nutrients for plant growth and is naturally occurring in upwelling ocean waters that support primary production. However, too much nitrogen and phosphorus from fertilizers used in agriculture and suburban lawn care can stimulate an overgrowth of phytoplankton resulting in a harmful algal bloom (HAB). When the phytoplankton sinks, dies, and decays, it can suck all the free oxygen out of the water, resulting in hypoxia (creating “dead zones” in regions that would otherwise be a marine environment teaming with life). Unwanted nutrients in runoff and groundwater seepage from agricultural and urban areas of the Midcontinent region of the United States is resulting in an ever-expanding **dead zone** in the coastal waters around the mouth of the Mississippi River in the Gulf of Mexico (Figure 17.28).

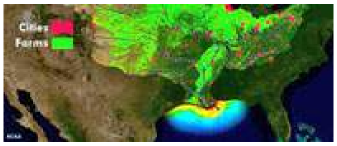


Figure 17.28. Map of the region near the mouth of the Mississippi River impacted by hypoxia caused by harmful algal blooms caused by nutrient pollution from farms and urban areas inland.

17.15: Synthetic Organic Chemicals and Medical Wastes

Synthetic Organic Chemicals

Many types of organic compounds produced by humans have a toxic effect on the environment. Many synthetic organic chemicals are manufactured or are a byproduct in the production of many industrial, agricultural, and household products. Large quantities of synthetic materials were produced and released into the environment in the period after WWII until environmental regulation and control began to prevail in the 1970s. In that time interval, a great amount of damage was done in many industrialized coastal regions.

Among the worst are chlorinated and halogenated hydrocarbons: DDT, TCE, and PCB's.

* **DDT (dichlorodiphenyltrichloroethane)** was heavily used as an insecticide throughout the United States, particularly starting after World War II. DDT is an insecticide that was initially used by the military in WW II to control malaria, typhus, body lice, and bubonic plague. After the war, this inexpensive-to-produce chemical was extensively used with agriculture for insect control (insecticide). In the 1960's DDT was found to cause adverse affects to wildlife, most notably causing predatory birds to produce thin shells, too thin for offspring to survive. DDT was banned from agricultural uses in 1972 over concerns of the unmitigated toxic effects on human health and many organisms in the natural environment. Unfortunately, DDT and other similar pesticides are still used in poor countries around the world to fight mosquitoes carrying malaria and other diseases.

* **PCBs (polychlorinated biphenyls)** are industrial products or chemicals, commonly used as insulator fluids in old transformers. PCB contamination is common in old industrial regions, particularly in the eastern United States. PCBs were banned in the U.S. in 1979 because of concerns about unintended impacts on human and environmental health. Like DDT, PBCs bio-accumulate.

* **TCE (trichoroethlene)** as originally introduced as a general anesthetic until it was linked to severe neurological disorders. After WWII it is was widely used as an industrial solvent, used primarily to degrease engine parts. TCE poisoning began to increase in many areas where the liquid chemical was dumped into sewers and wells, contaminating water supplies for many communities. It was later determined to be carcinogenic was banned in the 1980's by most developed nations.

Medical Wastes

Biologists are also reporting negative impacts of pharmaceutical compounds, medical wastes, and byproduct, including birth control pills, anti-depressants, and chemotherapy drugs finding their way into coastal waters. Illegal dumping of medical wastes at sea has been a large problem. Many coastal cities have had to deal with illegal dumping of medical wastes (commonly used hypodermic needles). Beaches were closed in many areas in the New York City region during the 1990s because of dangerous quantities of contaminated needles washing up on shore.

17.16: Coastal Dredging

Coastal Dredging

Dredging of sediments filling in submarine shipping channels and harbors re-releases environmental toxins that have already accumulated in nearshore marine sediments. Dredging also releases fine sediments rich in organic matter that contribute to anoxia and other detrimental benthic environmental impacts in the vicinity (Figure 17.29). The material that settles in harbors, shipping channels, and inland waterways are in constant motion during dredging operations, and wildlife habitats that might be able to tolerate a few days of high turbidity are endangered by the unending release of fine-grained sediments released by a long-term dredging operation.

A dredging operation

Figure 17.29. A dredging operation like this one works to remove silt from clogged shipping channels.

17.17: Protecting the Marine Environment

Protecting the Marine Environment

Many national, state, and local governments and organizations have been struggling for decades to manage marine pollution and protect coastal environments. In the United States, the National Oceanographic and Atmospheric Administration (NOAA) overseas large portions of the coastal waters around North America, attempting to stop overfishing and restricting coastal development in many regions. Expanding efforts involve protecting coastal wetlands, mitigating coastal hazards, ensuring public coastal access, protecting beaches and coastal park lands, locating of energy and government facilities, and managing sensitive habitats, fishery areas, and aquaculture. Efforts are underway nationwide to prevent and control polluted runoff by replacing outdated storm water runoff and sewage systems, reducing agricultural pollutants, preventing or mitigating development within sensitive habitats and erosion-prone areas, and finding ways for communities to reduce refuse and debris from entering coastal waters.

Focus on Coral Reefs

Coral reefs (or coral ecosystems) are among the most important and also most sensitive habitats throughout the world's oceans. Reefs provide habitat, spawning and nursery grounds for economically important fish species, and are hotspots of marine biodiversity. For humanity, coral reefs provide billions of dollars in economic and environmental benefits, including fishing, coastal protection, recreation, and tourism. Hundreds of millions of people worldwide depend of reef ecosystems for their livelihoods and food. However, coral ecosystems face serious threats from unsustainable fishing and land-based pollution (Figures 17-30 and **17-31**).

Unfortunately, many of the world's reefs have already been destroyed or severely damaged by pollution, unsustainable fishing practices, disease, introduction of invasive species, ship groundings, uncontrolled coastal development and other impacts.

Human activities are a primary cause for reef destruction. Pollutants from expanding coastal communities find their way to shallow coastal waters dominated by coral reefs, mostly in warm tropical waters. Many of the sea creatures, particularly invertebrates that attach to the seabed and filter seawater. Tourist visiting reefs step on fragile reef structures, introduce chemicals (such as zinc and other compounds in sun screen). Sewage and urban runoff carries silt (increasing turbidity) and introduce toxins that impact or kill reef organisms. Perhaps most alarming are the impacts of changes in water temperature and water chemistry associated with climate change.

A healthy Hawaiian coral reef

Figure 17.30. A healthy Hawaiian coral reef.

A bleached and dying reef

Figure 17.31. A dying coral reef.

Climate Change - The most important environmental issue of our times!

Studies conducted throughout the world's oceans show the coral ecosystems are showing the detrimental effects of climate change caused by the burning of fossil fuels, deforestation, and bad agricultural practices that release large quantities of greenhouse gases into the atmosphere.

Climate change impacts coral ecosystems by increasing sea-surface temperatures and increased carbon dioxide levels in seawater. Long-term studies of CO_2 concentrations in seawater show trends in reducing calcification rates in reef-building and reef-associated organisms. Increased sea surface temperature leads to coral bleaching (a result in the loss of symbiotic algae and bacteria) and death of skeletal reef-building organism. Weakened coral communities are susceptible to infection disease. Pollution from coastal development and agricultural runoff can also impede coral growth and reproduction, disrupt ecological functions, and cause disease.

Coal is the most carbon-intensive fossil fuel, producing the most carbon dioxide per unit volume burned. For every ton of coal burned, approximately 2.5 tons of CO_2 is released into the air. Globally, coal is the largest-used fossil fuel source and the highest production of carbon dioxide emissions. Although coal represents only about one-third of share of fossil fuels consumed by the world's total primary energy supply, coal is responsible for 43% of carbon dioxide emissions from burning fossil fuels.

Politics of Climate Change: Sadly, our world may be in big trouble because of the economics associated with energy and agricultural demands of a growing world population. Failure to address carbon emissions and the resultant impacts of rising temperatures and ocean acidification could make many marine and coastal management efforts futile. While reducing CO_2 and other greenhouse gas emissions is vital to stabilize the global climate is essential, the excess that already exists in the atmosphere will persist throughout the next century.

Climate changes will have many impacts on marine systems including reduction in marine biodiversity, sea level is rising, and long-term forecasts predict changes in the frequency, intensity, and distribution of tropical storms as atmospheric and ocean circulation patterns change.

Climate change map model for the late 21st century produce by NOAA

Figure 17.32. A map produced by NOAA showing changes in the mean sea surface temperature for the latter half of the 21st century. Estimates vary, but long-range predictions show that the ocean warming is greatest in the Northern Hemisphere where changes are currently more than 3° Celsius (~5.5° F). Weaker warming is seen in the North Atlantic and the Southern Ocean.

Politics vs. Technology: The key to saving or destroying our natural environments

The climate change issues will be every-increasingly important as the impacts become increasingly obvious as the number of natural and man-made disasters steadily rises. Humans have to collectively choose, through political means, to make the choices to change to cleaner technologies, and protecting and managing resources. The choices to move away from fossil-fuel consumption to alternative energy sources will be expensive and a hard fight because it will impact the livelihoods of many people (such as coal miners and workers in the petroleum industries). Predicted sea-level rise and global warming will impact all world's communities, both human and ecosystems. There will be many ***winners and losers*** in the transition to a cleaner, more **sustainable** world. Accepting the consequences for climate change will create many new jobs in the process. The longer humanity waits to make these changes, the greater the environmental problems will be in the future. **"We can't fool mother nature!"**

Oil fires in Kuwait

Figure 17.33. Major fires burned for months with the bombing of Kuwait's oil fields in 1991, resulting in a major environmental calamity, both on land and offshore.

Oil fires in Kuwait

Figure 17.34. Satellite views of burning oil fields in Kuwait.

17.18: Quiz Questions - Chapter 17 - Human Impacts- Marine Resources and Pollution

1. A naturally occurring ***material*** (mineral or biological in origin) that can be economically exploited through current technological means is called a:
a) resource.
b) reserve.
c) preserve.
d) all of the above.

2. **Aquaculture** is gradually replacing traditional ***capture*** methods used deep-sea fishing. Currently, about what percentage of seafood consumed around the world comes from aquaculture?
a) 10 %.
b) 20 %.
c) 30 %.
d) 80 %.

3. What year was large-scale commercial whaling operations cease (banned) by most countries worldwide?
a) 1900.
b) 1955.
c) 1987.
d) 2014.

4. According to NOAA studies, what percentage of marine pollution comes from sources on land?
a) 60 %.
b) 70 %.
c) 80 %.
d) 90 %.

5. Some pollutant chemicals accumulate in cell tissues as it is consumed, and then are passed along in higher concentrations to the organisms that feed on them. This increase in concentrations in higher orders of a food chain is called:
a) biologic amplification.
b) respiration.
c) carcinogenic.
d) hypoxia.

6. Which would be considered a **non-point source** of pollution?
a) a smokestack at a power plant.
b) a sewage outfall from a coastal community.
c) a large ship traveling at sea.
d) runoff from parking lots in an urban area.

7. Pollutants from overflowing sewers and urban runoff are a reason for many beach closures in San Diego County. If it rains more that 1/4 inch, how long is it recommend to stay out of the coastal ocean waters along San Diego beaches?
a) 12 hours.
b) 24 hours.
c) 48 hours.
d) 72 hours.

8. Currently, what is the largest contributor of man-made carbon dioxide emissions worldwide?
a) oil.
b) gas.

c) coal.
d) automobiles.

9. Worldwide about how many people suffer health effects or die from heavy-metal pollution each year?
a) 5 million
b) 10 million
c) 50 million
d) 100 million

10. What is considered by the world's Scientific Community to be the major contributing factor to climate change since the Industrial Revolution began in the 1850?
a) sea level rise.
b) melting of Greenland's and Antarctica's continental glaciers.
c) emissions of carbon dioxide from the burning of fossil fuels.
d) belching and farting cows in large feedlots.

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Glossary

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