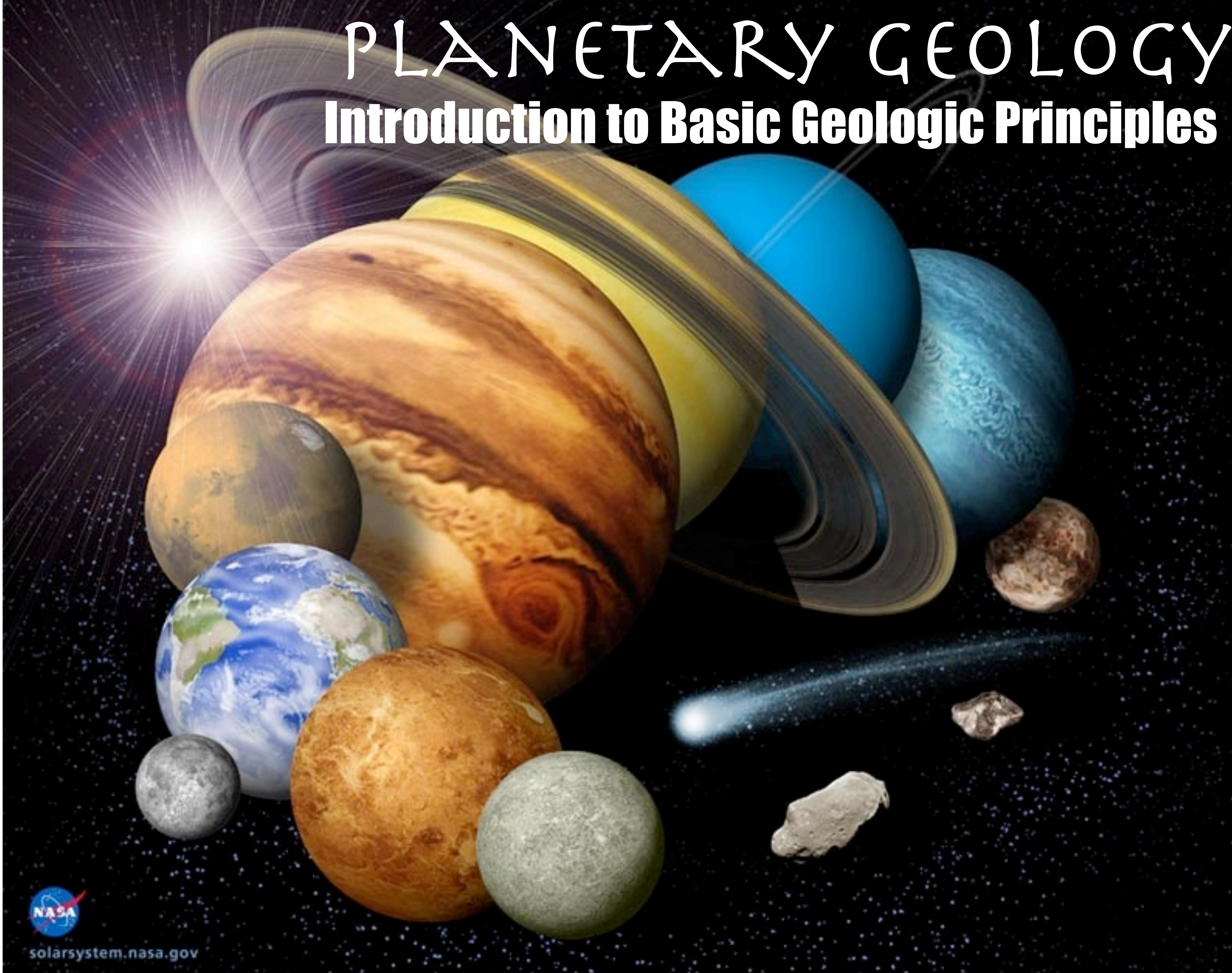
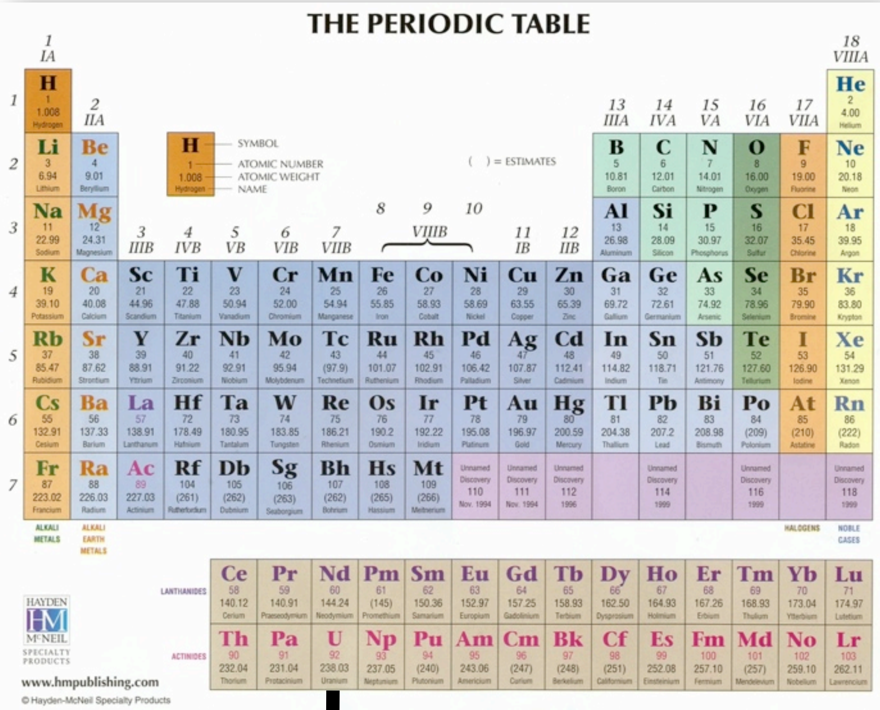
PLANETARY GEOLOGY

Introduction to Basic Geologic Principles



Basic Geologic Principles: Minerals & Rocks



Mineral:

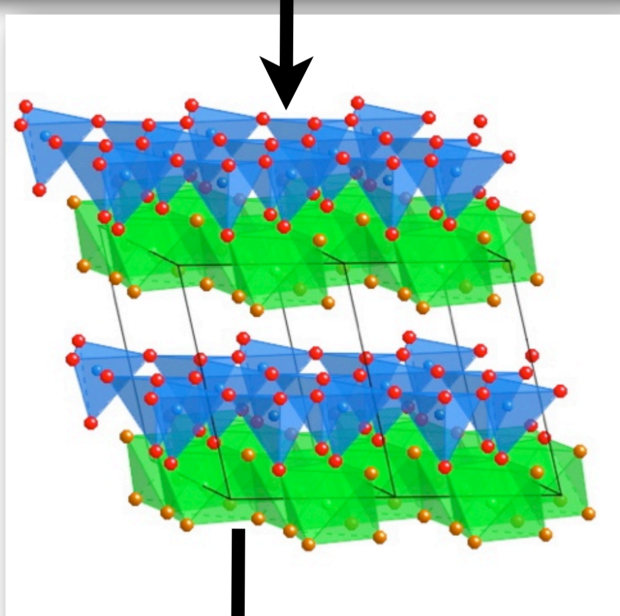
A *naturally* occurring *inorganic solid* that has an exact chemical composition with an orderly internal arrangement of atoms.

- formed primarily by inorganic processes

- stable or unstable depending on environmental conditions (pressure, temperature, humidity, fluid chemistry, etc.)

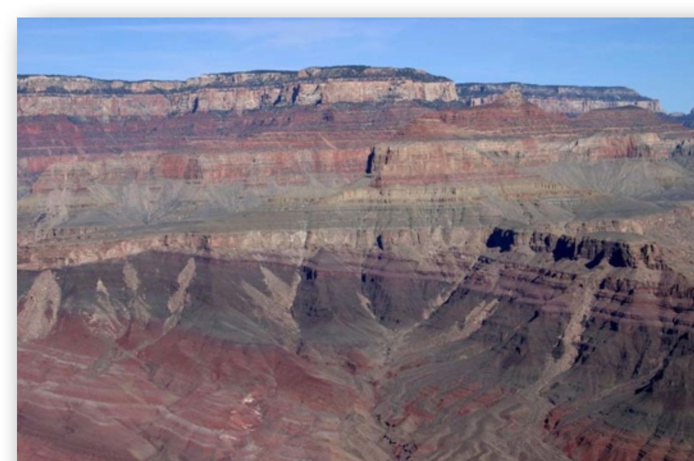
- vary in physical properties (color, crystal shape, hardness, etc.)

- some minerals form by alteration of other minerals



Minerals have internal structure, meaning that the atoms have a repeating geometric pattern.

Atoms are the building blocks of minerals.
Minerals are the building blocks of rocks.



A crystal can be very small (such as 1/1,000,000 of a meter)

or

VERY large!

Important Minerals on Terrestrial Planets & Asteroids

Olivine
$(Mg,Fe)_2SiO_4$

Pyroxene
$(Mg,Fe,Ca)_2Si_2O_6$

These minerals are relatively dark and make up 'mafic' rocks, such as basalt.

Feldspars

Plagioclase

Albite

$NaAlSi_3O_8$

Anorthite

$CaAl_2Si_2O_8$

K-Feldspar
$KAlSi_3O_8$

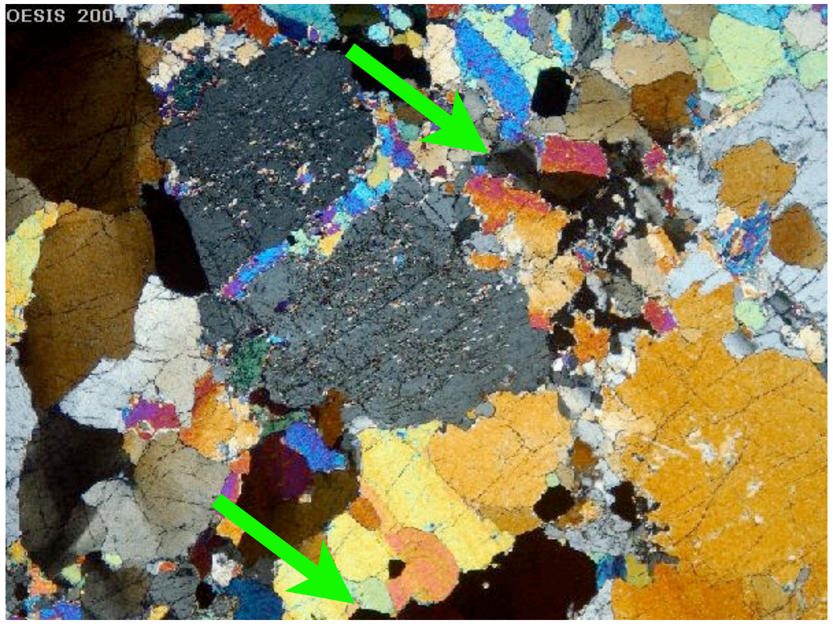
These minerals are relatively light and make up 'felsic' rocks, such as granite.

Basic Geologic Principles: Minerals & Rocks

We can cut rocks into very thin slices, polish them, and see how they reflect or transmit light. This can be used to identify minerals.

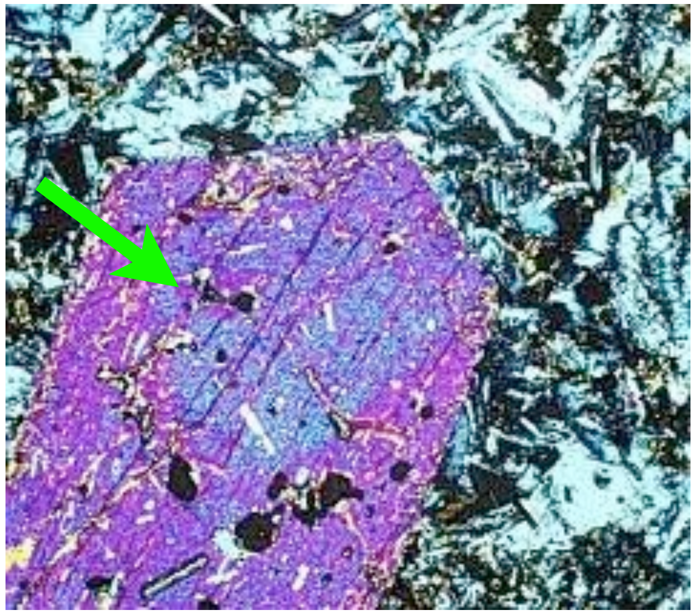
Olivine

$(Mg,Fe)_2SiO_4$



Pyroxene

$(Mg,Fe,Ca)_2Si_2O_6$



Feldspars

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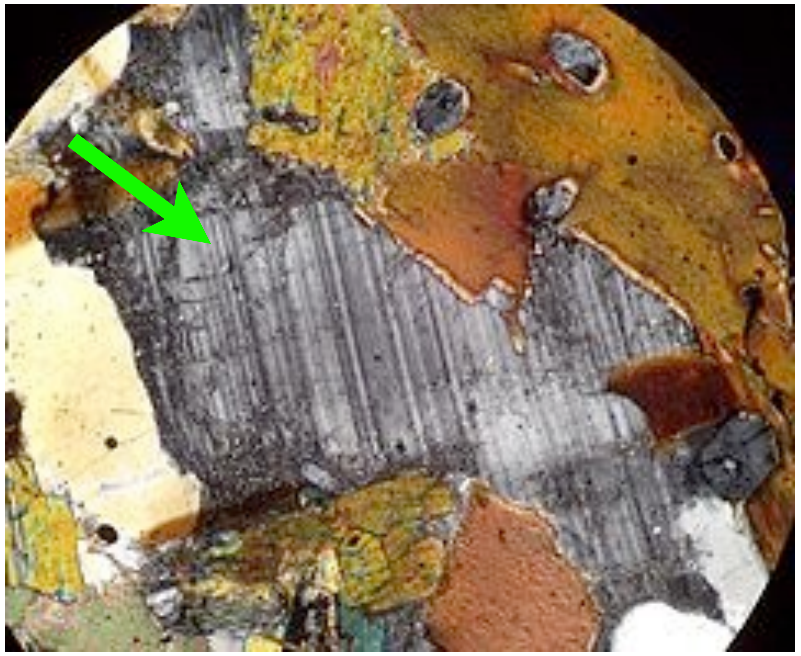
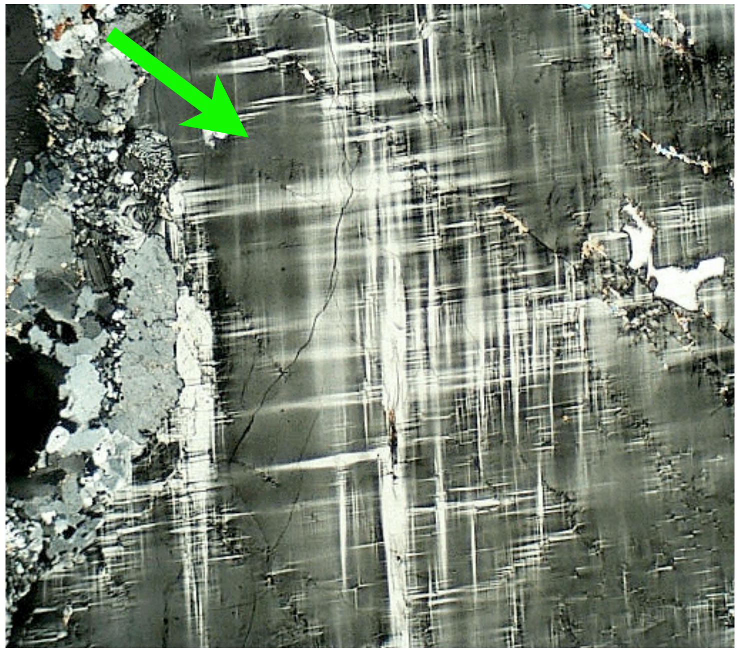


K-Feldspar

$KAlSi_3O_8$



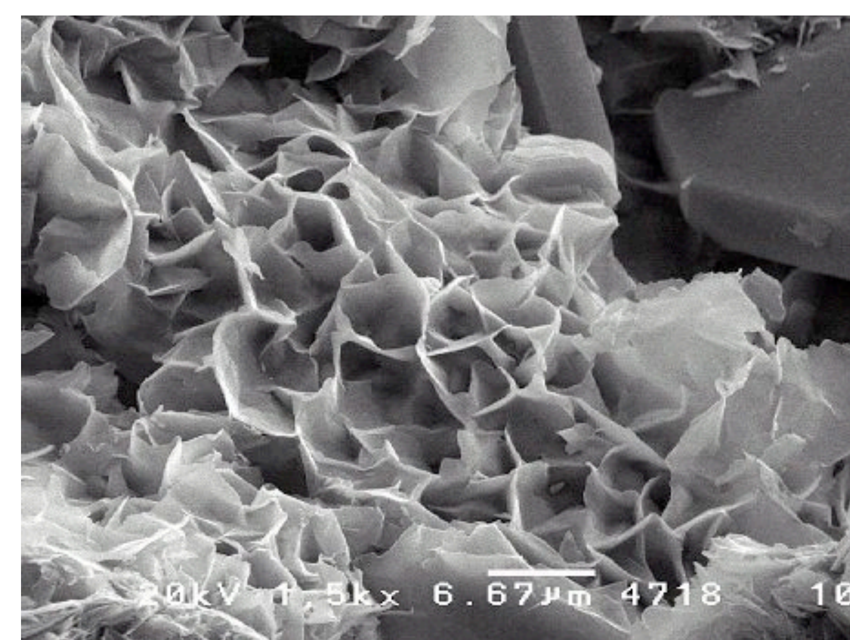
Important Minerals on Terrestrial Planets & Asteroids

Quartz
SiO_2

Amphiboles
Contains OH

Carbonates
Contains CO_3,
makes up limestone

Clays
Contains OH,
often H_2O



Basic Geologic Principles: Minerals & Rocks

A rock can be composed of one or many different minerals, but there are only 3 primary classes of rocks:

Igneous

Formed by cooling of magma that has flowed onto the surface (lava), or by cooling of magma in the interior of a planetary body.

Sedimentary

Composed of fragments of other rocks, chemical precipitates, organic matter, or biochemically produced materials.

Metamorphic

Formed by recrystallization of other rocks as they experience new pressure, temperature, and fluid conditions. New minerals are formed from old ones.

Basic Geologic Principles: Igneous Rocks

Igneous rocks are classified based on their chemistry/mineralogy and texture.

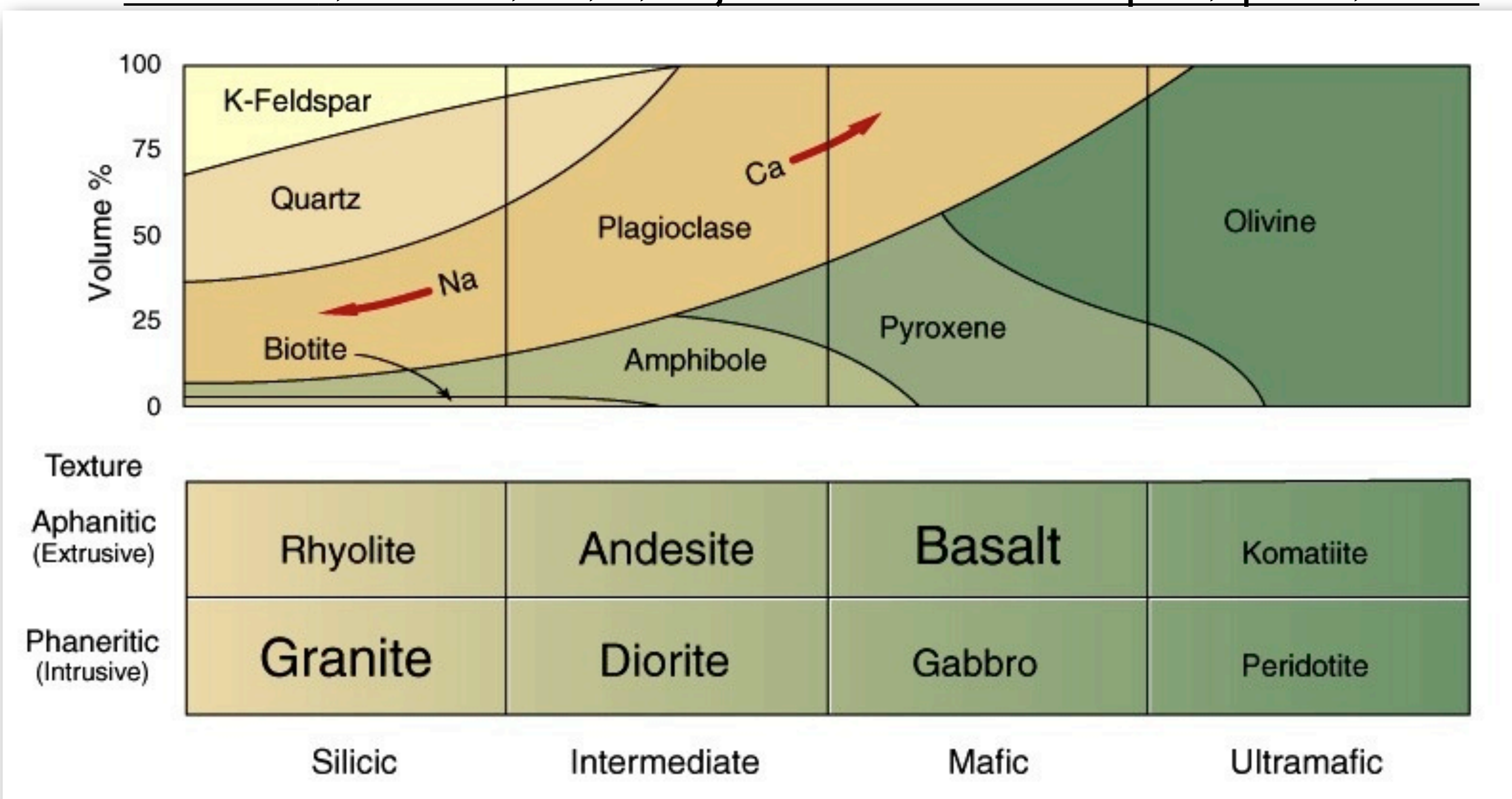
Rocks formed by lava that has *extruded* onto the surface and cooled are called **extrusive**.

Rocks formed by magma that has cooled in the interior or *intruded* into the crust are **intrusive**.

Intrusive and extrusive rocks are classified based on their silica (SiO_2) content.

Ultramafic and mafic rocks have lower SiO_2 tend to be relatively dark in color (e.g., basalt)
~50% SiO_2, lots of Mg, Fe, and Ca, major minerals are olivine, pyroxene, and plagioclase

Felsic, or silicic, rocks have higher SiO_2 contents and tend to be lighter in color (e.g., granite).
>65% SiO_2, more Al, Na, K, major minerals are feldspars, quartz, micas



Basic Geologic Principles: Igneous Rocks

As magma cools, mineral crystals begin to form, creating a 'slush'.

Magma can be a mixture of liquid, solid (crystals), and gas (H_2O, CO_2, SO_2, etc.).

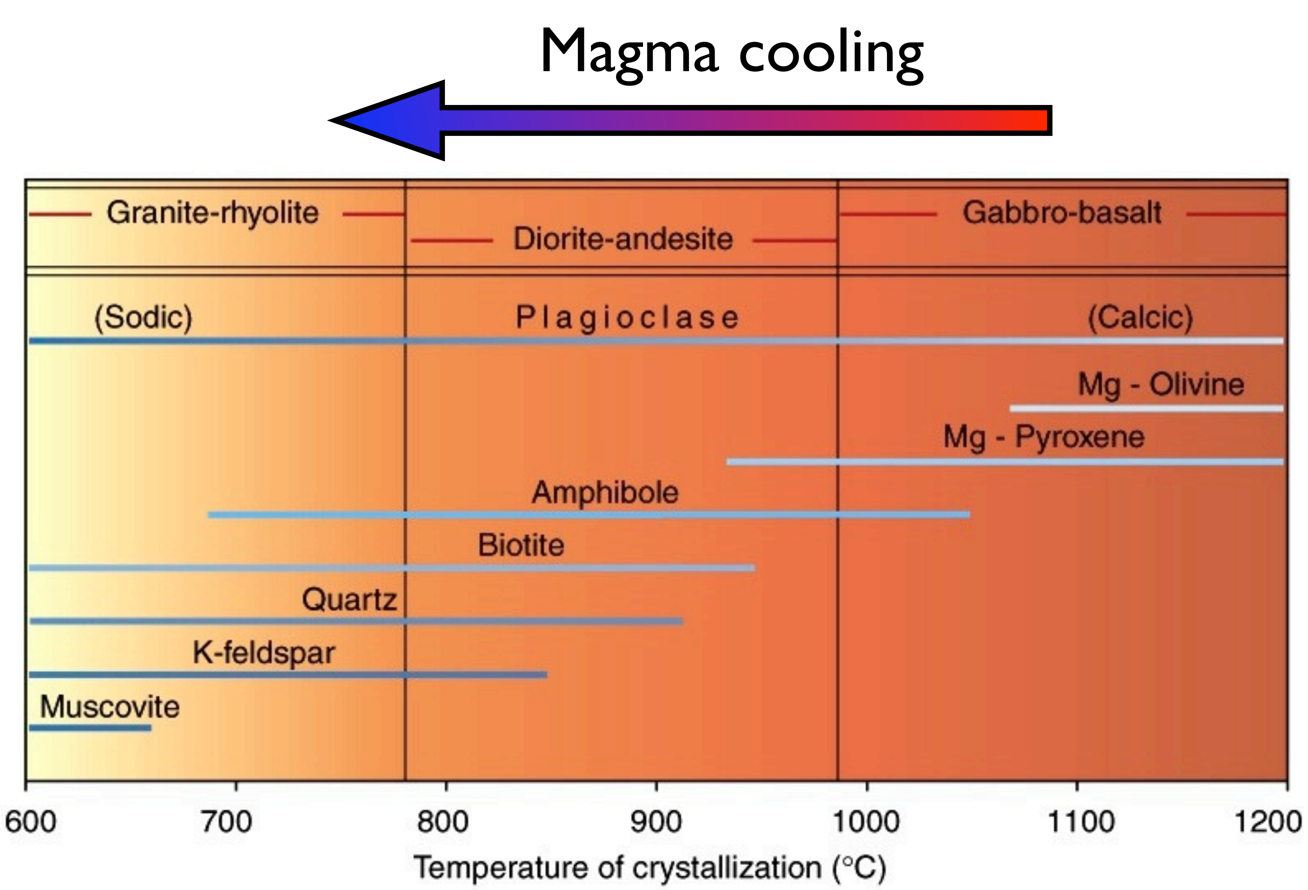
Different minerals have different densities, and some mineral crystals can settle to the bottom of a magma chamber because they are more dense than the magma.

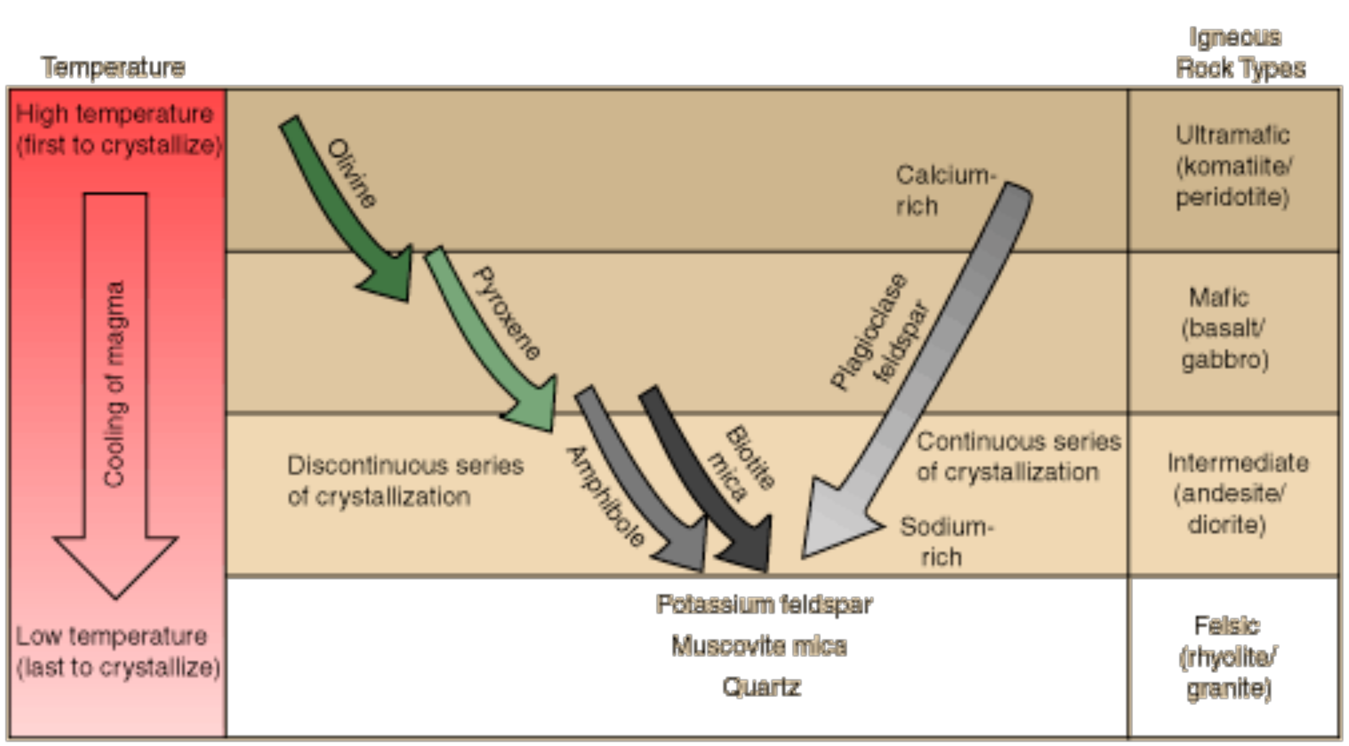
Different minerals have different crystallization (or melting) temperatures; as a magma cools, minerals will crystallize out in a certain order.

When a mineral crystallizes, the elements that go into that mineral will be removed from the magma, thus the magma will become *depleted* in those elements and *enriched* in others.

As minerals crystallize out of a magma, the residual magma becomes enriched in silica (SiO_2).

Whereas high temperature and low-silica magmas can cool to form basalt, this process of magma differentiation can lead to more evolved (silica rich) magmas that can cool to form felsic rocks.

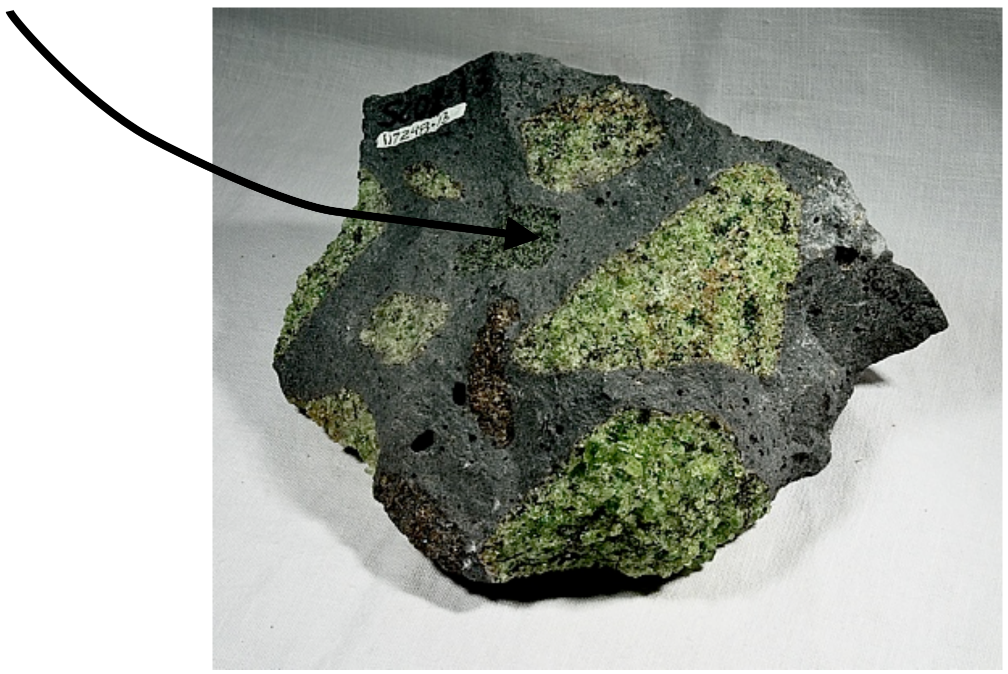


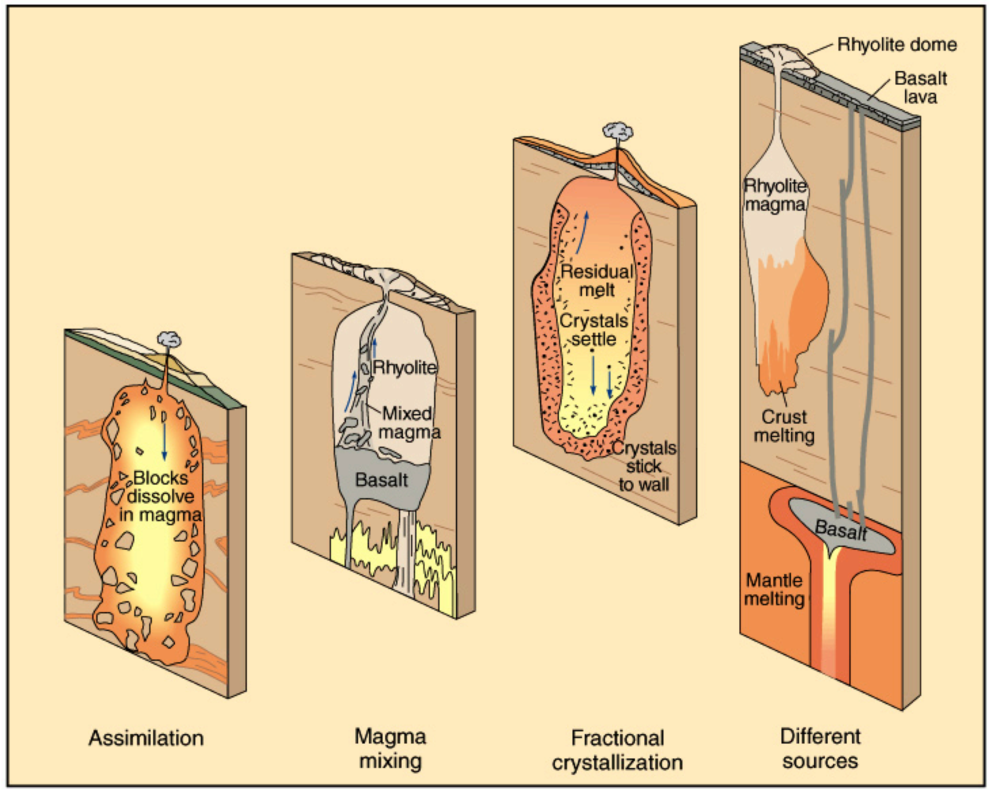


Basic Geologic Principles: Igneous Rocks

The Earth's mantle is very rich in Mg and Fe, and it contains significant amounts of olivine and pyroxene.

Partially melting the mantle gives rise to mafic/ultramafic magmas, which may reach the surface as lava flows and then cool to form basalt. Sometimes these basalt flows contain pieces of the mantle known as *xenoliths*.





The more silicic magmas that form felsic rocks (e.g., rhyolite) do not come from melting of the mantle. They require other processes to form (magma mixing, assimilation of other material, differentiation).

Therefore, different igneous rocks carry important information about the interior of a planetary body, such as the composition of the mantle and the processes that take place in the crust.

As we will see, the continental crust on Earth is largely 'granitic' in composition and the oceanic crust on Earth is largely 'basaltic'. This is ultimately linked to plate tectonics.

In contrast, other planets such as Mars are dominated by basalt and have little evidence for more 'evolved' magmas.

Basic Geologic Principles: Igneous Rocks

In addition to chemical information, we can also classify rocks based on their textural attributes.

Small crystals indicate faster cooling, large crystals indicate slower cooling.

Aphanitic Texture

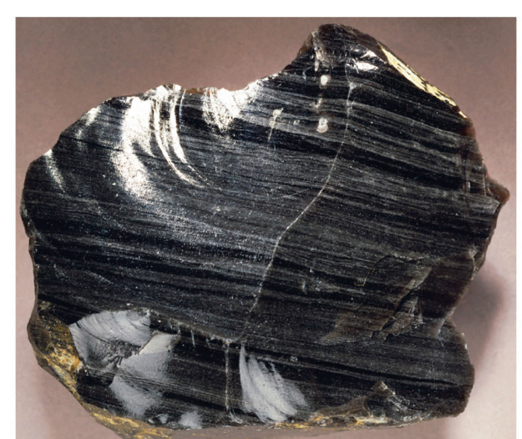
fine-grained,
few crystals seen in hand specimen,
relatively quick cooling,
gases in magma can lead to vesicles

Phaneritic Texture

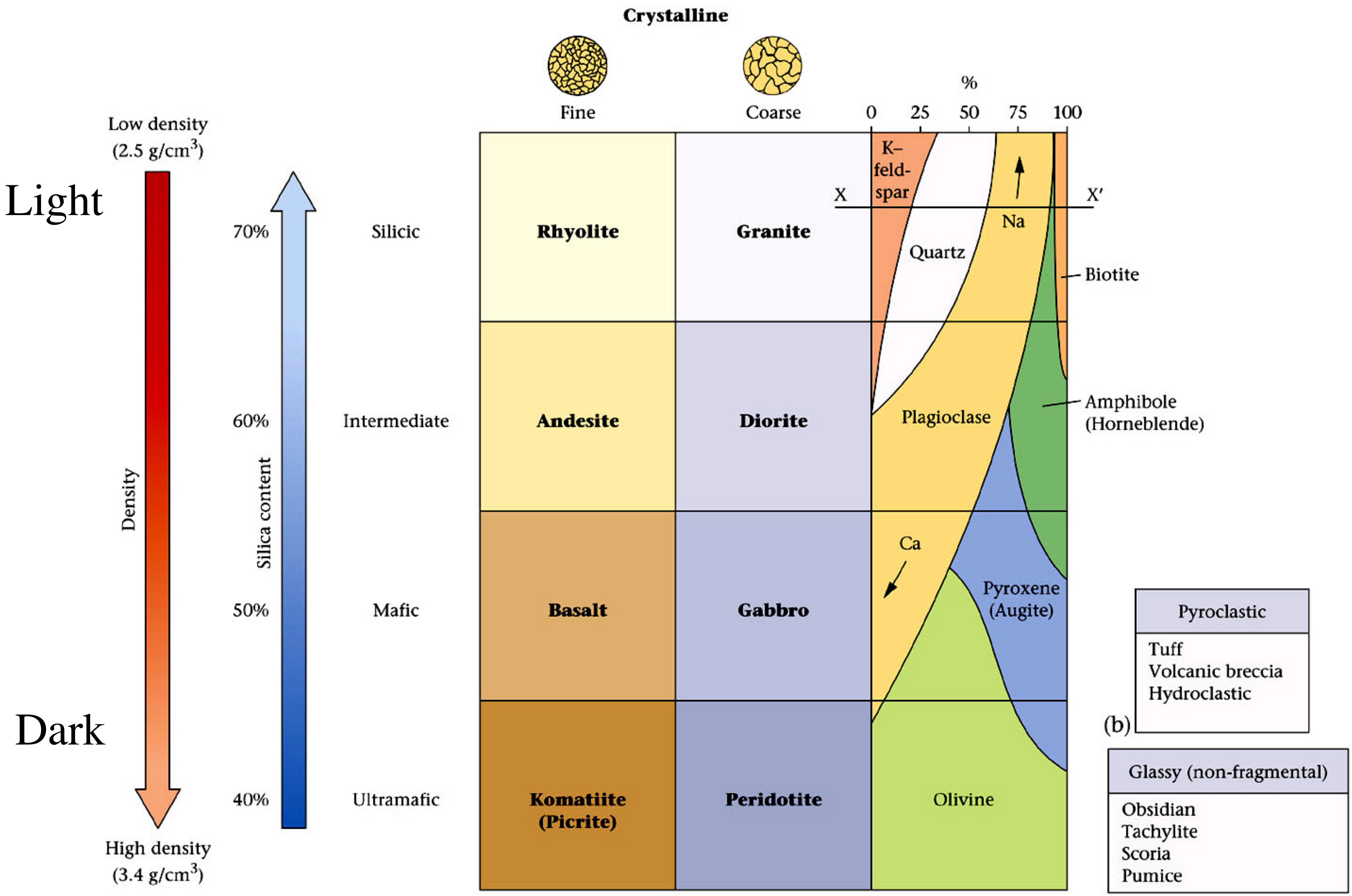
coarse-grained,
interlocking crystals,
relatively slow cooling,
crystallized at depth

Glassy Texture

such as obsidian,
indicates very rapid cooling
(often referred to as 'quenched').



Basic Geologic Principles: Igneous Rocks



Basic Geologic Principles: Sedimentary Rocks

Sedimentary rocks cover ~75% of the continents and most of the ocean floor.

Easy to erode relative to igneous and metamorphic rocks.

Commonly exhibit layering, which we refer to as *stratification*.

There are 2 major divisions of sedimentary rocks:

Clastics

Accumulation and lithification/cementation of sediments (fragments of other rocks).
The sediments are produced by erosion and are transported by wind, water, and/or ice.

sandstone

shale

conglomerate

breccia

Chemical & Biochemical

Precipitation of minerals out of fluids or precipitation/secretion of minerals biologically.
These rocks contain a lot of information about the chemistry of fluids in which they formed.
Examples: limestone, chert (opal & quartz), halite and other salts

Basic Geologic Principles: Sedimentary Rocks

Sedimentary rocks are capable of preserving evidence of life (animal and plant fossils, biomarkers).

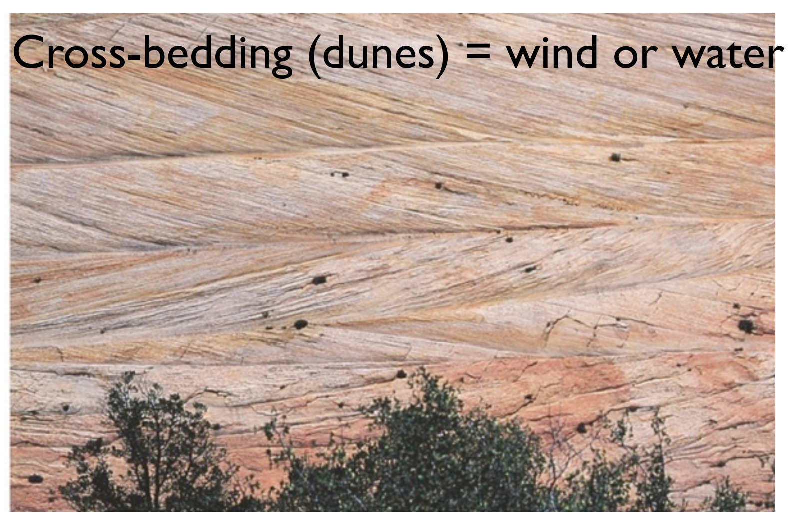
They often contain numerous clues about the environment in which they were deposited. (marine, coastal, lagoon, desert, etc.)

They make up a significant fraction of the rock record, but unlike igneous rocks it is often difficult to determine their absolute ages.

Sequences of sedimentary rocks are very important because they can tell us a lot about changes in environmental conditions, climate, and sea level.

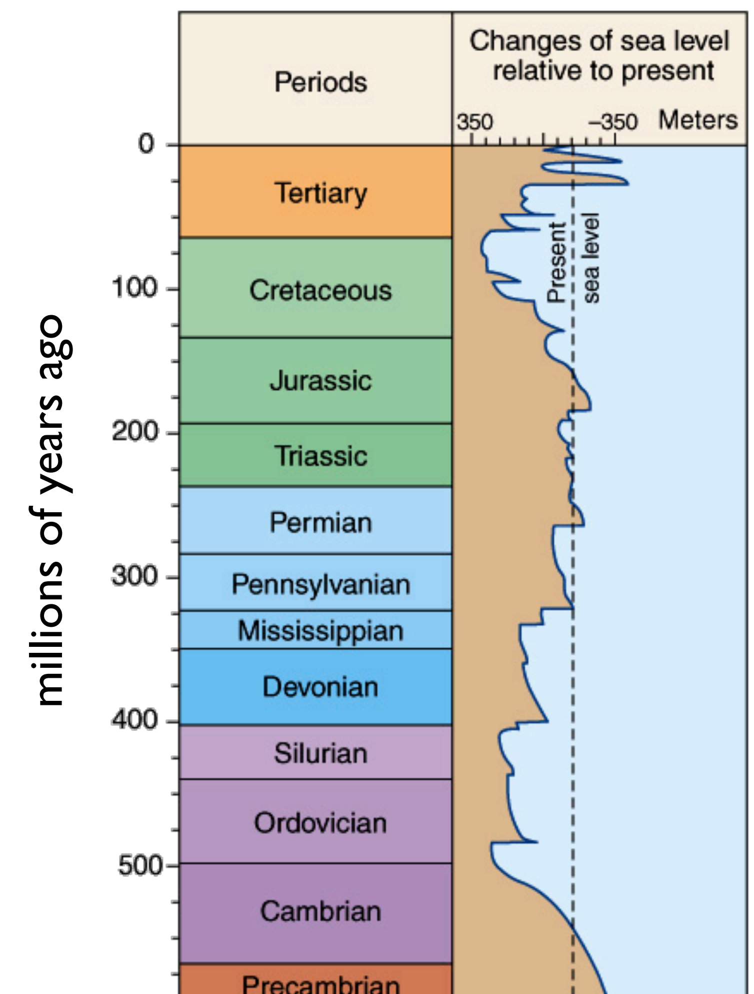
Different rocks tend to form in different environments; we want to be able to look at the rocks and determine the environment in which it formed.


Fossils(could be microbial) = life


Cross-bedding (dunes) = wind or water


Ripple Marks = wind or water


Mudcracks = wetting & drying



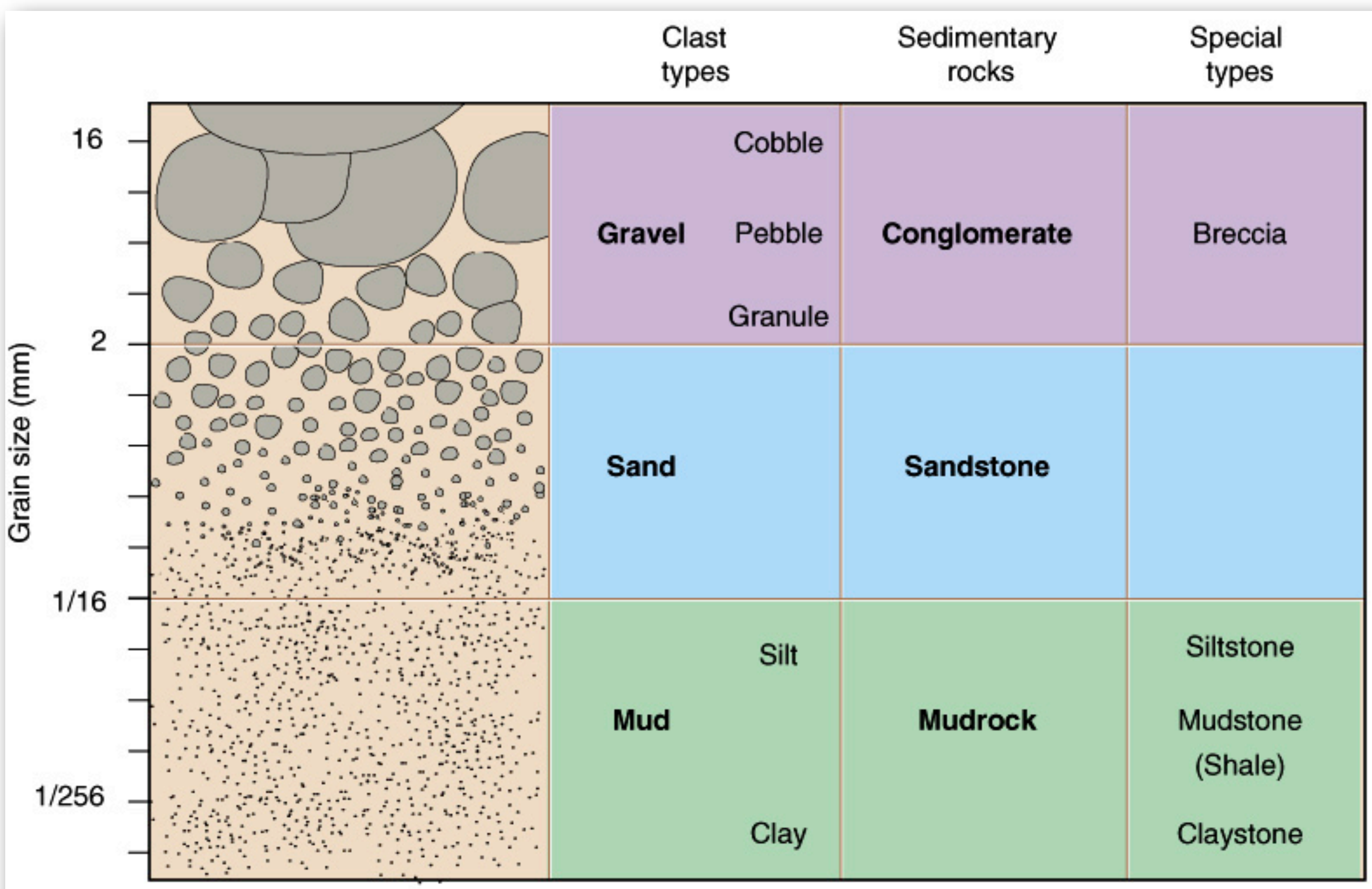
Basic Geologic Principles: Sedimentary Rocks

Clastic rocks are classified based on the grain size(s) of the clasts.

The larger the clast, the harder it is to move.
Therefore, clastic rocks with very large clasts (e.g., conglomerates and breccias) often form close to the source of the clasts (e.g., mountain ranges).

Wind can typically move sand-sized clasts and smaller.
Water can move a much larger size range of clasts, and mud only falls out of very still water.

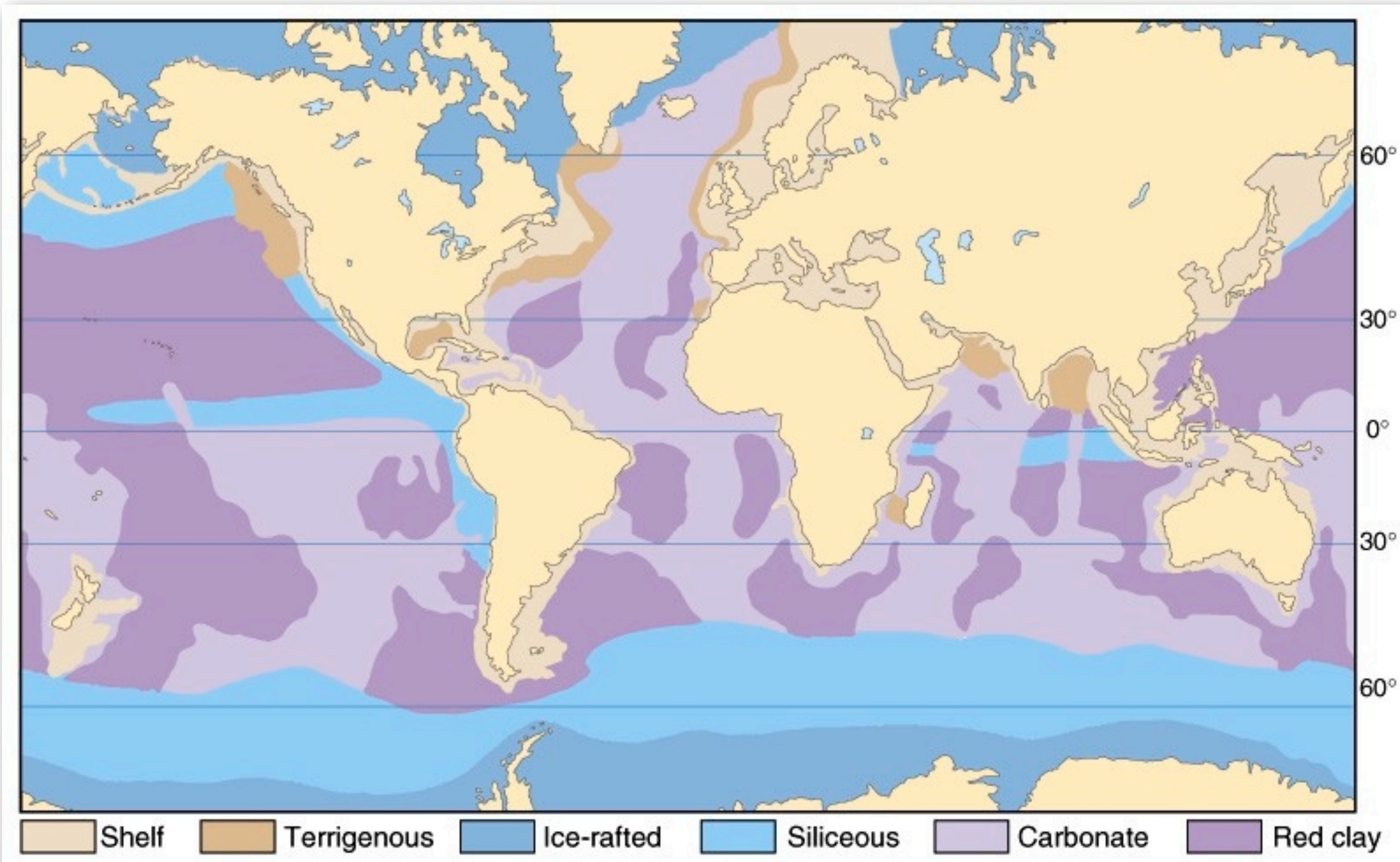
Therefore, small grains found in clastic rocks may be far removed from their source regions.
(Indeed, dust from Africa is carried all the way to South America)



Basic Geologic Principles: Sedimentary Rocks

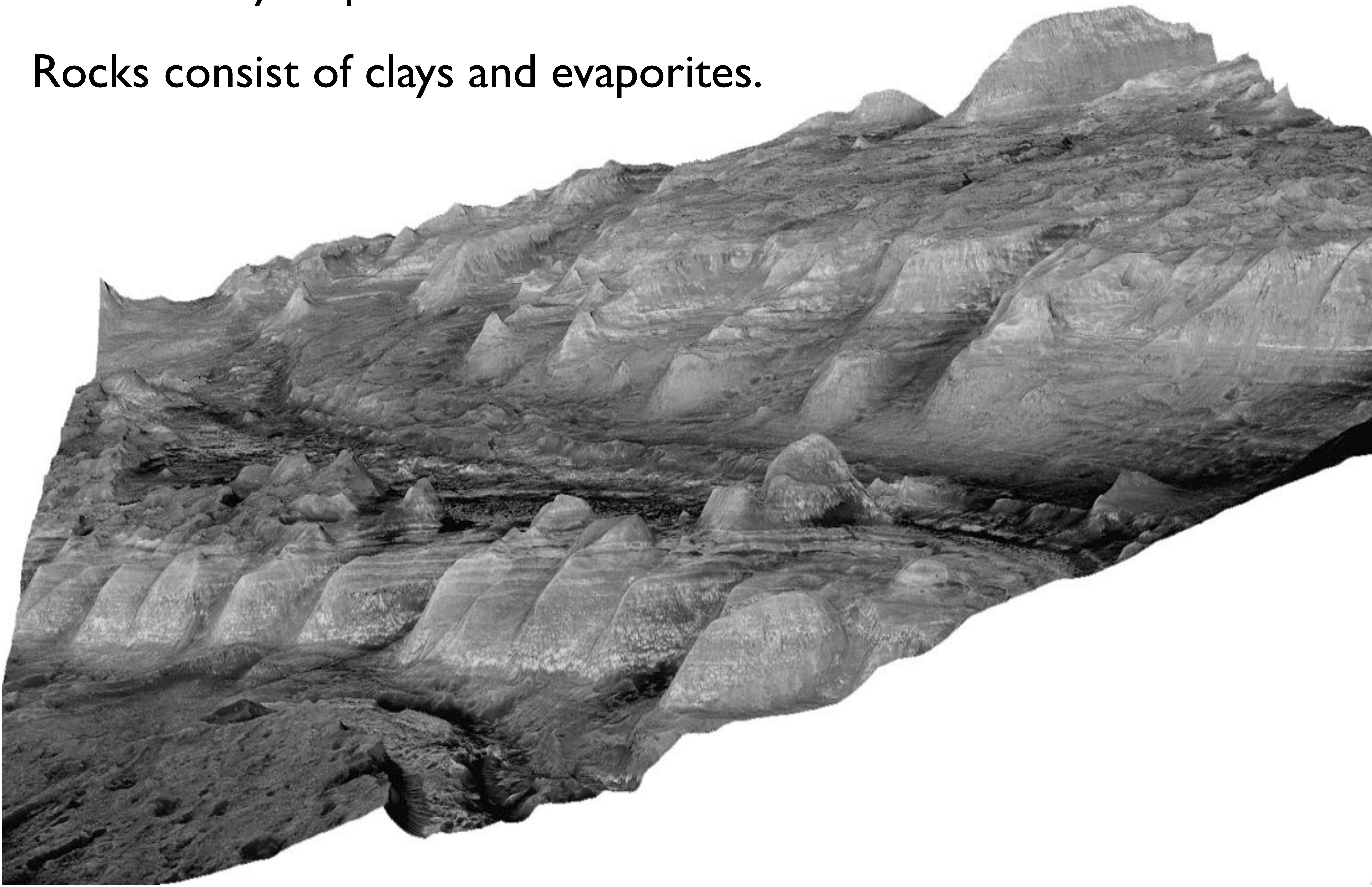
Ocean sediments exhibit distinct patterns and chemical/biochemical sediments dominate much of the seafloor surface (on top of the basaltic oceanic crust).

- Carbonate is dominant in shallow, warm, near-shore waters
- Silica (opal!) is dominant in deeper and colder waters
- Red (iron-rich) clays are transported from the continents by wind
- Terrigenous clastics (from continents) are close to shore and often deposited by river systems



Sedimentary sequence of rocks in Gale Crater, Mars.

Rocks consist of clays and evaporites.



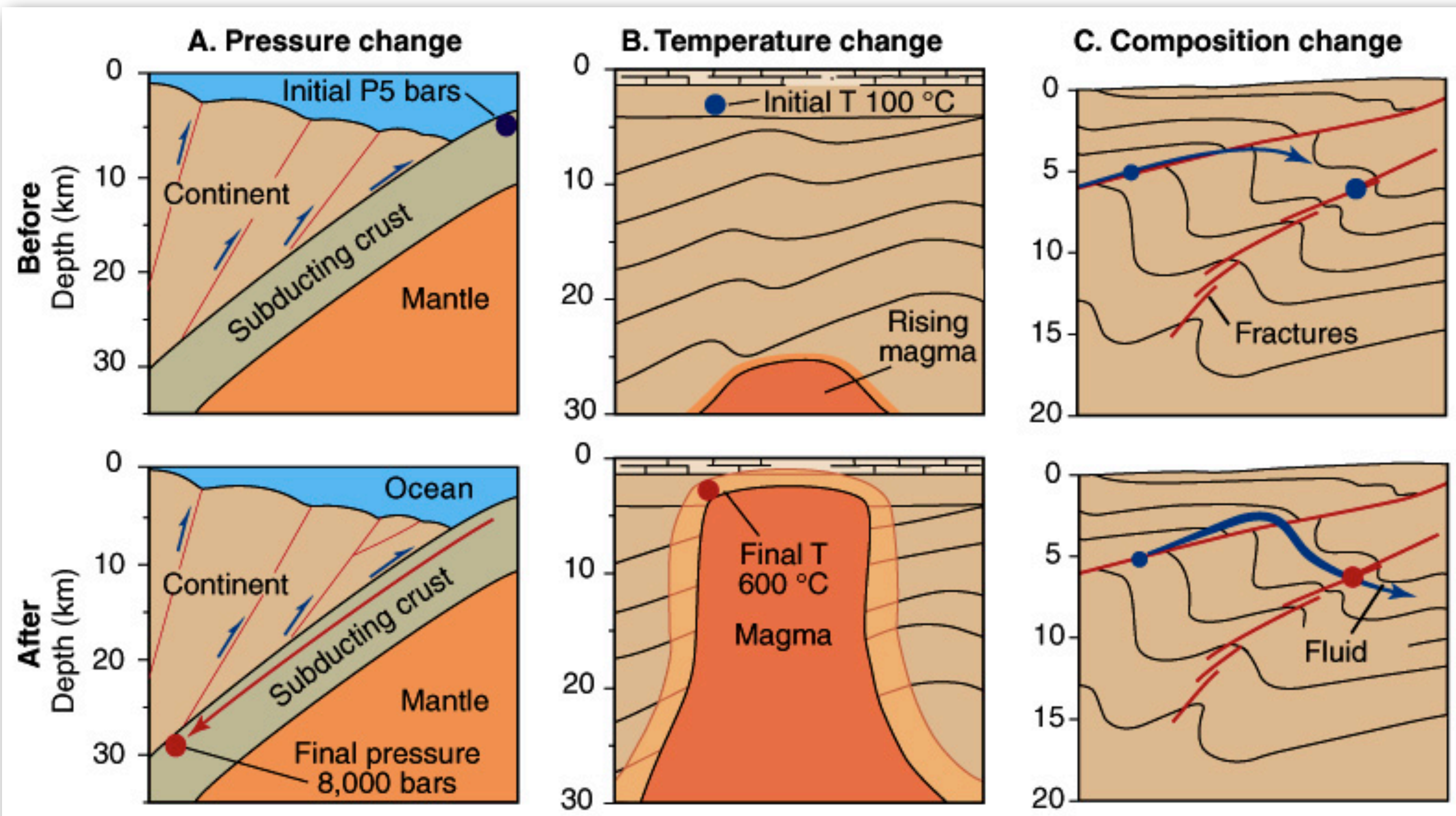
Basic Geologic Principles: Metamorphic Rocks

Metamorphic rocks represent *recrystallization in the solid state* (not melting and recrystallization).

This is caused by changes in temperature, pressure, or fluids in pore spaces.

The rocks are subjected to new conditions/environments, thus new minerals become stable and new textures develop in the rocks.

Diagnostic features of the original rock are masked or destroyed.



Basic Geologic Principles: Metamorphic Rocks

Metamorphism typically begins when....

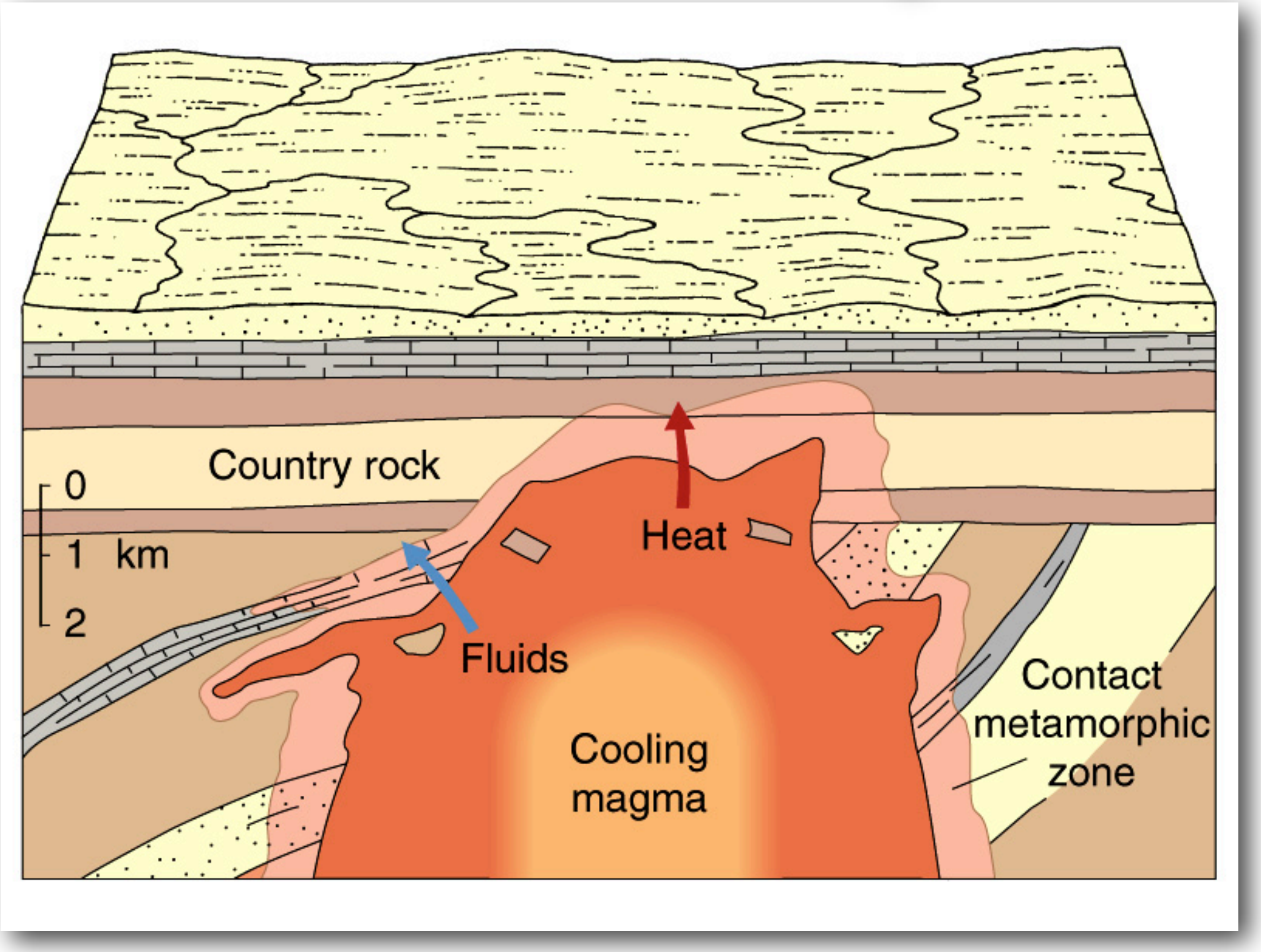
Temperature >200°C and/or Pressure >300 MPa (~10,000 ft depth on Earth)

Metamorphism ends when melting begins.

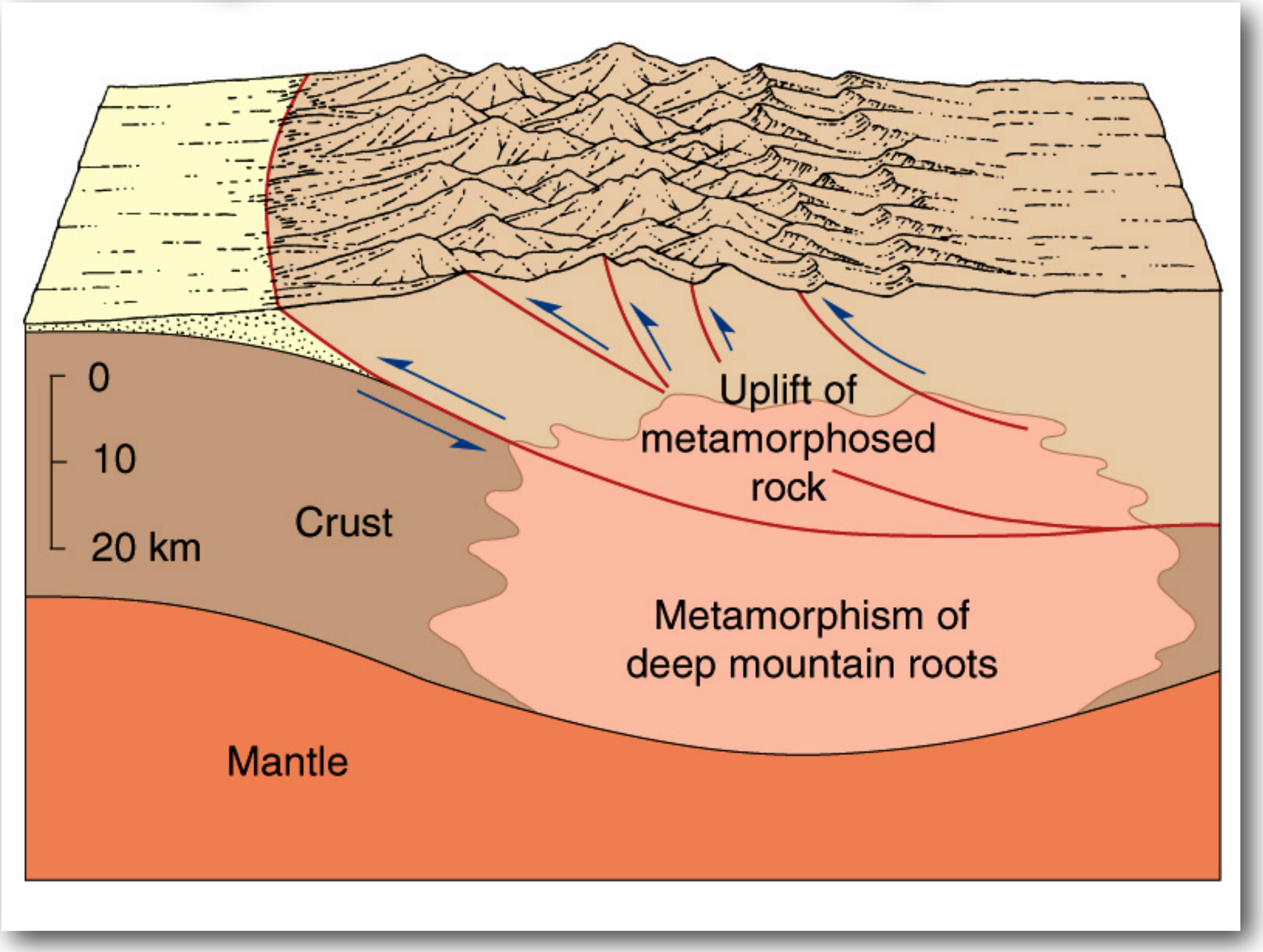
Sources of heat are nearby igneous intrusions and increasing temperature by burial.
Burial can often be regional in scale, related to mountain building events.

Geothermal gradient on Earth ranges from 15-30°C per kilometer (~25°C is a good average).

Contact Metamorphism



Regional Metamorphism



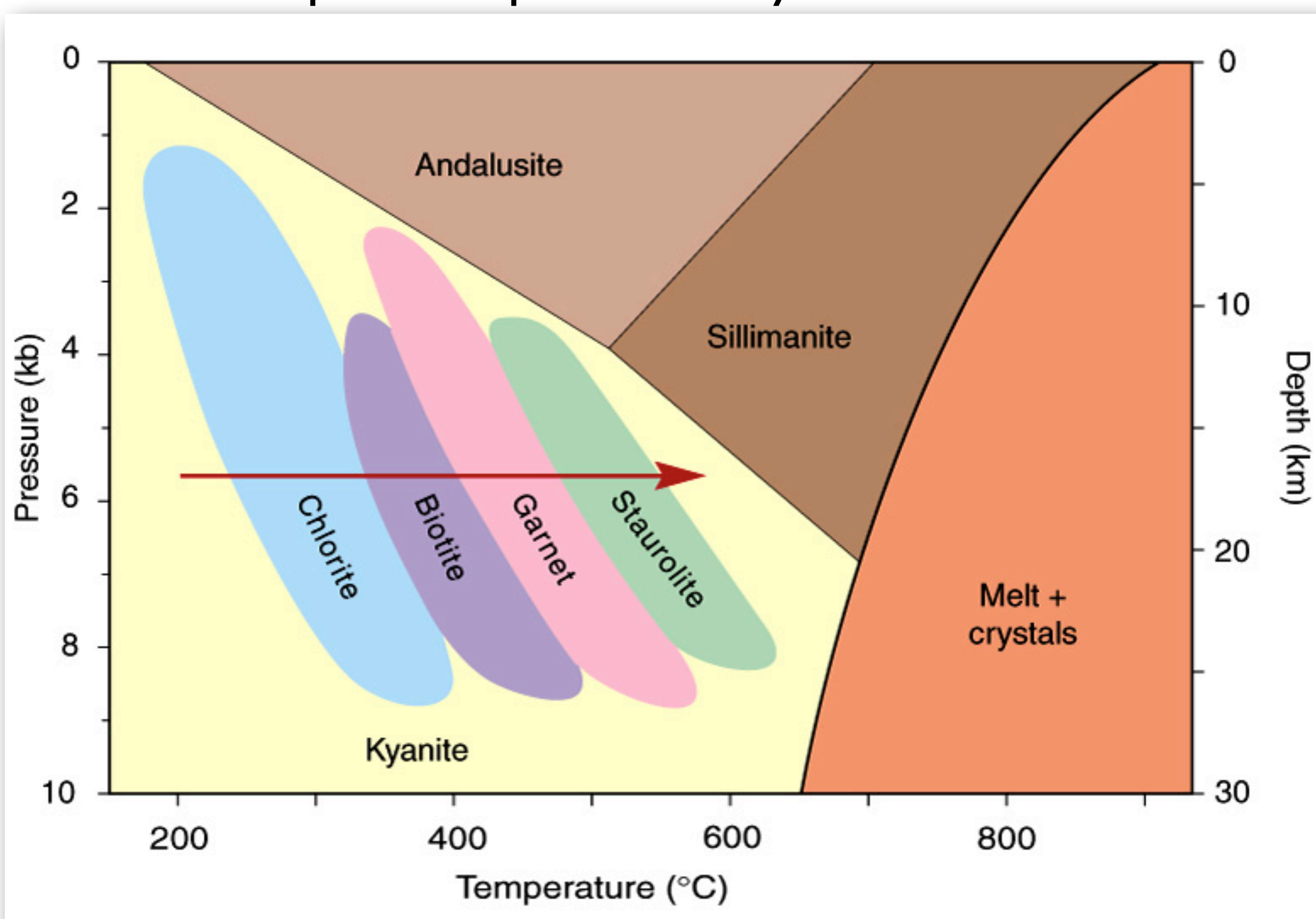
Basic Geologic Principles: Metamorphic Rocks

Combination of Temperature & Pressure determine degree of metamorphism and the types of new minerals that will be produced.

Fluids are at high T & P and help redistribute elements; often contain CO_2 and dissolved ions.

Fluids move along small fractures between crystals; hydrothermal alteration is the source of many ore deposits and valuable minerals.

Certain 'index' minerals are known to form at specific P-T conditions and can thus be used to estimate the degree of metamorphism experienced by certain rocks.

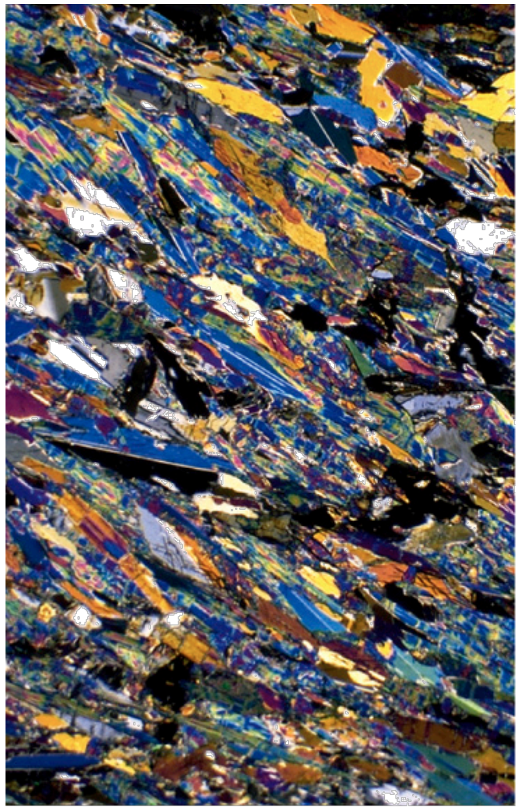


Basic Geologic Principles: Metamorphic Rocks

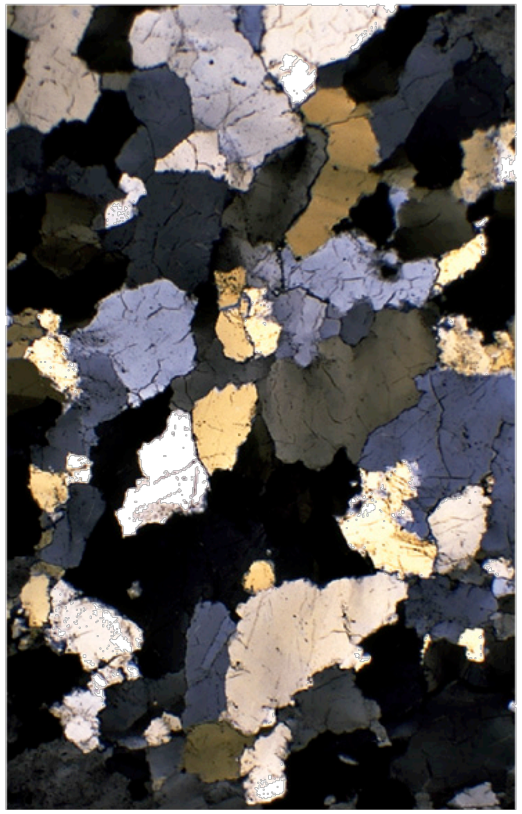
Metamorphic rocks are classified by *composition* and *texture*.

- at high T and P, rocks deform plastically (as opposed to brittle deformation)
- stress (application of pressure) can be the same in all directions (uniform stress) or greater in one direction (differential stress).
- **differential stress** produces distinct texture in rocks - **foliation**
- **uniform stress** produces **nonfoliated** rocks

Foliated



Nonfoliated

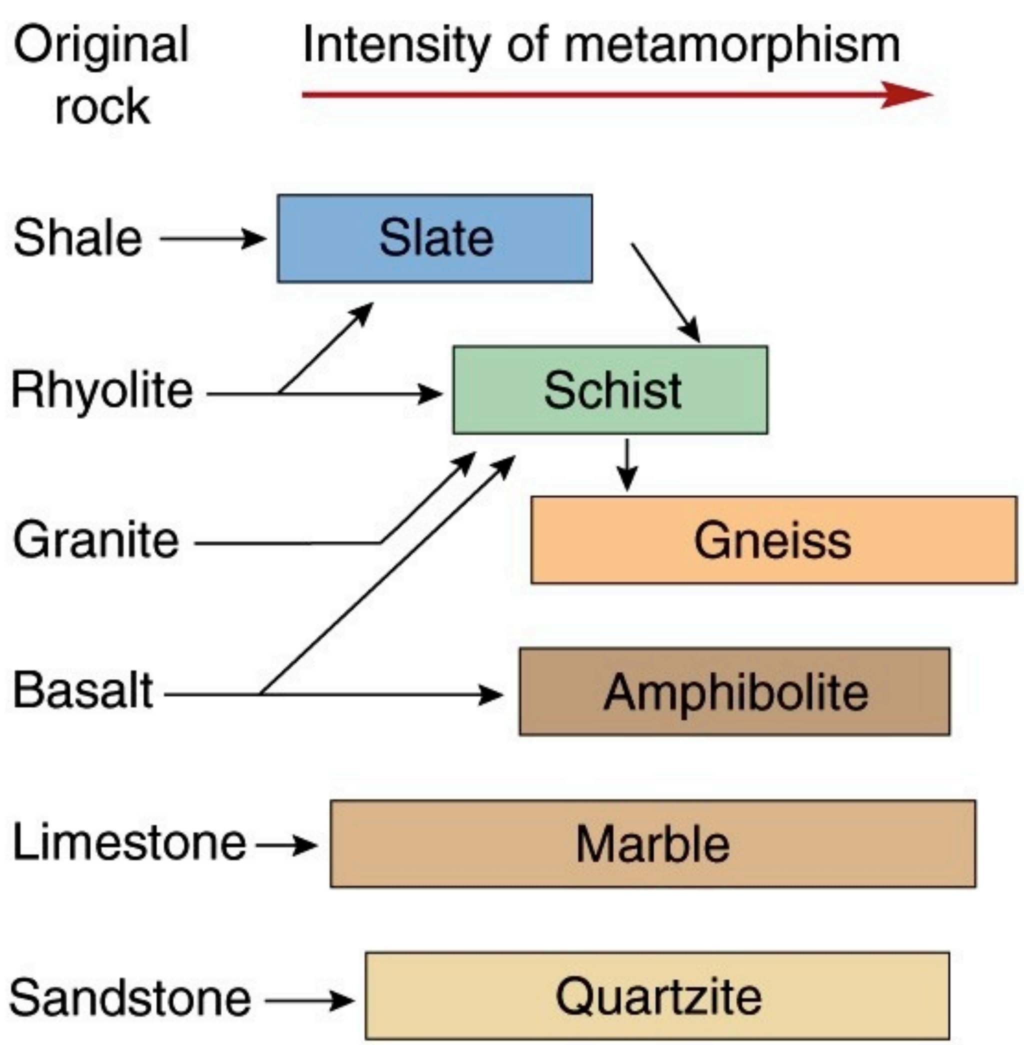


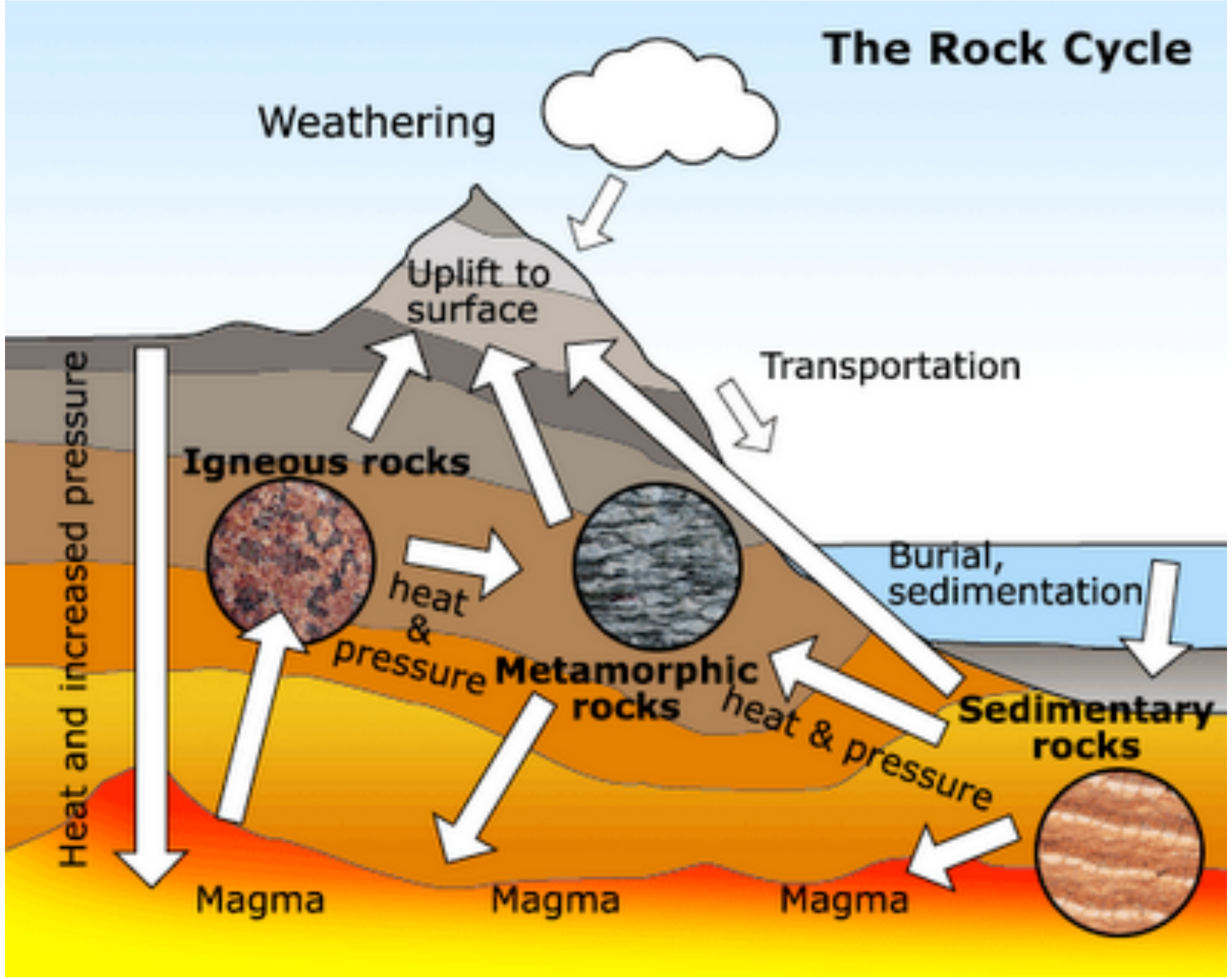
Basic Geologic Principles: Metamorphic Rocks

The majority of metamorphic rocks on Earth are formed as a result of plate tectonics.

Plate margins produce strong changes in pressure and temperature, which cause pre-existing sedimentary, igneous and metamorphic rocks to be metamorphosed.

Indeed, plate tectonics is a fundamental component of Earth's rock cycle and controls the diversity, distribution, and longevity of rocks.

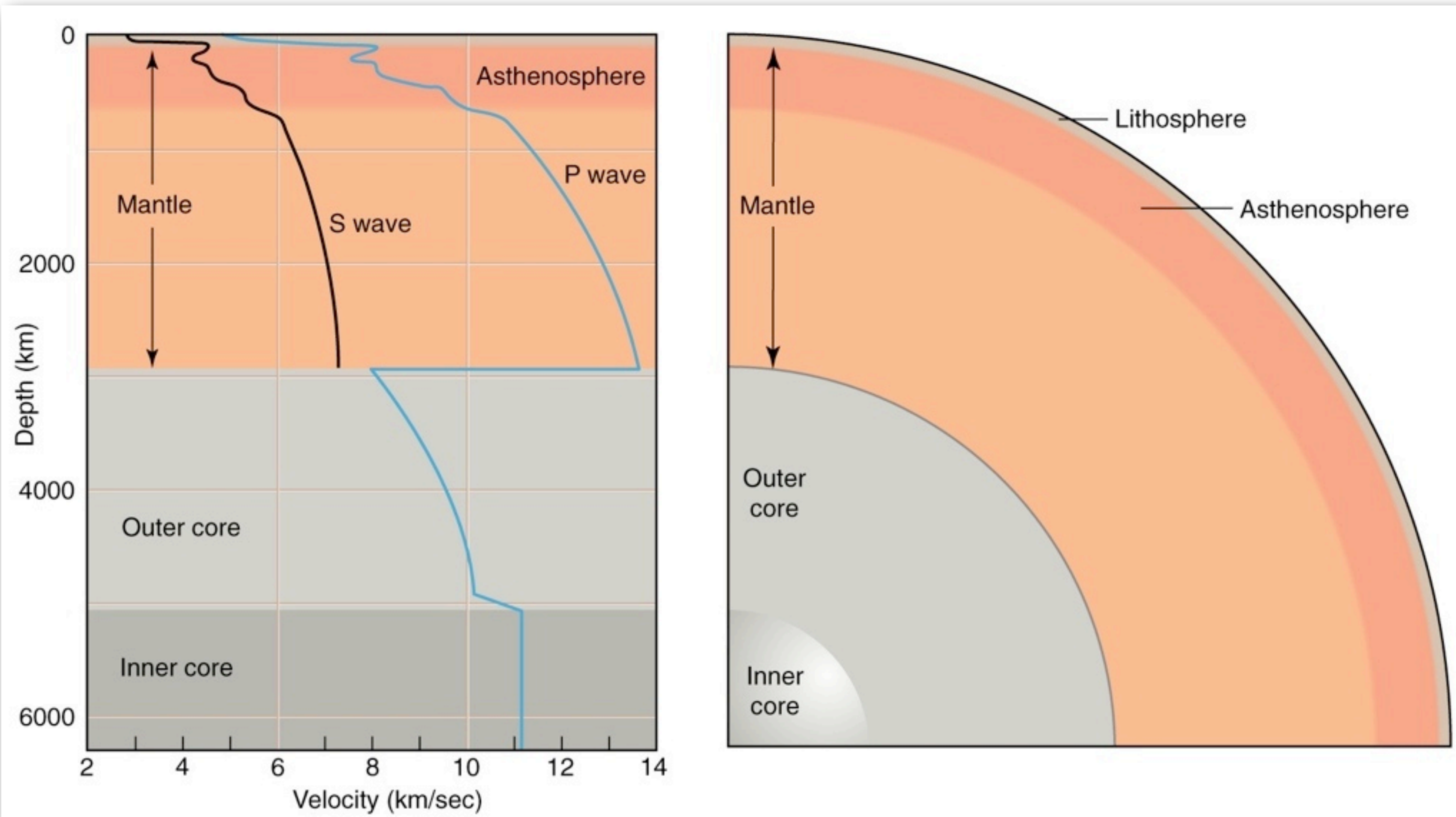




Basic Geologic Principles: Internal Structure

Earthquakes and seismic waves inform us about the interior structure of a planet.

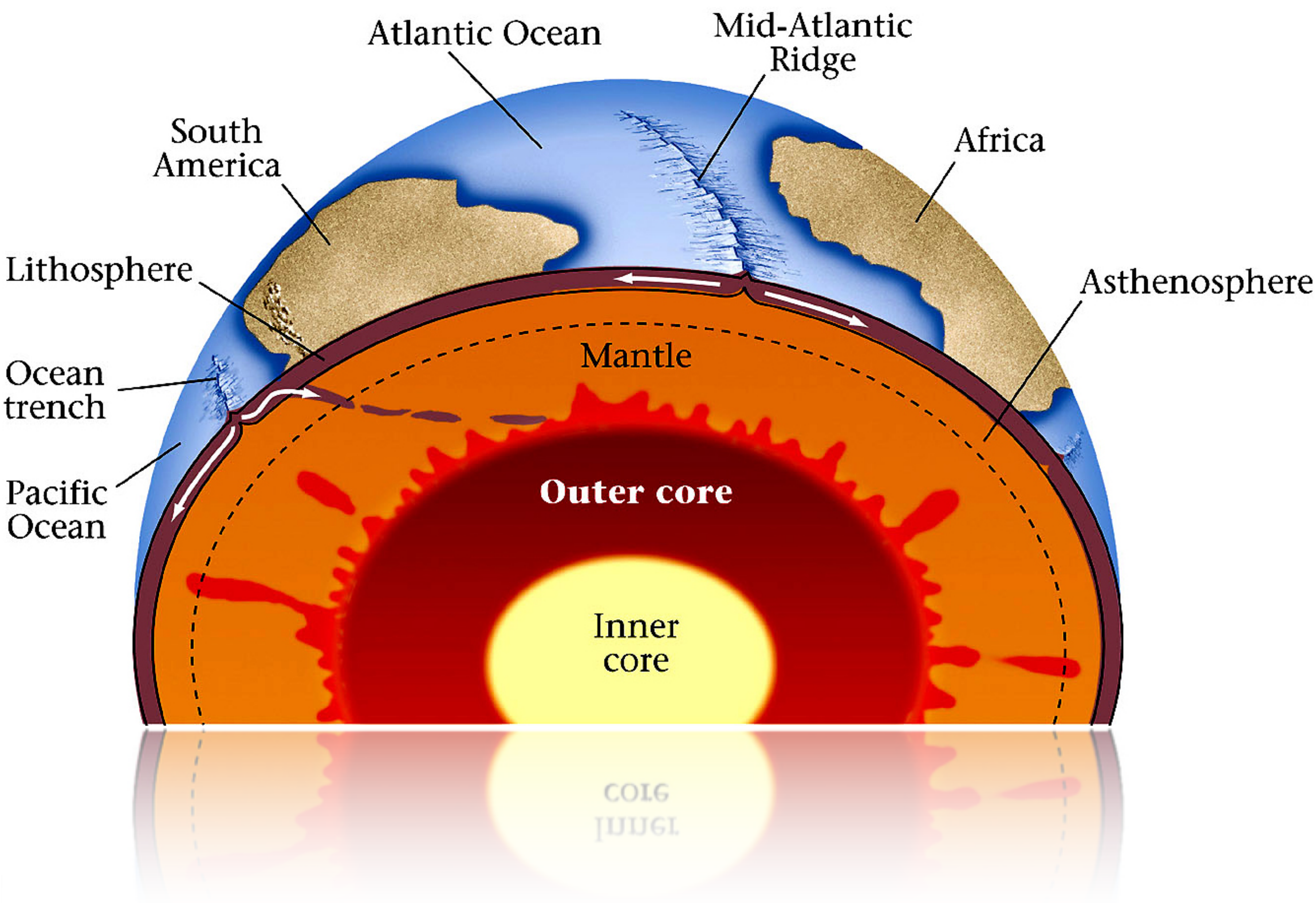
The crust is rigid; ocean is 'basaltic', continents 'granitic'; extends to 5-70 km depth.
The mantle is solid but *ductile* (can flow); Mg/Fe-rich; extends to ~2,900 km depth.
The core has a solid inner region and liquid outer region; made of Fe, Ni.



Basic Geologic Principles: Internal Structure

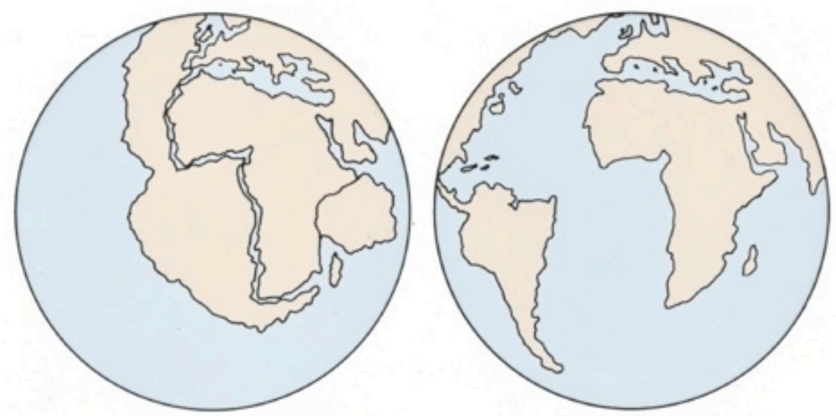
The lithosphere consists of the crust and the upper part of the mantle.

It is the lithosphere that takes part in plate tectonics, where plates sink into the lower asthenosphere (also part of the mantle).

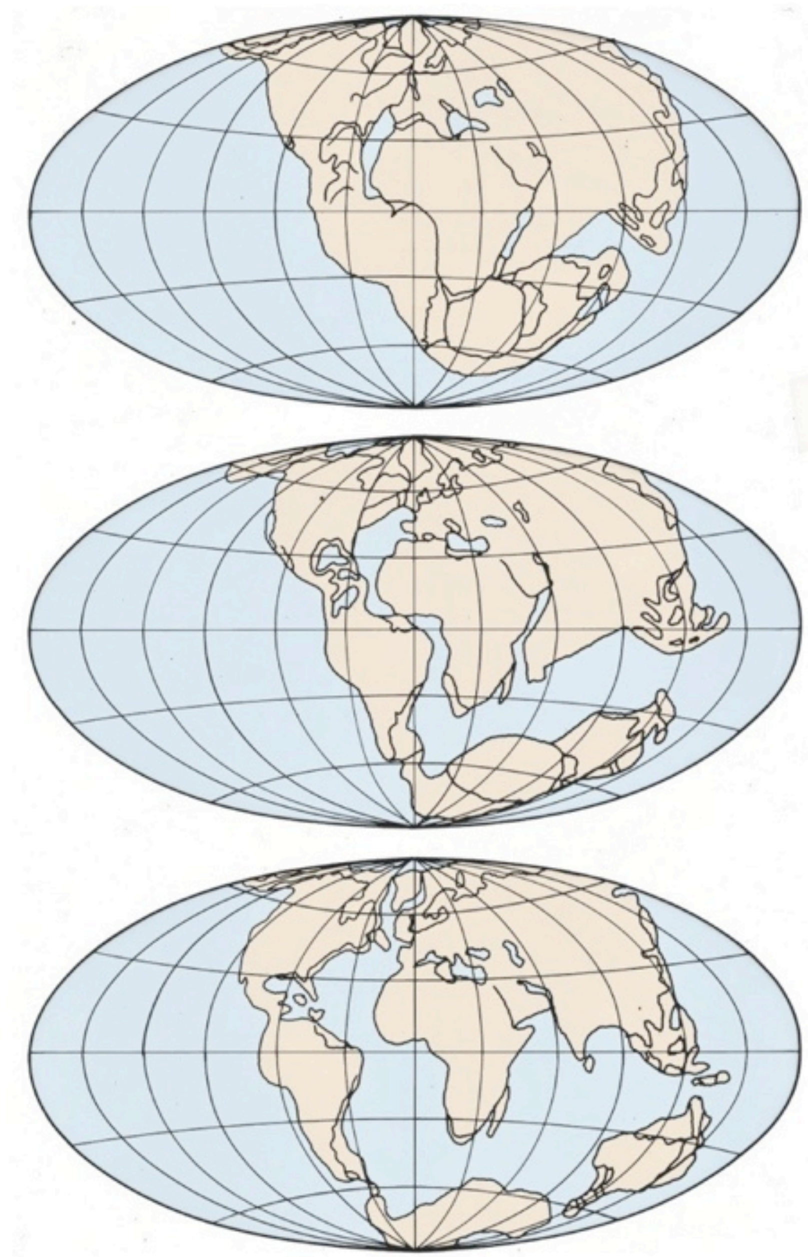


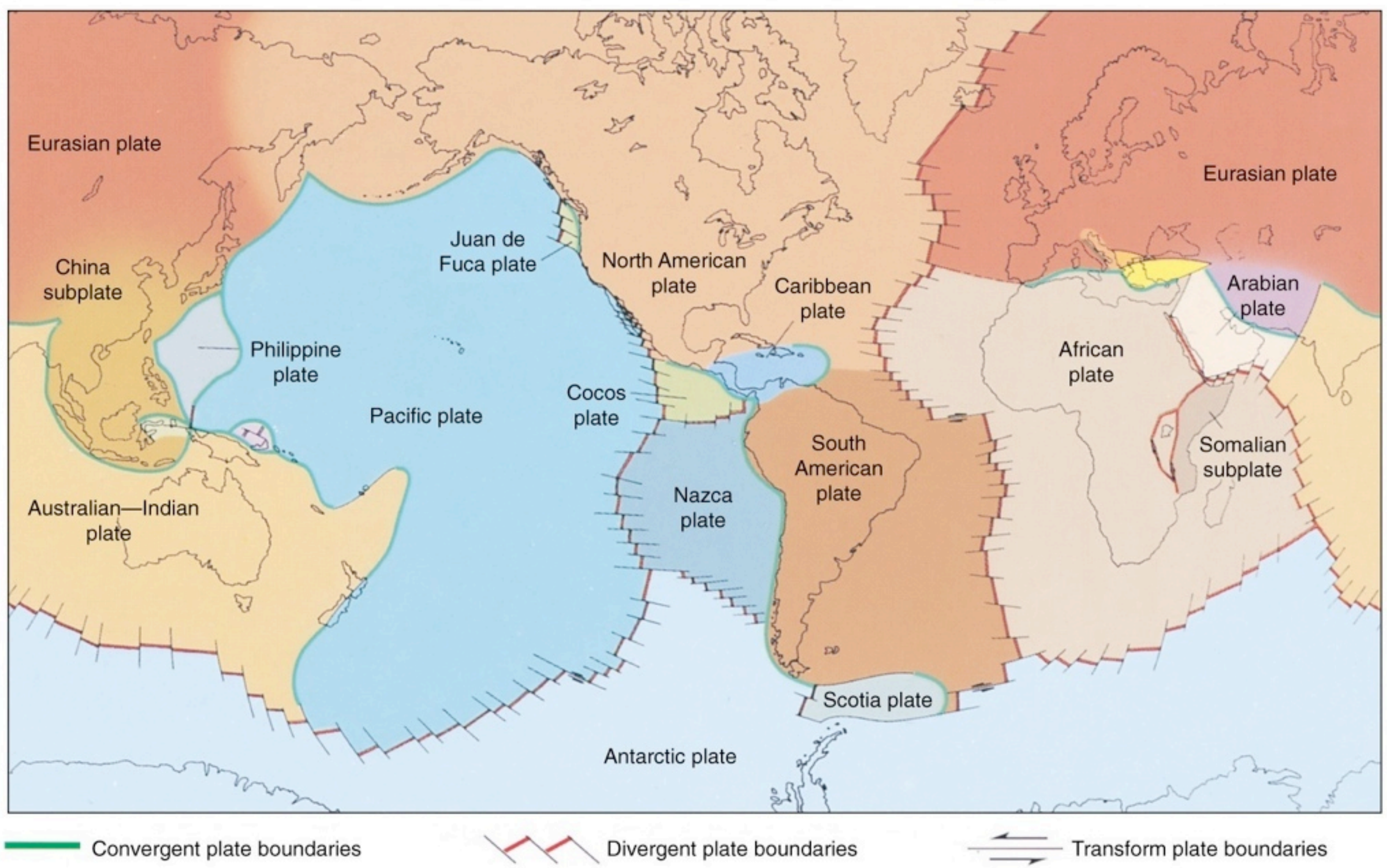
Basic Geologic Principles: Plate Tectonics

The Earth's crust is composed of a number of plates, most of which do not follow the shapes of the continents.



These plates shift over time, largely driven by convection in the mantle, which leads to rearrangement of the continents.





Mapping of the seafloor and examining the magnetization of rocks ultimately led to the acceptance of plate tectonics as a legitimate theory.

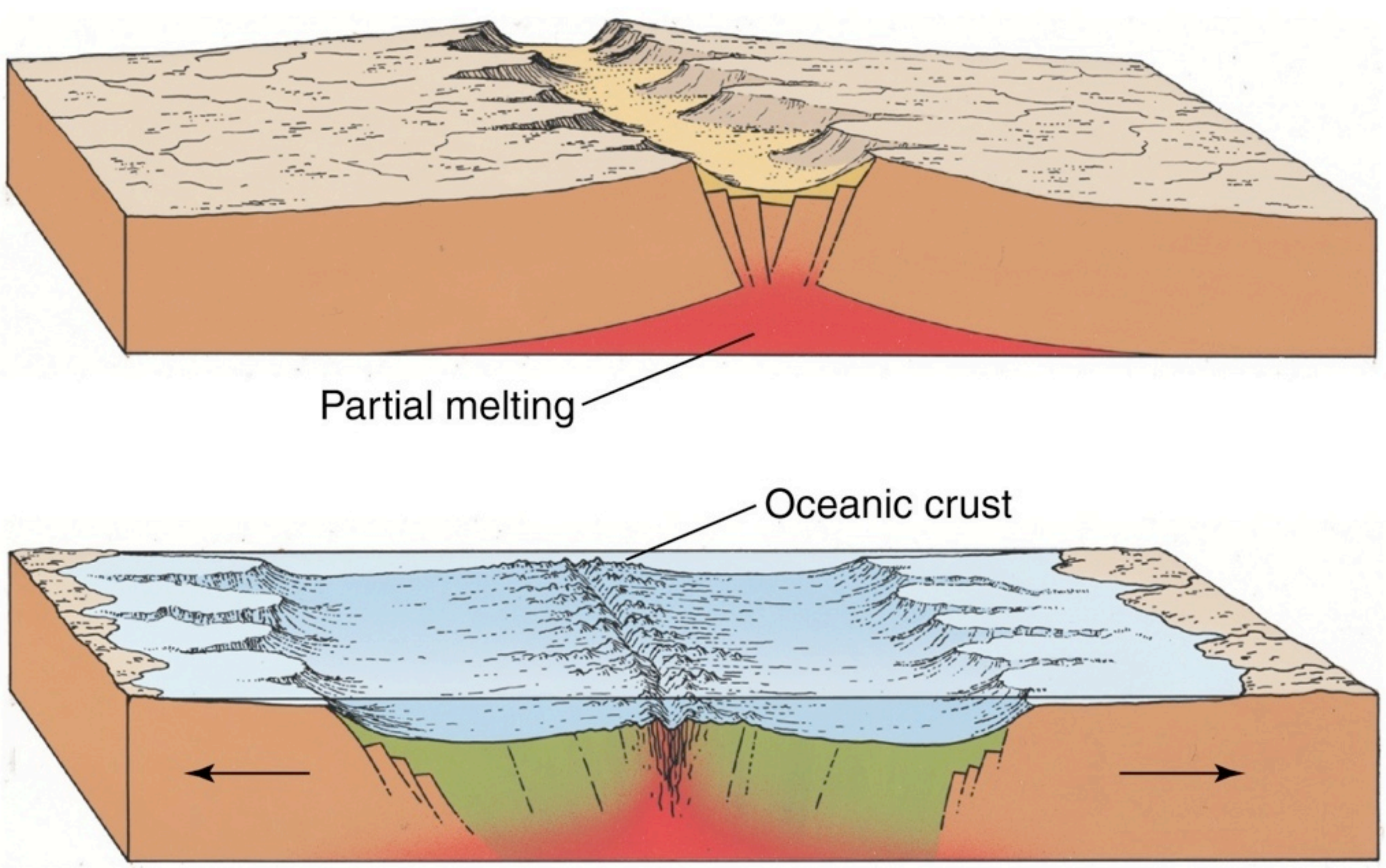
Basic Geologic Principles: Plate Tectonics

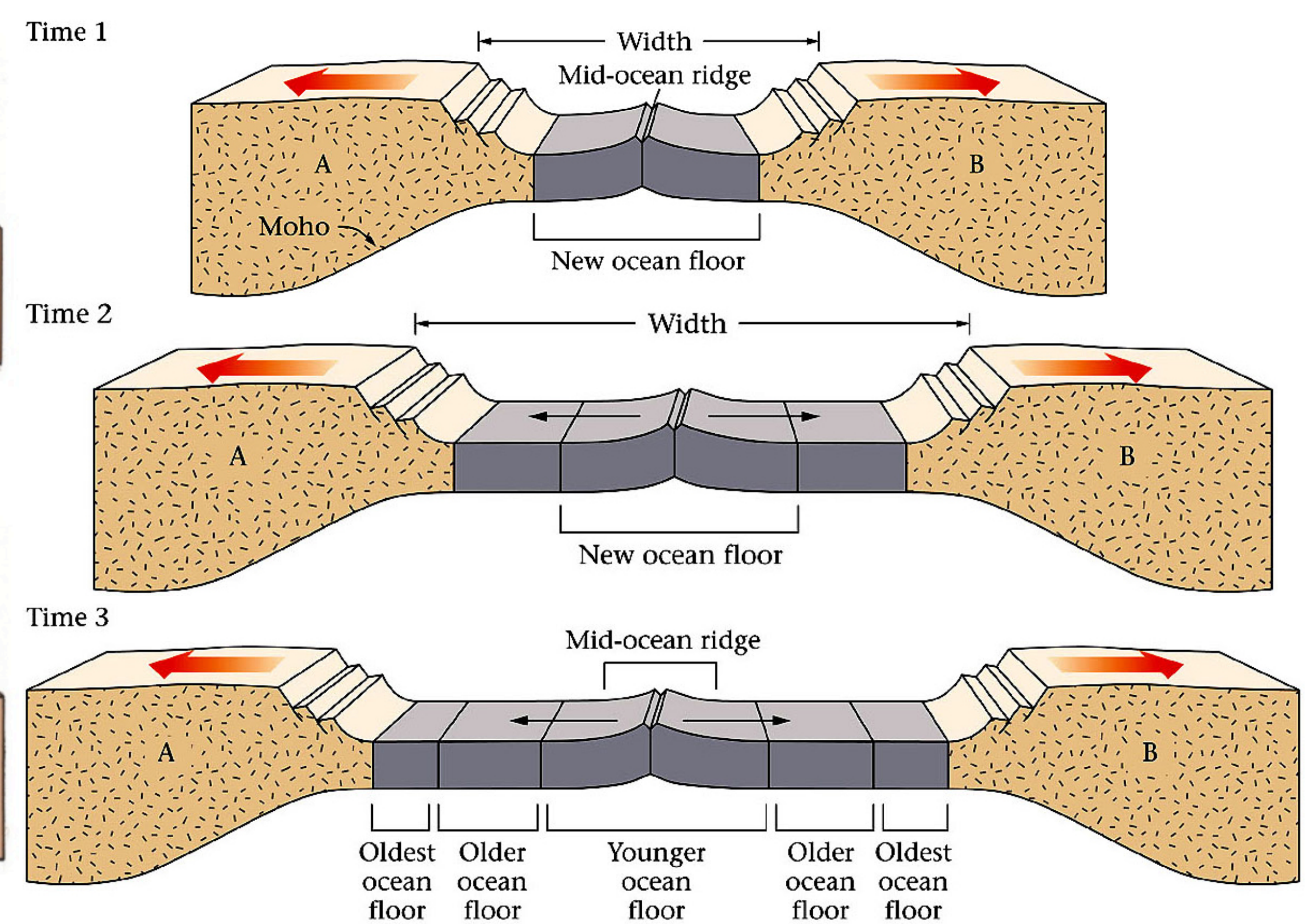
Divergent margins are regions where plates are pulled apart.
The oceanic crust is thinner than the continental crust and hosts many spreading centers.

In these regions where the crust is being pulled apart, magma from partially molten mantle material is brought to the surface to form basalt (oceanic crust is dominated by basalt).

New crust is formed at spreading centers, and older crust slowly moves away from the center as the plates continue to be pulled apart.

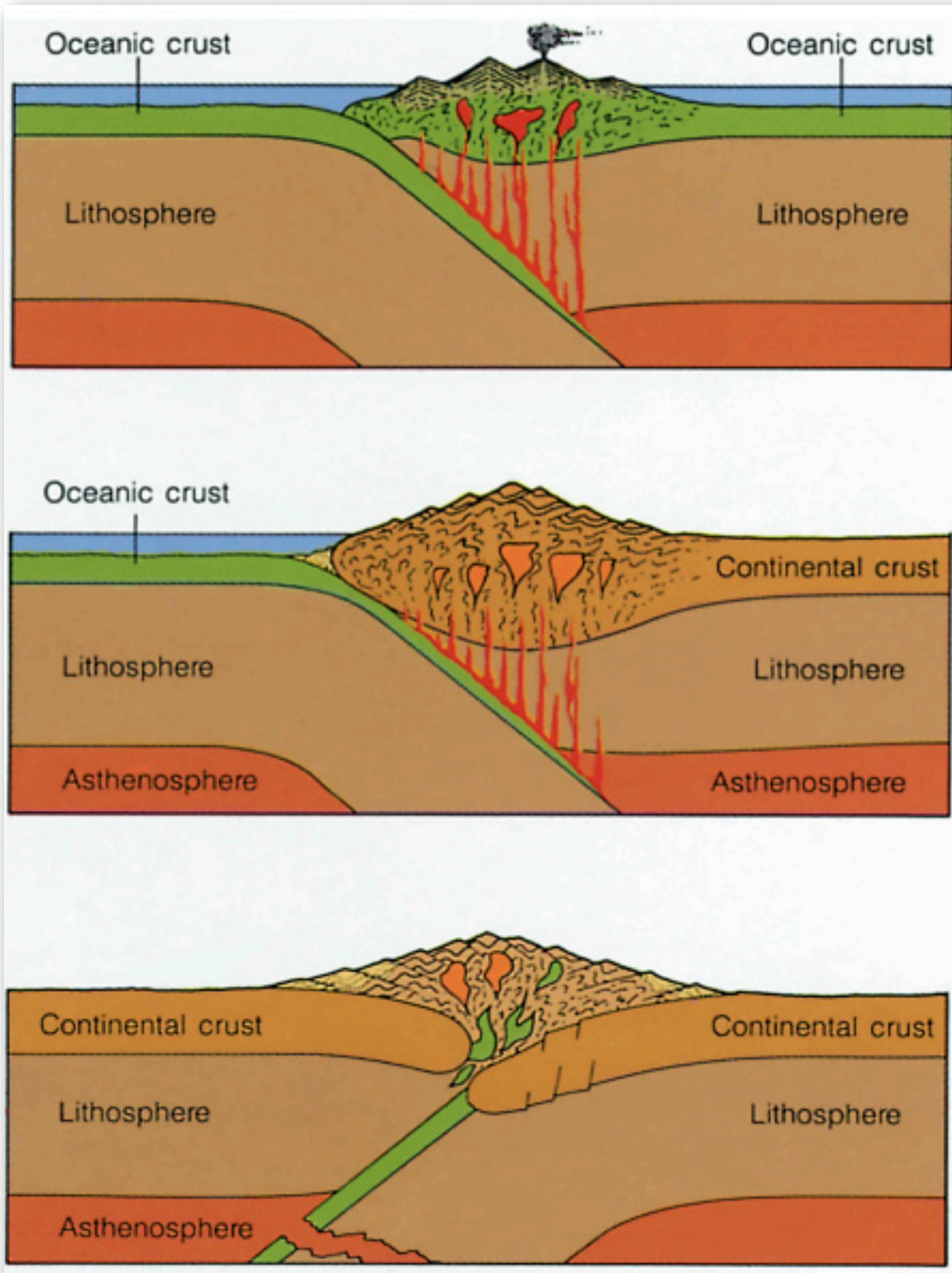
Spreading centers also occur on the continents, as in the East African rift zone; in addition to basalt from partial melting of mantle, melting of the thinned continental crust yields more evolved rocks.





Basic Geologic Principles: Plate Tectonics

Convergent margins are regions where two plates collide.



<u>Oceanic-Oceanic</u> collisions produce seafloor trenches and andesitic volcanoes in an 'island arc' (e.g., Japan).
Oceanic plate is subducted.
Shallow and deep earthquakes are common.

<u>Oceanic-Continental</u> collisions form subduction zones and produce andesitic volcanoes in a 'continental arc' (e.g., Cascade range in Washington & Oregon).
Oceanic plate is subducted.
Shallow and deep earthquakes are common.

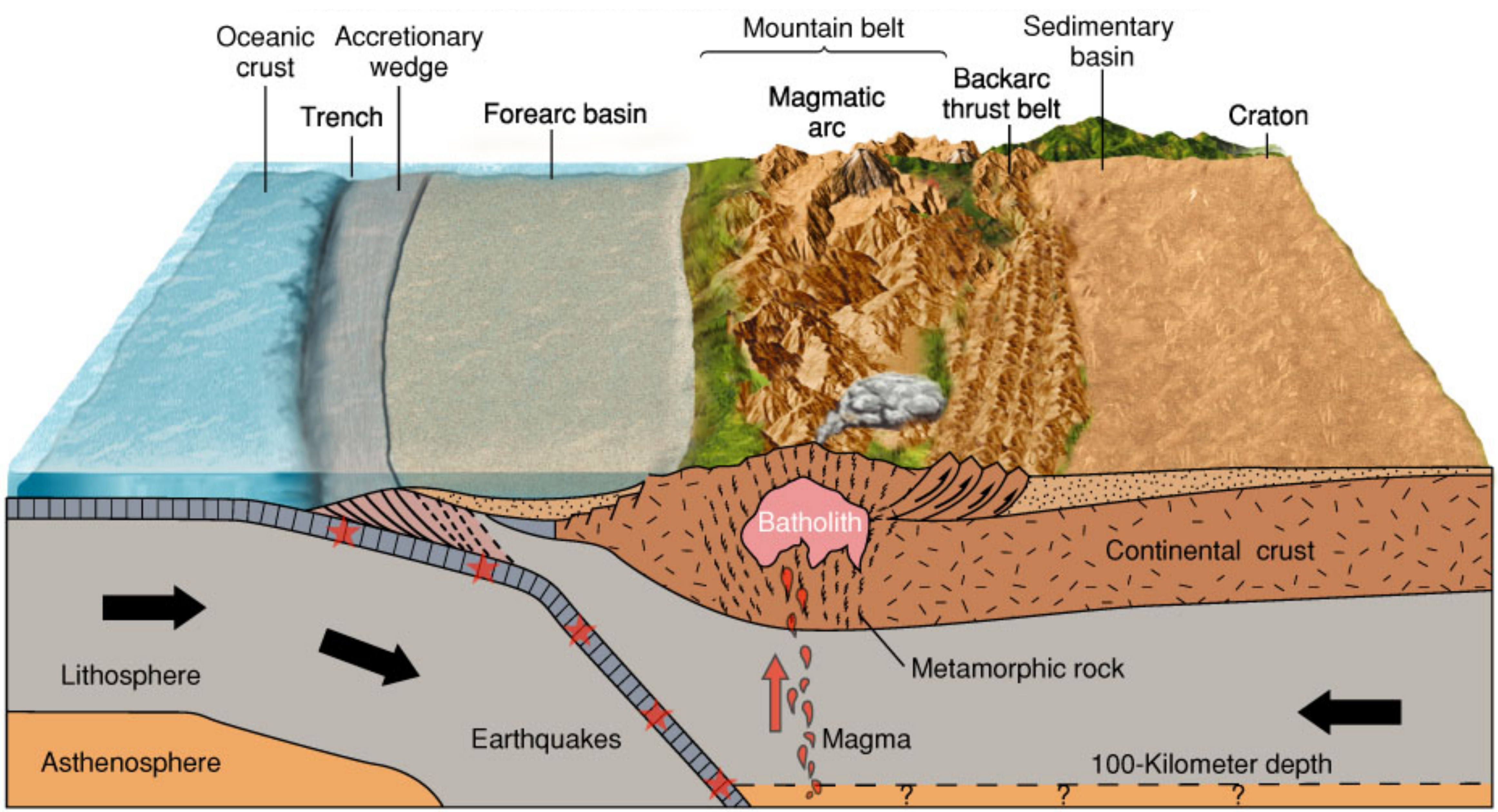
<u>Continental-Continental</u> collisions occur when enough of an oceanic plate has been subducted that two continental plates finally converge; the continental crust is too light to be subducted, so the plates smash together and form mountains & metamorphism occurs.

Basic Geologic Principles: Plate Tectonics

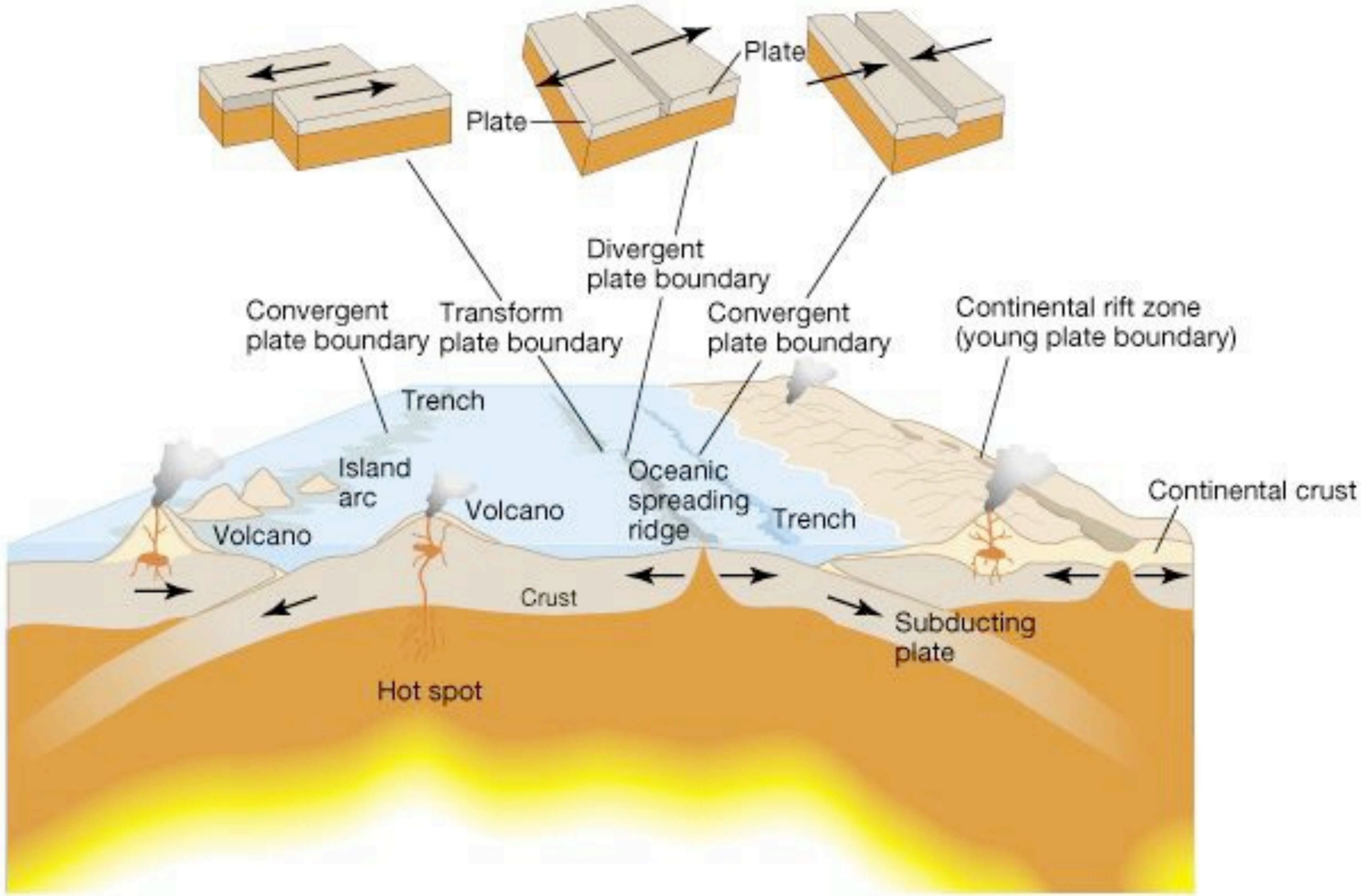
Subducted oceanic crust takes a lot of water and water-rich sediments with it as it sinks into the asthenosphere.

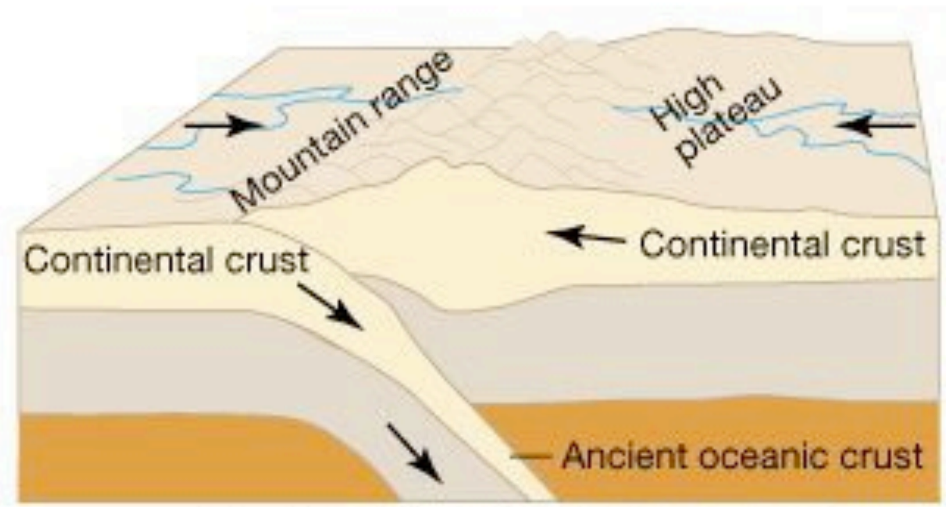
The presence of water lowers the melting temperature of the surrounding mantle rocks, creating water-bearing magma.

This magma then rises and melts crustal material, giving rise to more Si-rich melts. Therefore, plate tectonics is an important factor in generating non-basaltic and volatile-rich magmas.

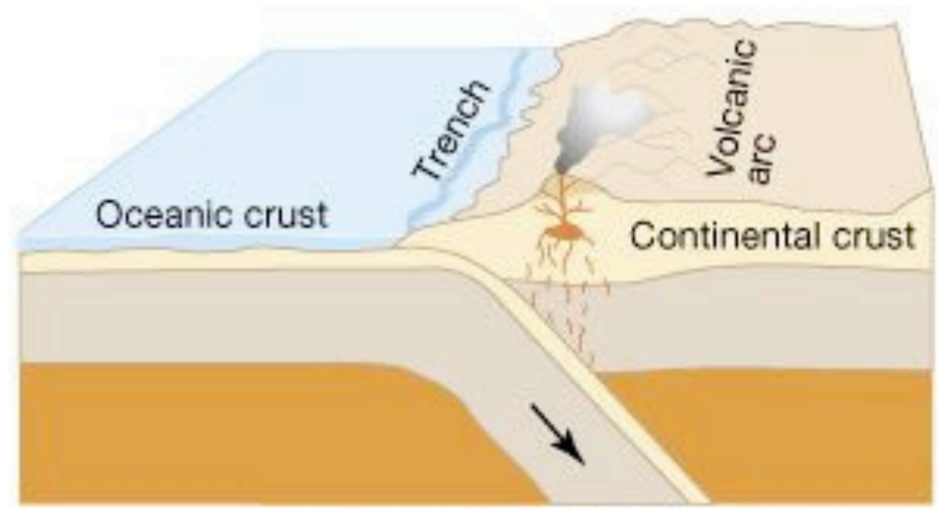


Basic Geologic Principles: Plate Tectonics





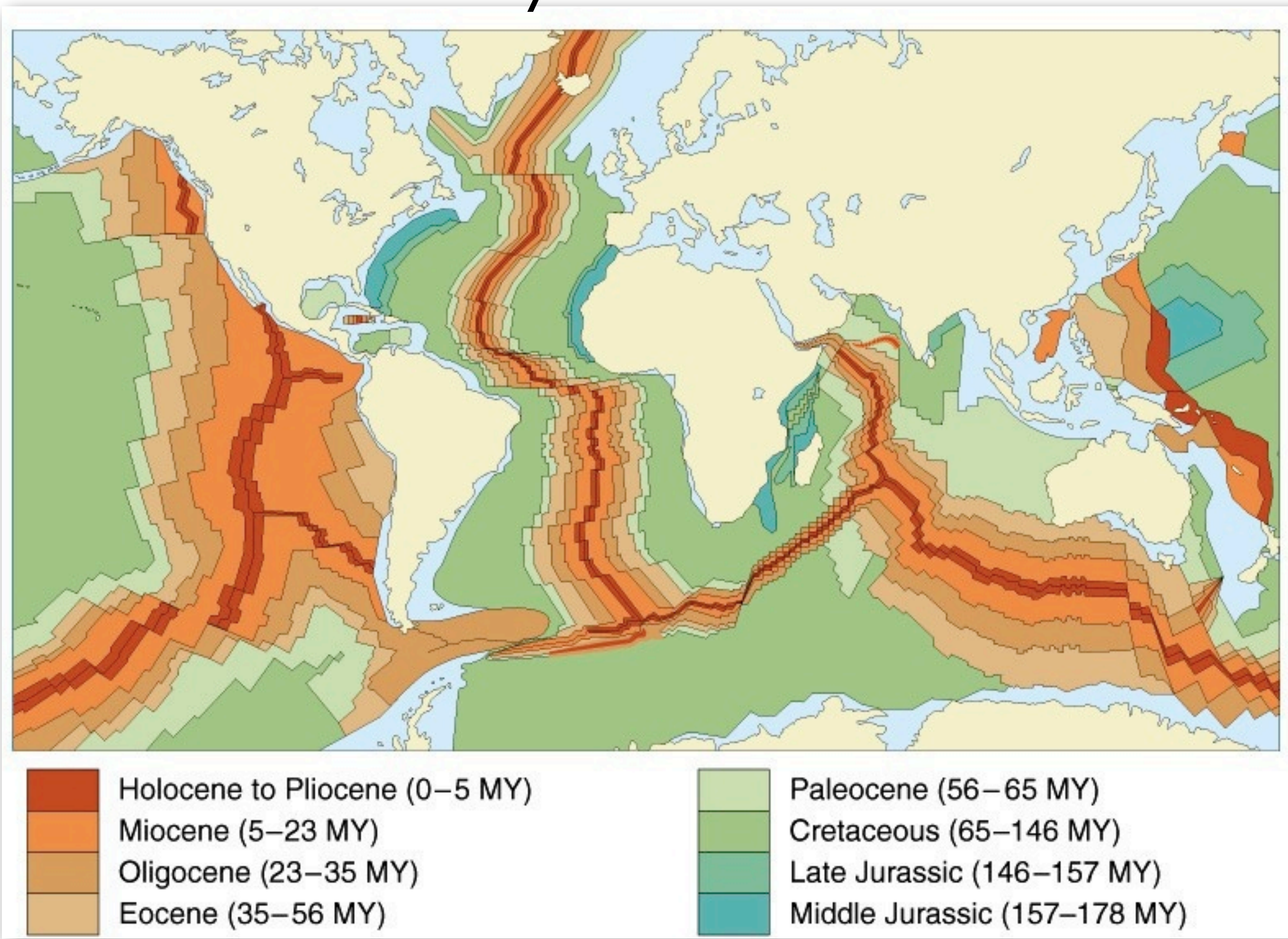
Continental-continental convergence



Oceanic-continental convergence

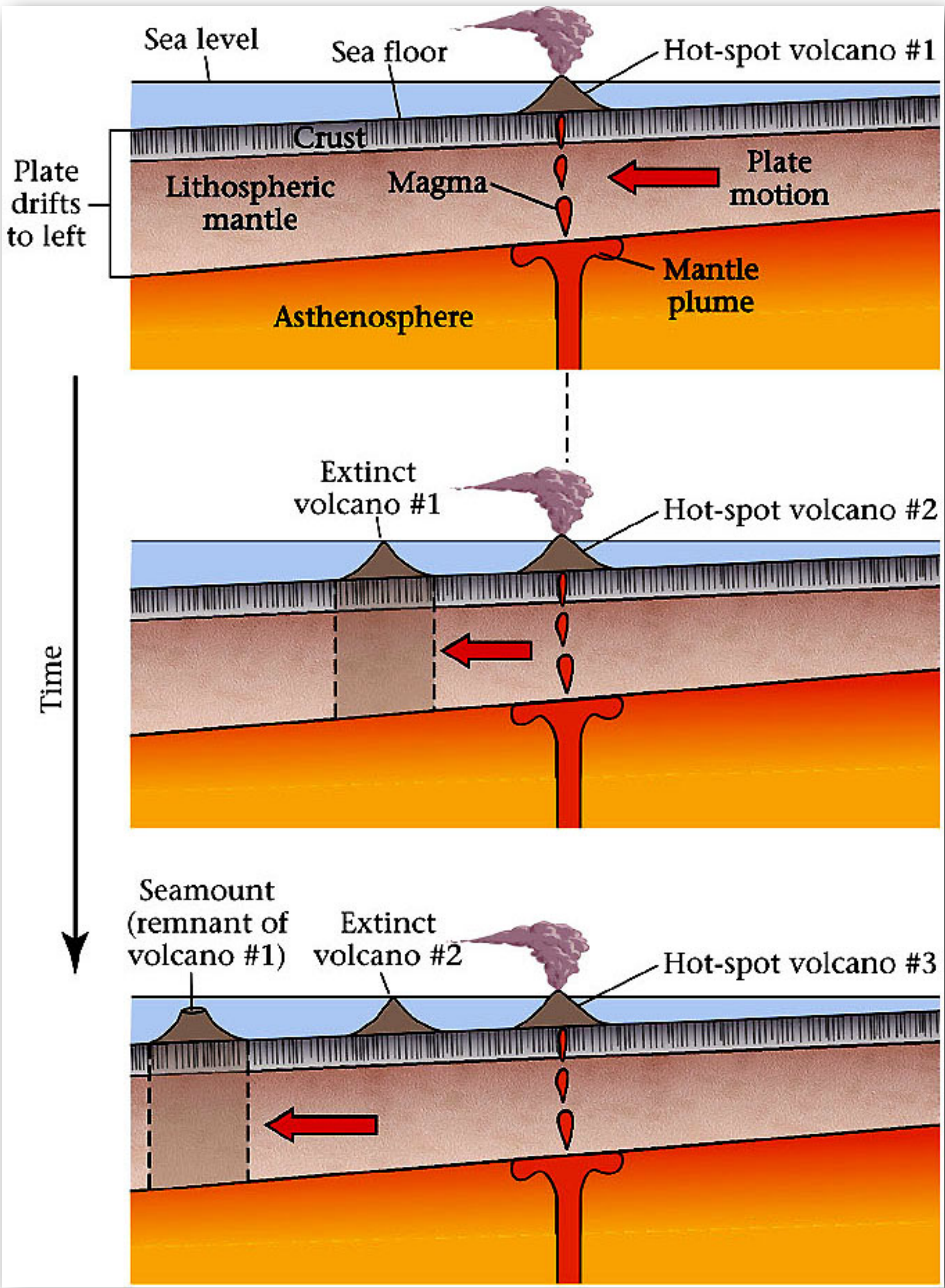
Basic Geologic Principles: Plate Tectonics

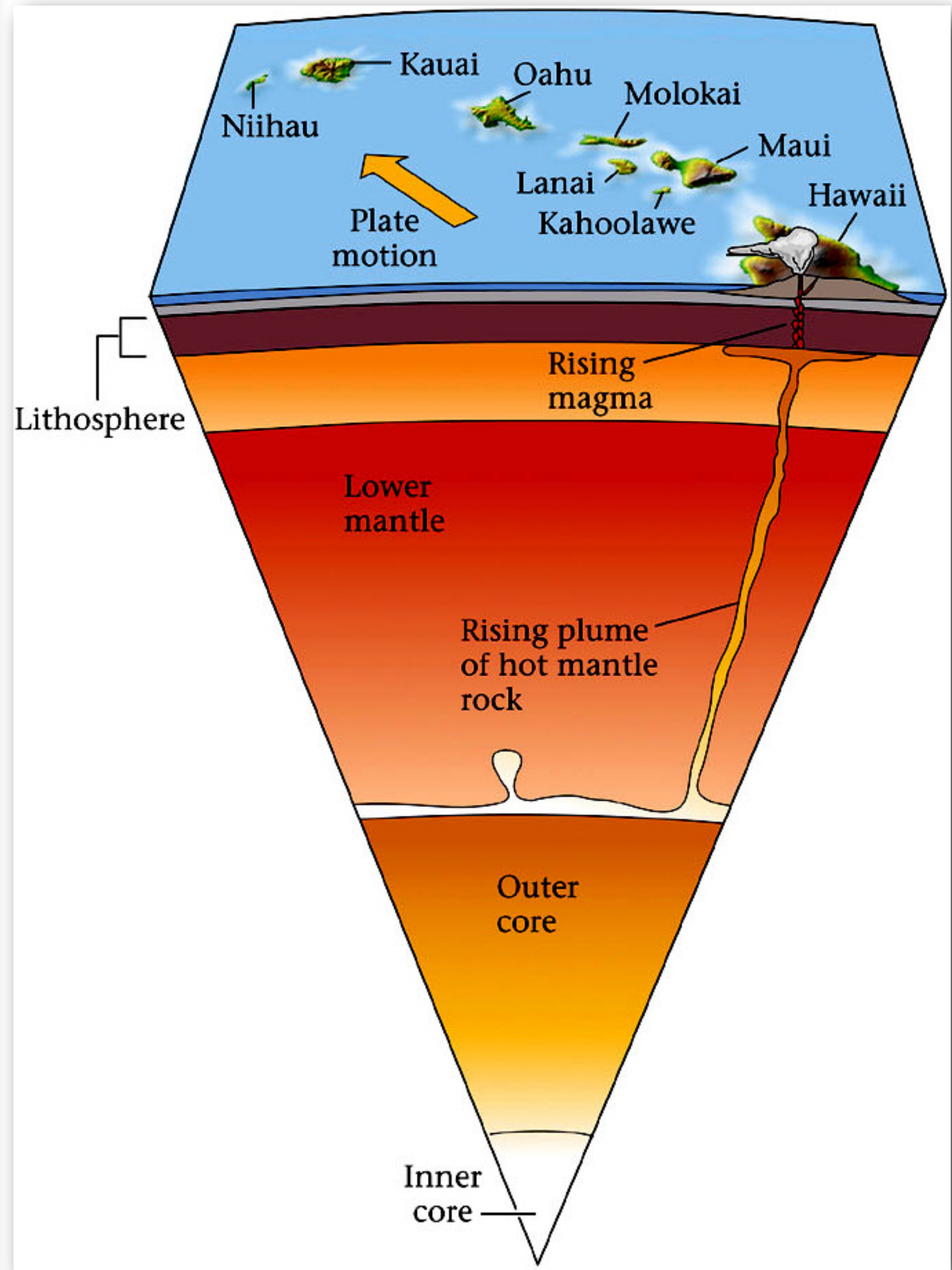
Oceanic crust is youngest near spreading centers and gets progressively older away from them; however, the ‘oldest’ crust in oceans is still <200 million years old.



Basic Geologic Principles: Plate Tectonics

'Hot Spots' appear to be caused by stable, deep-seated plumes and give rise to volcanic chains. The plume remains still, but the plate rides over it and makes new volcanoes (e.g., Hawaii).

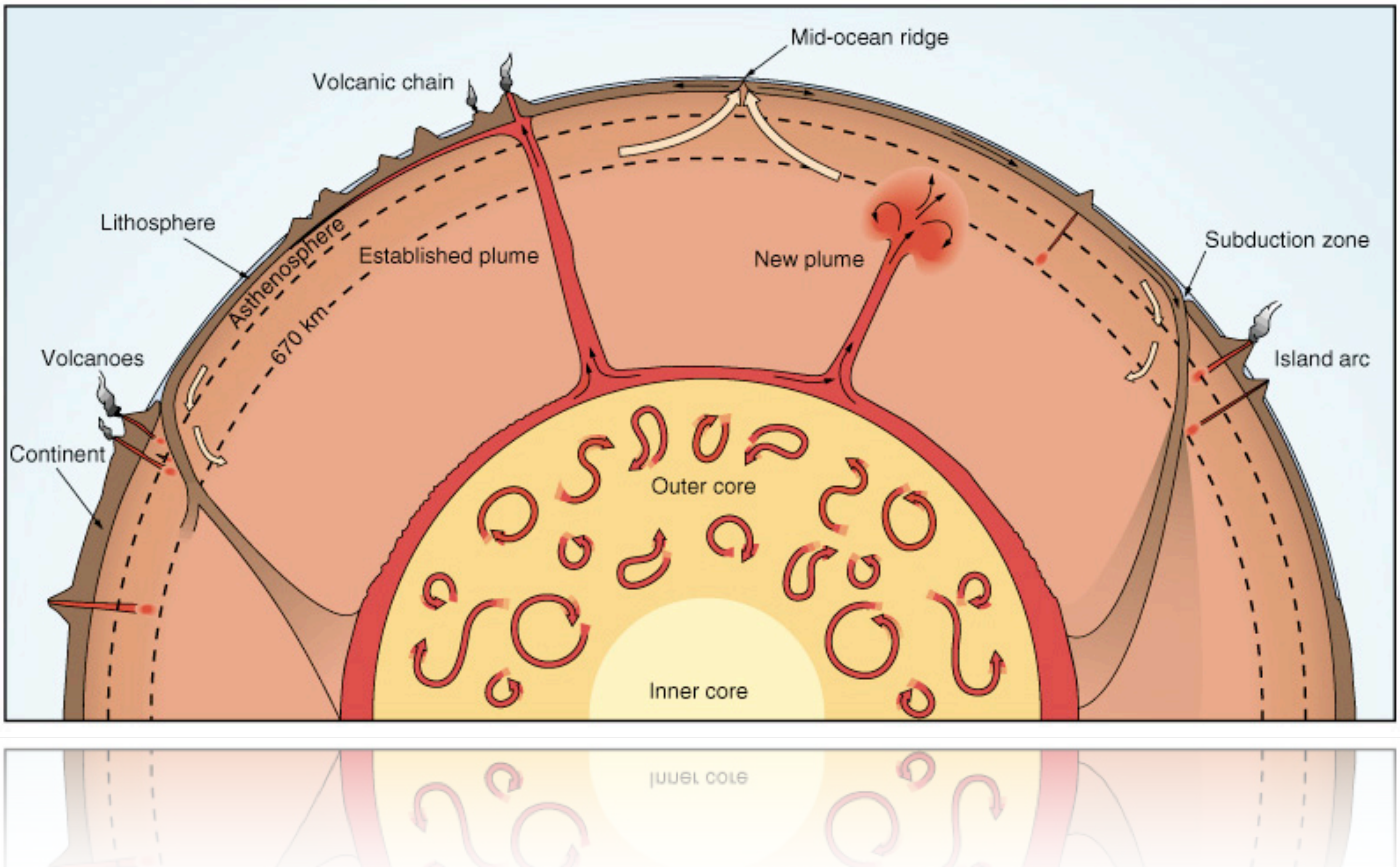




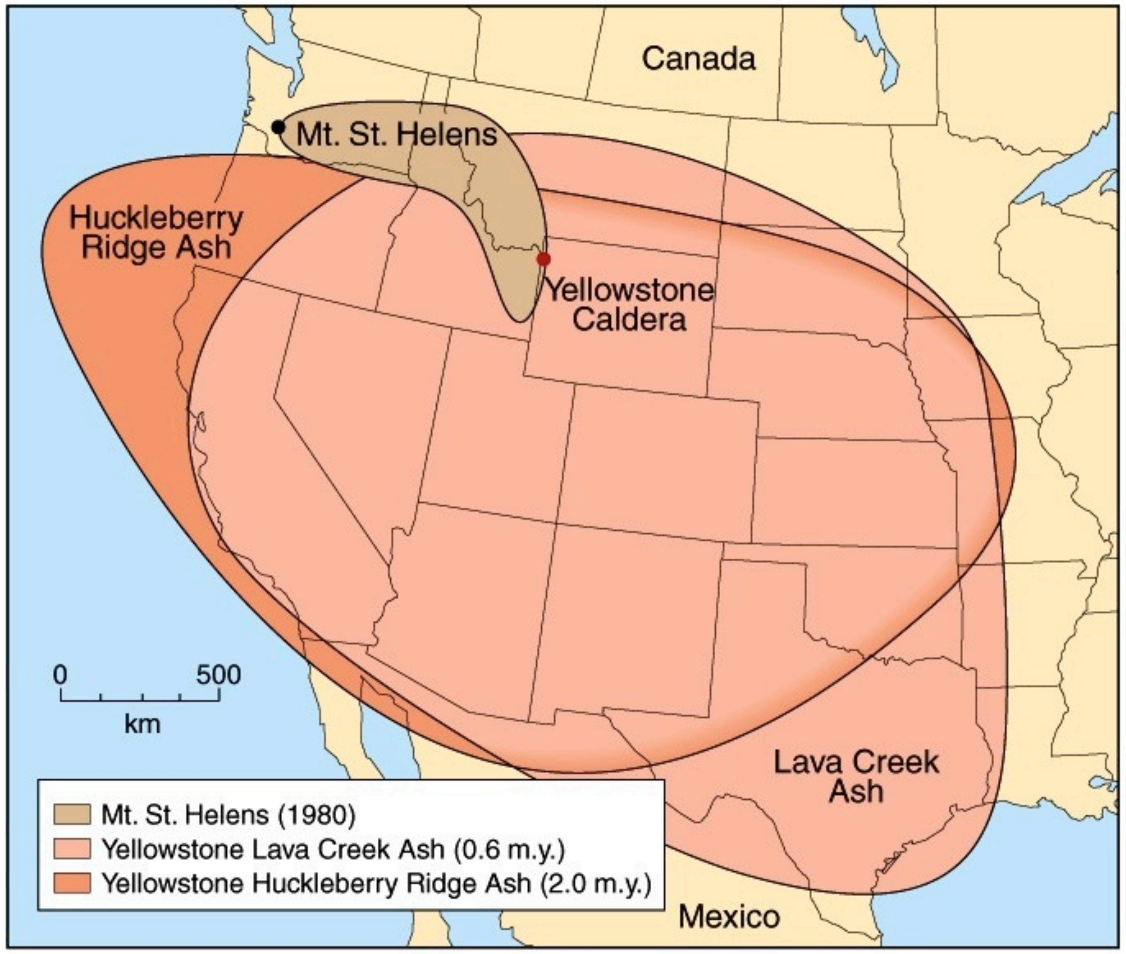
Basic Geologic Principles: Plate Tectonics

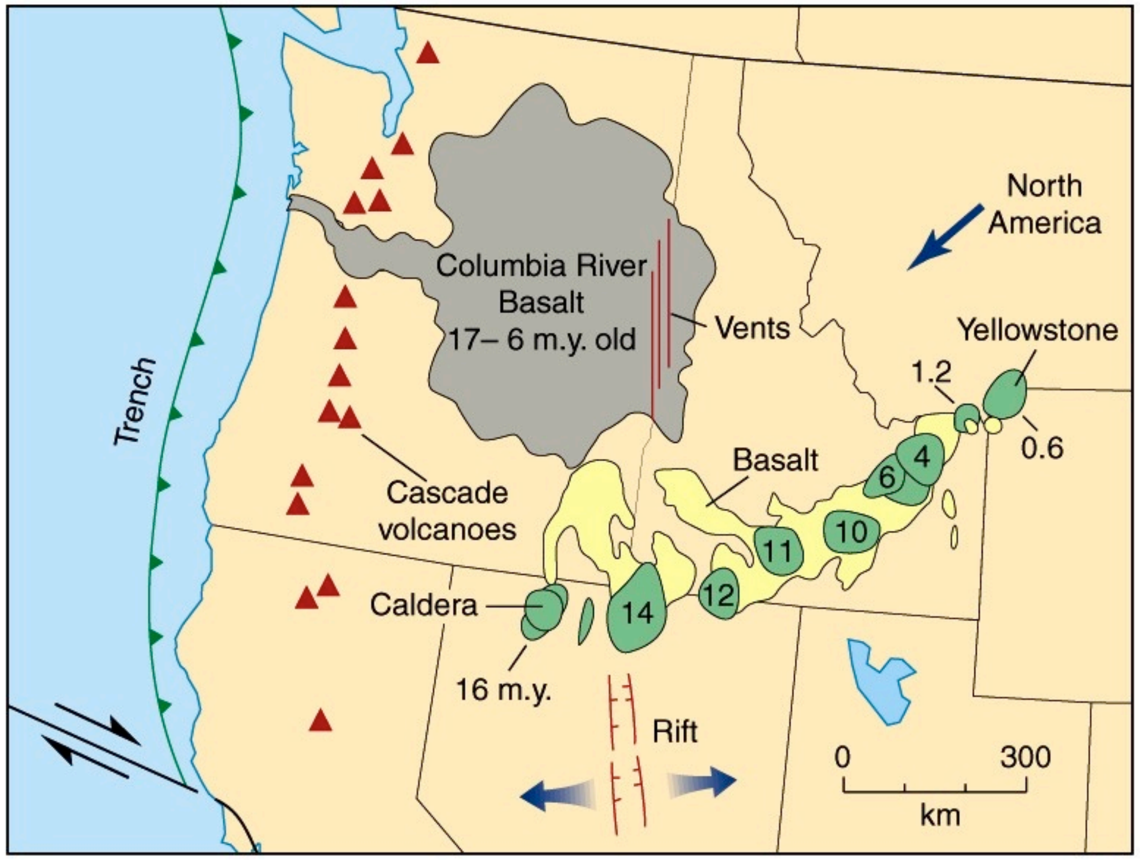
The origin of the plumes for hot spots is still a debate, but a potential theory is:

- heat is transferred across a boundary (outer core-lower mantle)
- plumes may be linked to the return of crust to the core-mantle boundary
- it is the accumulation of subducted material that gives rise to plumes & hot spots

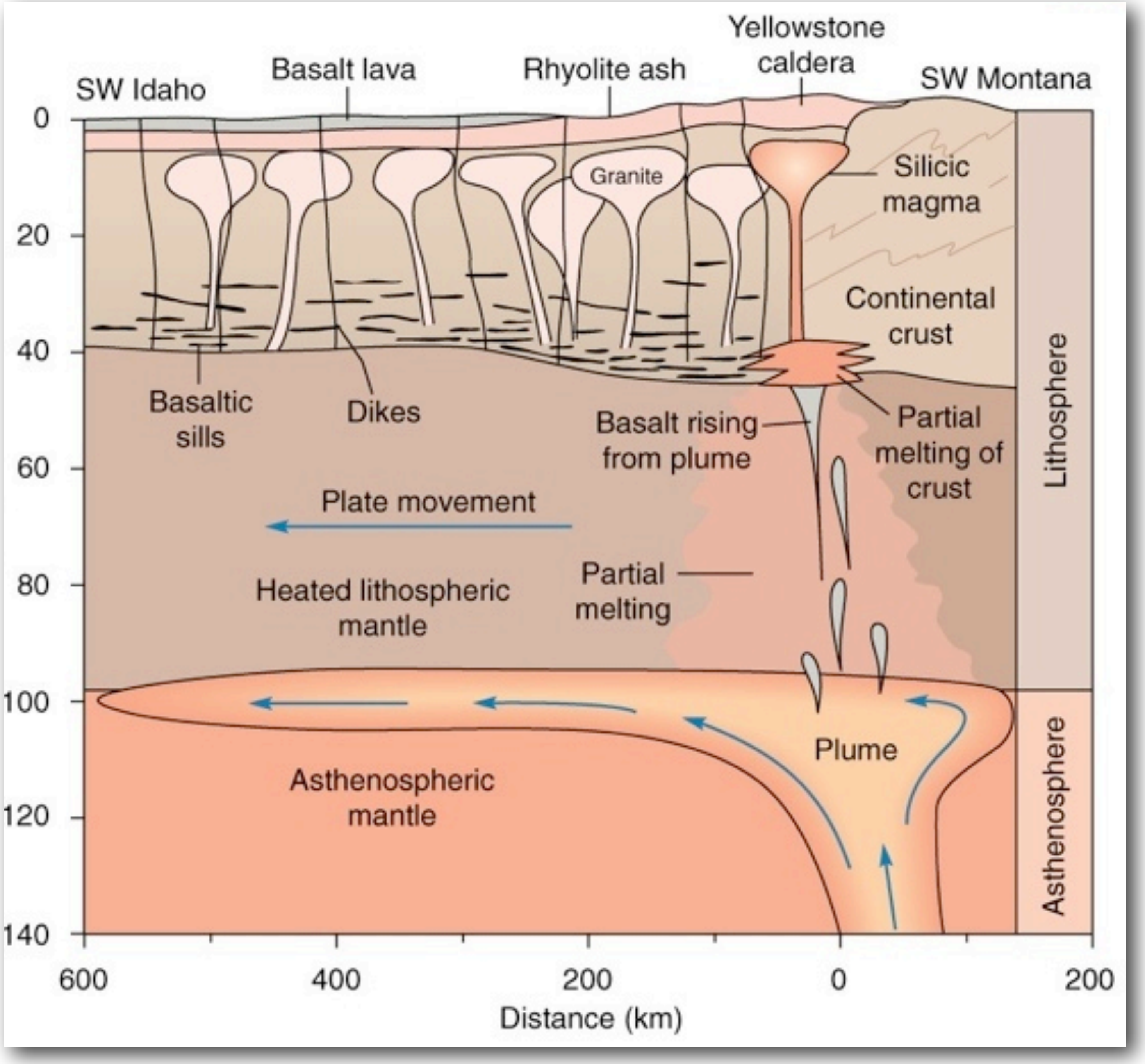


Basic Geologic Principles: Plate Tectonics





Hot spots can also occur beneath continents, as in the Yellowstone ‘supervolcano’.

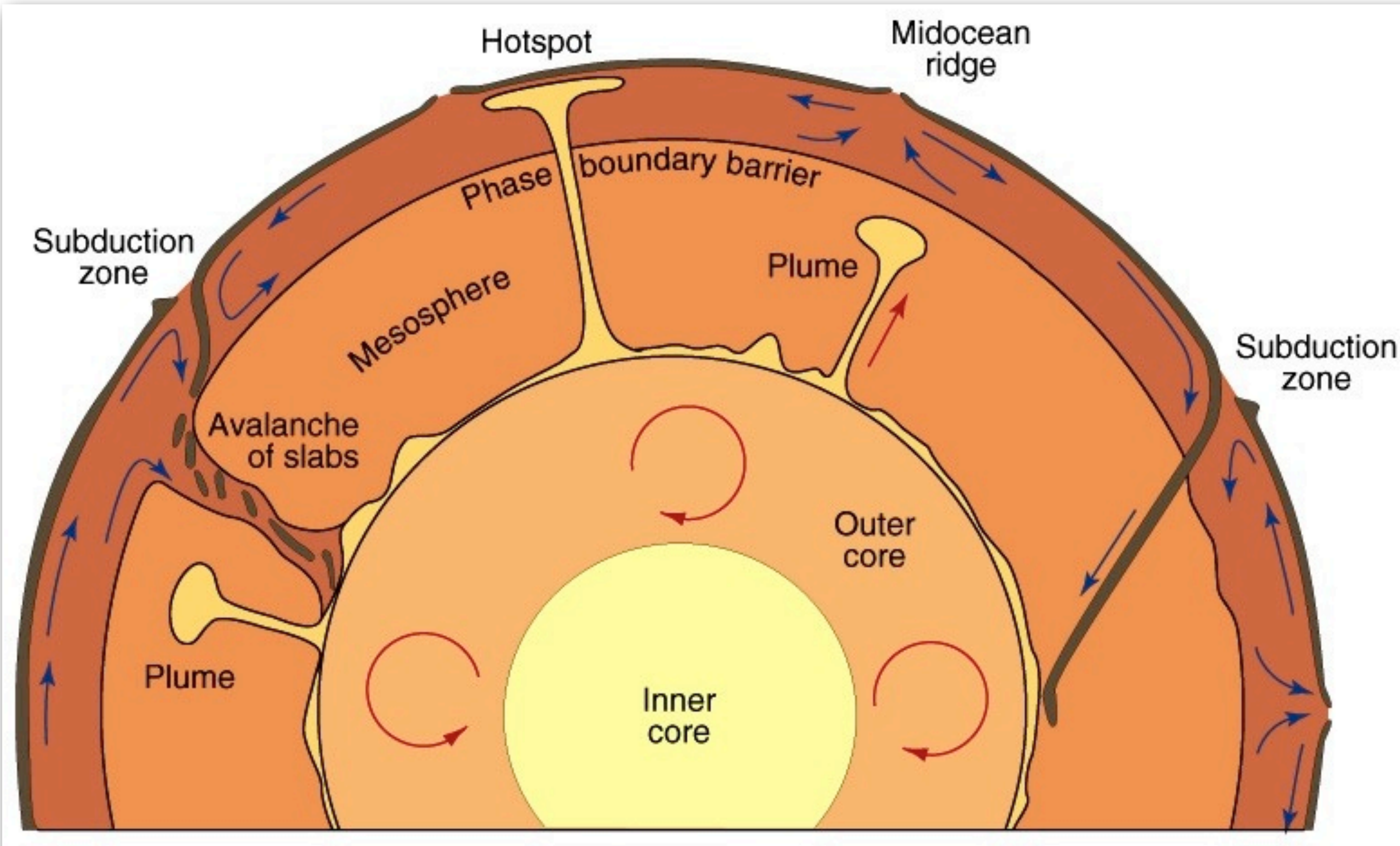


Basic Geologic Principles: Plate Tectonics

Some subducted slabs may reach the core-mantle boundary.

Hotspots may be sourced from the core-mantle boundary.

Importantly, convection in the liquid outer core is believed to cause the *'dynamo'*.

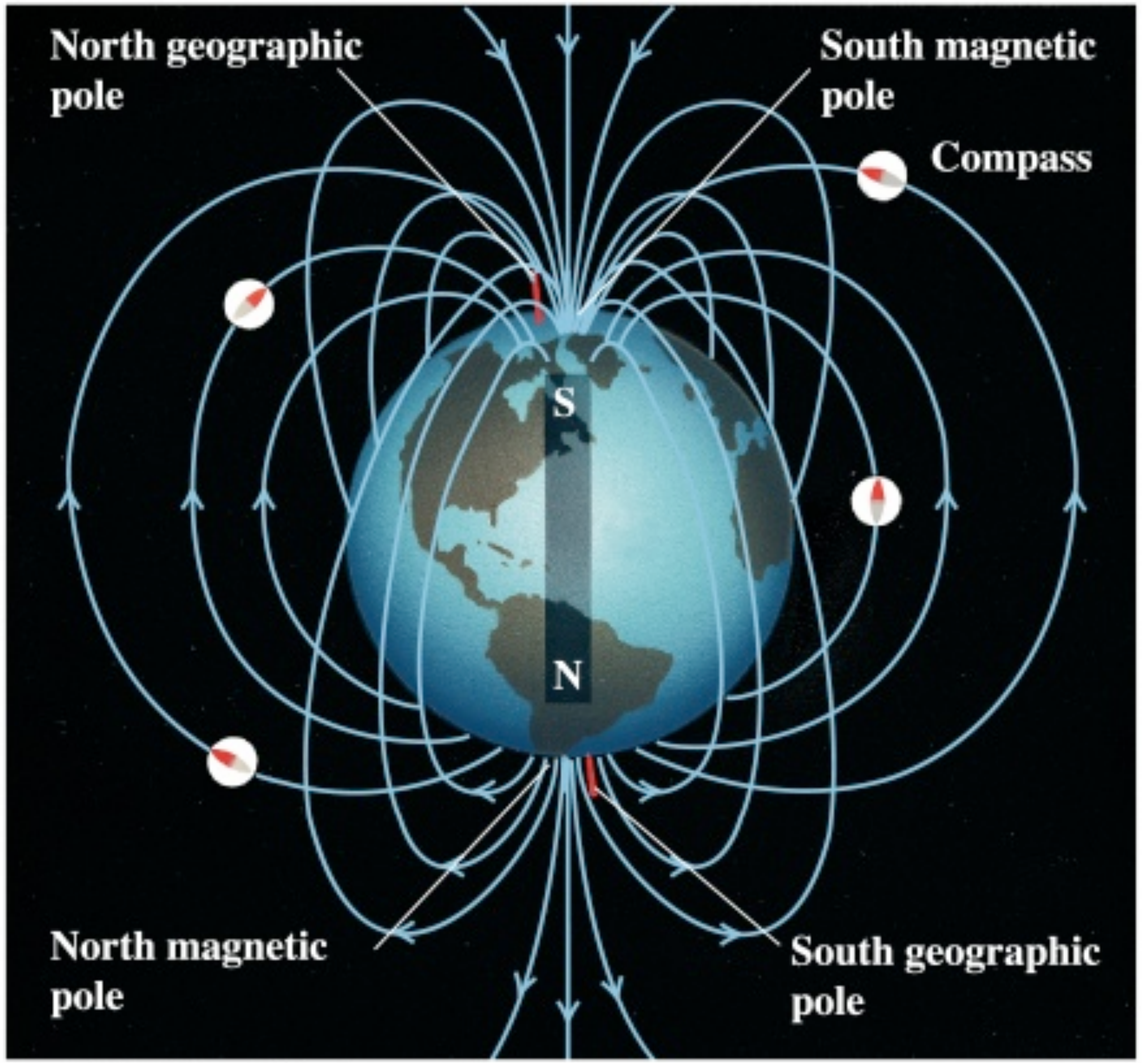


Basic Geologic Principles: Magnetization

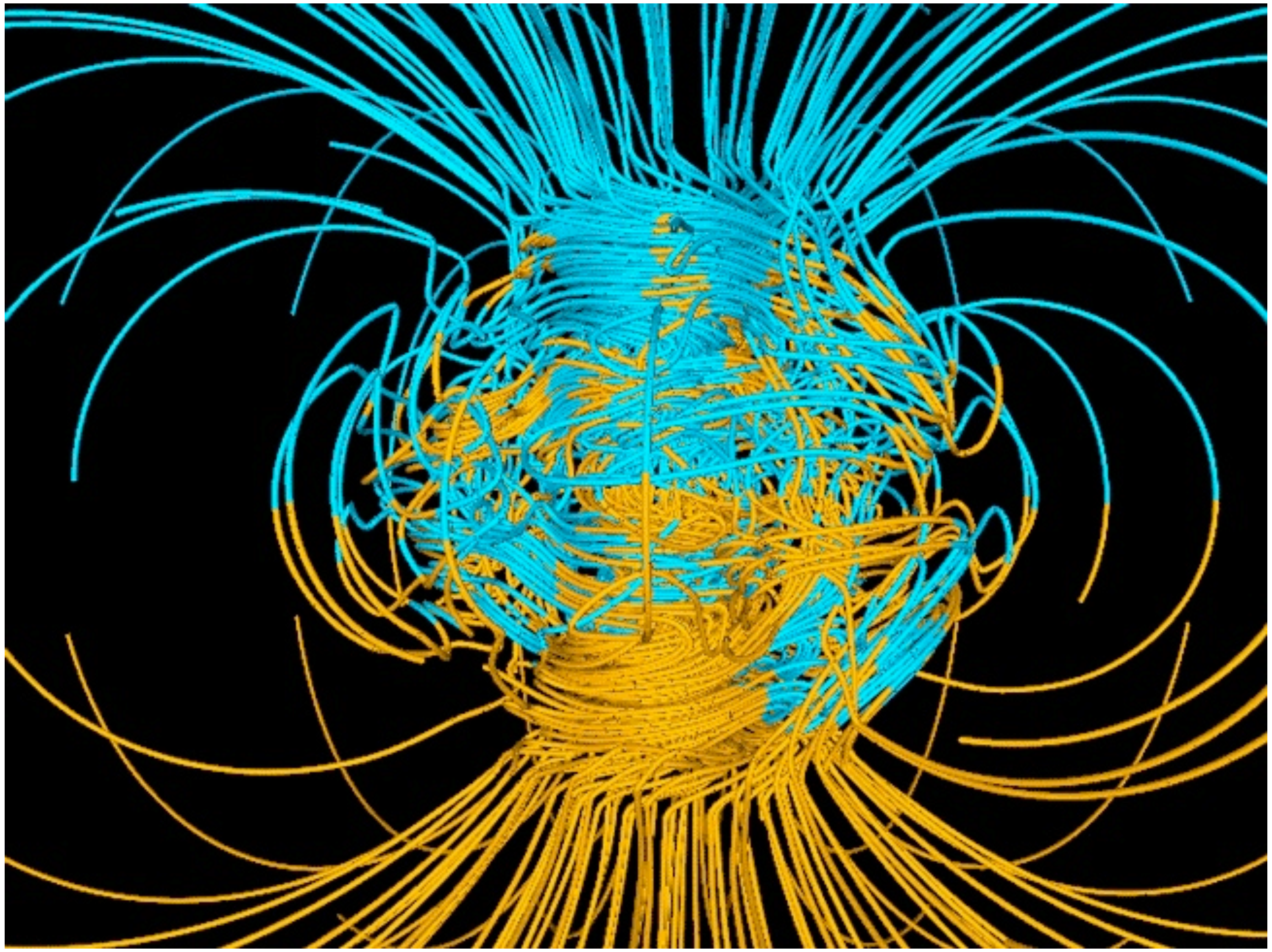
The Earth's magnetic field protects us from the harmful radiation of the solar wind.
The solar wind consists of energetic particles radiated by the Sun, and protection from such radiation has surely played an important role in the evolution of life as we know it.
But what causes the magnetic field?

The 'dynamo theory' postulates that a rotating, convecting, and electrically conducting fluid can sustain such a magnetic field. In the case of Earth this can be linked to the outer core.

Cartoon of magnetic field



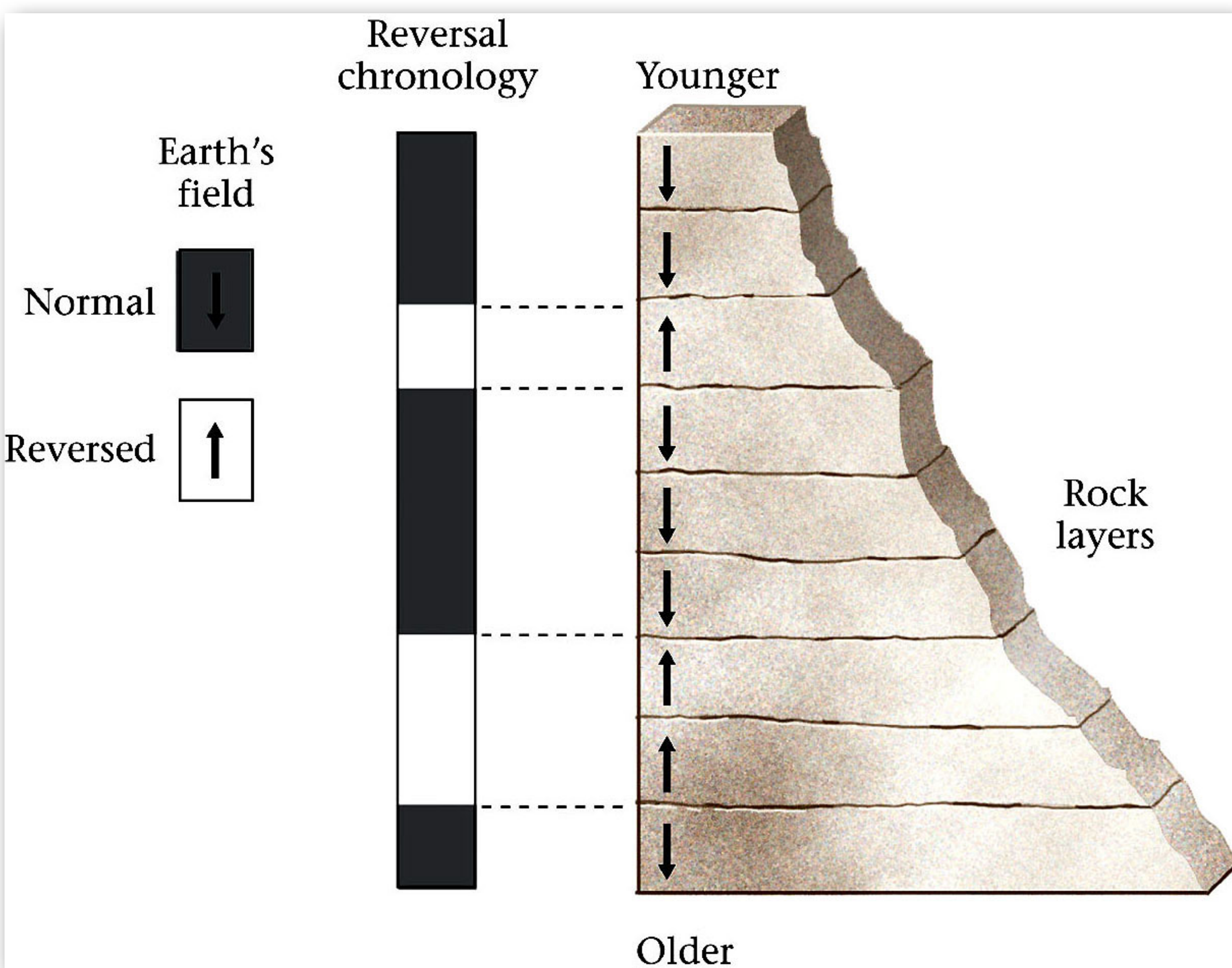
Computer model of Earth's field

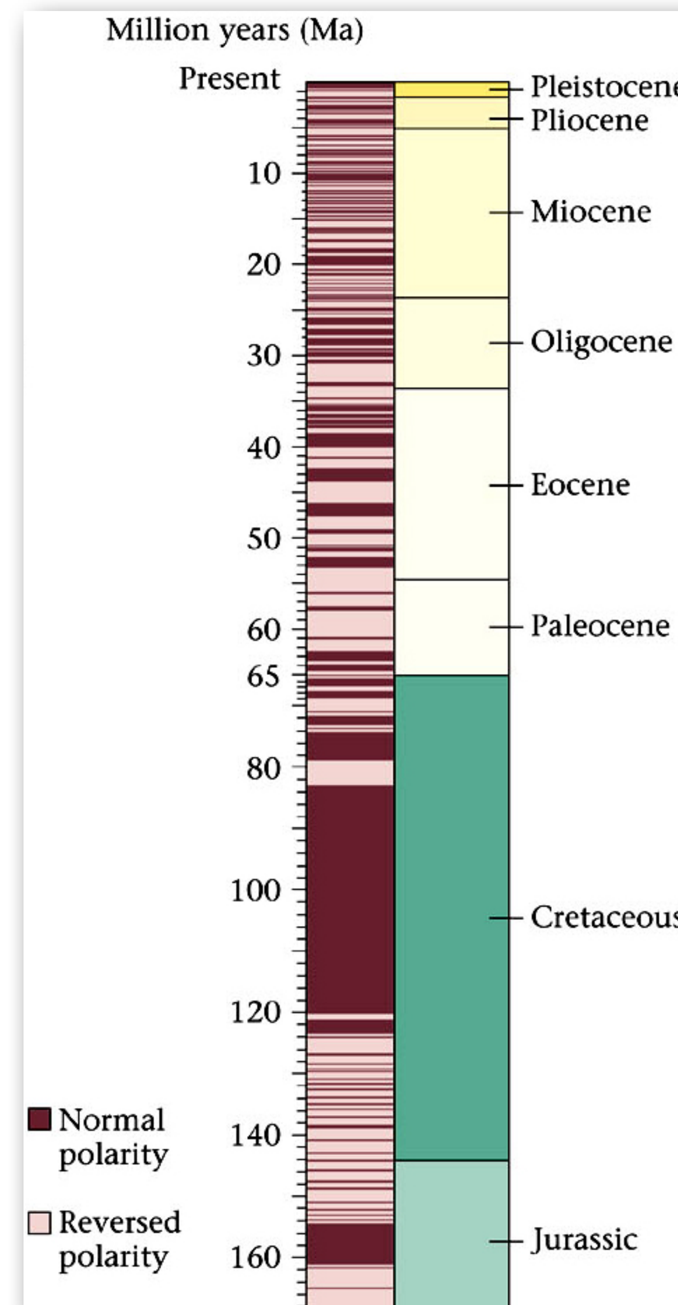


Basic Geologic Principles: Magnetization

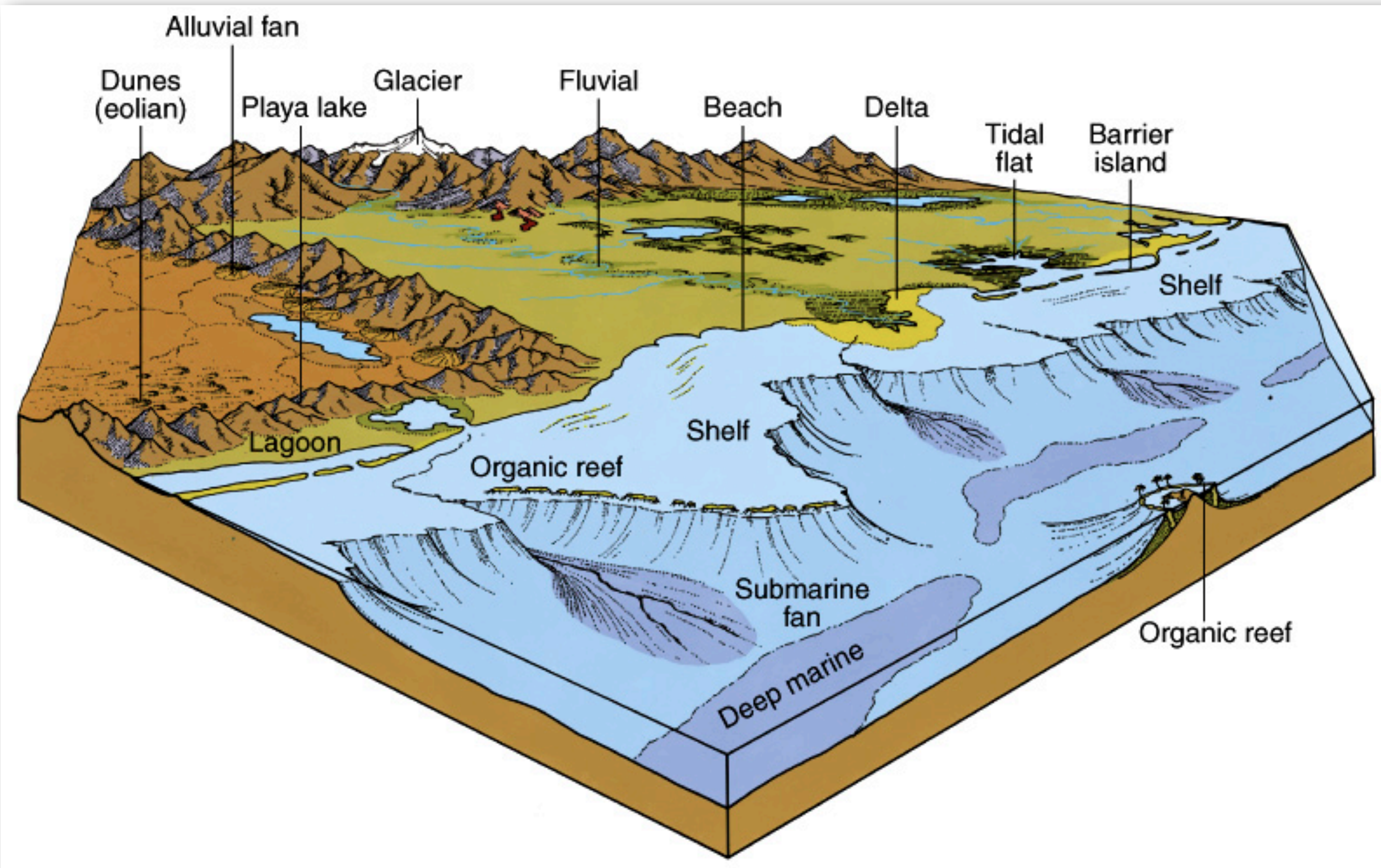
The Earth essentially acts as a giant magnet with magnetic field lines connecting the two magnetic poles. These poles reverse over time and can be recorded in rocks, which is one way the theory of plate tectonics was finally established.

By examining the strength and orientation of magnetization in old rocks (ancient crust) we can learn a lot about the internal dynamics and evolution of planets. If a planet does not exhibit magnetized crust then we can infer that a dynamo did not exist.





Major Sedimentary Systems



- fluvial (rivers)
- alluvial-fan
- lacustrine (lakes)
- eolian
- glacial
- deltas & submarine fans
- shoreline
- reef
- shallow-marine
- deep-marine

Basic Geologic Principles: River Systems

Alluvial fans represent accumulation of sediment in a relatively dry basin (often arid regions).

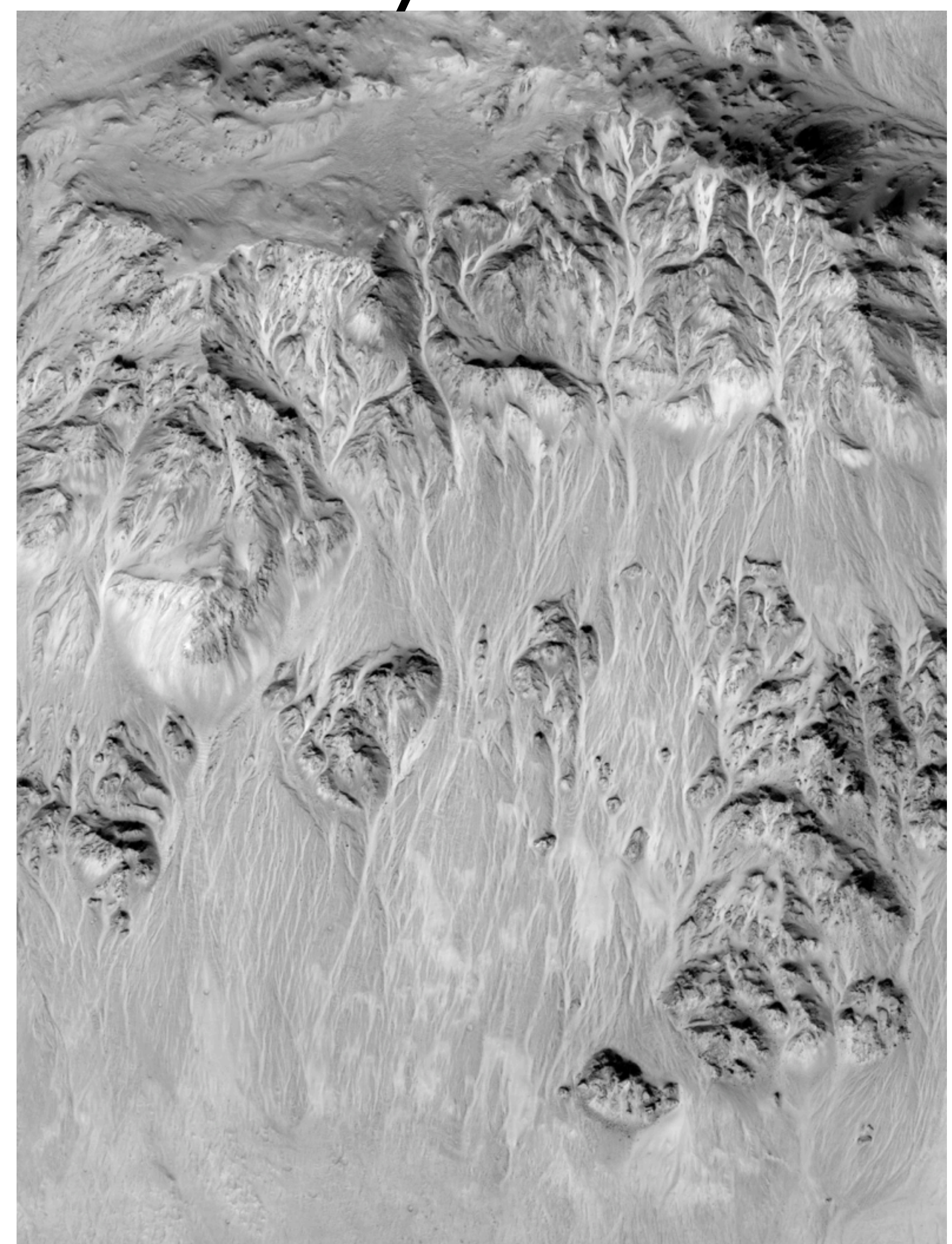
- deposition of sediment is caused by rapid velocity drop; result is fan-shaped deposits

- fan-shaped deposits differ from deltas in that they are not deposited in standing water

- characterized by braided streams with high sediment load

Alluvial fan in Death Valley, CA

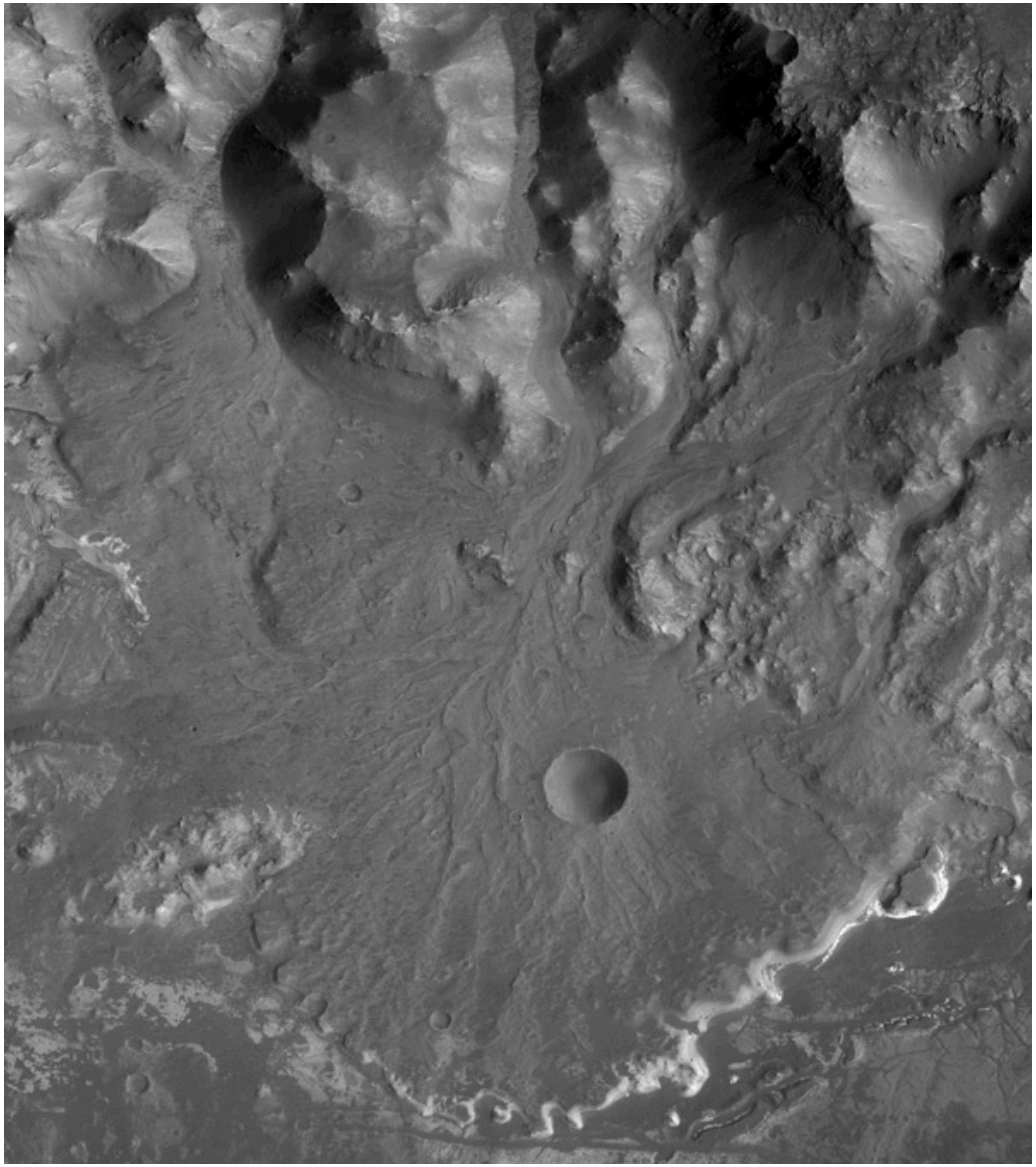
Alluvial system on Mars



Basic Geologic Principles: River Systems

Alluvial fan in China

Alluvial fan on Mars



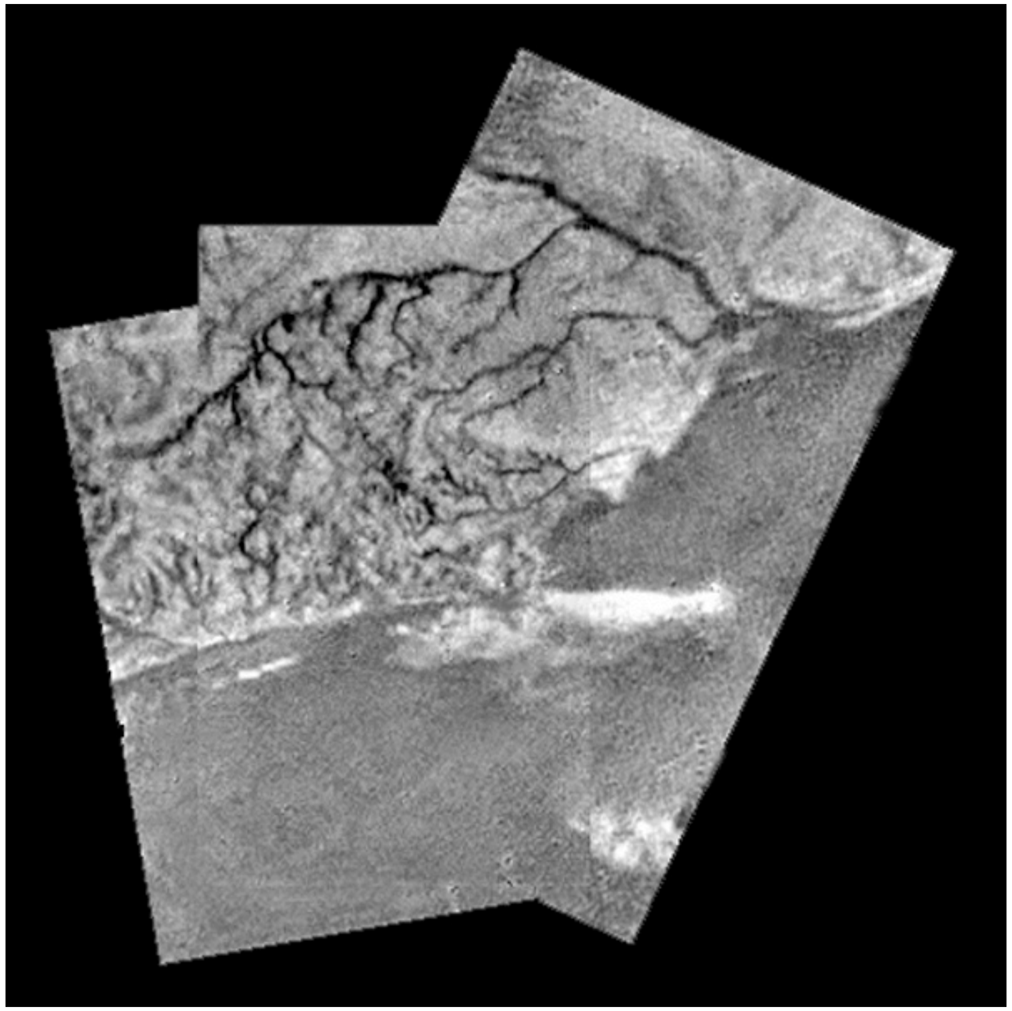
Basic Geologic Principles: River Systems

Braided stream systems are characterized by:

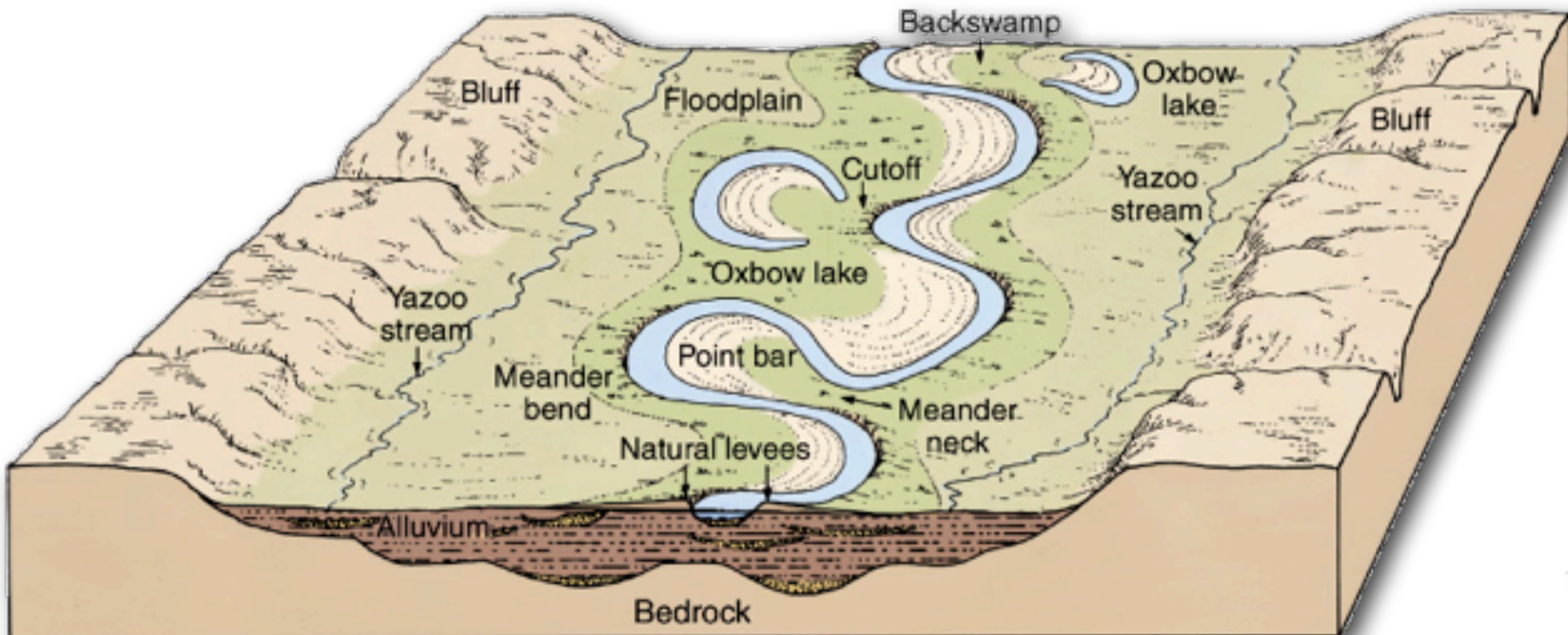
- interlaced channels with islands
- high sediment loads
- common in arid and semi-arid regions, where flow can be seasonally driven
- common in glacial areas (outwash regions in front of glaciers)

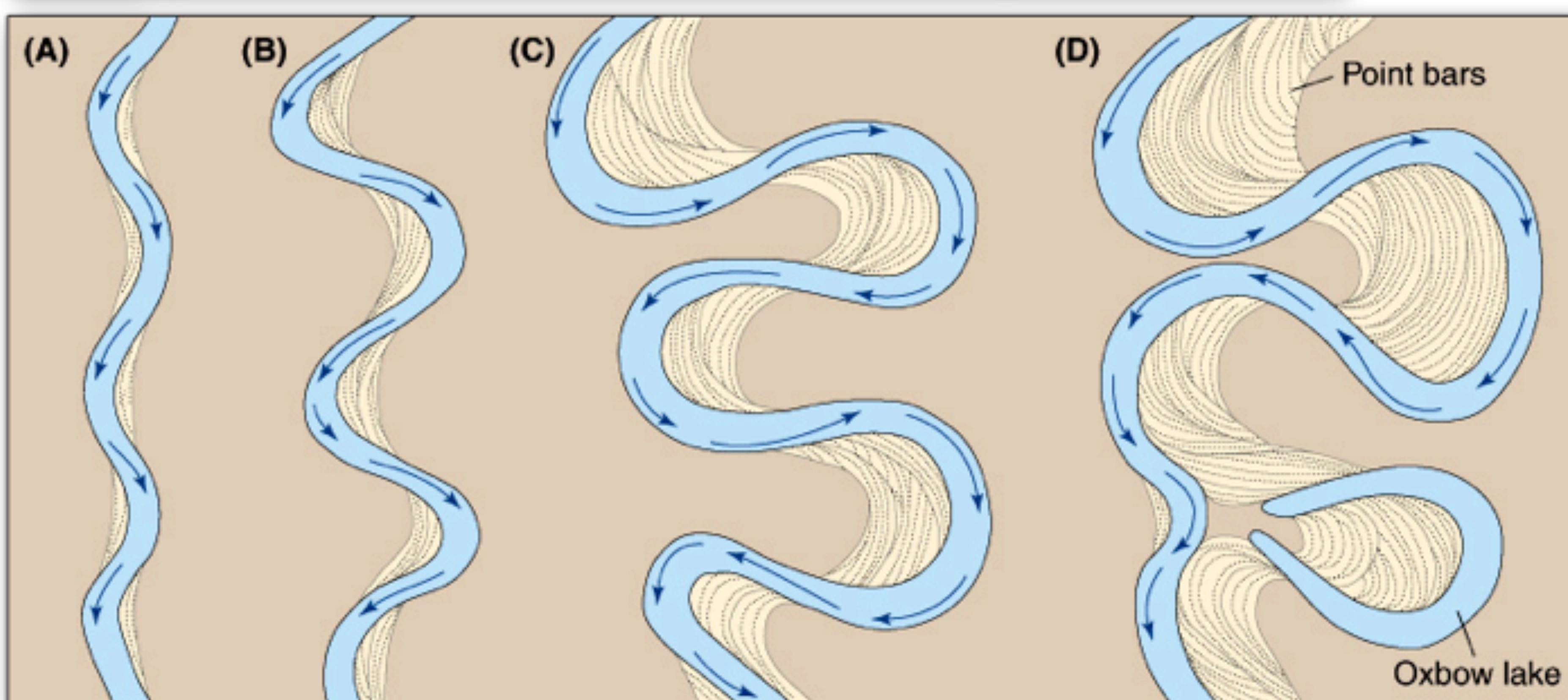
Braided streams on Earth

Braided(?) streams on Titan (formed by liquid methane)



Meandering streams are characterized by very sinuous patterns.





The turbulence of the water and the curvature of the path creates changes in velocity; this causes erosion on one bank and deposition on the opposite bank (known as *point bars*).

Point bars produce specific geometric patterns in the sediments they deposit. These can be observed in the rock record to identify stream paths.

Eventually, a loop of the stream can get cut off at the neck, creating an oxbow lake; the stream then takes a new path in this location.

Basic Geologic Principles: River Systems

Cohesion of sediment is required to form meanders.

- often related to plants, roots, etc. on Earth today
- ice could also provide cohesion
- could large amounts of clay provide cohesion?
- what provides cohesion on Mars to create meanders? Are meanders present on Titan?

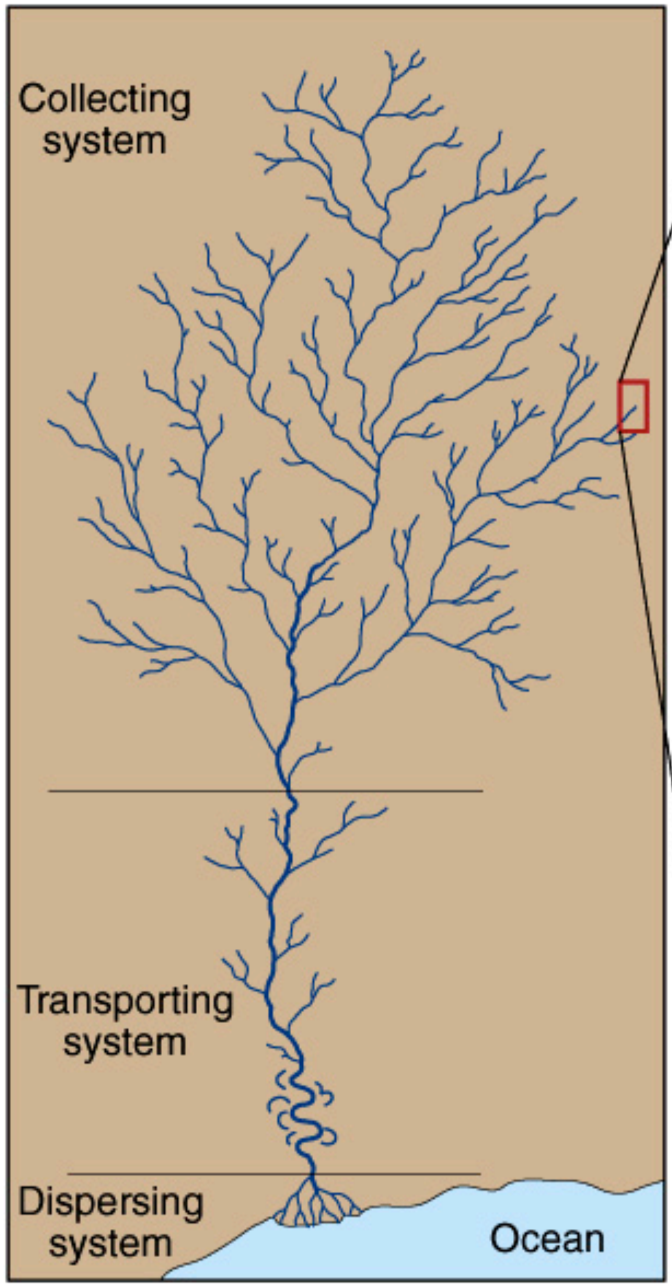
Creating meanders in the lab (UC Berkeley)

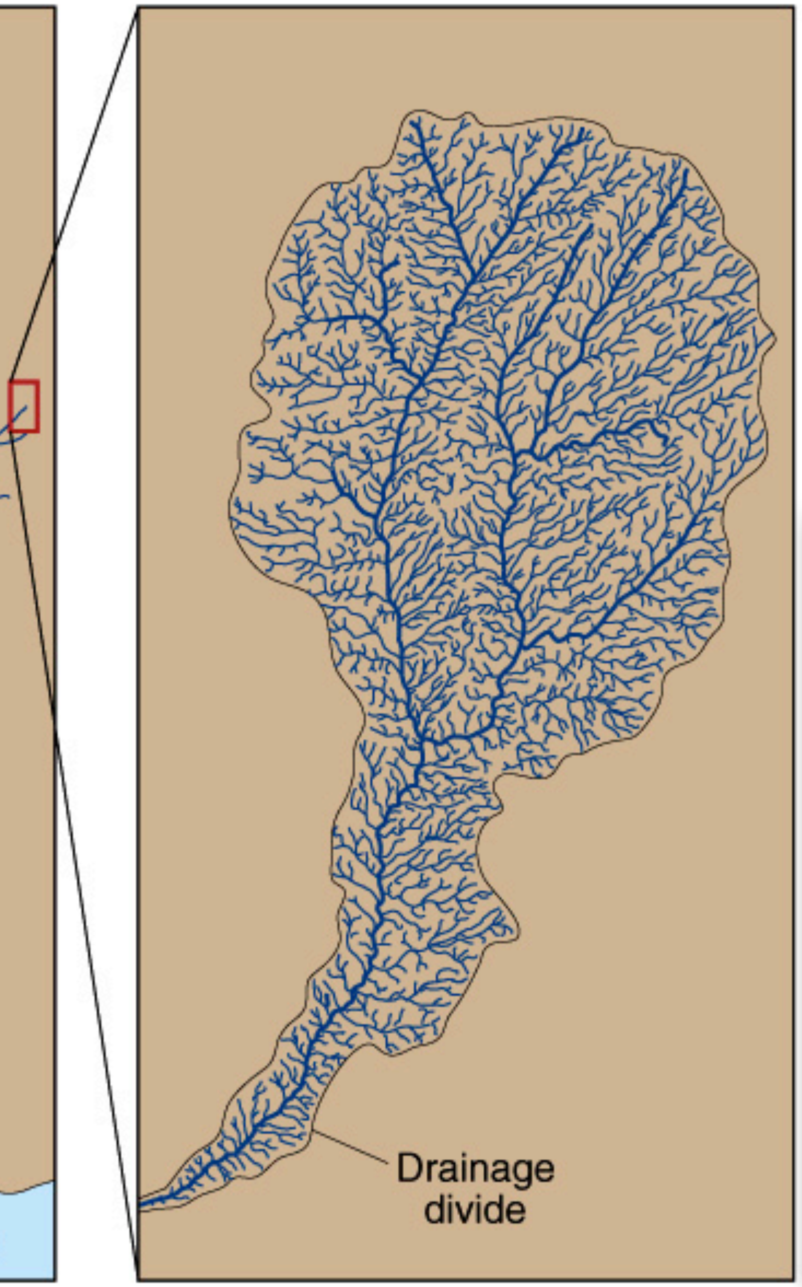
http://www.youtube.com/watch?v=55DQM_Ud8BQ

Basic Geologic Principles: River Systems

Headwaters form a drainage (collecting) system for gathering sediment and water, this is then transported downstream and ultimately dispersed to the ocean, lakes, or other basins.

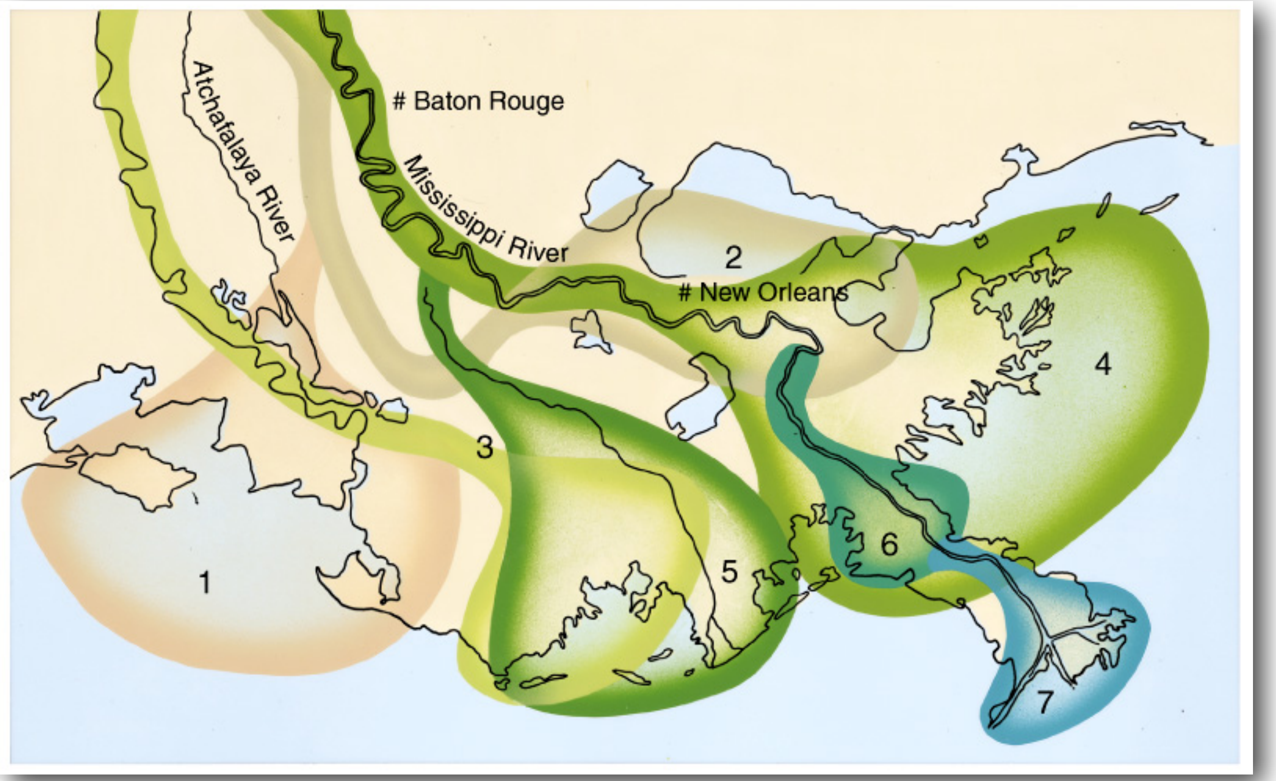
On Earth, the oceans are major sinks of sediment that is transported by water. In general, basins and other topographic lows collect sediment. On planetary bodies, impact craters can act as important 'sinks' for sediment.





Over time, rivers erode the land and reduce the topographic gradient (slope); they can then start to meander, deposit sediment, and possibly *avulse*.

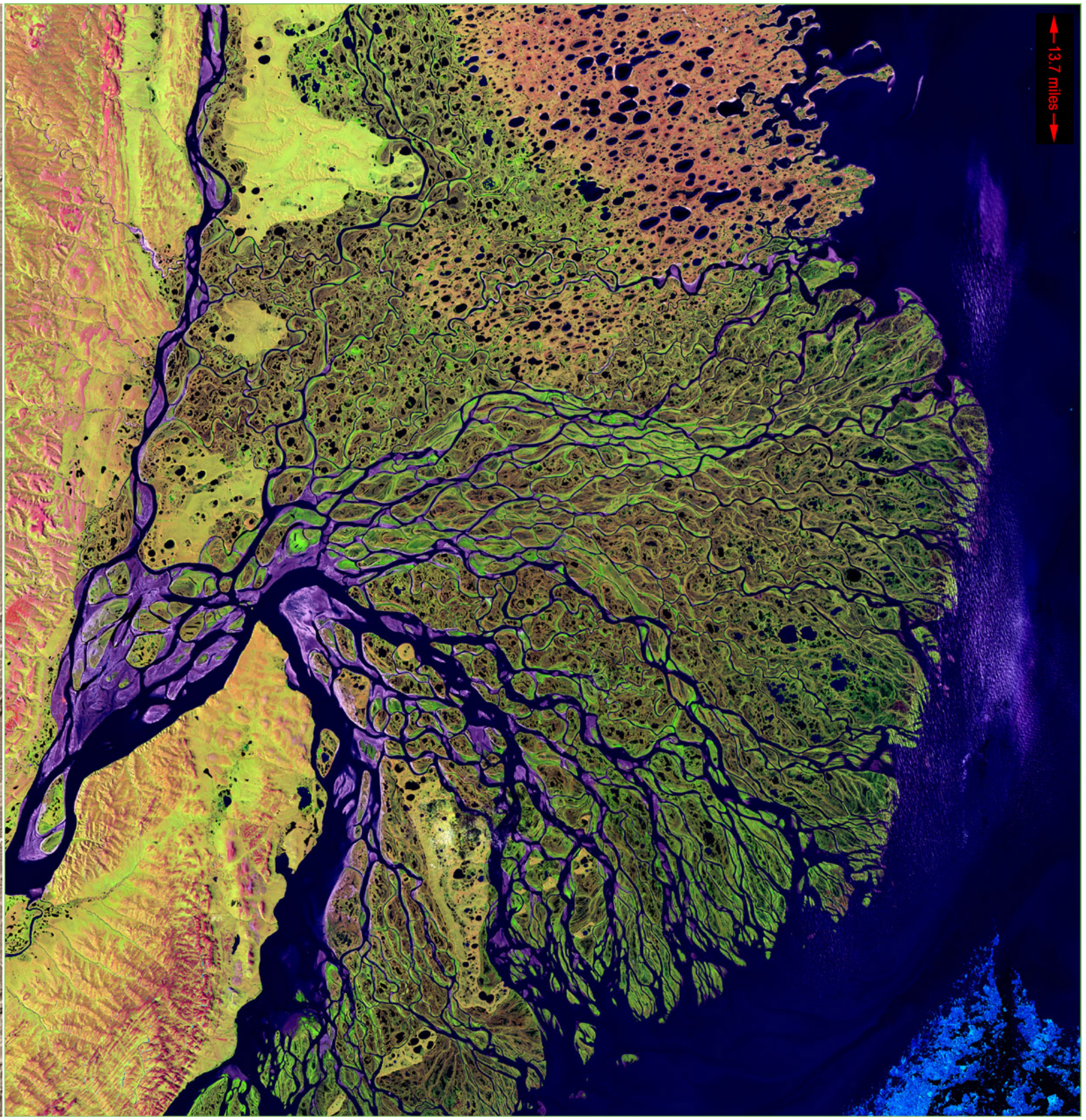
Avulsion is when a river abandons a channel to form a new one along a steeper slope; if by a delta it is often called 'delta switching'.



Delta Systems.....Evidence for Lakes on Mars?

Eberswalde Delta, Mars

Lena Delta, Earth



Basic Geologic Principles: River Systems

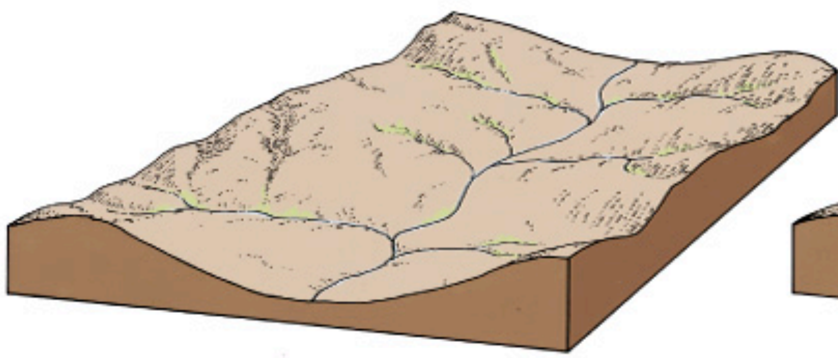
Valleys can fill up with alluvial sediment and ‘flatten’ out.

Meandering rivers in such valleys can erode down through the sediment, making terraces.

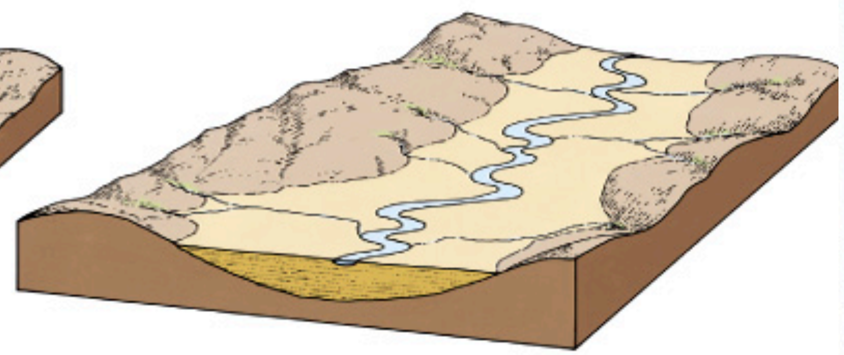
The river can shift laterally and cut through pre-existing floodplains, reaching lower levels.

These processes are recorded in the landscape by the distribution of terraces.

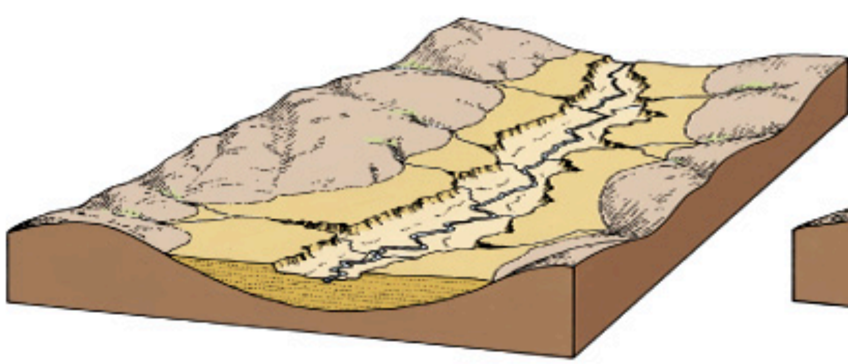
When present in bedrock, they are referred to as ‘strath’ terraces.



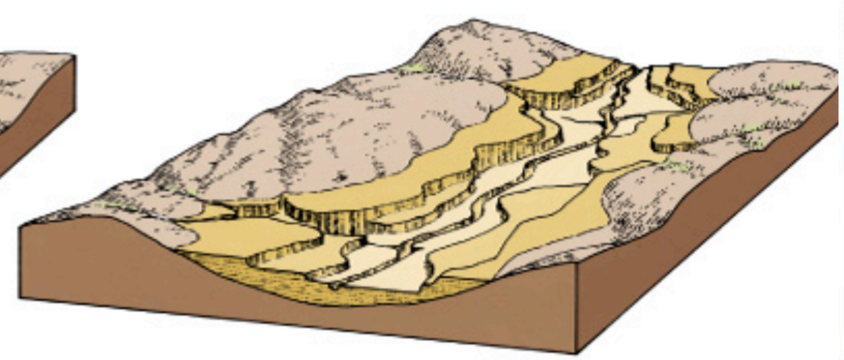
(A) A stream cuts a valley by normal downcutting and headward erosion processes.



(B) Changes in climate base level, or other factors that reduce flow energy cause the stream to partially fill its valley with sediments, forming a broad, flat floor.



(C) An increase in flow energy causes the stream to erode through the previously deposited alluvium. A pair of terraces is left as a remnant of the former floodplain.



(D) The stream shifts laterally and forms lower terraces as subsequent changes cause it to erode through the older valley fill.

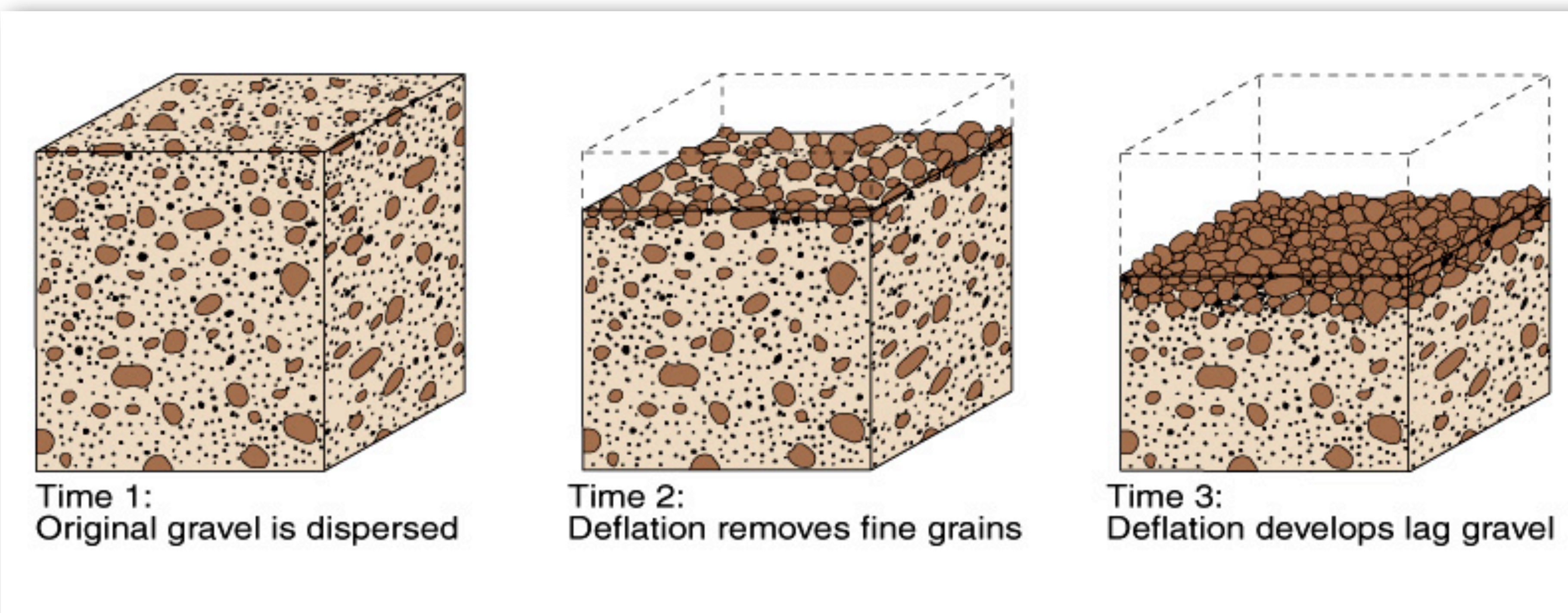
Basic Geologic Principles: Eolian Systems

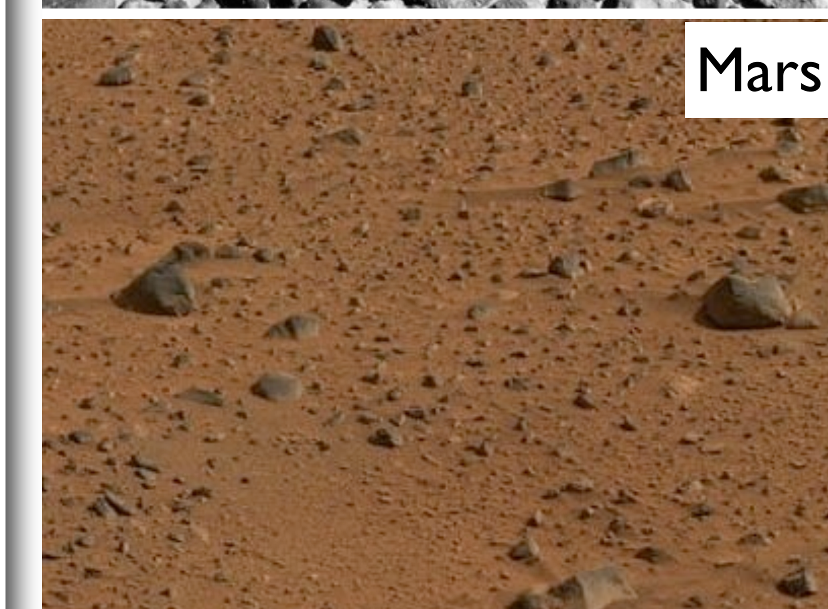
On Earth, water is the dominant fluid for erosion and wind is second, but on other planets this can be the opposite (Mars, for example, has been dominated by wind erosion for the past 3 billion years). Lack of vegetation and dry conditions promote erosion by wind.

There are 2 major ways that wind can erode material:

- **abrasion**: wind carries small particles (sand) that abrades and mechanically breaks down rock
- **deflation**: wind picks up and transports material

Deflation removes small particles (clay, silt, and sand) but leaves large particles behind. This creates *desert pavement*: a lag surface of larger particles.





Basic Geologic Principles: Eolian Systems

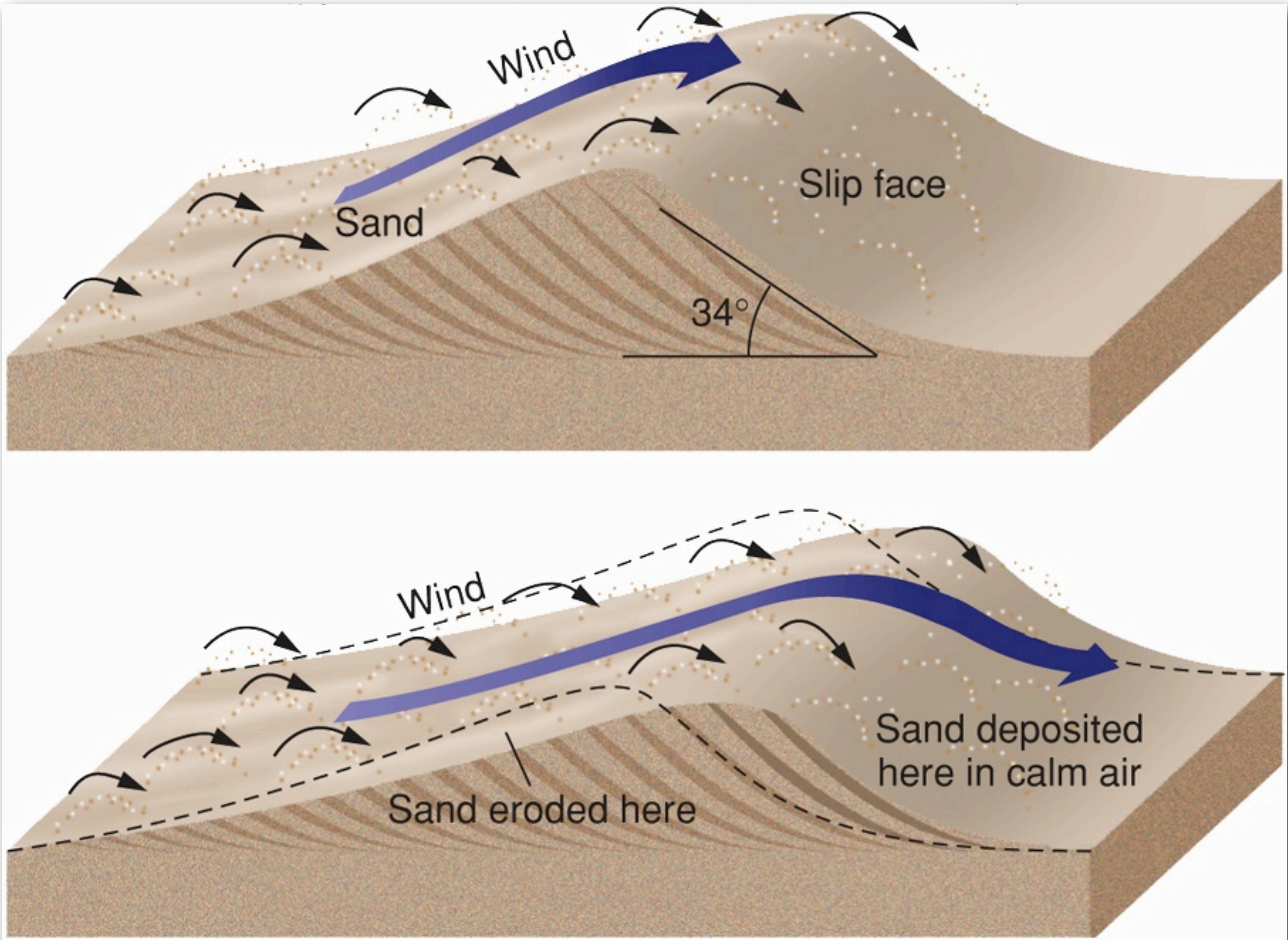
Abrasion is nature's version of sandblasting. It is effective at polishing rock surfaces and at eroding poorly cemented sediments.

Abrasion can create stunning erosional patters in rocks, including yardangs (elongated ridges that form parallel to the wind direction).

Yardangs on Earth (Iran)

Yardangs on Mars

Formation of Dunes



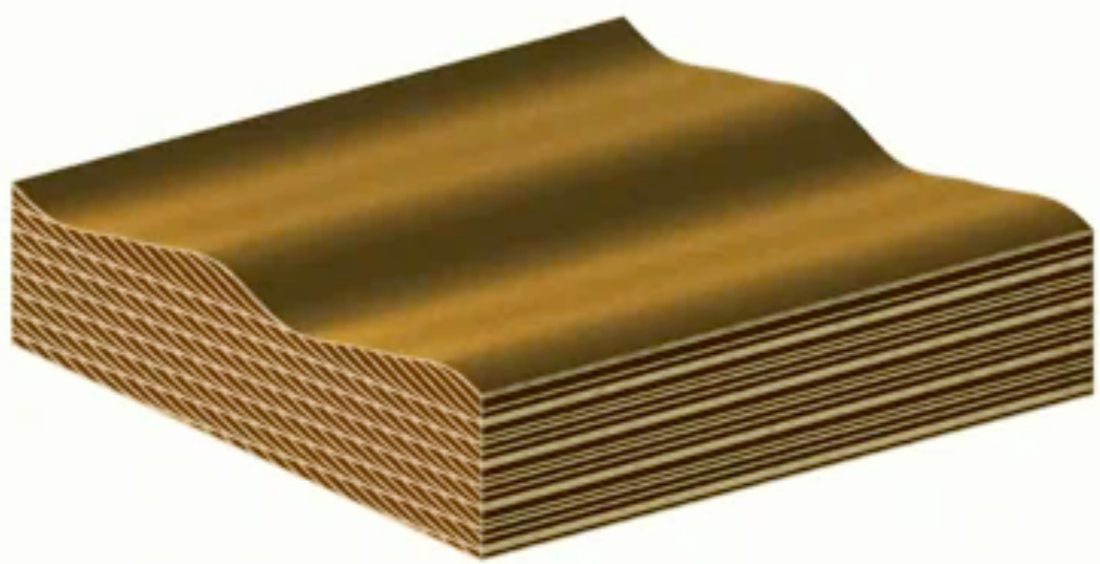
Basic Geologic Principles: Eolian Systems

The migration of dunes, their geometry, and the relative rates of deposition and erosion produce numerous styles of lamination and bedding.

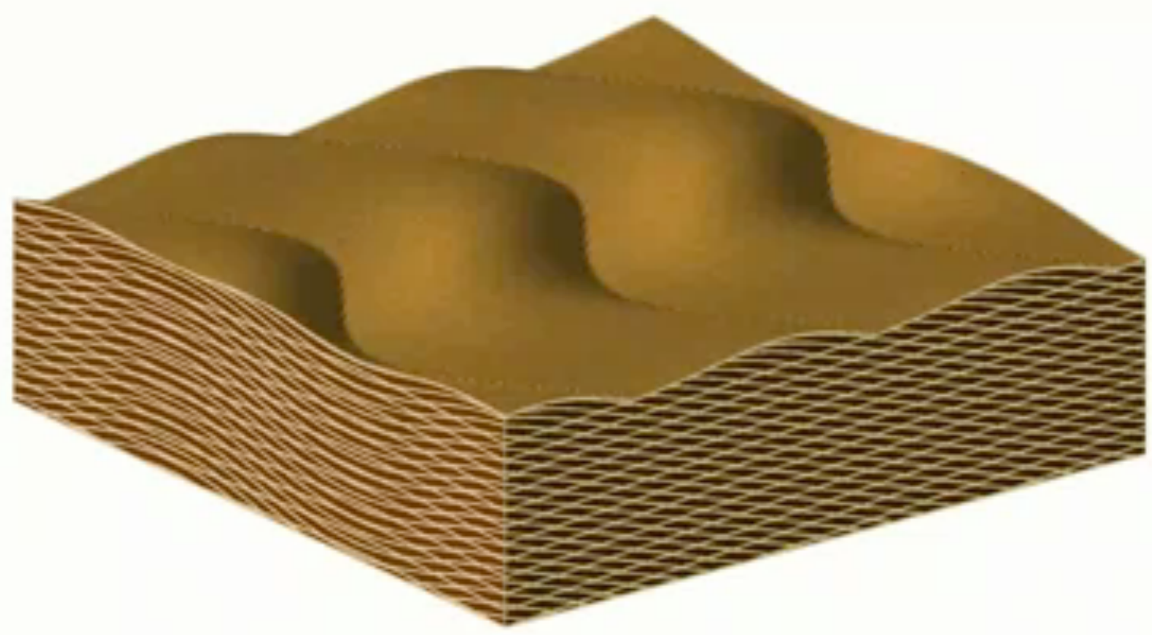
Bedforms such as dunes are formed by the interaction of a fluid...either wind or water....with sediment.

The details are very important when looking at bedforms in rocks and trying to determine if they were formed by eolian (wind) or aqueous (water) deposition.

Basic Geologic Principles: Eolian Systems



2-D Bedforms (Straight Crests)



3-D Bedforms (Sinuous Crests)

Basic Geologic Principles: Chemical Weathering

Different minerals weather at different rates, but as a rule of thumb the rate at which minerals weather tends to be the opposite of the order in which they crystallize by Bowen's reaction series.

- minerals that crystallize at high temperatures are less stable under surface conditions and weather rapidly (e.g., olivine, plagioclase, pyroxene).

- minerals that crystallize later at lower temperatures are more stable at the surface and weather more slowly (e.g., quartz; long transport distances and the stability of quartz gives us nice beaches!)

As 'primary' minerals weather, then can form new 'secondary' minerals that are more stable under the pressure-temperature conditions of a planet's surface:

$$\mathbf{2KAlSi_3O_8} + 2H_2CO_3 + 9H_2O = 2K^+ + 2HCO_3^- + 4H_4SiO_4 + \mathbf{Al_2Si_2O_5(OH)_4}$$

(**K-feldspar**) can transform into the more stable mineral (**kaolinite**)

This type of chemical weathering releases cations (note the leftover K^+ on the right side of the equation); these cations accumulate in the water and eventually end up in the ocean, making it salty.

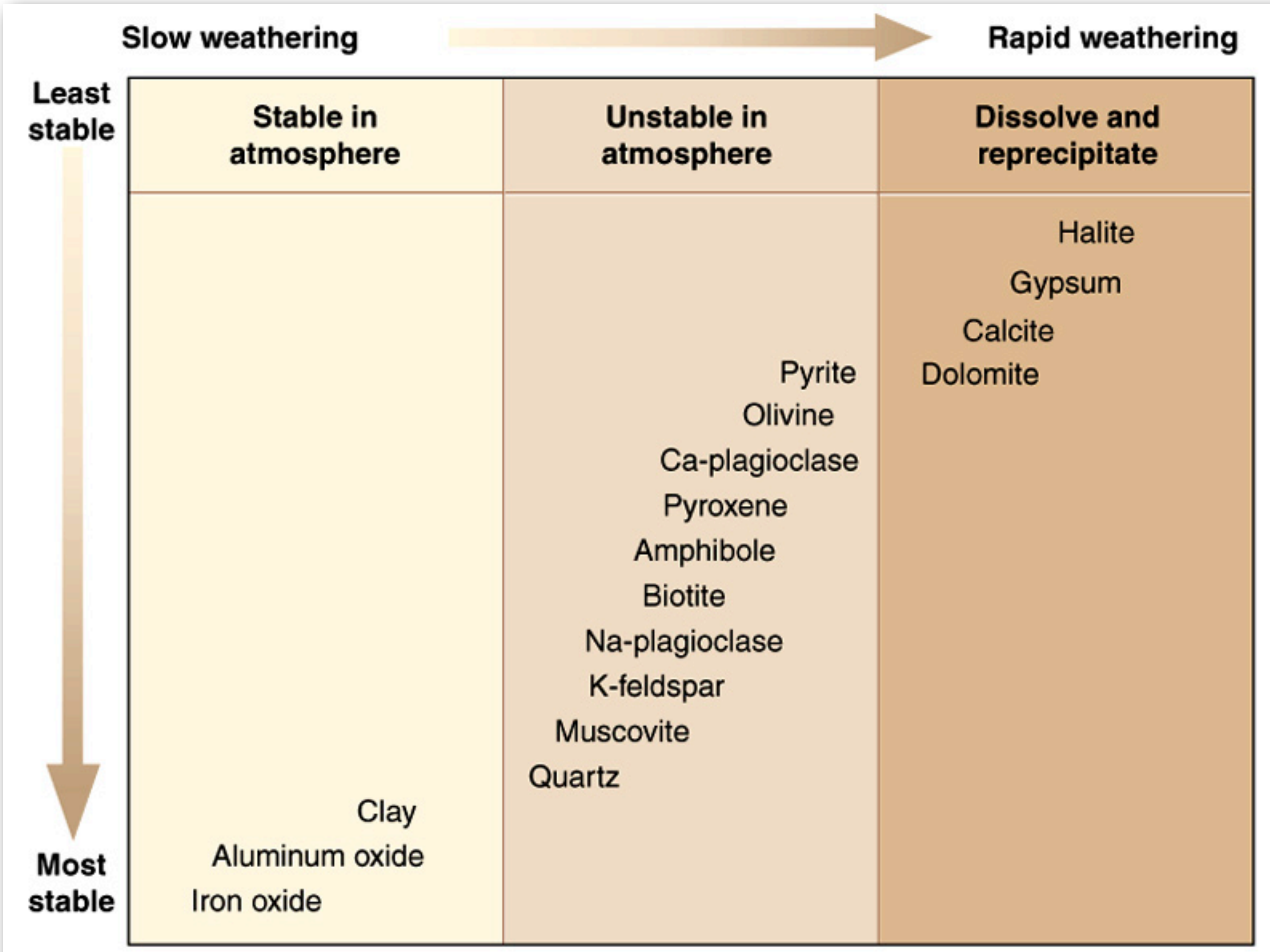
Major types of chemical weathering:

- Dissolution: minerals dissolve in water; halite (salt) dissolves in water.

- Acid hydrolysis: creation of acid to promote weathering; CO_2 mixes with water to make carbonic acid, H_2CO_3, which attacks mineral structures.

- Oxidation: An increase in the valence state (charge) of an element disrupts the crystal structure; rust, for example, is created when Fe^{2+} oxidizes to Fe^{3+} by interaction with O_2.

Relative stability of minerals



Basic Geologic Principles: Chemical Weathering

Chemical weathering produces several trends:

- Alkali and alkaline earth elements are put into solution (Na, K, Ca, Mg, etc.)

- pH is a measure of the concentration of hydrogen ions (H^+) in a fluid

  $pH = -\log_{10}[H^+]$; (so if $[H^+] = 10^{-7}$, then pH = 7; if $[H^+] = 10^{-2}$, then pH = 2)

  the more H^+ a fluid has the more acidic it is: pH < 7 is 'acidic', pH > 7 is 'basic'

- At moderate pH, Al^{3+} and Fe^{3+} are not easily dissolved in water (they have low *solubility*).

  This leads to aluminum and iron oxides being end products of weathering.

- Increasing temperature and the ratio of water-to-rock increases weathering rates.

- Clay minerals and oxides are common chemical weathering products of primary minerals:

TABLE 10.1 Weathering Reactions for Common Minerals

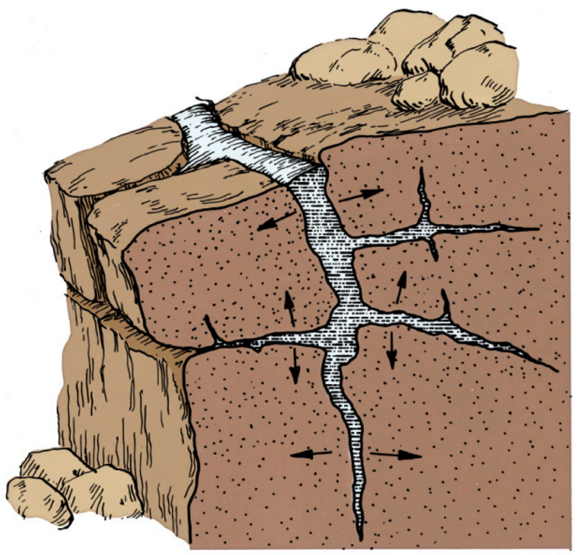
Original Mineral	General Formula	Weathering Reactions	Dissolved Ions	Residual Minerals
Gypsum	$CaSO_4 \cdot 2H_2O$	Dissolution by water	Ca, SO_4	
Halite	NaCl	Dissolution by water	Na, Cl	
Olivine	$(Mg,Fe)_2SiO_4$	Oxidation		Fe oxides
		Dissolution by acid	Mg, Fe	
Pyroxene	$Ca(Mg,Fe)Si_2O_6$	Oxidation		Fe oxides
		Dissolution in acid	Mg, Fe, Ca	
Amphiboles	$NaCa(Mg,Fe)_5AlSi_7O_{22}(OH)_2$	Oxidation		Fe oxides
		Partial solution by acid	Na, Ca, Mg	Clay
Plagioclase	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	Partial solution by acid	Na, Ca	Clay
K-feldspar	$KAlSi_3O_8$	Partial solution by acid	K	Clay
Muscovite	$KAl_3Si_3O_{10}(OH)_2$	Partial solution by acid	K	Clay
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(OH)_2$	Oxidation		Fe oxides
		Partial solution by acid	K, Mg	Clay
Quartz	SiO_2	Resists dissolution		
Calcite	$CaCO_3$	Dissolution by acid	Ca	
Dolomite	$CaMg(CO_3)_2$	Dissolution by acid	Mg, Ca	
Pyrite	FeS_2	Oxidation	SO_4	Fe oxides

Basic Geologic Principles: Physical Weathering

Physical weathering is the *disintegration or disaggregation of rocks*.
It does not cause a change in the chemical composition of minerals/rocks.
It can occur by many different mechanisms:

Ice Wedging

freeze-thaw cycles



Sheeting

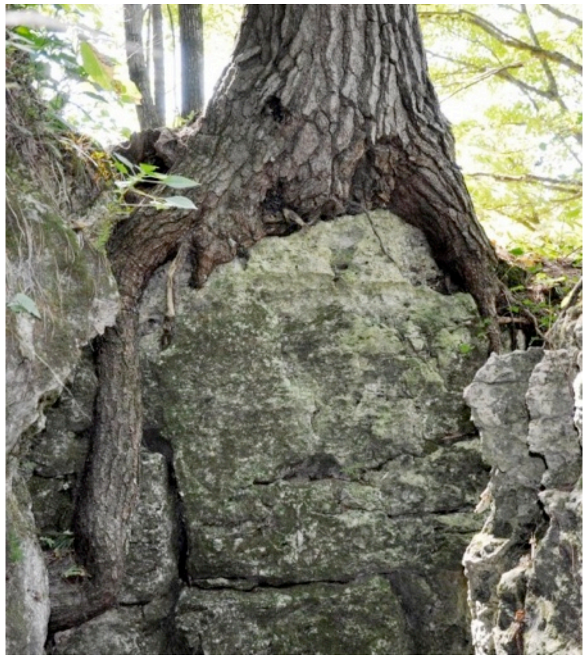
Rocks formed deep at high pressure fracture when brought to the lower pressure of the surface.

Crystal Growth

Minerals precipitate in fractures, similar to ice wedging.

Root Growth

Roots can exert very strong forces, and as they grow they wedge rock apart.



Basic Geologic Principles: Physical Weathering

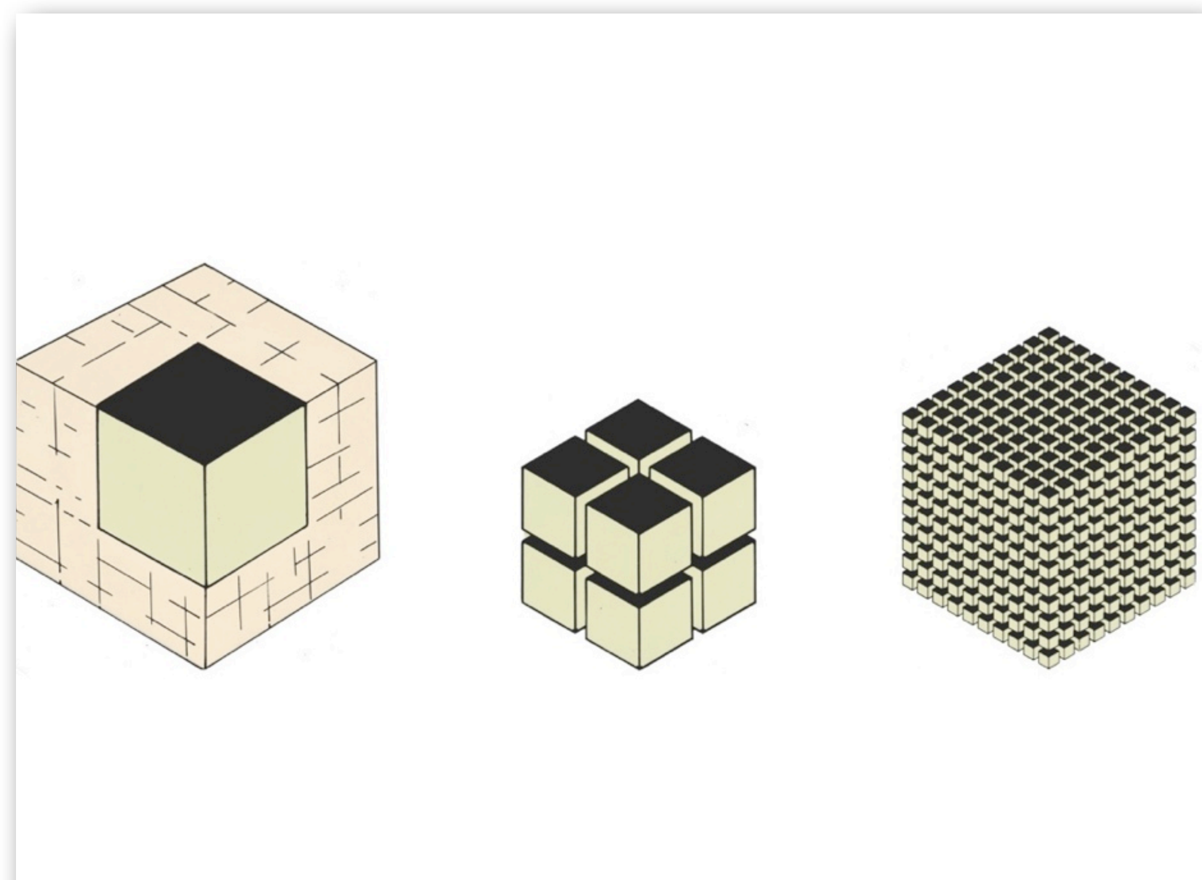
Breaking of rock along joints and fractures increases the surface area.

Increasing the surface area promotes physical and chemical weathering (increases weathering rate).

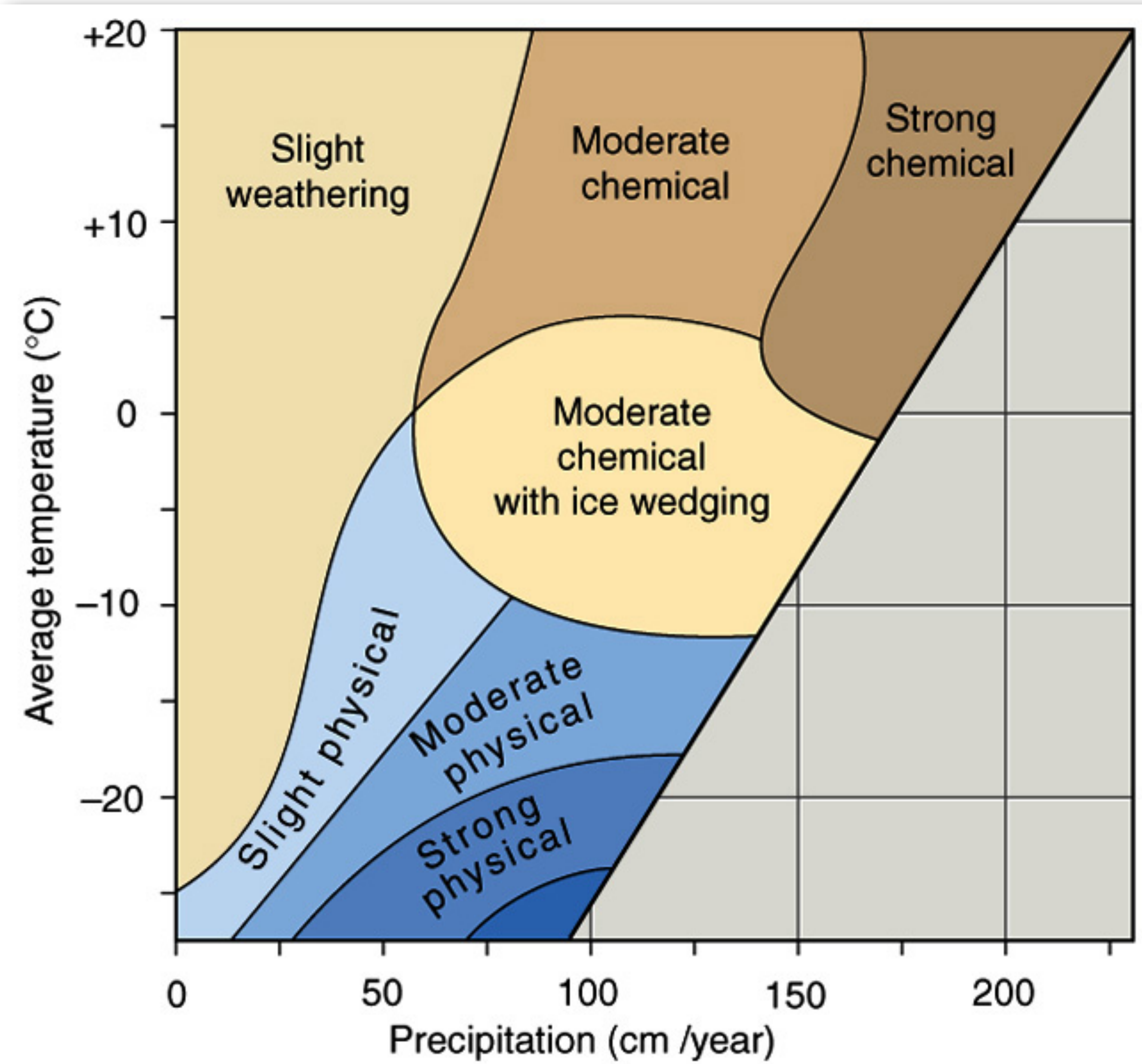
Joints and fractures are created by ice wedging, crystal growth, pressure unloading, or changes in temperature (heat makes rock expand and can cause outer layers to 'spall' off).

Applying stress to rocks also causes fracturing and jointing (e.g., during burial, uplift, mountain building).

Abrasion by wind also causes small pieces of rock to spall off (kind of like sandblasting); though not as significant on Earth, this may be the dominant mechanism for modern erosion on Mars.



Climate & weathering are intimately linked



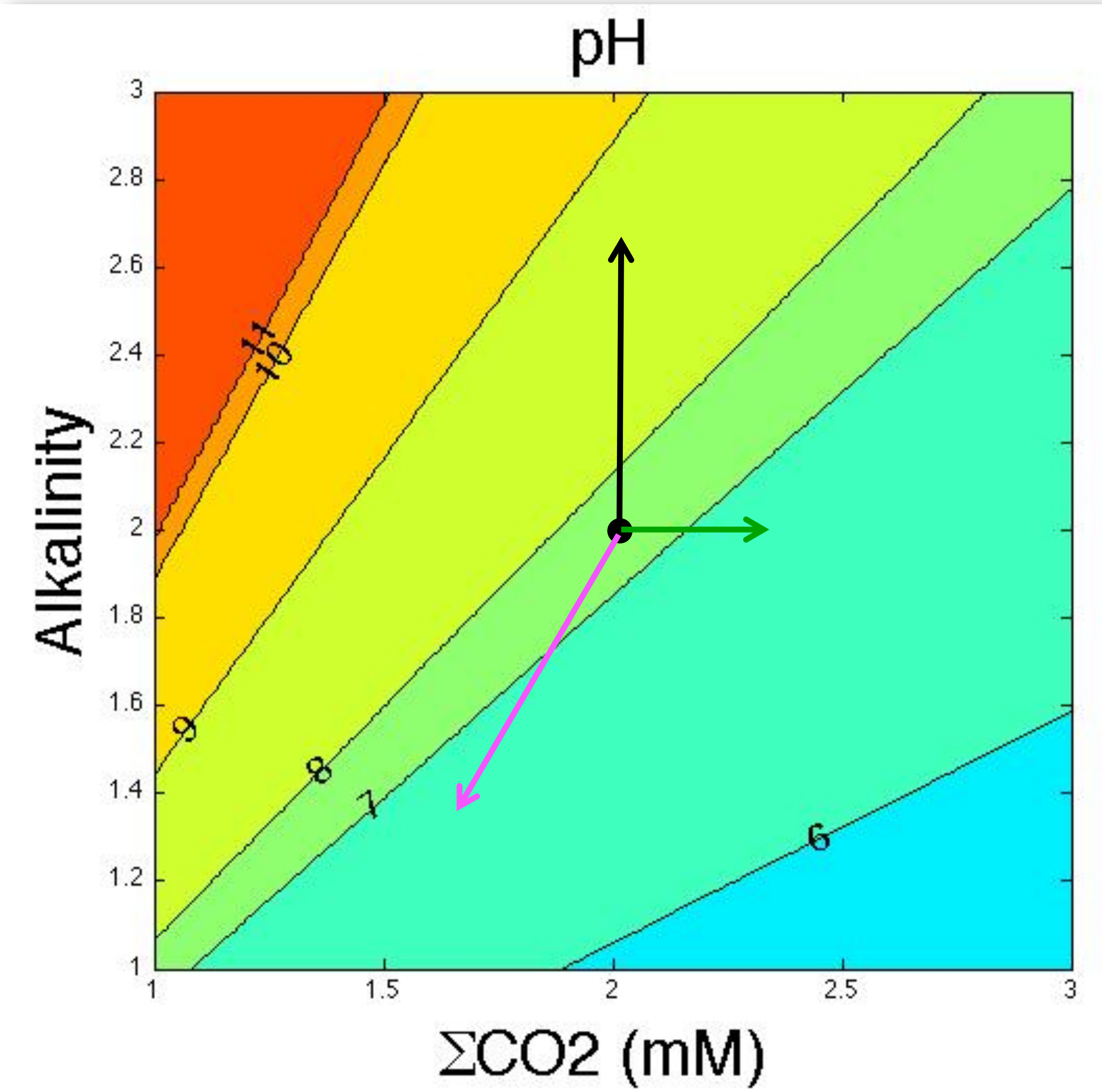
Increased temperatures and increased precipitation lead to strong chemical weathering. (e.g., the tropics)

In contrast, cold and dry regions are dominated by physical weathering. (e.g., polar regions)

However, even very thin films of water on rocks/minerals can cause chemical weathering over long periods of time.

The Atacama desert in Chile is the driest place on Earth, but chemical weathering still takes place, just at very slow rates.

The amount of CO_2 on Earth is regulated by a 'negative feedback cycle' consisting of several parameters:



Different colors represent different pH values.

Mineral (silicate) weathering

Mineral precipitation

Volcanic outgassing

If the black circle on this diagram represents typical seawater, then any changes in the rates of the factors above will temporarily shift the point to a new position (shift the pH, amount of CO_2, or 'saltiness' of seawater). However, given enough time the other factors will then work to shift it back to its previous position.

Example: If atmospheric CO_2 increases due to more volcanic eruptions, then the climate will get warmer and weathering rates will increase. This will cause more CO_2 and cations to be dissolved in the oceans, which then leads to precipitation of carbonate minerals, thus 'removing' CO_2 from the atmosphere.

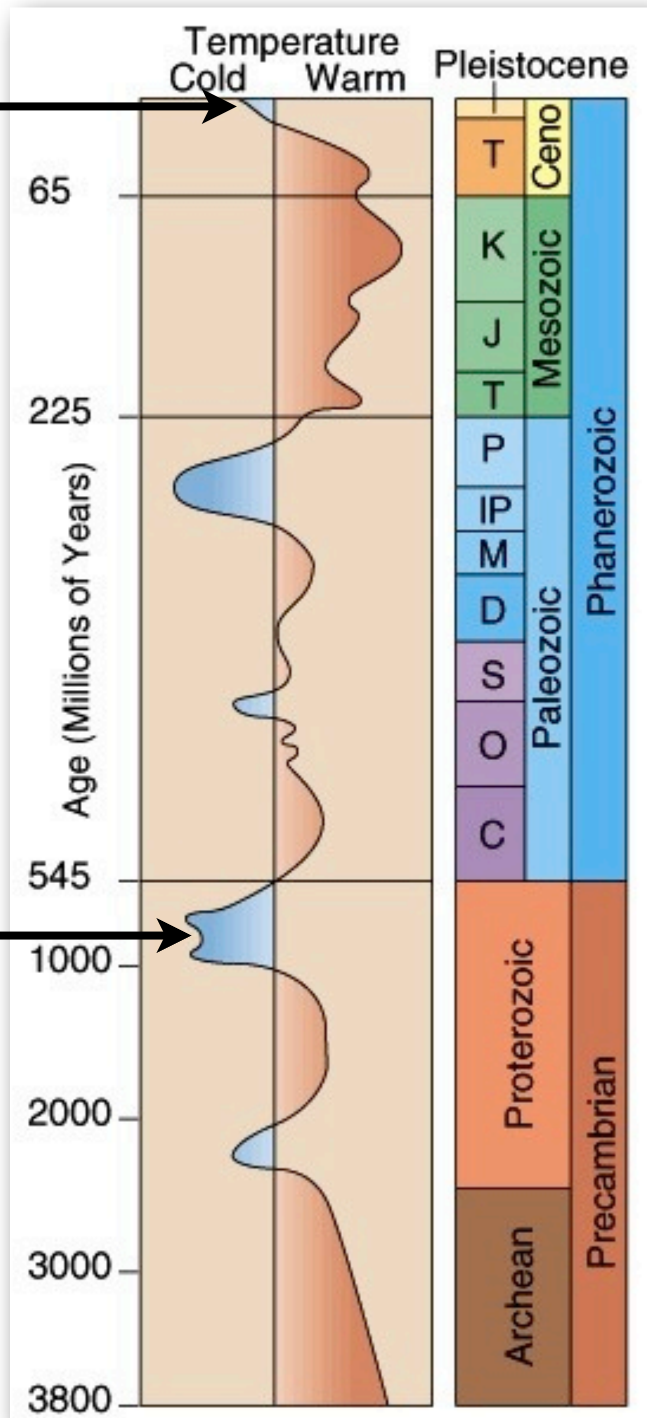
Basic Geologic Principles: Climate

The geologic record shows that Earth has experienced a number of ice ages, and in fact we are still in an ice age today. **Ice ages** are characterized by a number of **glacial-interglacial cycles**, and today we are in an interglacial period.

Some have suggested the entire Earth was once frozen ('Snowball Earth') >650 million years ago.

Current Ice Age

'Snowball Earth'



Extent of glaciation in North America.
Numbers represent thousands of years before present.

Basic Geologic Principles: Climate

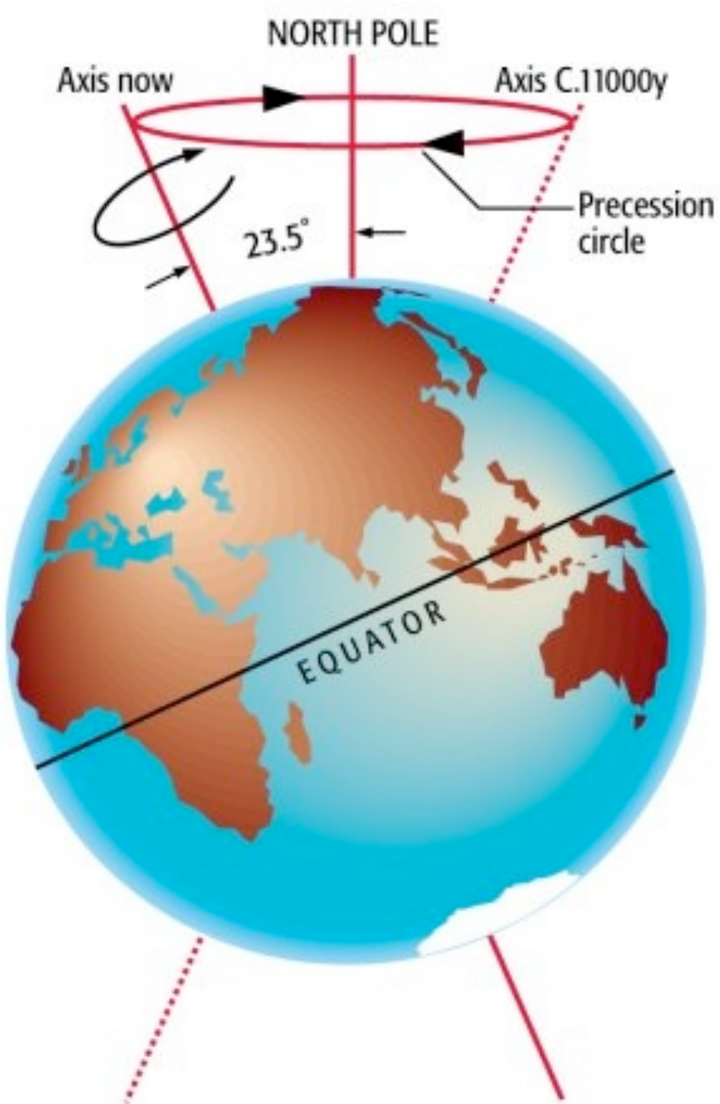
The orbital parameters of the Earth (eccentricity, obliquity, & precession) affect how much energy each place on the planet receives from the Sun. It is this energy, *in combination with the interaction of the oceans and atmosphere*, that controls our climate on local, regional, and global scales.

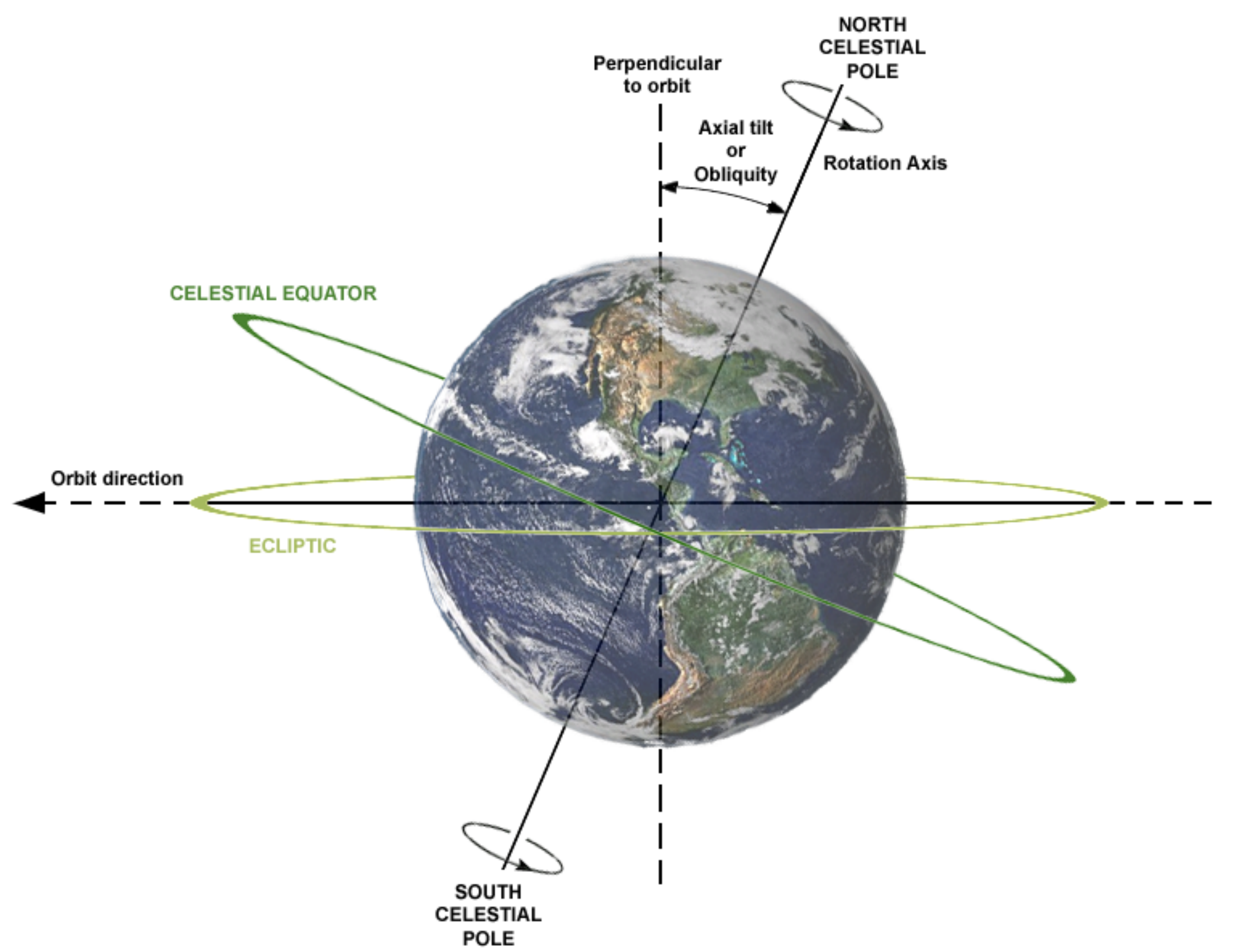
(just knowing the energy input isn't enough to predict climate!)

Eccentricity - measure of how elliptical a planet's orbit is

Obliquity - the *angle* between a planet's rotation axis and a line perpendicular to its orbital plane

Precession - the *orientation* of a planet's rotation axis (like the circle traced out by a spinning top)



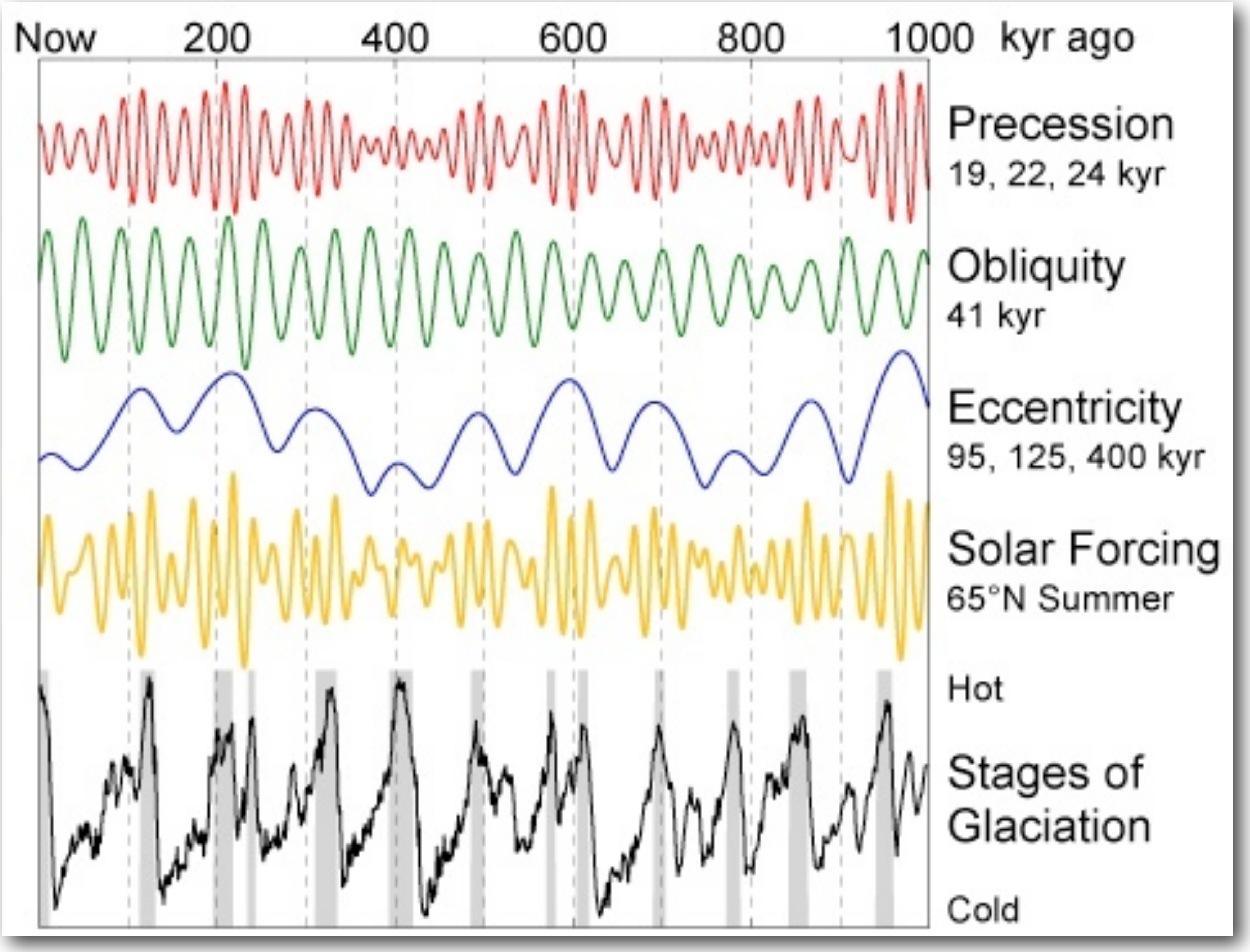


Basic Geologic Principles: Climate

It was shown by James Croll (1870s) and later in much more detail by Milutin Milankovitch (early 1900s) that cycles in the orbital parameters of Earth greatly affect the surface temperature.

These 'Milankovitch' cycles have been linked to glacial-interglacial cycles.

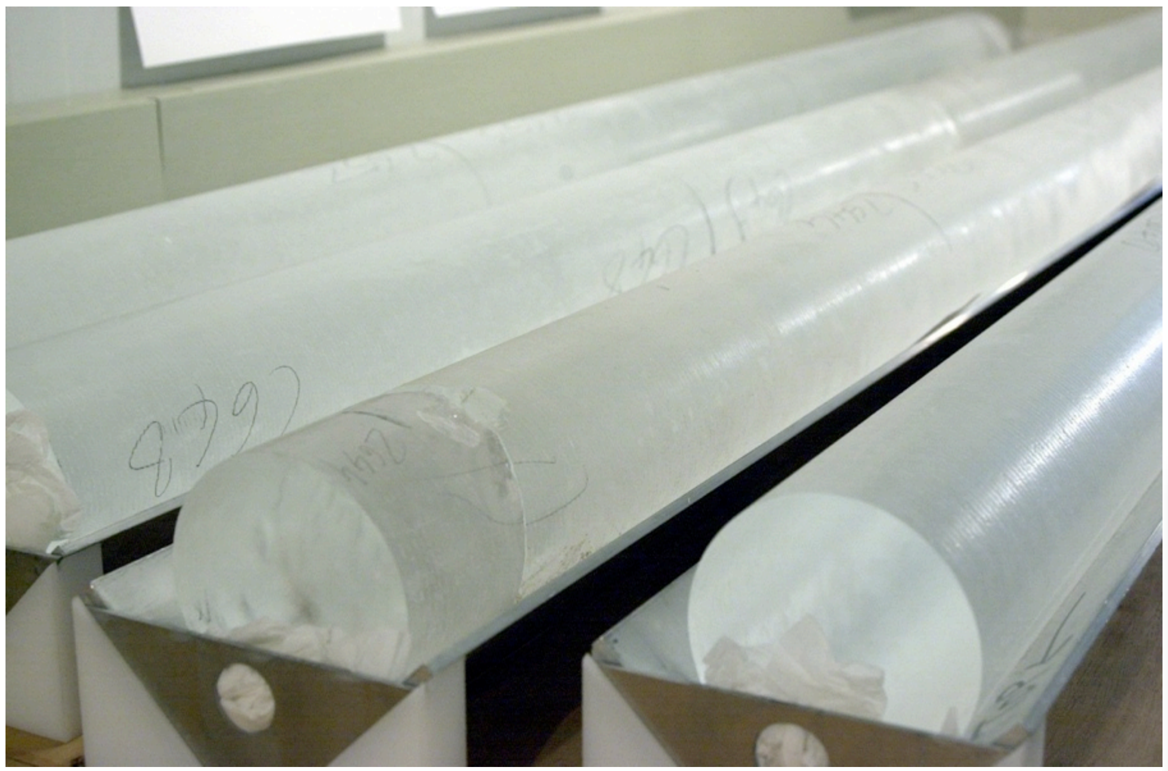
It has been proposed that similar orbital changes have produced "ice-ages" on Mars.



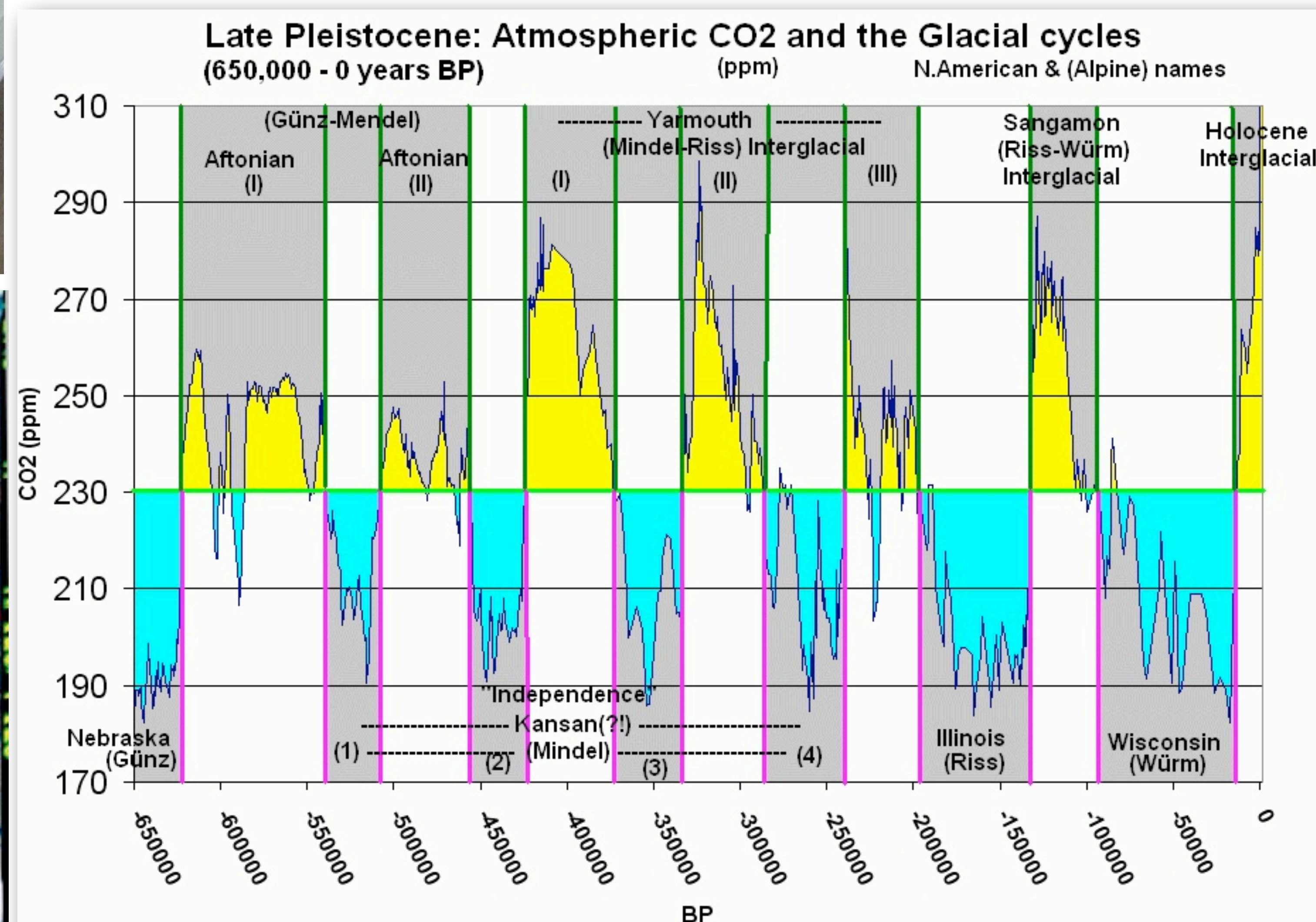
Basic Geologic Principles: Climate

We can get high resolution information about past climate by looking at ice and sediment (sea) cores.

Layers of ice correspond to yearly accumulation, and if the layers are relatively thin due to slow accumulation rates, then a long ice core provides a mechanism to look way, way back into the past.



We can't measure the historical temperatures directly, so *we must measure/estimate them indirectly using proxies.*

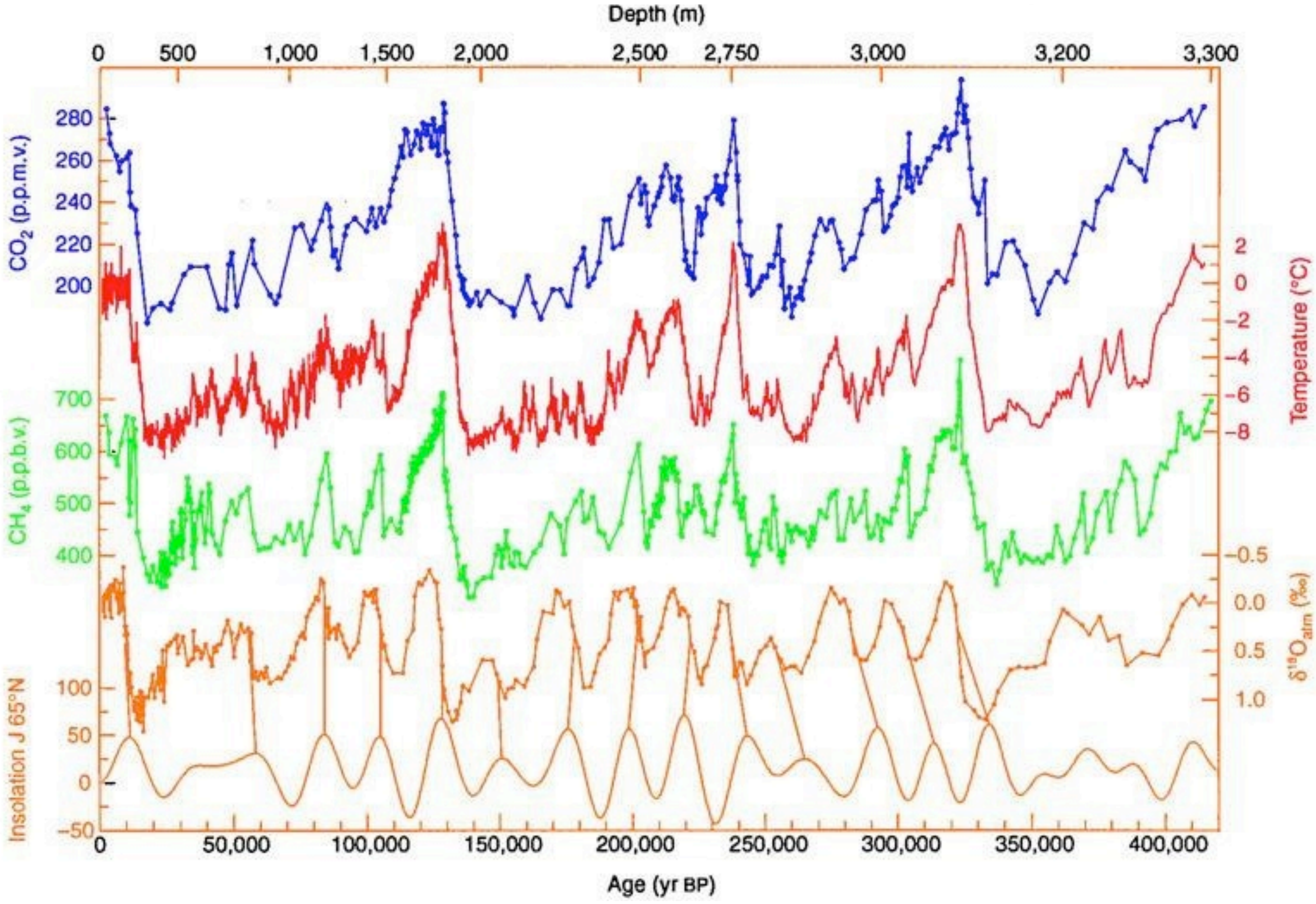


Basic Geologic Principles: Climate

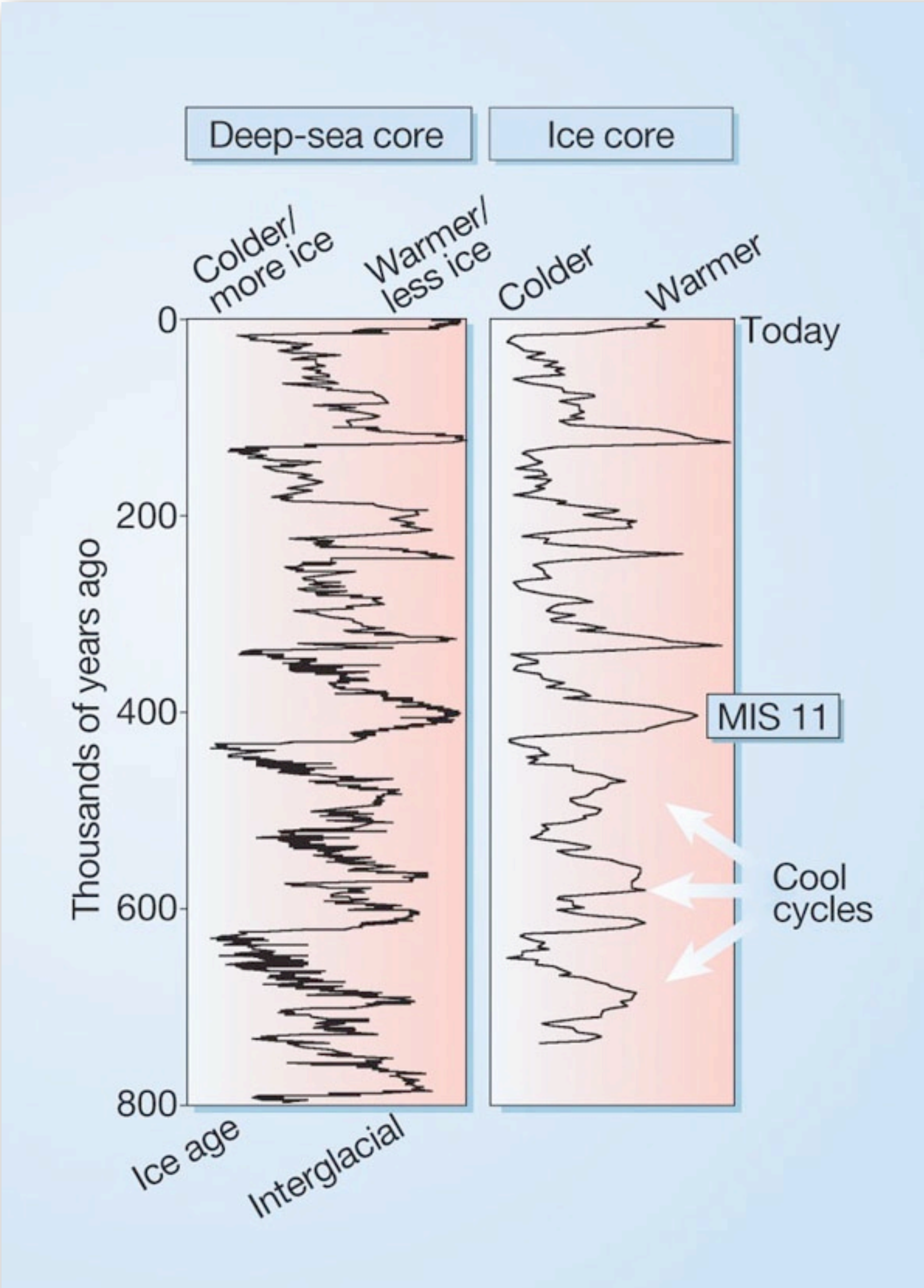
Proxies from ice and sediment cores can include a number of things:

- temperatures derived from compositions of organism shells
- oxygen isotopes (records changes in hydrologic cycle related to volume of ice)
- compositional changes in gas bubbles trapped in ice cores

All exhibit correlations with orbital parameters and each other, suggesting a strong link between climate and energy, atmospheric circulation, and ocean circulation.



Basic Geologic Principles: Climate



Recent results (2004) from ice core data in the Antarctic have pushed our detailed record of climate change back to ~750 kyr.

Sediment cores also go back to these ages, but the record is less clear in those data.

- don't preserve trapped greenhouse gases
- sediment layers are disturbed by burrowing organisms
- time not as well resolved as in ice layers

These results suggest there have been 8 glacial cycles in the past ~750 kyr.

Basic Geologic Principles: Climate

Orbital parameters affect all planets, but Mercury lacks a significant atmosphere and Venus is too hot for glacial cycles.

Can Mars inform us about fundamental climate cycles beyond Earth?

Snowball or Slushball Earth?

Martian Ice Ages?