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ENVIRONMENTAL GEOLOGY

INTRODUCTION

GEOLOGIC HAZARDS:
AN OUNCE OF PREVENTION IS WORTH A POUND OF CURE

There are enough clues in the landscape, local history, in similar settings around the world, and in common sense, to let you make a valid judgment on most geologic hazards. And your homework is much easier, now that we have the internet. But what if a place is risky, yet you love it? A geologist can't help you there - that's psychological. Some avoid all risk with a ten-foot pole, others think it's the spice of life. For you, it may not make sense to avoid all risk, but it does make sense to understand the type and amount of risk, and how to minimize it. If you wish to avoid geologic hazards, an ounce of prevention is worth a pound of cure.

Geologic hazards have plagued us through the ages. For historic perspective, here is what Pliny the Elder, one of the world's first scientific observers, had to say about the Rhine Delta in the later Netherlands, after he had served there as a soldier in the first Century BC: "There lives a miserable people at the highest known levels of tide and here they have built their huts, living like sailers when the water covers their environment, and as if shipwrecked when the water has gone." (McQuaid and Schleifstein, 2006). Ironically these "miserable people", in the course of two thousand years, have evolved into those most technologically savy at dealing with sealevel rise due to global warming.

The Dutch, of course, have dealt with it by creating one of the engineering wonders of the world. But for every success story like the Netherlands there are hosts of horror stories: Haiti's quake, Katrina's hurricane, Indonesia and Japan's tsunamis, Mt. Peli's pyroclastic cloud, and the Missouri River's almost yearly flooding, to give some diverse examples.

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whole forests to over 1700 ft above sea level, when an earthquake-generated landslide entered Litunya Bay, Alaska (fig.).

Fig. 21a. Simplified perspective diagram of the Litunya Bay Landslide and wave.

There's a fun barroom story goes with Litunya Bay - supposedly two guys, who had been drinking quite heavily, were fishing in a small boat on the bay. The wave carried them and their boat over the tops of a mature forest, that had been growing on the spit at the lower end of the bay, and deposited them in the open ocean, along with the forest. There the wave instantly dissipated, leaving them stranded in a forest of tangled debris in open ocean. Talk about two confused fisherman.

To call the Litunya Bay wave a tsunami is a stretch - it was an exceptional wave, caused by a local event, in a very small container. Classic tsunamis, on the other hand, are giant waves triggered by sea floor displacement during earthquakes, most often over subduction zones. The vast majority of subduction zones rim the Pacific and the vast majority of tsunami are confined to the Pacific Basin. But, as we saw in 2005, the short segment of subduction in the Indian Ocean in Indonesia is capable of a deadly tsunami. Because the Mediterranean Basin is a closing ocean that is tectonically active it, and to a lesser extent the Black and Caspian Seas, are also susceptible.

A ship in mid-ocean may not even know a tsunami is passing under them. Tsunamis may travel as much as 450 mph, but have wavelengths measured in hundreds of miles, and an amplitude of only a few feet - in mid ocean, so they are almost undetectable. But when they start to feel bottom, the water piles up into a monster that can be several tens of feet high. The runup of the wave can extend to over 100 ft above sea level (Fig.).

Fig. 21b Diagram showing how tsunamis act where they originate, in mid- ocean, and where they hit shore.

These waves are not unidirectional but do focus their destruction in a general direction, depending on the facing of the generating subduction zone. Alaska's Good Friday earthquake is a good example - because of the kink in Alaska, the generating sea floor faced almost directly toward the mega- headlands of British Columbia, Washington State and northern California, which sustained the greatest destruction.

Many Pacific beaches have tsunami warning systems. Another thing, that can give some needed time to evacuate to high ground, is the tendency of many tsunami waves (not all) to be proceeded by a withdrawal of water seaward - if the tide starts to go out abnormally fast, run for the highest ground you can find.

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FLOODS

RIVER FLOODS: Because river floods are so common they cause huge damage and loss of life...most of which is preventable. Build high enough above rivers to avoid flooding - that means at least one river terrace up from the active flood plane. If there is a large beaver dam or old man-made dam upstream, add another 50 vertical feet. If their are glaciers or a large old man-made dam upstream, add another 100 vertical feet to that.

Look up the high-water mark of the greatest recorded local flood - there is a small plaque built into the masonry, at about the top of the restroom door, in a Montpelier, Vt. gas station near where I live - “Flood height - November 1927”. I found the precipitation contour map for that storm on the internet - ten inches in 24 hours - probably a stalled tropical hurricane. But the other reason for floods in northern latitudes is less spectacular but more common - ice dams during spring runoff can back up temporary lakes that cause severe, if temporary and local flooding.

I hope the above paragraph will give developers pause when they begin to lay out tracts on active flood planes - by far the easiest place to build houses. It isn’t a case that an active flood plane might flood, they will flood - that’s how they were built! There’s another factor - the flooding will get worse with time - every man-made structure, such as docks, retaining walls, levees, and bridge abutments confine a stream’s cross section, and make it less efficient at getting rid of flood water. Erosion and eutrafication - over-fertilization from agricultural runoff, both accelerated by man, add to this decrease in efficiency, and increase in severity of flooding with time. Erosion by silting the waterway, Eutrification by promoting too much aquatic plant growth, that traps the sediment.

MAN-MADE AND NATURAL TAMPORING WITH DERANGED GLACIAL DRAINAGE: Almost all places that have been glaciated have had their preglacial bedrock-dominated drainage rearranged by unconsolidated glacial deposits.

The West Wilson Spit: I learned my lesson as a kid: The Great Lake’s basins are tilting south because of accelerated glacial rebound to the north. Drainages on the south side of Lake Ontario, where I grew up, have drowned estuaries, usually dammed at their mouth by spits built through the drier season by wave action and long shore drift in the lake.

Through the drier months filtration through the sands of the spit took care of the excess water from a rain. In spring flood however, a few to several feet of water would back up and flood all the camps on the estuary. A crew of the hardiest men would dig a trench trough the spit.

Just before the last shovel full, the most athletic guy would rope up, and several others would get ready to haul him from harms way if he lost his footing. As he removed the last shovel full, the dammed estuary took over and dug a canyon full of spectacular whitewater through the spit in less than a half hour. Kids were strictly forbidden... but we watched from a distance.

The Glover-Barton Flood: About forty miles north of where I live, there was Long Pond (since known as Runaway Pond) that contained just under 2 billion gallons of water and was located right on the valley’s drainage divide. It either drained south or drained by subsurface filtration. In 1810, about fifty men decided to dig a new outlet to the north, probably to build a water-driven mill. It was just like the Wilson sand spit - it got away from them and the pond drained in about two hours, flooded Glover and Barton down stream, and raised the water level of the very large Lake Mephramagog, still farther down stream, by about a foot.

According to legend, a Guy by the name of Chamberline took off on a run warning of the impending flood. Probably others on horses took up the baton and, amazingly, there were no deaths. They still celebrate his heroism in a Chamberline appreciation run commemorating the event. (Google “Runaway Pond, Vermont” for more details.)

HUMMOCKY TOPOGRAPHY: Avoid hummocky topography with closed depressions that indicates Glacial kame and kettle, landslides, or karst.

Glacial Kame And Kettle Topography: Glacial kame and kettle topography is usually an area of glacial-fluvial sands and gravel, a kame terrace, shed into temporary lakes in the cleft between the edge of a glacier and the adjacent bedrock hill (Fig.).

Fig. 21c Diagram showing a common setting for kame and kettle topography.

It is unstable twice: Immediately after active glaciation, while buried giant ice blocks from the glacier are still melting and collapse is active into the forming kettle holes. It becomes unstable again, as any unlithified material would be, in meander bends of rivers eroding it and in the faces of the large pits dug to remove the excellent sand and gravel. It is important if you visit such pits, which show excellent sedimentary structures, that you do and go exactly where the owner says you can - they are attuned to the hazards because they work with it every day. If they have a sign, “No trespassing allowed”, they mean it - it isn’t safe!

Post glacial, kame and kettle terrain may actually be pleasant territory to build on, and can be very economic - providing some of the world’s best sand and gravel pits. You do have to avoid over-steepened slopes - next to an eroding river, on the banks of a kettle, or adjacent to a gravel pit. Other than that, it is well drained and a joy to put a foundation into - if its well engineered for the soft materials. The many small ponds do eventually fill in, but slowly because there is little surface drainage into them.

Latex Peels: This is a good place to digress to the fun and dangers of a latex peel. A latex peel is done by putting gauze on a vertical face of unlitified material and painting it with several coats of latex paint. The paint differentially seeps into the intricacies of bedding and structure and preserves them in minute detail when you pull the dried peel away on a piece of plywood. Latex peels decorate the walls of many executive suites in the extractive industries, and they have killed a good number of geologists - a vertical face in unlithified material is inherently unstable. A good rule of thumb is never take a latex peel from a face over navel high and always have helpers with shovels standing by.

Karst Terrain ; is an area of caves, sinkholes, collapsed cave systems and spectacular residual hills. It takes its name from the Karst region of Slovenia on the shores of the Adriatic Sea. There is no more classically spectacular karst than that around Goulin, China, (Fig.). Wikipedia provides a long list of karst areas of the world.

Fig. 21e Diagram of classic karst topography around Goulin China.

Karst is caused by dissolution of carbonate rocks in areas uplifted enough to lower the water table, and in a humid climate (or what was a humid climate during glacial intervals - ie. Carlsbad Caverns in semiarid New Mexico). In youth there are a few caves in an extensive limestone. In maturity many cave systems have collapsed, leaving a mix of spectacular carbonate remnants, resembling canine teeth, surrounded by valleys at or near the new water table, near the base of the dissolvable carbonate. In old age, only the occasional insoluble remnant stands above the now-extensive plane because most of the carbonate formation has been dissolved and eroded away (Fig.).

Fig. 21f. Diagram showing the youth, mature and old age stages of karst topography.

From a hazards point of view you don’t want to be collapsed on or under. Sink holes occasionally swallow houses or close roads, and water systems are often disrupted by changes in the plumbing as karstification advances. Some otherwise fertile areas can be unfarmable due to lack of surface water, other areas provide rich farm land. The latter are sometimes called karst windows, there the water table is at or near the surface. To paraphrase an old dictum - when in karst do as the karst dwellers do - they have a bred-in feel for the hazards and the specific areas of danger.

MASS WASTING: Mass wasting is the umbrella term for down-slope movement of material without the aid of a fluid medium. As desert flash floods and volcanic lahars prove, there is a continuum between dry mass wasting and stream transport with a heavy bedload. Though there are many variations in detail, mass wasting can be lumped into three big categories - rock falls, coherent landslides, and chaotic debris flows (Fig).

Fig. 21g. Four principle types of mass movement. Note that rock falls accelerate at the speed of gravity (32 ft/sec squared), slump and debris flows can be slow or fast, and creep/rock glaciers are slow slow slow. Note also that rotational slumps have an extensional upper part, and a contractional lower part. A clue to most mass wasting is hummocky topography.

Rock falls indicate at least a partial free fall of blocks. Collapse of the “Old-Man-Of-The-Mountain” profile in New Hampshire is a famous example, at least in New England. We saw a scary one on Svalbard - while walking on the flat between a big cliff and the fjord - we noticed erratic mega-worm tracks with a boulder at the fjord end of them, well down toward the fjord from where we were walking - freeze-thaw was wedging boulders from the cliff, they were bouncing off ledges, and way out on the flat before they hit - we got out of there in a hurry.

Landslides start as coherent rotational slump blocks, break up as they develop, and end up as chaotic debris flows, if they travel far enough (Fig.). So it kind of depends on what stage of development they are arrested at, or you see them at.

Landslides have a verity of causes, often with many factors acting together to cause the slide. Steep slopes, water saturation, undercutting of the base of the slope by man, rivers, or wave erosion, and earthquakes are just a few.

Mass wasting can be slow or catastrophic. It can be as slow and boring as watching paint dry - when the whole weathered regolith moves down hill imperceptibly slowly it is called side hill creep - no relation to the famous melodrama villein. Creep tries to tip trees over down hill. Trees try to straighten back up. This creates millions, maybe billions, of potential walking canes - great business opportunity!

Just up from creep in terms of excitement, are the rock glaciers of the mountain west - large areas that look hummocky and chaotic on the ground, are hard to walk over, and look like they are flowing downhill on aerial photos. Blame freeze-thaw - nightly freezes expand the regolith at right angles to the slope, daily thaws drop it back down vertically - the net movement being a saw-tooth ratchet down slope. In the arid west the greater diurnal change in temperature (often 50 degrees F) makes for more freeze-thaw cycles and better rock glaciers.

SUMMARY OF VOLCANISM: Molten rock is called magma at depth but lava at the surface. Lavas of oceanic volcanos are usually basaltic and continental volcanos usually rhyolitic, though andesites of intermediate composition dominate composite volcanos over subduction zones around the Pacific's "rim of fire".

Basalt vs rhyolite: Basalts come from oceanic mantle and sub-granitic mantle in continental settings. Rhyolites come from melting of silica-rich continental crust, and sediments of like bulk composition eroded from it and dragged down subduction zones.

Basalt and rhyolite are opposites - nearly black basalt melts at about 1200 degrees C, light colored rhyolite at about 600 degrees C. Basalt lavas are fluid and lava flows dominate. Rhyolite lavas are viscous, making bulbs and domes more than flows. Gases bubbles freely through basaltic lava so pressures never build up and giant explosions are rare. More viscous rhyolitic and andesitic magmas "cork" the throats of their volcanoes, huge pressures build up, causing giant explosions.

These explosions both blast tops off the volcanoes and cause them to collapse into the now-part-empty magma chamber, giving Calderas - the classic being Crater Lake in Oregon. The blast contains everything from cold "country rock" that the magma intruded into, to molten magma, all pulverized and mixed with expanding gases.

This super-hot mix of expanding gasses and volcanic ash falls back to earth still red hot and flows down the sides of volcanoes at over 100 mph as pyroclastic flows. ("Glowing clouds" and the french word nuee ardents) are other terms for them.) They deposit ignymbrites or welded tuffs - so hot they fuse back together when they settle. Colder unwelded ashfall tuffs follow (Fig. 20a).

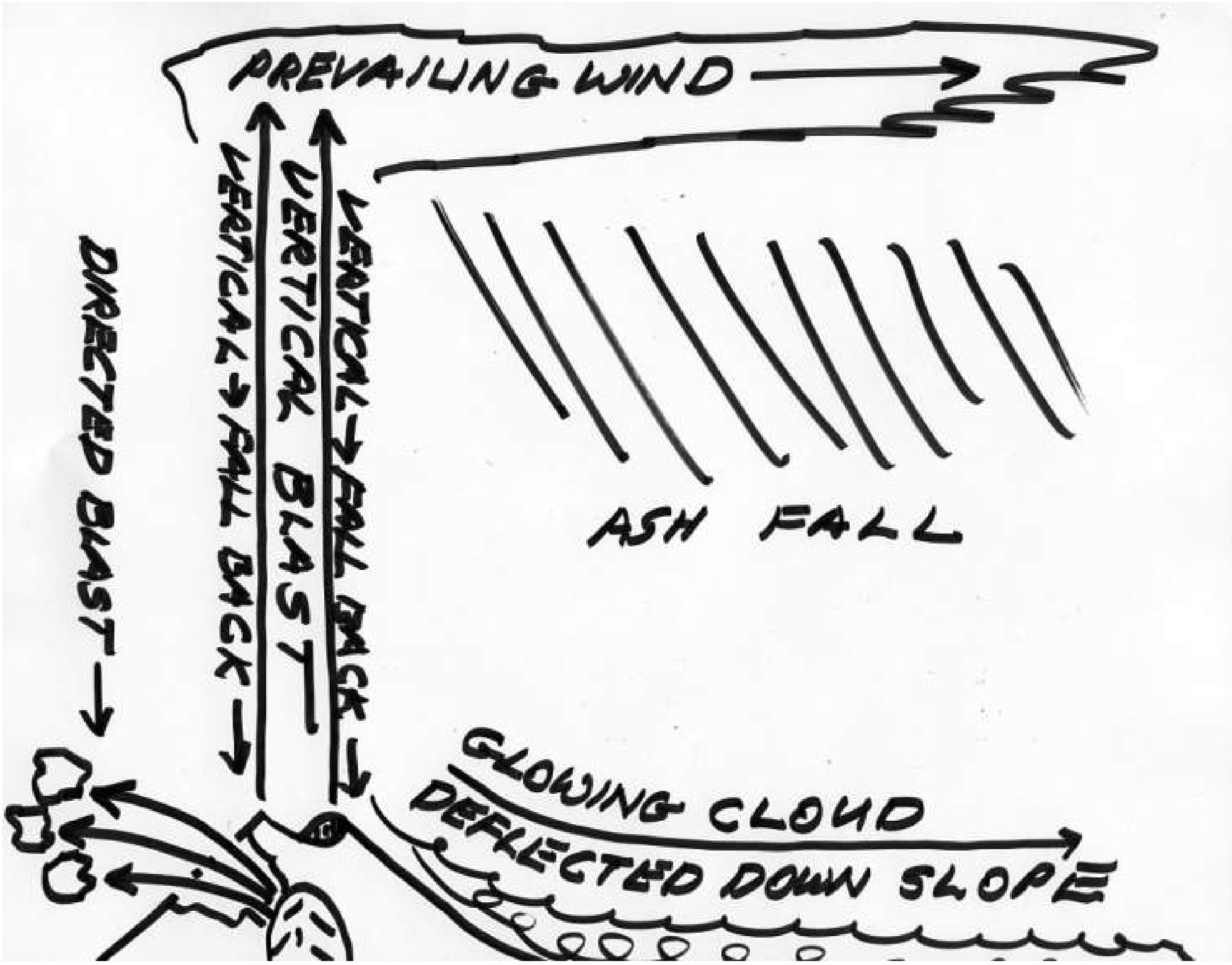


Figure 20a The basics of a pyroclastic flow. But these flows also may just "boil over" the lowest point in the rim of the volcano and flow down slope, without the big vertical fall back. Often, the side of the volcano is the weakest part of the system, giving rise to directed blasts. Directed blasts may or may not be accompanied by a pyroclastic flow.

A pyroclastic flow from Mt. Pelee killed the nearly 30,000 residents of St. Pierre, on the Caribbean island of Martinique in 1901 (except for one guy in solitary confinement in a deep dungeon - crime does sometimes pay) and that eruption deposited only a few inches of ash. There are many ash deposits many tens of feet thick - the potential for loss of life from pyroclastic flows is staggering.

Not much less distractive and more common than hot pyroclastic flows are volcanic mud flows, also known by the Indonesian term, "lahars". They get their water from crater lakes, snow fields, torrential downpours triggered by the ash, and rivers. They can move down valley at several mph and deposit completely unsorted boulders up to house size in a matrix of ash, soil, and water. Because they are so common, they actually cause more loss of life, in total, than pyroclastic flows.

Rule of thumb- the safest volcanoes are the constantly erupting ones with "no cork in their throat". So-called "dormant" ones are catastrophic accidents waiting to happen. Warning, this rule of thumb is not quite true - see "Arenal", under geology of Costa Rica.

VOLCANIC ARCHITECTURE

There are about five volcanic styles, dictated by the nature of the magma and tectonic setting (Fig.   ).

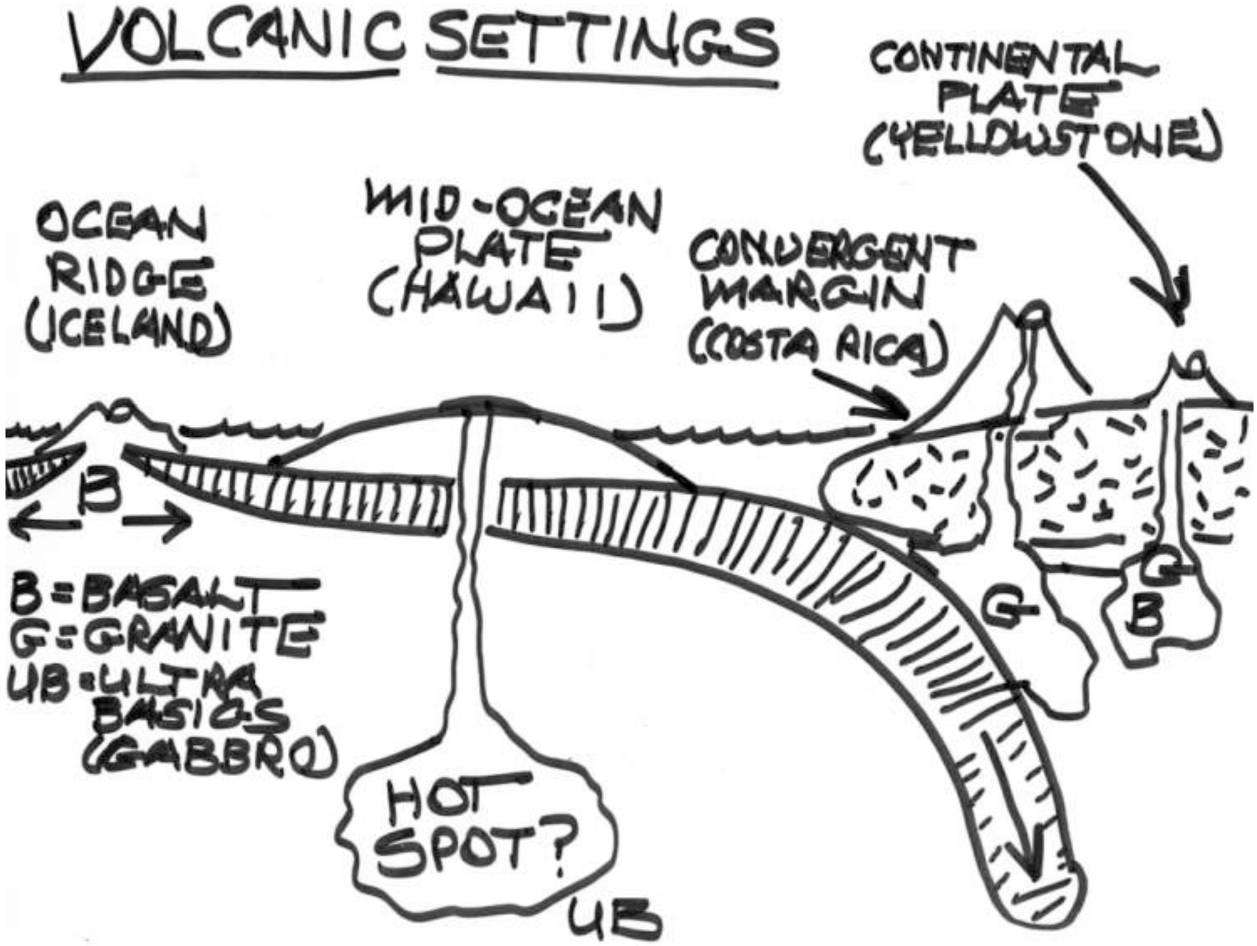


Figure   20b. The main styles of volcanoes. They boil down to two - broad and low shield volcanoes like Hawaii, and steeper and more explosive (strato or composite) volcanoes like Mts. Rainier or Fugiama.

(1)   Flood Basalts: The world's most voluminous volcanics don't even come from volcanoes - they well up out of fissures as flood basalts - flow upon flow of fluid basaltic lavas. In oceanic settings they cause oceanic plateaus. In continental settings they "pond" and fill whole huge valleys, often forearc basins. Interestingly, on edges of continents they may drape over the edge and onto the sea floor as a huge one-sided fold or monocline. One of the reasons they don't make volcanoes is that they seldom use the same fissure twice - the congealing basalt chokes it and a crack opens somewhere else.

(2)   Fissure ignimbrites are similar to flood basalts in their large volume and eruption from fissures along Basin and Range faults, rather than dominantly from central circular vents. A field of these ignimbrites, estimated at nearly 400,000 km cubed, coincides with the southern Basin and Range Province, from the southern margin of the Colorado Plateau in Arizona to the trans-Mexico volcanic belt, spanning over 10 degrees of latitude in the Sierra Madre Occidental of NW Mexico (Arguirre-Diaz, and Labarthe-Hernandez, 2003).

Note that though, like flood basalts, fissure ignymbrites aggregate as a huge thick sheet, the mechanism and chemistry are exactly opposite: the ignimbrites are silicic and explosive, while the flood basalts are mafic and dominated by passive lava flows with minimum explosive behavior. The Ignimbrites seem to have flared up when an intermediate to salicic batholith stoped it way close enough to the surface that overlying Basin Range faults could open in tension, allowing massive evacuation of the magma chamber. Alternatively it was when the East Pacific rise's mega slab window passed under the base of the then rapidly extending continental crust above. These two causes may not be mutually exclusive.

(3) Shield Volcanos: Hawaii is a cousin of flood basalts - think of it as a flood basalt confined to one central vent, even though the sea floor is moving slowly over it. (see "hot spots"). Because it is basaltic, lavas are so fluid the slopes of this, the world's largest and highest single mountain above its base (some 31,000 feet), are less than 5 degrees - thus the name "shield" volcano.

(4) Strato (composite) volcanos: These are the world's most numerous - almost all located over subducting slabs around the rim of the Pacific. They are constructed of alternating lava flows, mud flows, and ash falls, welded or not - thus the name stratovolcanos ("composite volcanoes" is a synonym).

(5) Calderas: are the hole left when a volcano either collapses into its emptying magma chamber, or blows its top off. If the former, huge blocks of country rock are engulfed and partially digested by the magma to form xenoliths, but few country rock fragments are scattered across the country side. If the latter, few blocks flounder back into the magma, but huge volumes are scattered across the countryside as tephra, or pulverized by the explosion as volcanic ash. Volcanic ash is called tuff after it has been lithified. The process may repeat to form resurgent domes in the caldera. Mt. Mazama collapsed to form Crater Lake, Oregon, a famous caldera.

(6) Volcanic necks (Devil's Tower, Shiprock) are the resistant conduit fillings of deeply eroded volcanoes.

(7) Sideward Collapsed Volcanoes: Many volcanos get so big so fast that their rock stength is exceeded by their mass, and they go into a state of continuous or sporadic collapse, sometimes called gravity flattening. Collapse morphology in the form of landslides is however continuously hidden by eruption of new volcanics that bury the scarps in a "growth relationship", not unlike that seen in deltas.

One of the most famous of these is the Sunlight Volcano in the Absoroka Range of N. W. Wyoming, where the extending flow in the base of the collapse dragged isolated Heart Mountain blocks apart over an area of hundreds of square miles (Figure).

VOLCANOES Stay well away from volcanos, but if you must be near them be high above drainages that could funnel pyroclastic flows or lahars, and have a high hill or deep valley between you and the volcano, and upwind of the volcano is better.

Pyroclastic flows (Nuee ardents, glowing clouds) are gravity flows steered by the slope of the volcano and valleys below it- picture a bobsled run. The sled hugs the valley bottom on the straight stretches, but ramps up on edge as it banks into the turns. Pyroclastic flows do the same thing, but can actually top the ridge and spill into the next valley on a turn. Two of the world's most-experienced volcanic researchers were killed by misjudging the eruption and topography in such a setting.

Lahars are the bigger cousins of desert flash floods. With desert flash floods, scant vegetation holds the regolith down, and the seldom water that does come picks up soil and boulders and heads down valley like a freight train. Speaking of freight trains, one flash flood carried a steam locomotive down slope for the better part of a mile.

Figure 21h. Map of western Washington, State, between Mt. Rainier and Puget Sound. Volcanic mudflow (lahar) deposits within the last 5,600 years, from Mt. Rainier, shown shaded. Note that there are over a dozen towns shown within the mudflow deposits - mudflows and people both love valleys, there's the rub. Note also that the three major flow routes are over 50 miles long and hadn't expended their energy when they went into Puget Sound and continued on as turbidites. This is a very bad accident waiting to happen, especially if it is the middle of the night with everybody sleeping. From Session's 1995, USGS open file Report 95-642.

I got converted on flash floods the day we drove down Titus Canyon, an "hour-glass" canyon draining into the east side of Death Valley. Hour-glass because the canyon walls overhang until you can hardly see daylight. But enough daylight to see flood-born debris wedged in cracks 30-50 feet above the top of the vehicle. Needless to say, we were very thorough in checking the weather forecast, and looked around for any trace of a cloud just before we entered the canyon, which, is impossible to get out of except at the bottom on Death Valley's floor. In hindsight, we should have been even more apprehensive - had we encountered a debris dam, I'm not sure even a 4X4 could have made it back up the canyon in the soft gravel. Makes more sense to drive up such a canyon.

EARTHQUAKES: Earthquakes are concentrated at plate boundaries, but no place is immune - the very large Reelfoot Lake quake in the American mid continent in 1811 proved that. Earthquakes are caused by stick slip - stress builds up slowly (about the rate your fingernails grow) until faults finally snap, and then it starts to build up slowly again. The stronger the rock, the more stress can build up, and the bigger the quake, but the longer beween major quakes. The faster the plate movement, the more frequent the quakes. An excellent example of stick slip, that students just hate, is to screech a piece of chalk across the chalk board - the consistent periodicity of the dots is amazing, and the consistency of the pitch indicates that each "quake" was of the same magnitude.

The periodicity of quakes often exceeds both the historical record and our attention spans; The San Andreas pops off somewhere along its length about every 20 years - no problem there. Puget Sound, on the other hand, appears to have very large quakes (potentially like Alaska) but a periodicity of about 400 years, with a local written historical record of less than 200 years. Interestingly, the last big one around Seattle was recorded in Japan as a tsunami - their written history goes back much farther than that in the western U. S.

Earthquake-generated tsunamis are one of the main ways geologists date quakes in the geologic record. The tsunami sweeps all sorts of regolith into local depocenters, where it is preserved. The ample organic material swept in with it allows good carbon dating of the earthquake.

Earthquake intensity is measured by the Richter Scale, named after the US seismologist, Charles Richter, who devised it. It goes from 1 to 10, with each successive digit emitting ten times as much energy as its previous one (1=1, 2=10, 3=100, 4=1,000, 5=10,000, 6=100,000, 7=1,000,000, 8=10,000,000, 9=100,000,000, 10=1,000,000,000 units of energy). The biggest quakes yet measured are in the low nines, in Chile and Alaska. Fukushima's tsunami was caused by a 9.0, offshore.

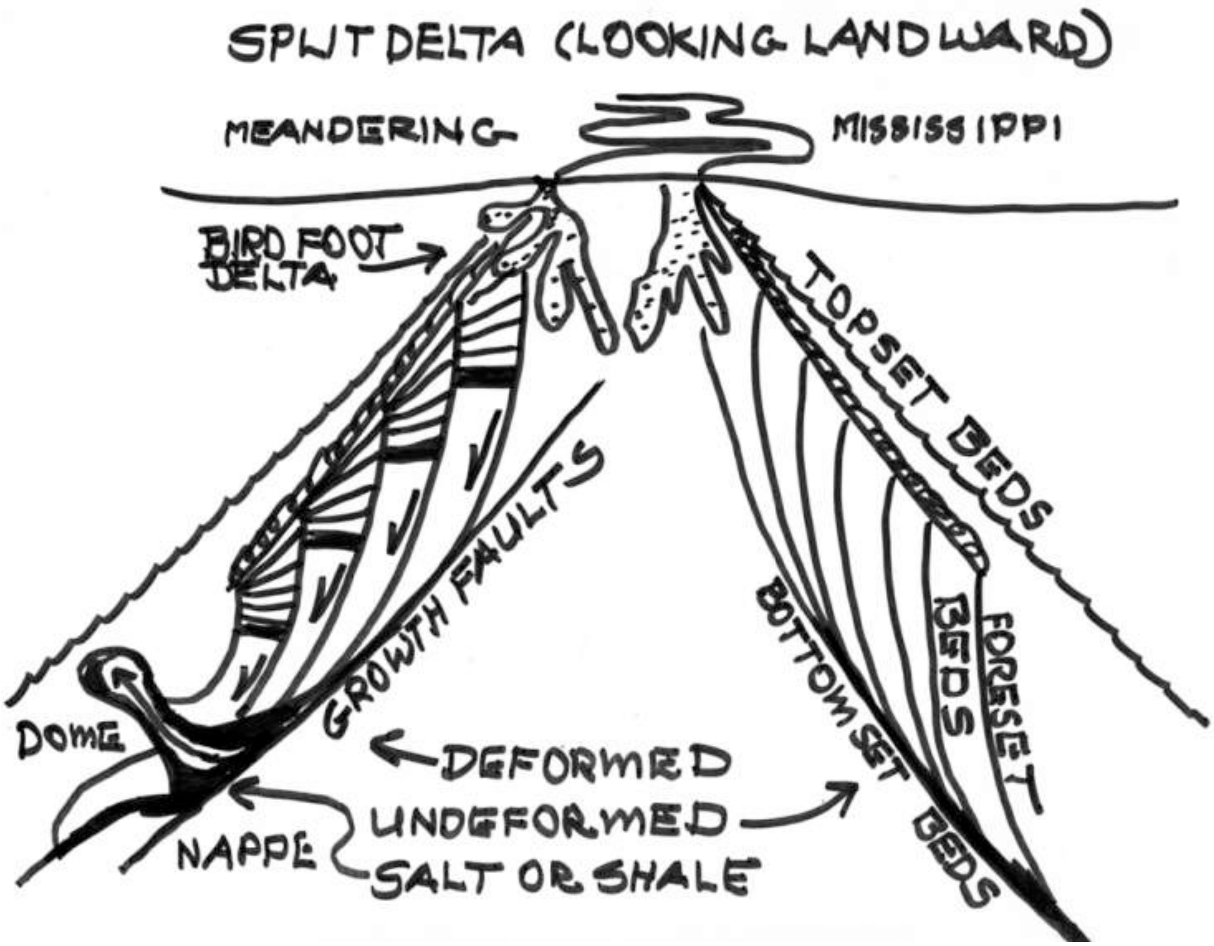


Fig. 7a. A delta split to show internal character. Right side shows undeformed topset, foreset, and bottomset beds. Left side shows growth faulting nearer shore and salt domes and nappes near its deep-water toe. Growth faults are a form of landslide, with extension on growth fault at the top and contraction on thrusts, nappes and salt domes near their bottom. Growth faults may have great stratigraphic offset at deep levels, but no scarp or offset at the surface - over-ample sedimentation continually buries the scarp. The actual Mississippi Delta is many of times more complex than the complex side of this diagram.

Figure 7b. Model turbidite done by pouring a paper cup full of 1/1 mixture of plaster and water into one end of the same jig used for the rest of the plaster models. But you may have to dab the corners with clay to get it completely waterproof. This model is applicable both to water-born turbidites and air-born volcanic pyroclastic flows.

Very the color of successive flows with powdered tempra pigment for a vivid stratigraphy. Admix crushed dried plaster shards, of a different color, to get graded beds and sole markings. Do it in a broad box with plaster or clay topography to see how turbidites can be steered by topography, as is chronically seen along thrust fronts. Note that, in the example above, the faster laminar flow has reached the end of the tank before the slower turbulent flow above. Velocity also decreased downward in the flow, transitioning into normal fault extension downward and with time as velocity dissipates in the gravity flow.

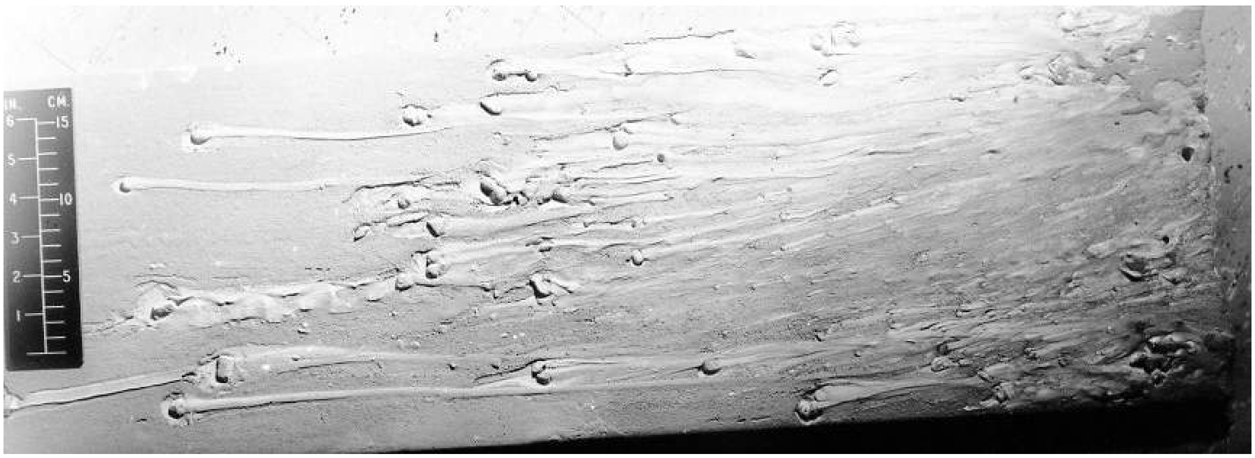


Figure 7c. Sole markings as directional indicators in a model turbidite. Proximal end of turbidite is to the right, transport to the left. This is a "worms eye view" of sole markings in the coarse base of a plaster turbidite separated from the pelagic fine top of the previous turbidite after the plaster hardened. Clasts (tools) of pre-hardened crushed plaster are still in place at the ends of the grooves they have cut.

Figure 7d. Worms-eye view of the bottom of a pyroclastic flow in rhyolite in an outcrop east of Silver City, New Mexico. It shows both the shards and the sole markings they caused. Compare with the previous figure. Is transport toward the left or right?

Figure 7e. This outcrop, seeming to defy both gravity and logic, has got to be one of the best what-done-it pictures in geology. A retired Mobil executive, Ken Keller, and his wife, still actively doing field trips long after retirement, took it in the South-American Andes, and all I can remember is that it was volcanics - Ken wrote minute detailed notes on his 35 mm slides but I can't find the original.

It appears to have been made by successive pyroclastic flows moving left, with velocity and fluidity increasing upward. Strength should have been increasing downward, from ultimate fluidity in the dilute laminar flowing suspension, to consolidated material below, that can only move by normal-fault extension, just before it becomes completely stationary. As the horst "stuck its head up", the faster-moving laminar flow clipped it off and moved it in the direction of transport. Then, as the higher material became strong enough to extend by normal faulting instead of laminar flow, that newer set of faults was a mismatch with the slightly older faults below. Every feature in this photo may have formed within minutes, as the pyroclastic flow lost its energy.

Its harder to explain the strong color contrast between layers. The upper dark layer, especially, looks shiny and may be welded nearly to glass - a classic "welded tuff". The light layers may have been cold enough to remain as un-welded ashfalls. Alternatively, there could have been real composition changes in the material being blasted out of the throat of the volcano.

Velocity of gravity flows: The velocity profile of a pyroclastic flow is interesting. Early on, on the upper slopes of the volcano, the glowing cloud may be riding frictionlessly on an expanding mass of volcanic gas and heating air, that has been equated with a hoover craft effect. There are even eye witness reports to being able to see under a pyroclastic flow to the other side as it passes down valley. Farther down the volcano's slope this frictionless flow is replaced by the opposite - huge frictional drag as the coarse basal part of the flow cools and starts to glue itself to its substrate. It is in this fleeting instant that it is in normal fault extension mode seen in the photo above.

The pyroclastic flow that destroyed the town of St. Pierre on Martinique stopped clocks successively in overwhelmed dwellings as it roared down the side of the volcano. As I recall, peak velocity was on the order of 100 MPH. The Grand Banks slope failure off Nova Scotia in the early 1900s, degenerated into a strong turbidity flow that successively broke transatlantic telephone cables laid out on the sea floor farther and farther down slope. As I recall, its speed was about half of the airborne pyroclastic flows. See Gilluly, Waters and Woodford, 1975, for additional detail on both of these events.

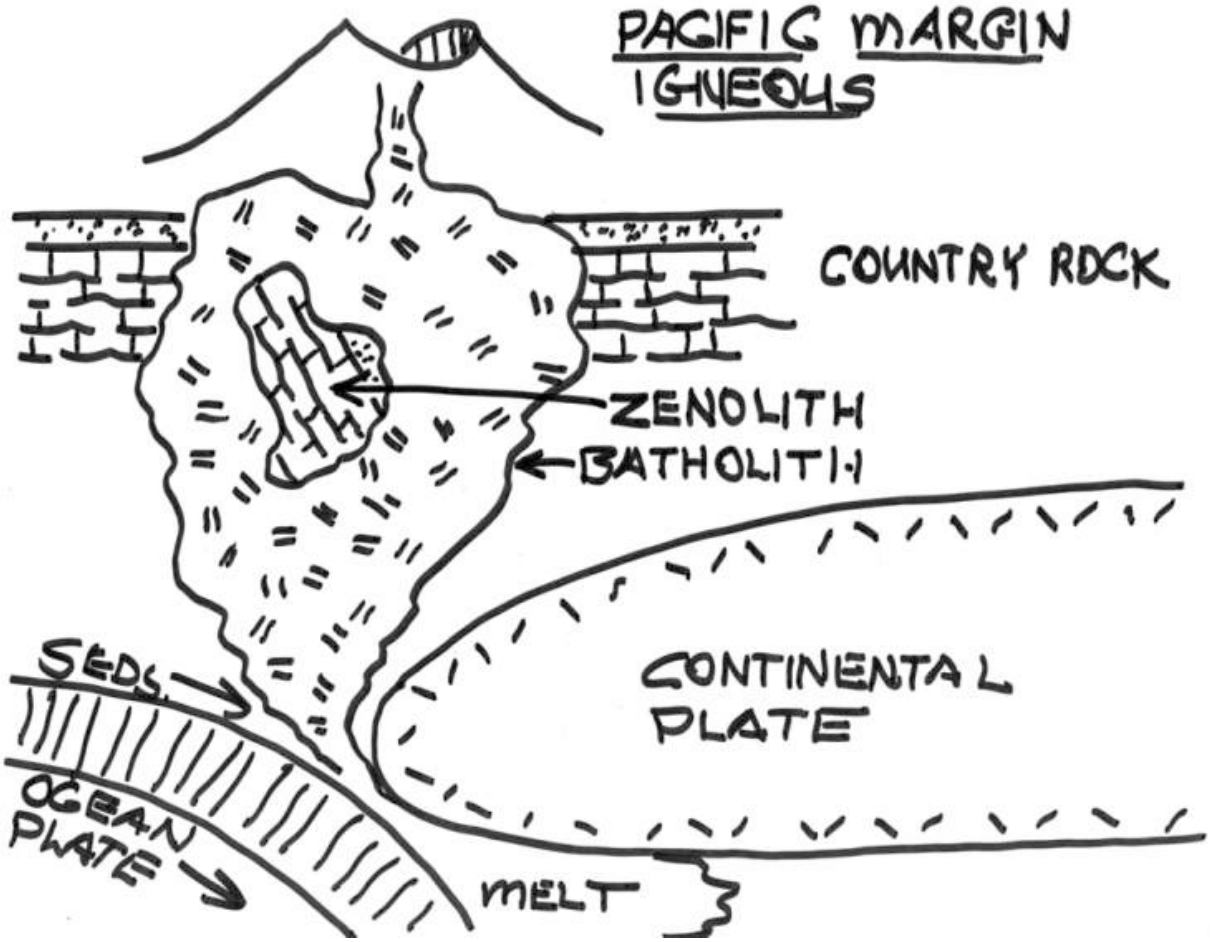


Figure 8a. The setting of igneous rocks generated over a subduction zone. Note - most people spell "zenolith" with an "X".

Building a mountain belt is like pouring a pancake upside down. To keep a low profile demanded by the weakness of scale, and still grow in volume, the margins of the growing mountain belt have to spread over both the top of the continent and the sea floor. That spread seaward is called an accretionary prism, that spread cratonward, a foreland fold-thrust belt, with the basin in front of it being called a foreland basin (Fig. 2). The batholithic core of the fold-thrust mountain belt spreads laterally, forcing the thrusts ahead of it (Fig. 9a).

Fig. 18d. Simplified diagram of the "<u>Messinian salinity crisis</u>", when the Mediterranean Sea, dammed at Gibraltar, dried up. This <u>tectonic dam</u> finally broke and reflooded it. Main evidence are evaporites under its deep basin, and the <u>buried Nile Canyon</u> under the lower Nile, that is longer and deeper than the Grand Canyon.

HEART MOUNTAIN - SUNLIGHT VOLCANO COLLAPSE, NW WYOMING

Ode to the old field mappers:

"The recognition in 1919 of blocks of Madison limestone (Mississippian) overlaying beds of the Bridgerian epoch (Middle Eocene) in the McCulloch Peaks region, 12 miles east of Cody, Wyoming, shows that the overthrust fault recognized by Dake (2) in 1916 is much more extensive than first suspected. Dake mapped the fault in a belt 30 miles long, within which the extent of the overthrust was estimated at 16 miles. He also noted the existence of thrust faults along the east front of the Beartooth Plateau, where Precambrian rocks overlie ""red beds" (Chugwater formation) but did not assume continuity with the Heart Mountain overthrust. The residuals on McCullochPeak show that the extent of overthrust is at least 28 miles..." (Hewett, 1920)

From my perspective, everything in this 1920 abstract remains correct.

<u>Notes on terminology:</u> The giant landslide that is the Heart Mountain feature is named after Heart Mountain, north of Cody, in northwestern Wyoming. Rightly so - it is the single most-foolproof evidence that something unusual happened - a small mountain-sized chunk of Paleozoic carbonate sediments (about 300 million years old) somehow shoved on top of much younger (about 50 million years old) sediments of the Big Horn Basin.

But, in perspective, Heart Mountain is just one of probably hundreds of such blocks, dragged along in a great landslide of volcanics. The Sunlight Volcano, the real culprit - was the feature that caused the landslide. The Sunlight Volcano is largely eroded away, but its throat underlies Sunlight Peak.

But the evidence is still there, in the form of hundreds of dikes (cracks full of volcanic rocks) radiating like spokes in a wheel, from a central hub in the Sunlight peak area. (for perspective, famous Shiprock, New Mexico only has a handful of dikes) These hundreds of dikes are too big to get your arms around in the field, but they show clearly on the geologic map of Wyoming. I show one that is just north of the main road between Cody and Yellowstone National Park - millions of tourists have driven by it. This dike shows clearly on Google Earth - just follow the road west from Buffalo Bill Reservoir west of Cody, and its a nearly straight hairline feature, trending north, on the north side of the road.

Purists might not like it, but I use “detachment”, “landslide”, “debris flow”, “structure”, and “feature” interchangeably in this overview.

Summary: The Heart Mountain - Sunlight Volcano collapse, in northwestern Wyoming, is one of the largest sub-aerial landslides preserved in the geologic record. It took place in the Eocene, about 50 million years ago.

After several decades of arguing over field relations, velocity, and mechanism, the Heart Mountain structure may be turning out to be simplicity itself - the huge Sunlight Volcano got too big too fast. As its mass exceeded its strength, it began to squash like a pancake. Probably steady-state and not catastrophically. Because the rocks under it dipped a few degree southeast, the great majority of the rock slid in that direction. As the volcanic rocks moved down slope, they dragged a lot of the underling Paleozoic carbonates with them, as huge (really huge - some miles across) blocks.

Its statistics stagger: It’s 65 miles from the breakaway near the northeast corner of Yellowstone Park to the McCulloch Peaks east of Heart Mountain - they are the blocks farthest out in the basin, but smaller than Heart Mountain. It’s 28 miles from those same peaks to the west side of the transgressive ramp, the closest place they could have come from - 28 miles of contraction (overthrusting) at the toe. A reasonable outline drawn around all the evidence encompasses about 1,600 square miles. And we know a huge amount of the evidence has been eroded away and another huge amount is still buried. Lets just say about 2000 square miles (curdely 40x50 miles square) of real estate was moving southeast in northwest Wyoming in the Eocene.

Was it fast? Probably not. It had over a million years to move an average of 20 miles - 28 at the toe, but progressively less westward toward the breakaway. Say 1/10 of a foot a year. This is, crudely, the rate of the West’s much different and smaller freeze-thaw rock glaciers - you can walk across them if you are careful not to turn your ankle. You probably could have walked right across the Heart Mountain landslide while it was forming too - but carry a lot of grub - it might take weeks.

Figure 19a. Near the northeast entrance to Yellowstone National Park the beautiful Pilot Peak, (the lesser peak to the right being Index Peak) eroded in coarse Eocene volcanics, sits on lighter finer-grained volcanics, that rests on an inconspicuous flat strata in the trees. Everything above that flat strata seems to have moved southeast (left), everything below it seems to be in place. The highlighted white line at the top of this horizontal bed is the crux of the enigma, and for years was interpreted as a sedimentary contact of younger volcanics over older Paleozoic carbonates (see W. G. Pierce et al for several summaries and maps - they were the USGS field mappers that made all interpretations possible).

The alternative interpretation is now popular that that surface is not sedimentary, but a decollement of volcanics that have slid miles southeast on this one hard horizon - The Heart Mountain Detachment mega landslide. Photo by the Author. (See T. A. Hague, 1983, for an early summary of this newer interpretation). Note also, in the intermediate slope, the well developed set of conjugate shears with clastic dikes in them, formed during the extension.

Figure 19b. One of the hundreds of resistant volcanic dikes radiating from the Sunlight Volcano like spokes in a wheel. The core of the volcano is out of sight through the saddle. Notice how ragged and beat up the skyline mountains look - they've been involved in the landslide. This dike shows as a hairline, just north of the main road between Cody and Yellowstone on google earth. Photo by the author.

Figure 19c. Several tens of miles to the southeast of Pilot Peak, at Foster Reservoir on the east side of Carter Mountain, a cliff exposes contorted giant volcanic clasts in a finer matrix. Mature forests for scale - note especially that perched on the giant block. Photo by the author. Everything you see in this cliff was sliding toward you in the Eocene.

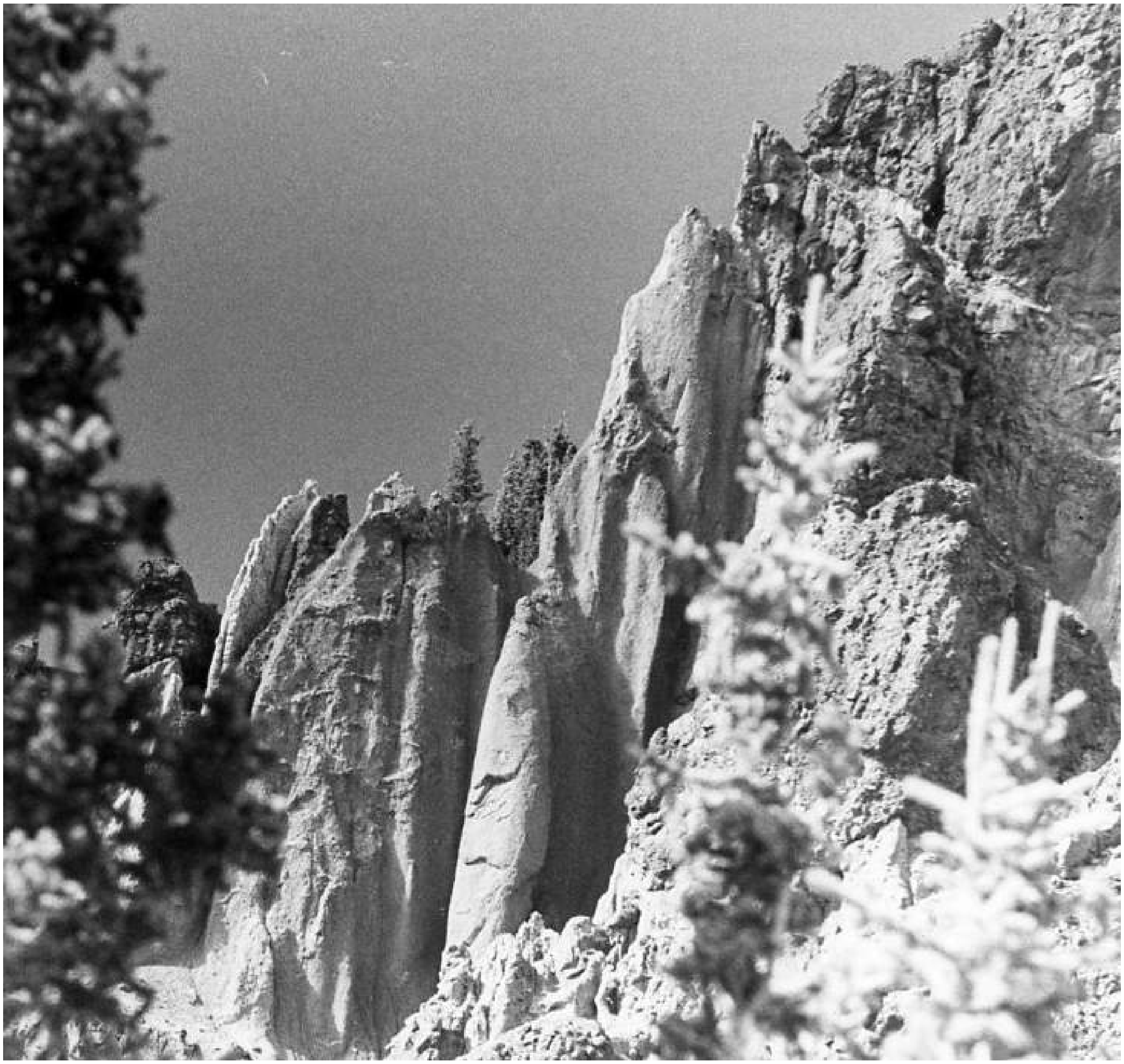


Figure 19d. One area near the top of the cliff is especially scenic, with classic Voodoo spires in the matrix of fine-grained volcanics, adjacent to ragged dark and coarse blocks of volcanic agglomerate. Mature forest at top center of cliff for scale. Voodoos are caused by resistant rocks acting as an umbrella to protect the spire under them from eroding. Photo by the author.

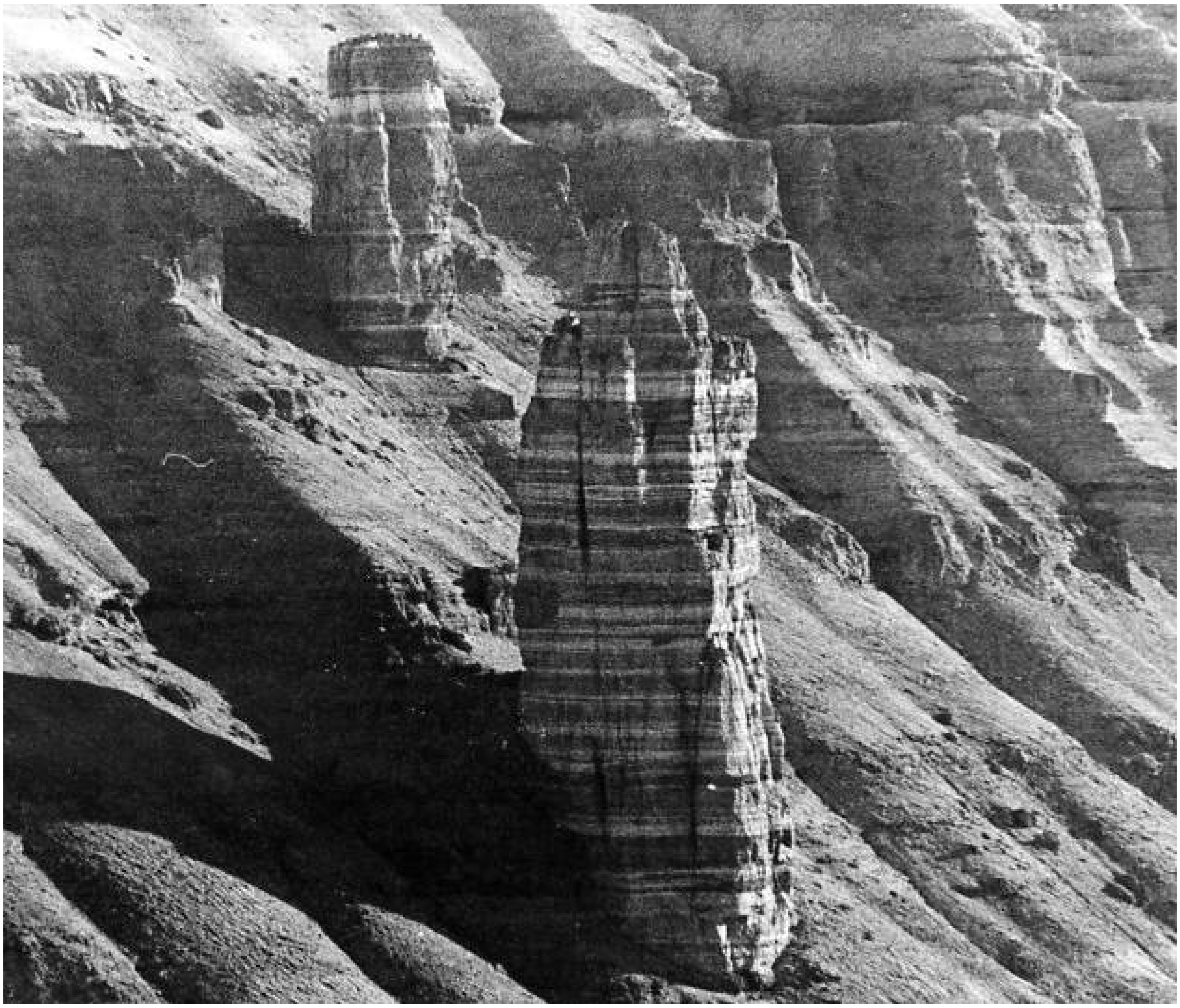


Figure 19e. Spires higher on Carter Mountain, eroded in water-lain volcaniclastics, above the Trout Peak trachy andesite, and deposited after movement on the landslide halted. This was a long telephoto, but I think the front spire may be a couple of hundred feet high. Notice the extremely even bedding compared with the chaos above Foster Reservoir. Note: These show on Google Earth - zero in on them by their long shadows. Photo by the Author.

Figure 19f. View south with Foster Reservoir in the lower left and a high shoulder of Carter Mountain on the skyline. The jagged slope in the foreground right is an oblique view of the mega breccia shown head-on in a previous two photos. The well bedded sediments high on the mountain are the ones shown in the giant spire - they are volcaniclastics that were eroded from the mega landslide/volcano after it stopped moving. The resistant cliff former in the middle distance Is the Trout Peak trachy andesite, the key unit timing-wise. It may have been formed by the last gasp of the volcano - a giant last pyroclastic flow after movement stopped on the landslide. Thus, it is not dismembered like all earlier such flows. After that, sedimentation was almost all volcaniclastics - volcanic material, but deposited dominantly by water. Photo by the Author.

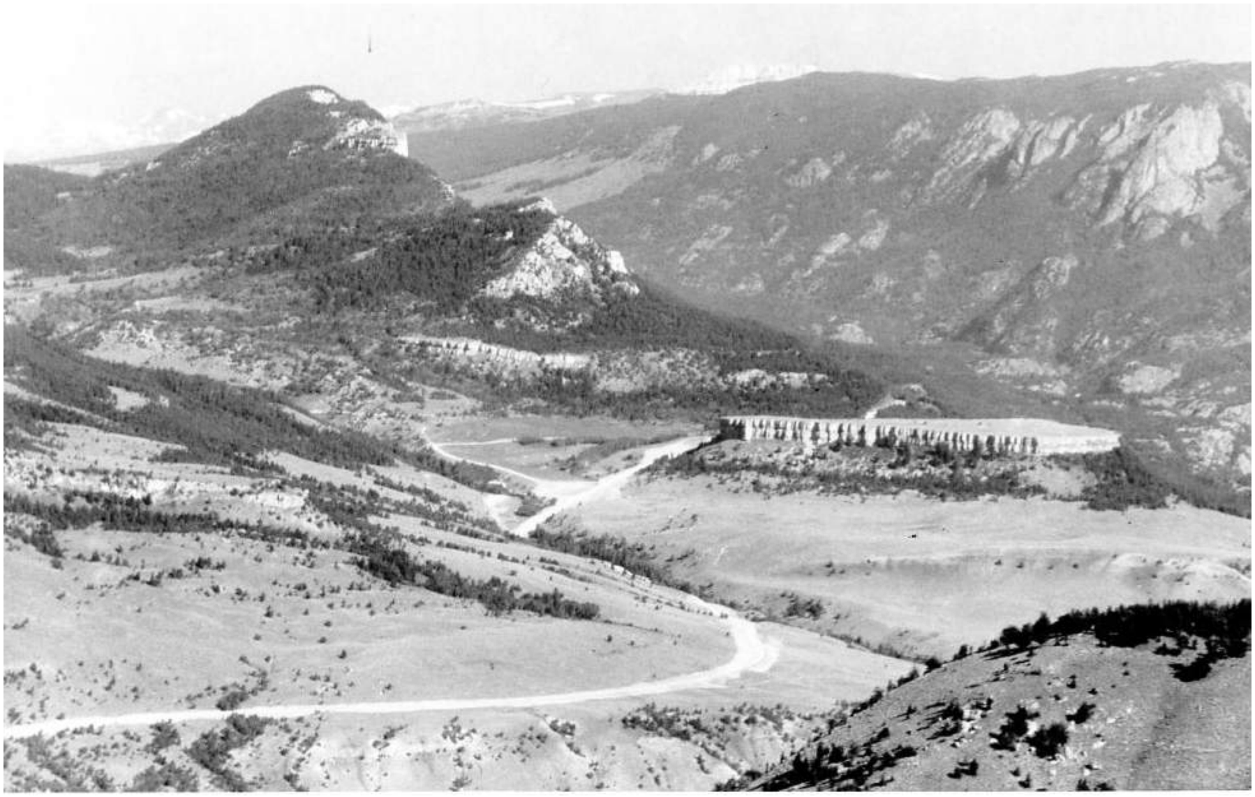


Figure 19g. A few tens of miles to the north of Foster Reservoir sits the beautiful table top of Antelope Masa, the same strata as the flat layer below Pilot Peak. Just to the left, west, a small mountain is tilted on edge and it appears not to be in place. - tilted as it was moved in the landslide. View is north west from Dead Indian Pass - this is the road you can see on the aerial view of the transgressive ramp. Pre Cambrian of the high Beartooth block in the background, Clark's Fork Canyon in front of it. Photo by the Author.

Figure 19h. A few tens of miles east of antelope Mesa and north of Cody sits famous Heart Mountain *- a giant block of Paleozoic carbonate sitting on Eocene sediments. The nearest place it could have come from is on the west side of the transgressive ramp, that cuts up through the steepening monocline that defines the western boundary of the Big Horn Basin. This distance is about 16 miles (Dake, 1916) to the west.*

Though photographically poor, this shot is geologically great, in that, in the foreground, it shows the Laramide angular unconformity - tilted pre Eocene beds below under still-level younger beds above. The Paleozoic blocks of Heart Mountain were deposited stratigraphically below the beds in the foreground. But they now rest on these younger beds - older over younger - the classic criteria for thrust faulting. Photo by the Author.

Figure 19i. Aerial view north along the monocline that separates the Beartooth Mountain block, and the bedding plain segment of the detachment surface south of it, from the Bighorn basin on the right. The forested west-facing slope of this view contains the same strata seen in Heart Mountain, several miles to the east. Antelope Masa and the moved blocks still on the bedding plane segment of the detachment, are a few miles to the west of this view. Heart Mountain had to have been transported from west of this view up across the monocline and came to rest on the younger sediments several miles to the east.

If you look carefully you can see bright little cliffs of west dipping Paleozoic carbonates, sitting on the transgressive ramp. Even more subtle, you can see the switchbacks on the Dead Indian access road on the left (shaded and wooded) side of the transgressive ramp - where the picture with Antelope Mesa was taken from. PreCambrian of the high Beartooth Uplift in the background, with the canyon of the Clark's Fork in front of it. Notice how rugged the Clark's Fork Canyon gets as it exits the mountains. Photo by the Author.

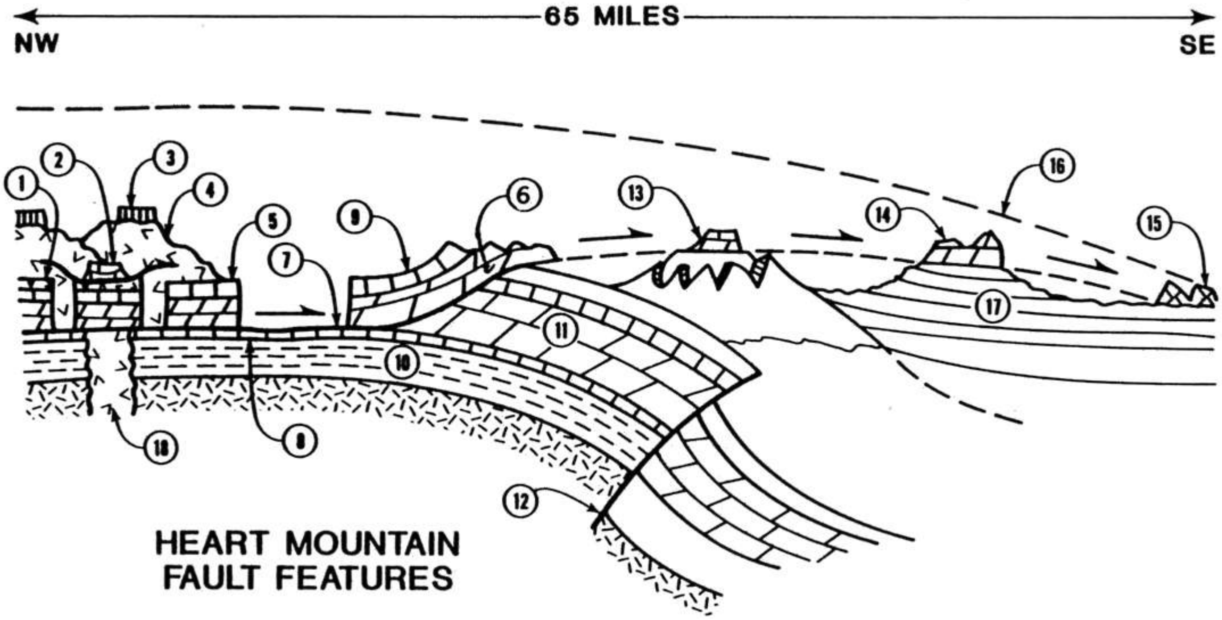


Figure 19j. Condensed cross section of features in the Heart Mountain detachment: the fault that it moved on can be divided into three segments (1) a northwestern bedding plane segment (everything NW of the circled figure 10), (2) the transgressive ramp (between the circled figure 10 and circled figure 6) where it cut up through the same strata (transgressive ramp) that had been moving on the bedding segment, and (3) a southeastern overthrust segment (between circled figure 6 and circled figure 15).

Circled features: 1=breakaway, 2=early Reef Creek imbrication, 3=erosion remnants of Trout Peak trachy andesite, 4=main mass of volcanics involved in the detachment, 5=moved block on bedding detachment, 6=bedding-transgressive segment of detachment. 7= barred detachment surface as at Antelope mesa, 8=thin Grove Creek member that didn't get ripped up, 9=moved Paleozoics stranded on the transgressive ramp, 10=incompetent lower Paleozoic shales that shouldn't have been able to support the Grove Creek strata in a free slide, 11=sub-detachment section on monocline, 12=basement thrust seen on seismic, 13=block remnant on Pat OHara mountain, 14=Heart Mountain, 15=McCulloch Peaks (farthest blocks out), 16=diagrammatic profile of repose on the "Pancake" (it should have been under the Trout Peak, but I couldn't fit it), 17= younger sediments of the Bighorn Basin.

Note: the aerial view shows all the features in about the center third of this cross section, Carter mountain isn't on here (too far south), but would fit about at the arrow between Pat OHara Mountain and the transgressive ramp.

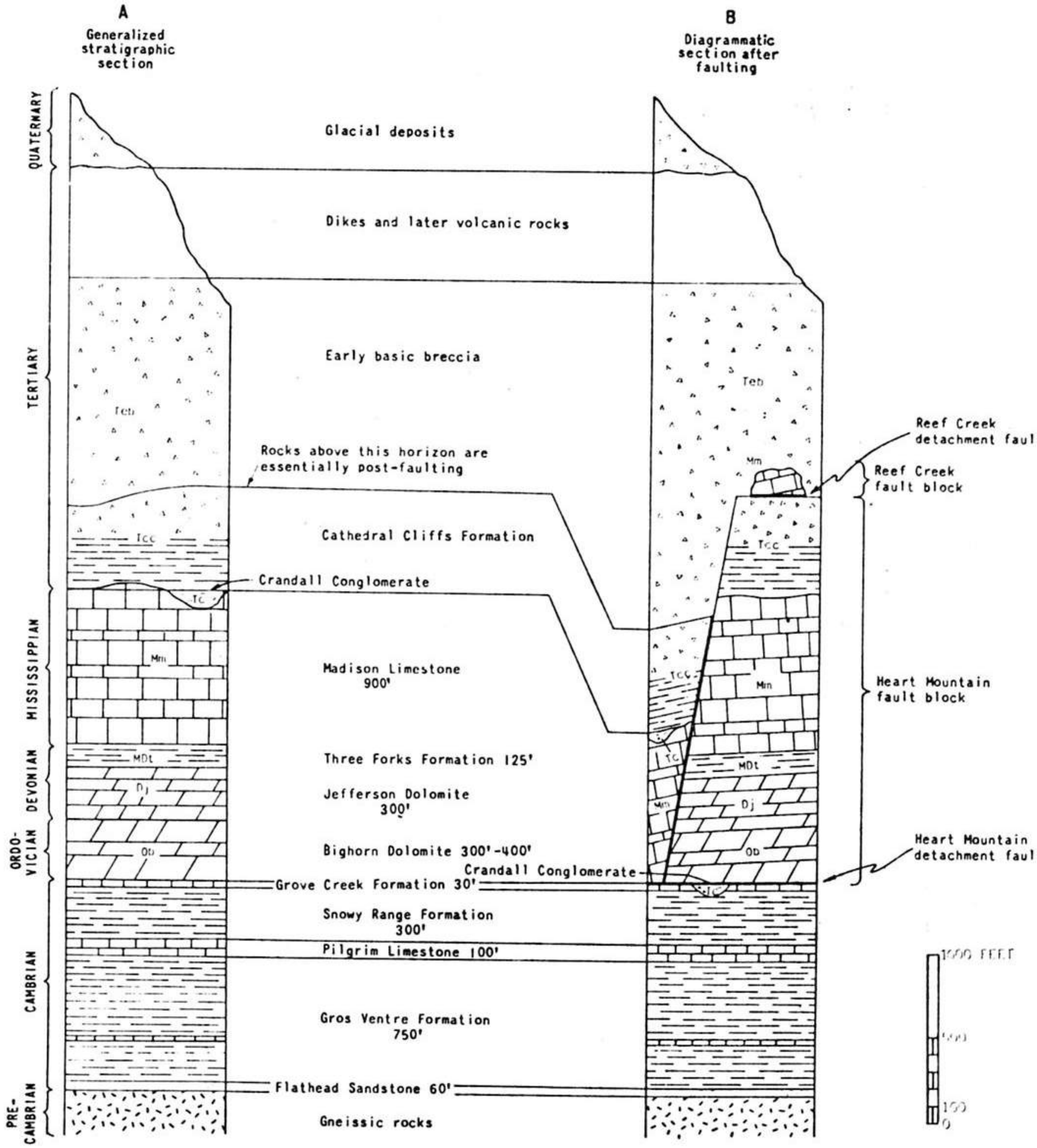


Figure 19k. Bill Pierce's stratigraphic sections of relations before and after detachment. This dates from when the detachment was considered a free slide of blocks covered by later volcanics. The later interpretation, promoted here, is that it was a debris flow of volcanics, with Paleozoic blocks dragged along in it, like eratics in a regular ice glacier.

HEART MOUNTAIN–SEQUENTIAL DEVELOPEMENT

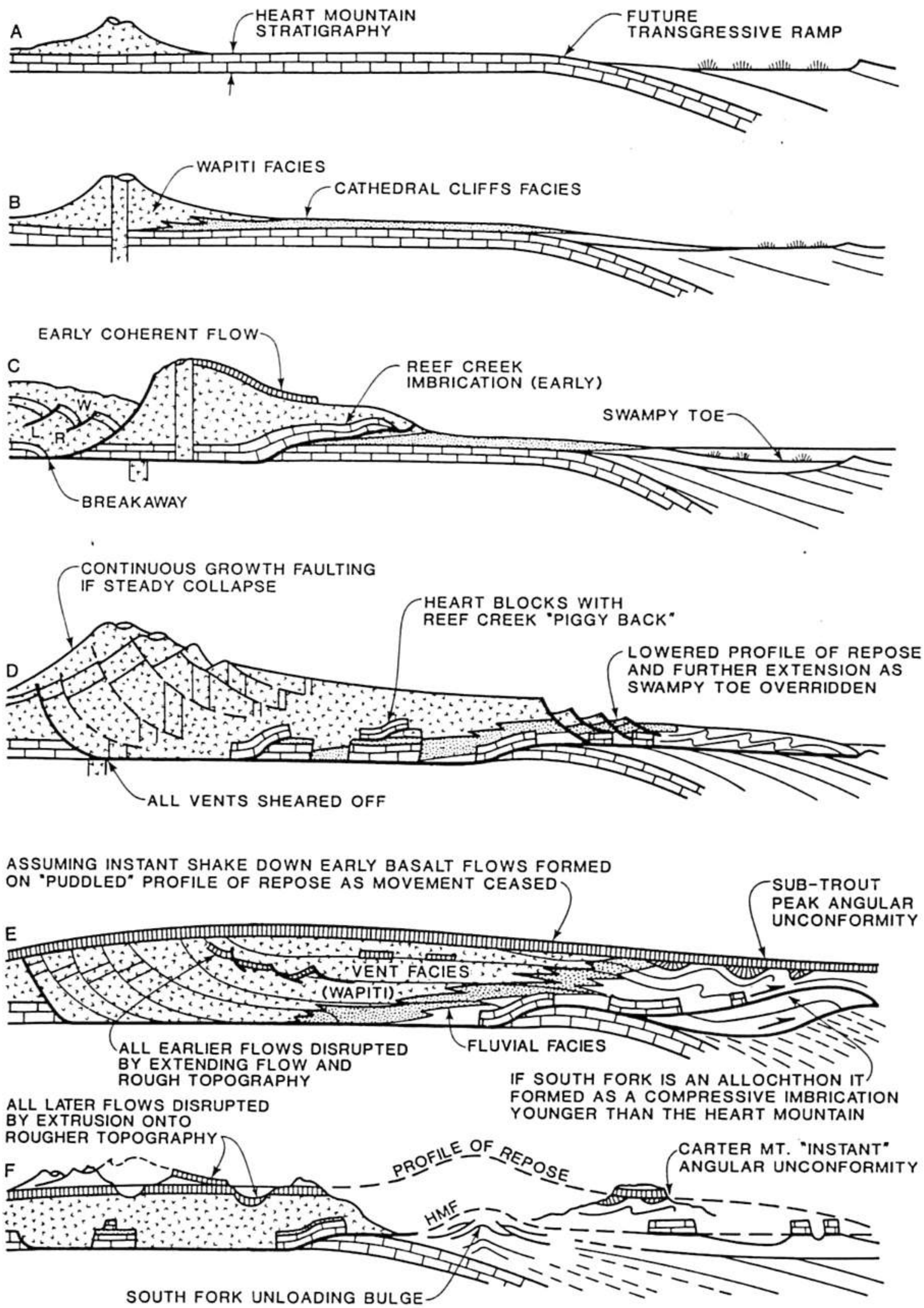


Figure 19l. Sequential development of the Heart Mountain detachment, breakaway on the left, Bighorn Basin on the right. The distance across each cross section is about 65 miles, with the northwest left (high) end near the northeast entrance to Yellowstone National Park and the low (right) end well out in the Bighorn basin east of Cody.

(A) The stratigraphic and structural setting at the beginning of volcanism: Competent Paleozoic carbonates (brick pattern) rested in an open, gently southeast plunging paleovalley, the southeast end of which steepened into a monocline toward the Bighorn Basin. The little bunches of vegetation are to suggest that swampy conditions in the basin may have helped in the thrusting.

(B) The center of the mega-volcano seems to be in the area of the Sunlight volcanoe, with hundreds of dikes radiating from it in all directions - like spokes on a giant bicycle wheel. As the giant Sunlight Volcano began to form, it was dominated by proximal (near-vent) Wapiti formation, (called "early basic breccia " in the older literature), and distal (farther from the vent) Cathedral Cliffs formations. The latter was both finer grained and more reworked by fluvial processes. Because the volcano was growing, the coarse vent facies prograded over the finer fluvial facies.

(C) The volcano began to collapse like a pancake as its mass exceeded its strength. Because its foundation rocks dipped southeast, it dominantly slide southeast, continually shearing off its vent, causing a breakaway fault upslope to the northwest, and causing a compressive imbrication that duplicated the carbonate section at the early compressive toe of the slide - the Reef Creek structure. Coherent flows on the sides of the volcano would later be fragmented in the collapse.

(D) The height of extrusion of volcanics and their collapse down slope. Extrusion was trying to build a Mt. Fugiama-Ranier-Shasta type tall strato volcano. Down-slope collapse was trying to force it into a low-profiled "pancake". This put the entire mass into extending flow, as it got bigger and weaker it got relatively thinner and wider. Normal faults helped this extending flow, as can be see below Index Peak in the first photograph. This in turn separated the massive carbonates into isolated blocks sliding along the base of the fault plane. They were never free sliding blocks - always encased in volcanics that were the crux of their transport on that low dipping (only a degree or two) surface.

(E) This cross section is after collapse , but before erosion. It has some problems - the collapse is much more likely to have been continual rather than instant, and the Trout Peak trachy andesite was probably better described as a pyroclastic flow, rather than a lava flow.

At the end of collapse the surface of the gigantic pile (minimum volume of 100 cubic KM (Malone, 1995) was of low relief and pretty flat, but was hummocky enough to produce an angular unconformity when the Trout Peak pyroclastics flowed over it - pyroclastic flows only need a minute slope to travel for miles (see the section on pyroclastic flows and turbidites). In strong contrast, the earlier flows had been fragmented and contorted in the debris flow, as seen at Foster Reservoir.

(F) The bottom cross section is a composite of relations along the northern (deeply eroded) and southern (less deeply eroded) edges of the debris flow, as they exist today, after several thousand feet of erosion. The allochthonous blocks of Paleozoic carbonate have been separated by extending flow of the volcanics along the detachment. At the extreme left is the breakaway, next a block on the bedding plane segment with a small early-formed Reef Creek thrust "piggyback" on it, one perched on the transgress ramp, then Heart Mountain itself, well out in the basin, sitting on Eocene strata (right under the "C" in Carter in the reconstruction), and finally the small extreme distal blocks of the McCulloch Peaks way out in the Basin.

The hump in the last cross section west of Carter Mountain has been called a separate "South-Fork" Detachment, and the transitory contractional toe of the Heart mountain detachment. I believe It is just a Neogene unloading bulge - As the nearly mile-deep valley was eroded, the soft Cretaceous shales were forced from under the high topography on either side and welled up in the middle of the valley. (But the other alternatives are viable.)

Figure 19m. View south of steep dipping beds on the east side of the south Fork erosion bulge. Shale-rich Cretaceous strata tilted by an erosion bulge, as the weight of the mountains on either side forced soft sediment to flow toward the valley. 12,000 ft Carter Mountain (background) makes up the east side of the South Fork Valley. (see bottom cross section of summary figure for location and setting). Photo by Author.

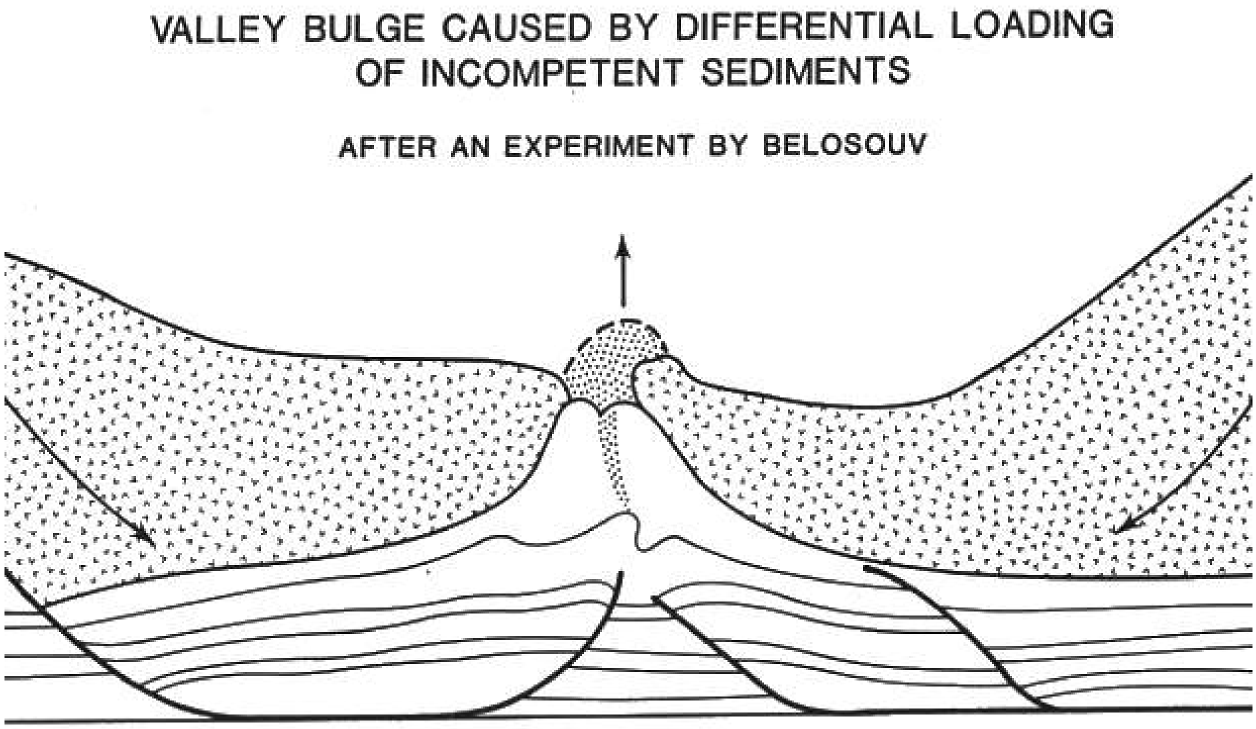


Figure 19n. Experiment in which sand sitting on soft wax was removed to form a valley. This “unloading” caused the soft material to flow toward, and upwell in, the axis of the valley - a good model analog for the South Fork anticline.

Timing: While, in the lower two cross sections, I seem to be advocating instant collapse, I’m actually agnostic and suspect that collapse was nearly of the same duration as extrusion of the volcano. It had to be fast enough that erosion couldn’t keep up, continuously removing the need for a coherent slide. Where the volcanics transition into fluvial and lake deposits with datable fossils, it seems to have taken place in the Bridgerian (49.5-47.5 Ma.). Thus, at its upper bound, it could have taken up to two million years to form - the volcano just got bigger fast enough that volume exceeded lithification, and/or exceeded rate at which erosion could remove the excess edifice, and it went into collapse mode. As exotic as Heart Mountain seems to be, it is still uniformaterian - Mt. Rainier lost almost two thousand feet of its top several thousand years ago in a similar debris flow.

See also Siebert et al 2006 for an overview of collapse hazards in the Central American volcanoes. Their article documents 40 major collapse events from about two dozen volcanoes. These workers point out that collapse correlates positively with elevation and dip of the support stratum, and volume, height and growth rate of the edifice. They seem to correlate inversely with plate dip, again a possible explanation for the huge volume of the Absaroka volcanics. They point out a possible 1000-2000 yr. periodicity in collapse - an intriguing possibility for applying stick-slip and periodicity for a quazi-steady-state Sunlight-Heart Mountain collapse spanning up to the 2 million years of the Bridgerian.

Keep in mind these collapse events tend to be quazi-cryptic - rapidly totally or partially buried by younger volcanics. Thus we have been slow to recognize both their size and frequency of occurrence.

<u>Exotic mechanisms:</u> The more I study the Heart Mountain detachment , the less I am inclined toward exotic mechanisms - the Sunlight Volcano just got too big too fast and spent most of its time (up to 2 million years) squashing.

Recall that, for several decades (to about 1980), the detachment was considered a free slide of giant blocks (some miles across) on a single bedding plane that dipped only 1-2 degrees. Even more amazing, these moving blocks, made up of Paleozoic strata a couple thousand feet thick, didn't plow up the 30 foot thick Grove Creek strata they moved on, even though it was underlain by weak shales. These constraints truly would demand an exotic mechanism(s), but the constraints weren't real - there was actually an even weighting of volcanics surrounded these blocks when they moved. Under these new constraints, it is the profile of repose on top of the collapsing mass, and not the dip of the foundation that it sets on, that matters most.

If we take mighty Aconcogua Volcano in South America as a model (el - 22,931 ft.), and the highest mountain outside the Himalayas), the Sunlight Volcano could have had nearly 20,000 feet of topographic relief, maybe more because the site of the Volcano was at least a few thousand feet higher than the Bighorn basin, when the volcano was born. It may never have achieved that height, but rather collapsed as it was extruded. "Critical wedge" theory of thrust belts points out that the basal decollement of thrust belts actually moves up hill, the deformation forced by the slope on top of the deforming pile. So movement on a single bedding surface dipping a degree or two in the direction of trasport would be entirely logical.

Thus, we can lay to rest both the hovercraft theory for single blocks, and velocities near the speed of sound. Plain old ground water, however, could have played a roll: Recall that the water table is usually a subdued replica of the topography. It would be many thousands of feed higher up in the volcano, than it was in the Bighorn Basin. If there was a confined permeable conduit between, pressures generated in the volcano, could have floated the toe in the Bighorn basin. It should not be considered the basic reason for the slide, merely an auxiliary mechanism that lowered the profile of repose and extended the distance of deformation.

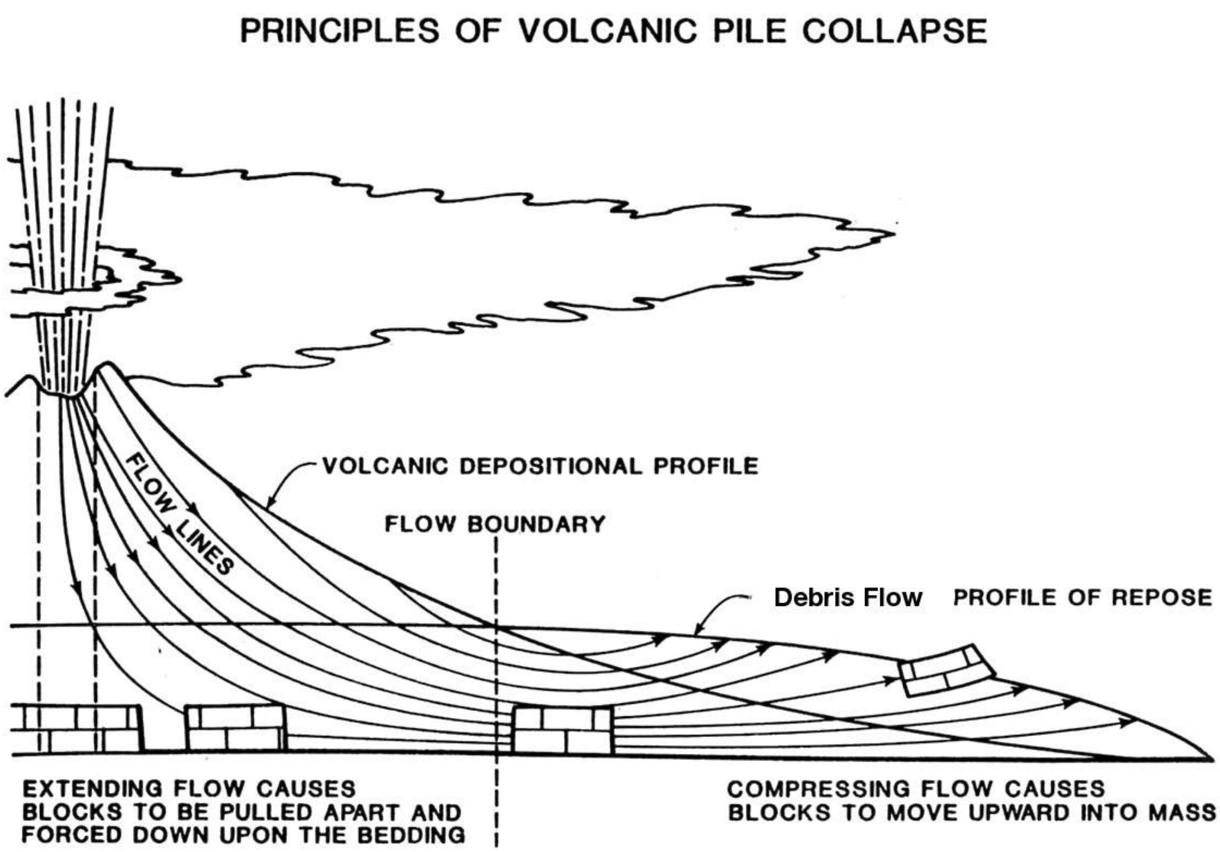


Figure 19o. This is a summery diagram of the mechanism for the Sunlight Volcano downdip-directed volcano collapse, better known in the literature as the Heart Mountain detachment. Here the Heart Mountain et al Paleozoic carbonate blocks are brick patterned, the volcanics are left unpatterned except for diagrammatic flow lines.

A strato volcano tends to build a high steep cone-shaped Mt. Fugi-like edifice. The Sunlight volcano collapsed to more the shape of a thick pancake during the great debris flow.

It could have been anything from a quazi-steady-state to an instantaneous collapse, the former being more likely. Extending flow up near the volcano, separated the Heart Mountain-type blocks in its base, and transported them miles down slope. They transitioned to compressing flow that caused some blocks to ride up into the mass of the volcanics, but with the majority remaining along the base.

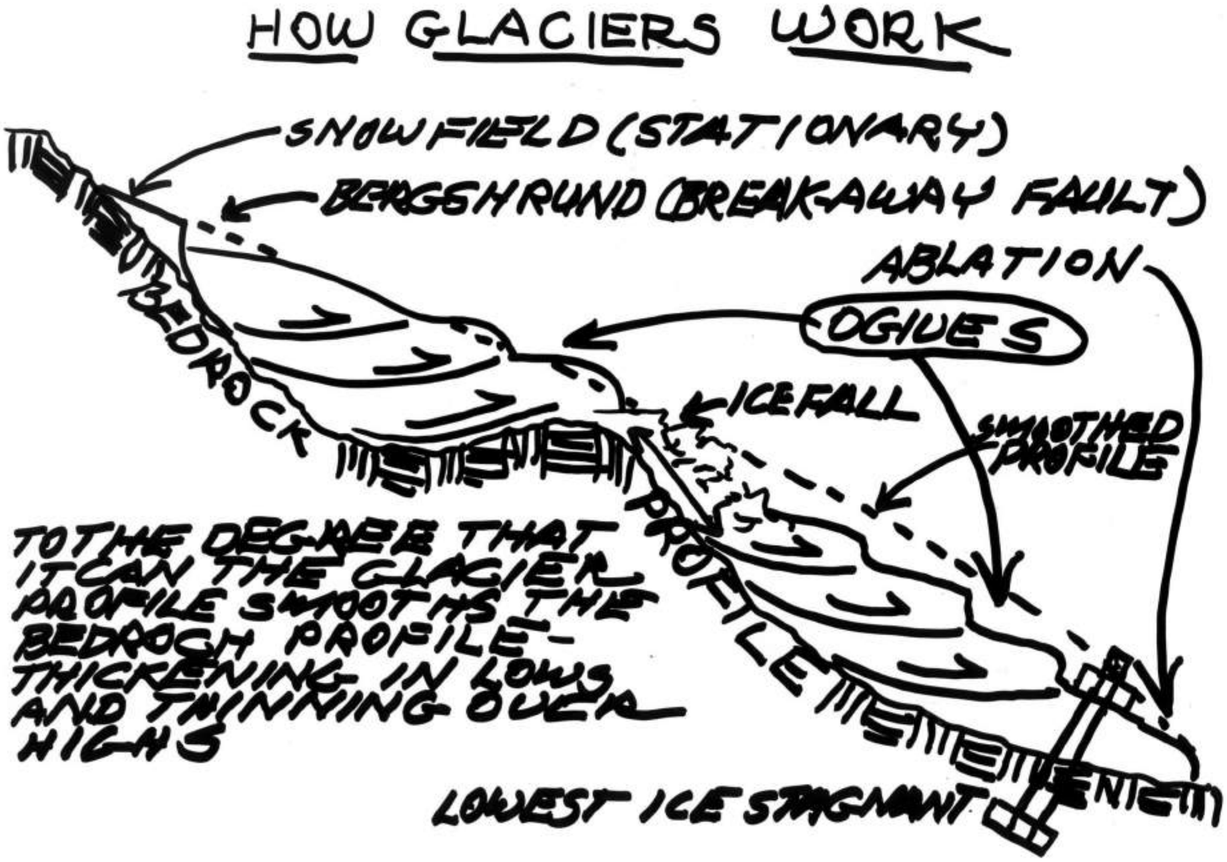


Figure 20a. Simplified longitudinal profile of a valley Glacier.

Weak plaster is an excellent medium for reproducing glacial flow features (Fleisher and Sales, 1972 and Fig. 9d). Ice is only about 9/10 as dense as fresh water and even less dense relative to salt water. Thus, about 9/10 of icebergs calved from glaciers are submerged (Fig.).

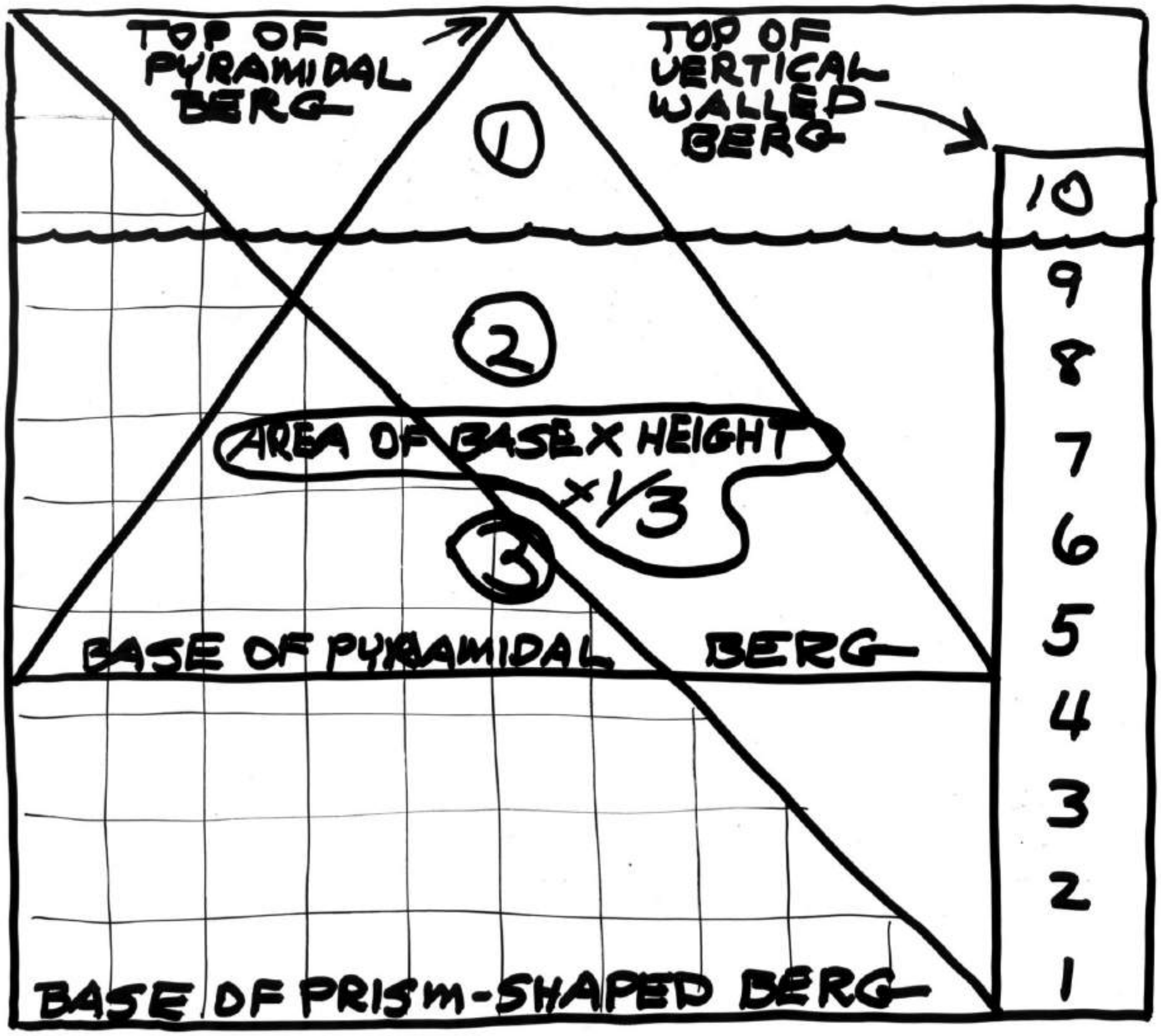


Figure 20b. The basics of buoyancy demand that icebergs float with 1/10 of their mass above water and 9/10 below water. The amount they stick up, however, depends on block shape. As in rift blocks, a pyramidal shaped block stands highest, a prism is intermediate, and a vertical-walled block floats lowest.

Glaciers are really dirty - they scrape up ground moraine from their base and drag it up into the ice on thrust fault-like shears. Debris is also dumped on the ice of valley glaciers from over-steepened valley walls as lateral moraines. Where ice-filled valleys come together, a medial moraine is formed. Large trunk glaciers have multiple medial moraines in a beautiful candy-striped pattern (See the south side of the Alaska Range on google earth). Glaciers slow as they reach the flatter piedmont, their moraines become contorted into the world's best flow folds, as seen on the Malaspina piedmont glacier in rhe bight of Alaska (Figs. 9d and 9e).

Melting glaciers leave debris behind in several forms. Till is the general term for poorly sorted glacial debris deposited directly by the ice with little water reworking. Lodgment till is clay-rich material plastered on by the active weight of the ice. It is very tough - we had to dig a septic system in it - it almost ate our lunch, even though we had a really big back hoe. When lodgment till over-thickens, it takes on streamlined drumlin form, like a teaspoon upside down - steepest face up-ice.

Glaciers retreat when melting exceeds advance. During equilibrium, glaciers act like conveyer belts dumping in the same place and an abnormally large pile of moraine forms. The farthest advance of the glacier is clued by the terminal moraine, temporary standstills up-ice from the terminal moraine are called recessional moraines. Those along the valley wall are called lateral moraines and those elongated down valley medial moraines.

Glacial-fluvial sediments are those deposited by the copious water from the melting ice. They include kame terraces built by rivers beside the ice, kame deltas into lakes dammed by and in front of the ice, and eskers - snake-like tunnel fillings deposited by sub-glacial streams. Kame features are characterized by hummocky "kame and kettle" sometimes "knob and Kettle" topography caused by melting ice blocks in the newly formed sediment. In the flat mid continent glacial outwash plains support some of our best agricultural land. Because newly deglaciated terrain is almost devoid of vegetation vast loess (wind blown silt deposits) are common. Loess has a peculiar interlocking grain texture that causes it to stand in a vertical face more stably than in a sloping face.

Valley glaciers, because of the grinding of the rock-laiden ice, form the world's greatest cliffs. Those in Yosemite in the lower forty eight are famous. Mt. Thor on Baffin island's Cumberland Peninsula may have the world's highest vertical cliff. But this is only because the lower half of the cliff on Mt. Dickey is still buried under ice of the Ruth Glacier just south of Mt. McKinley in the Alaska Range.

Mountain glaciers gouge deep cavities called cirques in the upper ends of valleys. Three or more cirques may erode headward into a mountain mass and generate the world's most beautiful mountain form - the glacial horn, the Alp's Matterhorn being the classic. If headward erosion is less advanced, parts of the summit plateau may be preserved, with cirques "biting into it. This is called "biscuit board topography" - the Bighorn Range in Wyoming is classic.

During formation, these cliffs are partially supported by the fluid pressure of the ice. When it melts they are vulnerable to collapse - The largest landslide in Europe is caused by a valley wall collapsing into its glacial valley in Norway. This gigantic landslide, with its apartment building-sized blocks, was the last stand of the Norwegian Resistance during W.W.II.

Of recent years, glaciers have come into their own politically - they are among the most definitive evidence for global warming. A single New England winter may seem like it will never end, but the world-wide recession of glaciers gives a longer-term record that can't be denied.

Naysayers on global warming point to surging glaciers (sometimes called galloping glaciers), that may advance their snouts tens (sometimes a few hundred) of feet a day, as evidence against global warming. Not so - a surging glacier is a glacier in big trouble. It speeds up by orders-of-magnatude when it unfreezes from its bed and becomes lubricated (sometimes floating actually) by over-pressured meltwater. In doing so its profile of repose, mass, and longevity are being drastically diminished. There is accumulating evidence that the entire ice mass of Greenland's ice cap may now be surging toward extinction (Zwally, et al, 2002). Recent seismic research has documented over 300 subglacial lakes in Antarctica, indicating that it is also largely floating and surging, This is also evidenced by the unstable extension of the ice shelves, with chunks as large as Rhode Island breaking off.

Himalayan glaciers are of special concern because rivers flowing from them support agriculture that feeds billions. These rivers are increasing in flow with accelerated melting, giving a false sense of security. As the glaciers fully melt, later in the century, these rivers may dwindle geologically instantly to ephemeral streams, drastically reducing agricultural productivity in China, India, and the smaller countries of Southeast Asia.

In a longer, but not much longer, time frame the final melting of all the world's glacial ice will raise sealevel enough to severely negatively impact a significant percentage of the world best agricultural land and population - the king of the Mouldive Archipelago, only a few feet above sea level, is already trying to buy real estate on higher ground, and the Netherlands is in big trouble. On the other hand, the Dutch are among the world's most resourceful and technologically advanced people - the majority of their new housing is built on rafts tethered to vertical posts, so the house rises as the waters do.

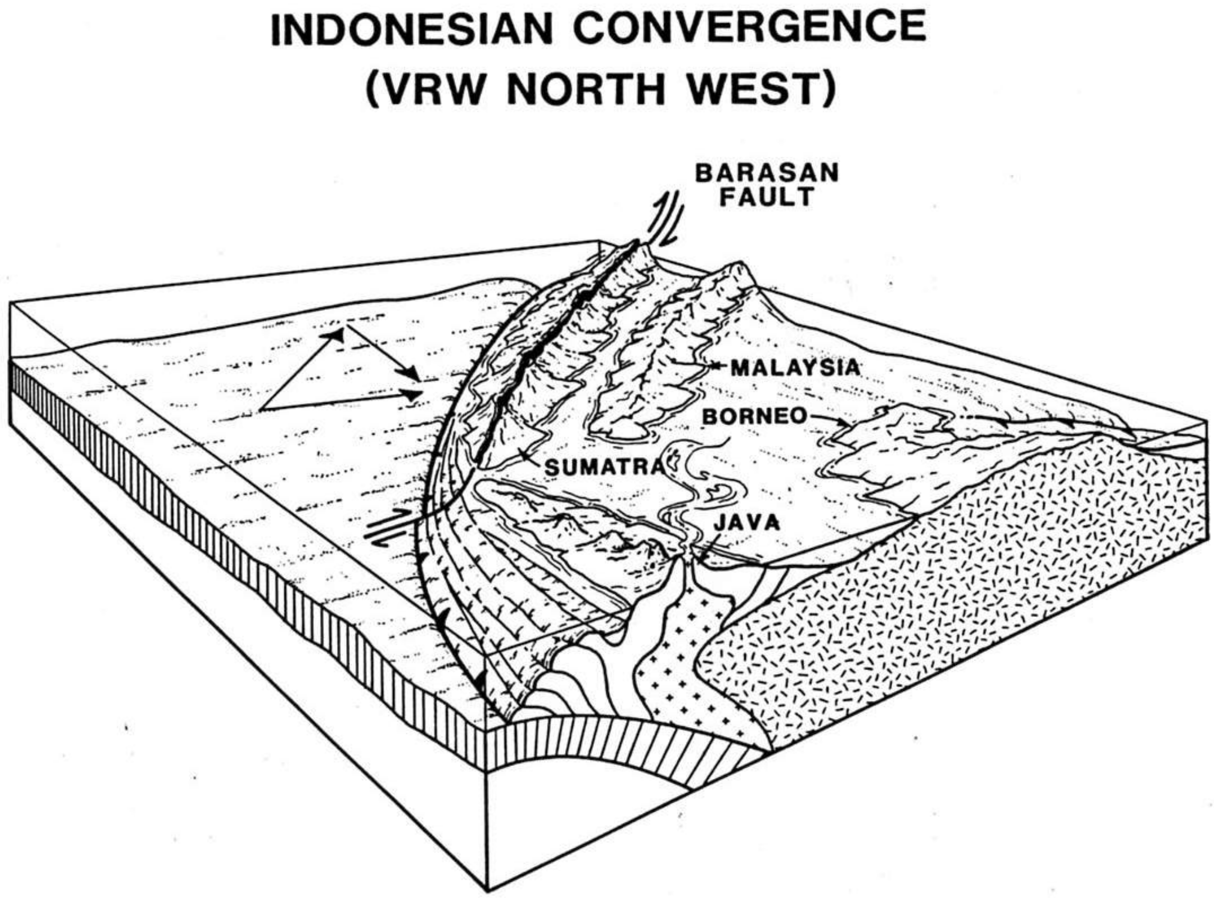


Figure 26f. Block diagram looking north west of the nearly straight-on subduction in Java transitioning into dominantly strikeslip of the Barasan Fault north west of Sumatra. This is the setting that produced the devastating tsunami of 2004. (VRW should have been VIEW)

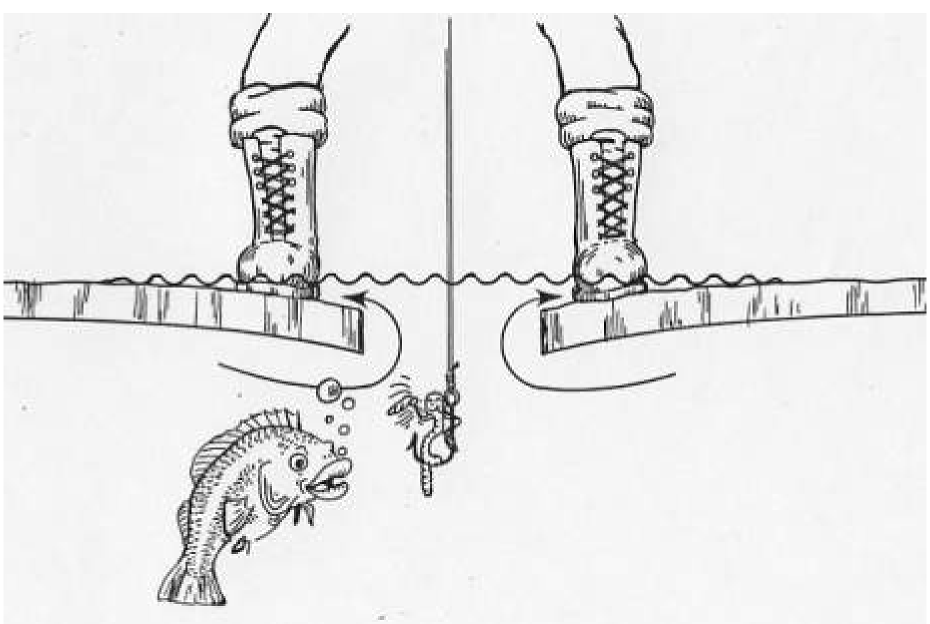


Figure 15a. Beam-strength of the crust: Fisherman on thin ice not exactly in isostatic equilibrium - though he is creating two mirror image "foreland basins".

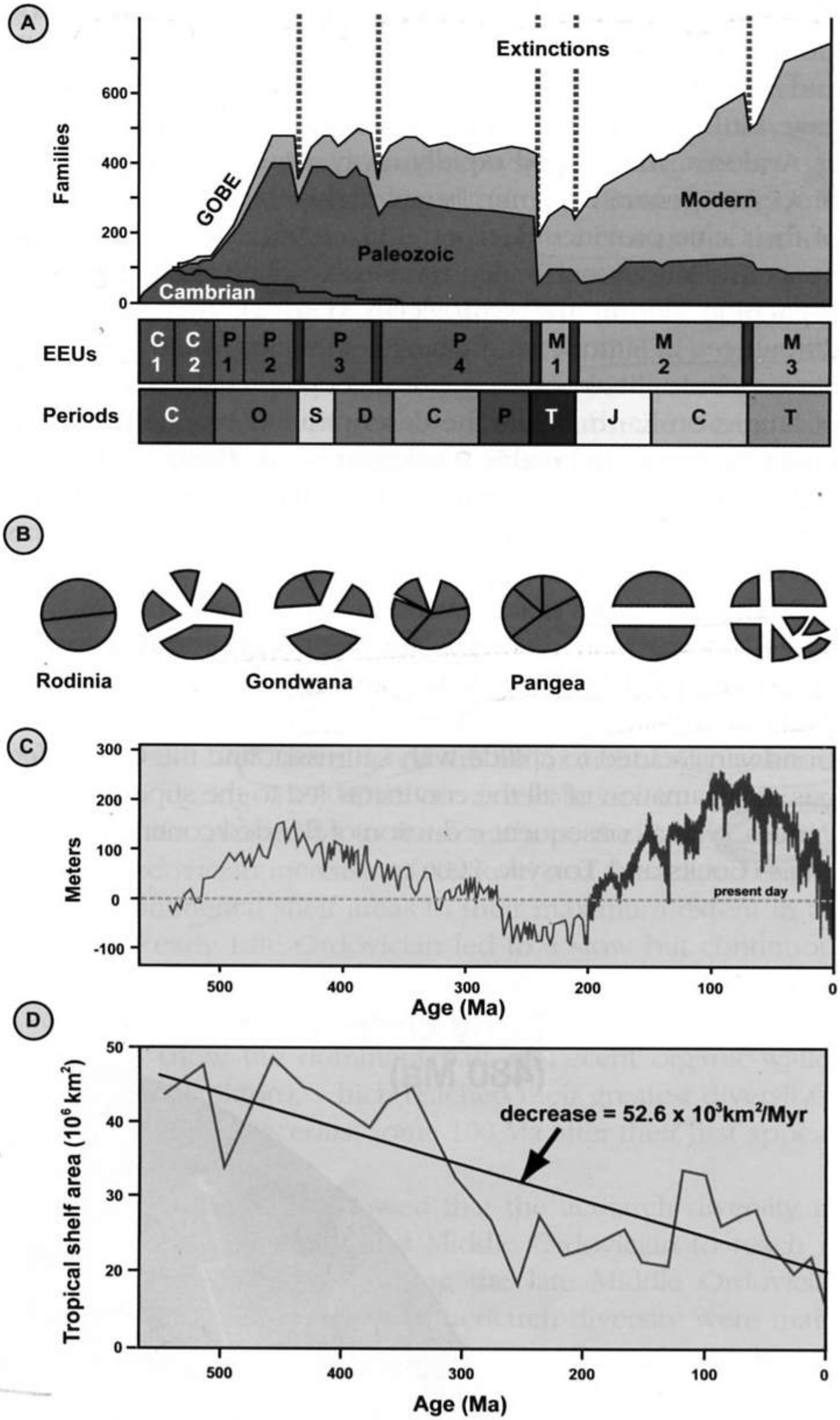
We have been able to quantify strength of the lithosphere by studying glacial rebound when an ice sheet melts. Temporary glacial lake Bonneville in Utah had mountain ranges sticking up through it as islands, each with a beach at high water level. Lake Bonneville was large enough that it depressed the crust, which rebounded when it flushed/ evaporated. Shorelines were warped up by the rebound, giving excellent quantitative data on lithosphere strength.

Mountain belts are so big they have to have a thickened and often less dense "mountain root" to support them - this was first discovered in India where pumb bobs were deflected less toward the Himalayas than they should have been if the crust was all the same density. When foot walls are relieved of the weight of their hangingwalls, the biggest normal faults arch up into metamorphic core complexes. As ocean crust ages, thickens and densifies, it subsides. Continents, built of silica-rich less-dense rock, float with their upper surface above sea level, ocean crust, made of denser basalt, with its surface thousands of meters below sea level. Ocean crust finally gets dense enough to subduct. These are all varied expressions of Isostacy.

ASTEROID IMPACTS, SPECIES DIVERSITY AND EXTINCTION:

The old saw, "I wouldn't have seen it if I hadn't believed it myself" is a major psychological driver in science. Impact skeptics wouldn't see an asteroid if it hit them in the head, an impact enthusiast will see a hundred impact structures before breakfast. I'm toward the enthusiastic end of the spectrum. For those interested (Earth Impact Data base, 2004) gives a compilation of possible impact sights.

Evidence has accumulated to such a degree that we can no longer downplay the importance of extraterrestrial impact on earth history - especially species diversity, extinction and evolution. There now appear to have been five impacts in the Phanerozoic - the last 600 my - roughly 1/7 of earth history, that caused major extinctions, apparently geologically instantly (Fig.).



A
Extinctions
Families
600
400
200
0
GOBE
Paleozoic
Cambrian
Modern
EEUs
C 1
C 2
P 1
P 2
P 3
P 4
M 1
M 2
M 3
Periods
C
O
S
D
C
P
T
J
C
T
B
Rodinia
Gondwana
Pangea
C
Meters
300
200
100
0
-100
present day
500
400
300
200
100
0
Age (Ma)
D
Tropical shelf area (10^6 km^2)
50
40
30
20
10
0
decrease = 52.6 x 10^3km^2/Myr
500
400
300
200
100
0
Age (Ma)

Figure 16a Summary figure from Servais et al. 2009 comparing biological diversity, sea level. and impact history through the Phanerozoic (roughly the last 600 my).

Extinctions: The best known "Chicxulub impact" (65 my) appears to have caused extinction of the Dinosaurs, along with a significant percentage of the rest of the earth's biodiversity. Its crater is hidden under the geologically extremely rapid tropical carbonate shelf buildup of the Yucatan Peninsula in Mexico. But both its geophysical signature (seismic and gravity) and its geologic record scattered along the Cretaceous/ Tertiary (K/T) boundary (its blast surface) seem clear. With its far-flung evidence of impact in the form of shocked quartz, tektites, nano diamonds, elevated iridium levels, and evidences of burning, the K/T boundary layer is now perhaps the most studied single horizon in the geologic record.

An even larger Permian-Triassic extinction "The Great Dieoff", (about 250 my) appears to have cut marine biotic diversity by as much as 90%. A crater is still in dispute, the recently discovered Bedout structure under the northwest Australia continental shelf being the best candidate. Initial coring gives a date of about the age of "the great dieoff." At roughly X3 the diameter of Chicxulub, it seems correctly sized to accomplish the work. The other three impacts during the Phanerozoic each made a dent in biotic diversity large enough to be recognized.

A much younger "Clovis event" is starting to be speculated about: About 13 thousand years ago the record of highly evolved Clovis spear points, and the advanced hunting culture capable of making them, disappeared. At about the same time the giant ice-age mammals they hunted (mammoths, mastodons, saber tooth tigers, giant sloths and bears) also became extinct. Enthusiasts suspect an impact, cynics say the Clovis hunters were too good at what they did, over hunted, and starved themselves to death, or were out-competed by other cultures.

Coming forward into the historical record, the 1908 "Tungusta explosion (Google 1908 Tungusta blast in remote Siberia) leveled and burned 2000 sq. km (700 sq. mi) of forest and killed all life. It is most often considered a bolide, a meteor that exploded as it entered the upper atmosphere, the blast being calculated at roughly the size of the Hiroshima A-bomb (20 kt).

Is Jupiter the Solar System's "cow magnet'? They feed cows small magnets that lodge in their first, very tough, stomach and collect metallic debris, especially fence-post staples, they might eat. This has saved a good many cows form extinction. Fragments of Comet Shoemaker-Levy left a well documented swath of multiple impacts across Jupiter, over the course of about a week, in 1994. Jupiter apparently literally makes life on earth possible: With its immense gravity field, it apparently sweeps up the great majority of loose asteroids (and fence-post stables) that might otherwise impact Earth (Google: Jupiter meteorite impacts save Earth). New studies by Heidi Himmel and another by Agustin Sanchez-Lavega (Science News, 7/3/10, p. 10) suggest that Jupiter absorbs a giant (by earth standards) impact possibly every 10-15 years, and just shrugs it off. Imagine if Earth had a Chicxulub size event every 10-15, or even every 10-15 million years - no life on earth...Thanks Jupiter!

Wild Idea - A Shoemaker-Levi On Earth?: Consider the Gulf of St. Lawrence and Chicxulub impacts as two ends, and the lower Chesapeake Bay impact the middle of such an impact chain, with lesser-preserved possible events in the Gulf of Maine, and the reentrants in the continental slope with accompanying deep holes on the sea floor off New Jersey and Georgia. I don't know if the details of timing will eventually support this idea, but they are all in a line, and Shoemaker-Levy allows us think in that direction.

HUSON BAY (NASTAPOKA ARC) STRUCTURE: Wild extrapolations from Shoemaker-Levi should be followed by the cautionary tale of the super giant Eastern Hudson Bay Structure centered on the Belcher Islands. It is easily the largest and sharpest circular on earth, and the most contentious: Its geometric credentials (1/3 of a perfect circle 270 miles in diameter (the Nastapoka Arc) centered on the Belcher Islands as a contorted central uplift) are very suggestive of impact. Its geologic evidence is anemic - no shocked quartz, tektites, nano diamonds or horizons with fire have been found.

There are many reasons why this type of field evidence should not be found: Basically, all the geologic evidence remaining (or at least so far considered) is post impact. This can be put into perspective by analog reasoning: The closest relative to impact structures are rifted basins - thinned and weakened crust above an asthenosphere swell. When rifted basins stabilize, they decay thermally and a successor sag basin forms above them, its beds dipping toward the axis of the rift. If you google-earth the rim of the Nastapoka arc, beds along it dip toward the Belcher Islands (best preserved in the middle of the arc, between Hudson Bay and the largest lake east of the arc) - if they were uplifted blast rim they should dip away from, not toward, the Belcher islands. Thus, the preserved and exposed part of the arc are post-impact sag basin and not impact uplifted rim in age.

Contortion of Belcher Island strata is more like gravity sag toward the center of that post impact sag basin, than a true central uplift produced at impact. Just as sag basins over rifts are broader than the rifts, sag basins over old impacts should be broader than the uplifted blast rim - the actual impact crater diameter is probably smaller than the surface feature - but still a huge impact. That older rim was probably completely planed off by the post-impact, pre-sag basin transgression, but may still show seismically.

THE BIOTIC RECORD - SLOW GROWTHS IN DIVERSITY PUNCTUATED BY DIE OFFS: The earth's biotic diversity record is neither linear nor uniformaterian. It consists of an overly long Pre-Phanerozoic very low plateau followed by the Great (Cambro) Ordovician Biological Diversity Explosion (GOBE) (Servais et al, 2009), followed by a gently descending plateau from Late Ordovician to Late Permian). This was followed by catastrophic Post-Permian extinction, and a long-term buildup to the present, except for the K/T boundary dieoff and sharp recovery. It seems possible that biologic diversity rising from almost nonexistent at the beginning of the Cambrian, to full-blown by the end of the Ordovician, is the result of rapid buildback from a really catastrophic extinction in latest Protorozoeic, perhaps by the Hudson Bay impact.

In the Hudson Bay case, suppression of the geologic evidence is not surprising: With impacts, the great majority of the evidence lies along the blast plane - the earth's surface surrounding the point of impact at the time of impact. The exposed eastern rim's evidence has been wiped out by continental glaciation. The western rim's geologic evidence may have been highly diluted and dispersed by the high-energy Pre-Shelf transgression along the "great unconformity". Alternatively, the blast plane may still be hidden under the unconformable lower Paleozoic carbonates.

It might be argued that, in contrast with the original evolution of life, build back from a catastrophic impact could be relatively rapid - just as we see in the Cambrian and culminating in the Ordovician. This is probably because so many life forms survive the impact, probably in the world's trenches, and probably methane tolerent forms that quickly [geologically] readapt to oxygen breathing and re-populate the Earth.

Such a large impact may have vaporized most of the ocean, activated the world's ocean's methane hydrates and continental swamp gas into the atmosphere, mixed them with oxygen, and flashed them in a titanic explosion. It would have wiped out the great preponderance of biologic diversity, leaving only methane breathing organisms, adapted to eutropic environments in the deepest recesses of deep sea floor muds. Biologic diversity would have literally had to crawl back out of the trenches and relearn to breath oxygen... but that's a simple chore compared with the original evolution of life.

Isn't that what we see in the geologic record? British Columbia's famous Burgess shale may record just such a salvaged environment, and the Great (Cambro) Ordovician biotic diversity explosion may just be a rapid build-back from massive extinction caused by the Hudson Bay impact.

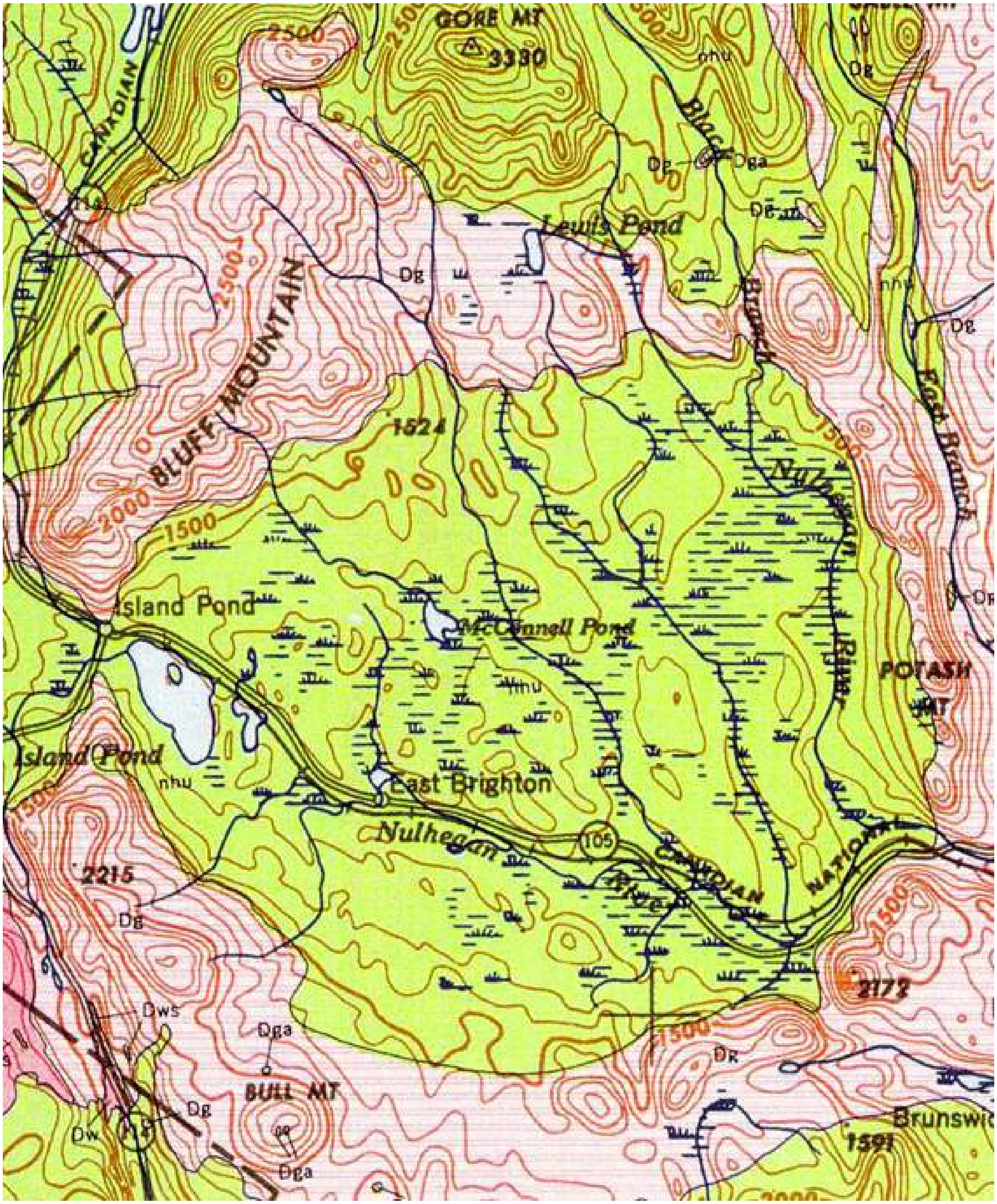


Figure **Nulhagen and Victory Bog Basins of NE Vermont:** After impact arm waving that spans the Earth, Solar System, and most of geologic time, let's end this with an intriguing little problem about fifty miles north of my house - the Nulhagen and smaller Victory Bog Basins of northeast Vermont. The Nulhagen Basin is about 6 miles in diameter, the Victory Bog basin about two. (the best overview can be seen on the Geologic Map of Vermont (google: Geologic Map of Vermont, choose the Doll 61 version, and pick and enlarge the Northeast section). They are noticibly circular, swampy, and surrounded by rimming hills and mountains. Both basins and their surroundings are dominated by granite. Here's the rub, as explained in a few sentences from Meeks, 1986:

“In northeastern Vermont most of the higher elevations are predominantly granite.*” The footnote at the bottom of the page says this: “*The great Nulhagen Basin of Essex County is an exception. here the granitic rocks are weaker than the surrounding metamorphics.”

I haven’t canoed the swamps of the Nulhagen, but have canoed Victory Bog, and one thing is very noticible - though granite dominates the stream bottom and its banks, none of it appears to be bedrock - just boulders and cobbles of every assorted size. Yet, the granite looks as fresh and strong as in the bedrock granite of the surounding small mountains. In short, I don’t believe we should close the book with the simple explanation that these are caused by two nearly circular non-resistant granite plutons. None of the other plutons are that circular and all of them are of superior hardness and resistance to erosion. We should give equal or greater credence to an impact origin.

he other plutons are that circular and all of them are of superior hardness and resistance to erosion. We should give equal or greater credence to an impact origin.

ALTERNATIVE TO ASTEROIDS:

Allegorically, if a puddle contains X species found nowhere else, X species will become extinct if it dries up. If there were no other puddles near as good, that catastrophe would annihilate most of the world’s species.

As an alternative to impact, **Sengor and Atayman, 2009,** seem to make a strong case that this actually happened coincident with the massive Permian/Triassic extinction: Pangaea began to draw together in the Late Paleozoic, as the only Phanerozoic supercontinent (study the previous figure). As it did so, it enclosed a dyeing ocean much like the present Mediterranean - Black- Caspian seas, but extending the full breadth of Pangaea, basically from Central America (the Atlantic was still closed) to east Asia. This Paleo Tethys Ocean lay along the equator, was warm, and had shallow shelves followed by shallow foreland basins and was the most productive part of the sea and, like the Mediterranean during the Messinian, basically cut off from the much larger ocean exterior of the Pangaea supercontinent.

By contrast, the great majority of ocean exterior of Pangaea (Panthalassa) was either too far from the equator and/or too devoid of shallow shelves to be productive, even though it was the largest ocean basin that existed in the Phanerozoic. This time span has the lowest sea level of the Phanerozoic, averaging about 60 meters below the present (Miller et al, 2005). This would have left continental shelves, normally the breeding ground for diversity, nearly high and dry.

Thus, when the Paleo Tethys ocean finally did close to form a precursor of the Alpine-Himalayan Mountain Belt, it caused the extinction of most of the world’s oceanic species. Even though this would not be the instant extinction of an asteroid impact, it would be geologically very rapid - over the course of a few million years maximum, if we can believe the Messinian salinity crisis as an analog. Sengor and Atayman make the case that they can start to see the diversity decline well back in the Permian and that it was not instantaneous. This non-impact interpretation is reinforced by the fact that the single greatest reduction in continental shelf area in the entire Phanerozoic took place in the 100 million years before the “Instant” of the “Great Die off” (Walker, et al. 2002). That decline in the major crucible for marine diversity was equal to the total averaged reduction in shelf area for the entire Phanerozoic.

MEDITERRANEAN'S MESSINIAN SALINITY CRISIS AS AN ANALOG: What if the Mediterranean had not reopened to the Atlantic after the Messinian salinity crisis at Gibraltar? Realize that such a salinity crisis will happen one final time and will basically cause the extinction of the entire Mediterranean-Black-Caspian biota geologically instantly. Likewise the Paleo-Tethys ocean had to have finally closed one last time and its entire “swept together” biota, including much of the world’s marine diversity, would have been forced to extinction geologically instantly.

Sanger and Atayman’s idea is an excellent example of the “multiple working hypothesis” concept in action, and why we should refrain from “a rush to judgment.”

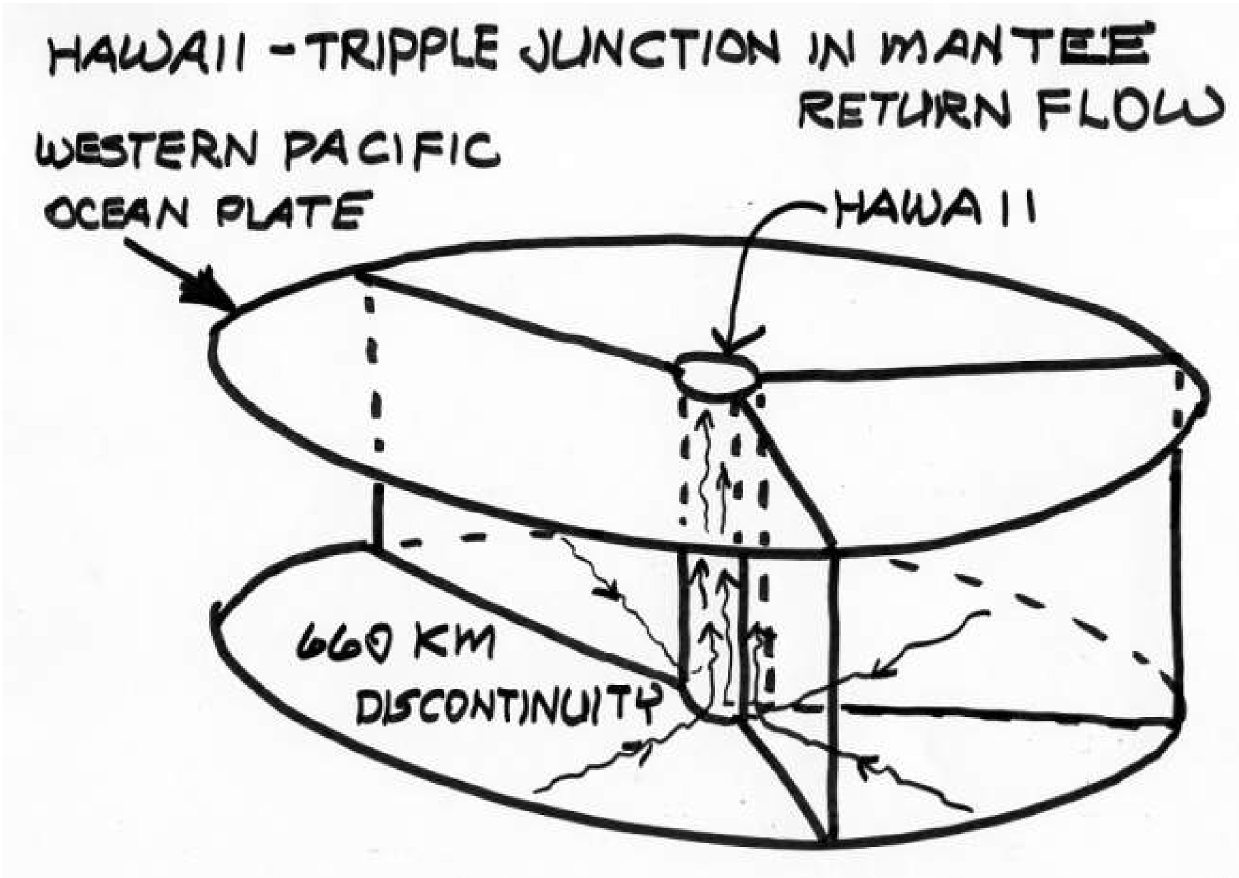


Figure 19a Concept that Hawaii is not caused by a hot spot fixed below the mantle, but is the vertical pipe at a major triple junction in the mantle return flow. It is a pipe characterized both by lower pressure and by contaminated mantle caused by "sweeping up" debris accumulated along the 660 km. discontinuity caused by old subduction. Both lower pressure and contamination should trigger melting.

Most workers seem to think that, on a sphere, the return flow pattern has to be independent of the surface flow pattern (Brad Hagar of MIT wrote a computer program on this), but that there should be roughly as many triple junctions and cell boundaries in the return flow as there are plate boundaries and triple junctions in surface plates. That's about what we see. Thus, it is not surprising that there is a major mantle cell triple junction in the return flow (Hawaii) right under the center of the world's biggest (western Pacific) ocean plate. It should roughly have the form of a vertical pipe the depth of the convecting mantle, and be filled with slightly anomalous mantle that melts a little easier than the regular mantle encasing it:

1) The dirty floor analogy - If surface slabs have sunk, laid along and remelted at the floor of the convecting mantle, they should have brought a lot of debris along - any debris that "stuck" to the subducting pure ocean crust, and did not get regurgitated back up as volcanics. Visualize a dirty kitchen floor. This debris should melt cooler than pure mantle/ocean crust, but not have enough mass, when spread flat along the 660 discontinuity, to diapir to the surface.

The special case of water deserves additional discussion. Even though water is super-mobile compared with rock types descending as contaminants, it might, on the near-molecular level, be both dragged down and retained, with distributed mass too small to work its way upward through the mantle. However, once it is swept into the master Hawaiian vertical conduit, it both gains buoyancy of mass and helps promote melting of its enclosing contaminated mantle.

2) Convecting cells should sweep this debris into a linear pile at linear cell boundaries and a really big pile at their triple junctions. Not only that, but if motion is up at linear plate boundaries, it should be up several times stronger and with several times the residual debris at a major return cell triple junction like Hawaii (Fig. 19b).

3) This pipe should also have reduced pressure, that would further promote melting, being made up of slightly contaminated and more buoyant material than the mantle around it. There is yet another pressure-reducing principle - air around thunderheads has basically no strength. Mantle, in contrast has huge strength, even though it convects due to the huge masses (about 400 billion trillion tons according to Frank Press) involved. (M. King Hubbert explained this in his "theory of scale modeling" in 1934.)

HAWAII HOT SPOT

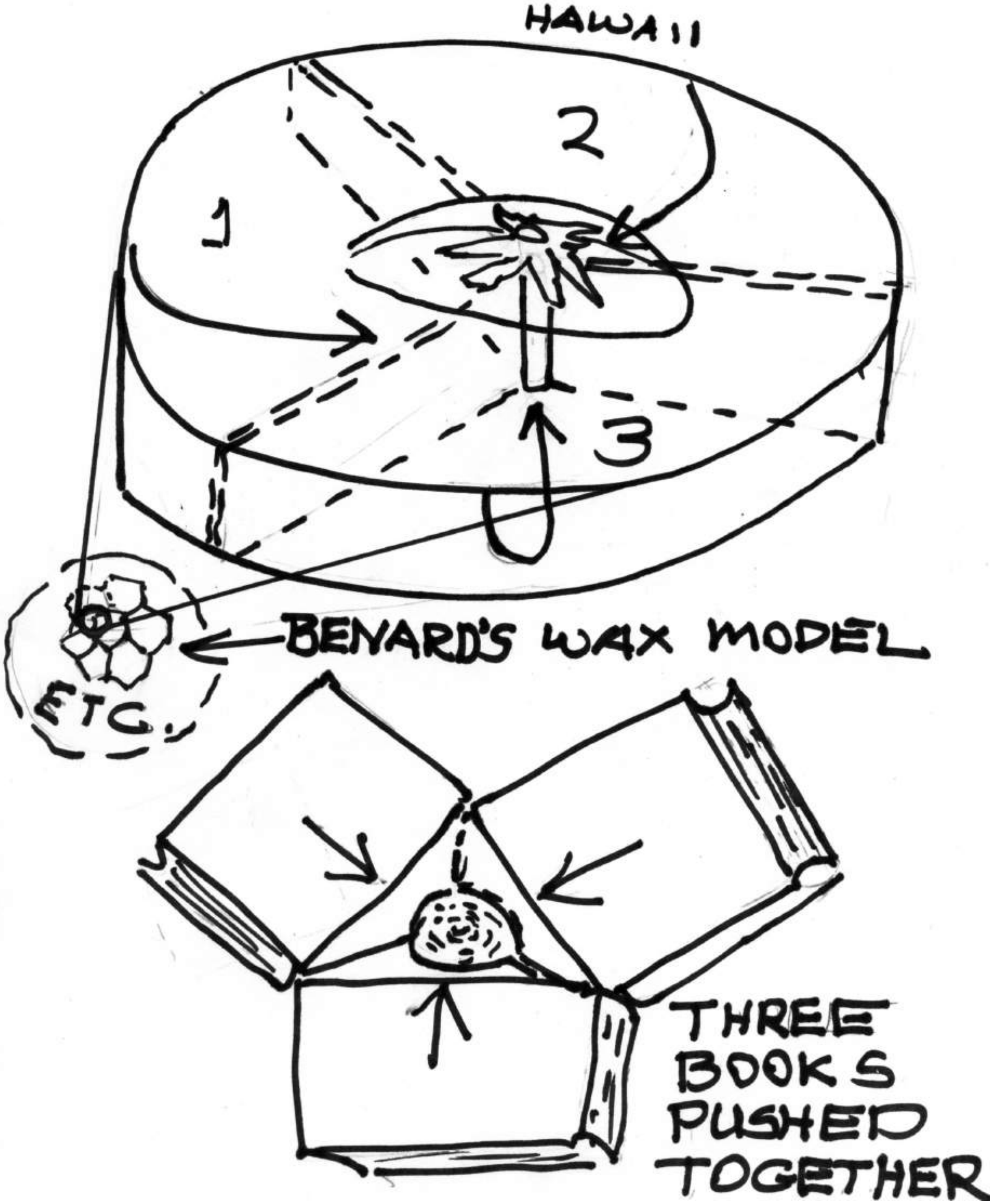


Figure 19b Try this conceptual experiment - lay three books on a table just touching each other at their corners. Try, borrowing a friend's third arm, to push the three books together to eliminate the triangle gap in the middle of them - can't do it, they are too strong. But now visualize these books, the three cells impinging on the Hawaiian triple junction, becoming bigger and bigger and therefore weaker and weaker as scale dictates, as Hubbert said. The triangular gap will close up, but it will always be a zone of anamolously low pressure because of the finite strength of the mantle.

Summary: Hawaii may lie over a vertical pipe the depth of the convecting mantle at a major triple junction in the return flow. Contaminants "swept up" off the base of the convecting mantle, and lower pressure in the conduit, promote melting. Thus the Hawaii-Emperor Seamount Chain has been chugging away for the better part of 100 million years. Midway in that history either the mantle return flow or the surface plate changed motion.

Hotspots On Linear Sections of Ridges: Hawaii is in the middle of the world's largest oceanic plate. Lets now consider hotspots on spreading centers, at plate boundaries. Hotspots on linear segments of ridges, like Iceland in the North Atlantic, and at Tristan de Cunha, the focus of the Walvis Ridge and Rio Grand Rise in the South Atlantic (and maybe the the Galapagos hotspot off Costa Rica) may not be caused by hot "spots", but rather by upwelling hot linear mantle cell boundaries in the return flow, crossing under the ridge (Fig. 19b).

Both the surface ridge and the mantle cell boundary has to have different motions. This allows the Walvis and Rio Grande Ridge tracks to form a "V" that "points" to the place on the ridge (roughly Tristan de Cunha), that the mantle cell boundary is currently migrating under it. This is the only mechanics that can explain mirror-image V-shaped tracks on opposite sides of the spreading center, if the spreading center is not fixed in space - ie. if it is following the plates around at half their summed velocity, as the Oldenberg and Brune wax experiment suggests (Fig.). And as a mega east west cross section through Africa suggests (Fig 17i).

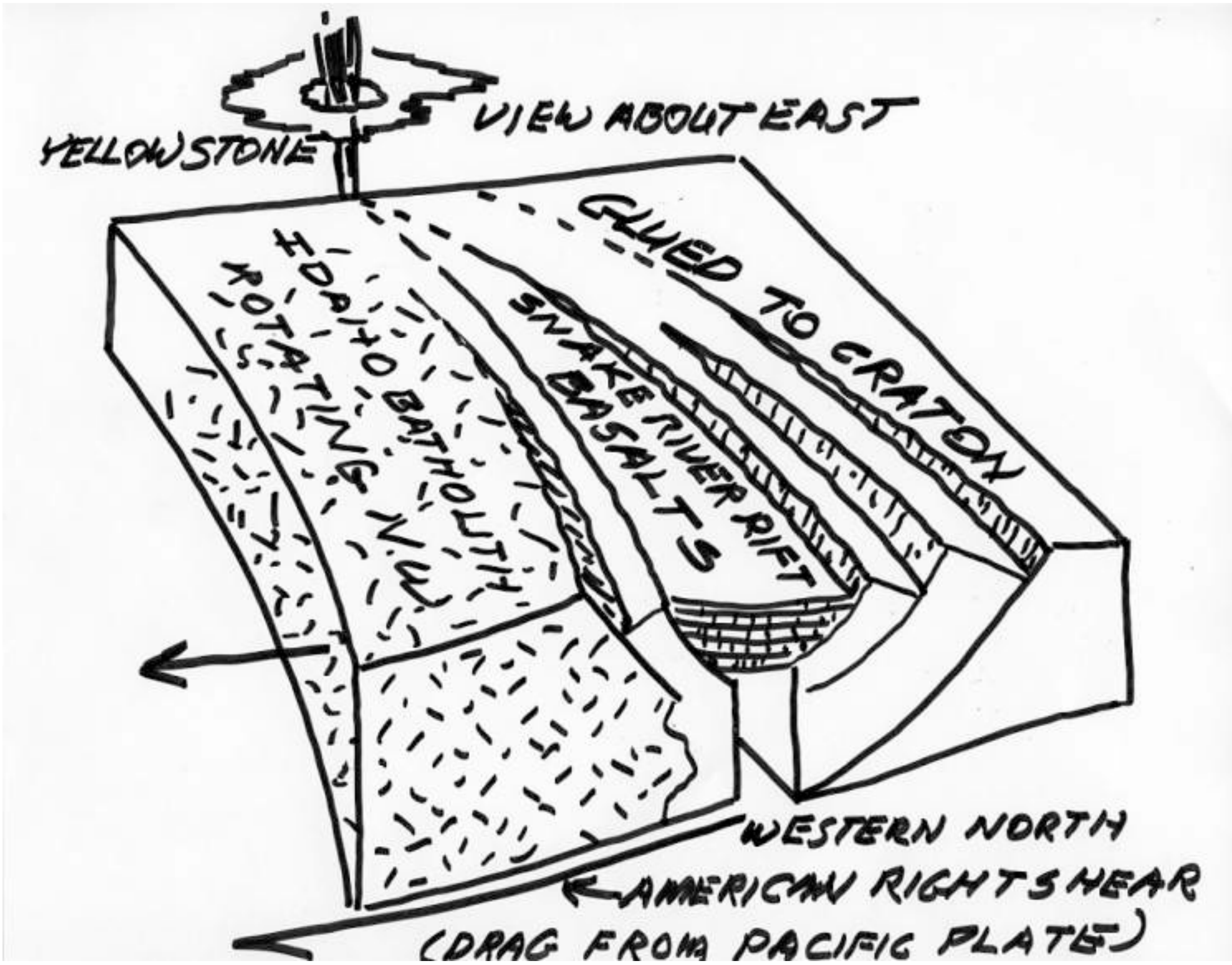


Figure 19e . Block diagram looking north east of the expanding-crack interpretation for Yellowstone and the older plateau basalts filling the Snake River Rift farther west, as the Idaho batholith is rotated northwest on its trajectory toward Alaska.

Recent seismic, young fault scarps and GPS data led Payne et al 2008 to say, “These (seismic) velocities show regional clockwise rotation suggestive of driving forces beyond those associated with the Yellowstone hotspot.” From their maps, seismicity seems to avoid the three big chunks (Idaho Batholith, volcanics ponded in the Snake River rift, and the craton). Extension is intense between the edge of the craton and the east end of the rift and then swings west through Hebgen Lake and Borah Peak (Idaho’s two largest historic earthquakes). Thus, the Lemhi, Lost River and Beaverhead ranges absorb the brunt of the extension necessary for this to happen.

It seems most likely that the Idaho batholith is being torn away by the same northward Pacific plate motions that have transported earlier terranes to Alaska. Under this interpretation the Yellowstone hotspot is not fixed in space, with the continent moving southwest over it. Rather, the tip-end of the propagating crack is moving northeast relative to the North American plate, the absolute motion of which is not defined by Yellowstone.

The Yellowstone - New England Seamount geometry: The Yellowstone hot spot tracks northeast, the New England Seamount hot spot tracks southeast, almost at right angles to each other, and they are both on the same plate (Western Atlantic-North America). One of these can’t be stationary and I think neither are. If one of these is on a sideward moving ridge like Tristan De Cuna, and the other is a north east propagating crack, as the Idaho Batholith is torn north west on its trip to Alaska, there is no geometric or mechanical problem with either.

GEOLOGIC HAZARDS:
AN OUNCE OF PREVENTION IS WORTH A POUND OF CURE

There are enough clues in the landscape, local history, in similar settings around the world, and in common sense, to let you make a valid judgment on most geologic hazards. And your homework is much easier, now that we have the internet. But what if a place is risky, yet you love it? A geologist can't help you there - that's psychological. Some avoid all risk with a ten-foot pole, others think it's the spice of life. For you, it may not make sense to avoid all risk, but it does make sense to understand the type and amount of risk, and how to minimize it. If you wish to avoid geologic hazards, an ounce of prevention is worth a pound of cure.

Geologic hazards have plagued us through the ages. For historic perspective, here is what Pliny the Elder, one of the world's first scientific observers, had to say about the Rhine Delta in the later Netherlands, after he had served there as a soldier in the first Century BC: "There lives a miserable people at the highest known levels of tide and here they have built their huts, living like sailers when the water covers their environment, and as if shipwrecked when the water has gone." (McQuaid and Schleifstein, 2006). Ironically these "miserable people", in the course of two thousand years, have evolved into those most technologically savy at dealing with sealevel rise due to global warming.

The Dutch, of course, have dealt with it by creating one of the engineering wonders of the world. But for every success story like the Netherlands there are hosts of horror stories: Haiti's quake, Katrina's hurricane, Indonesia and Japan's tsunamis, Mt. Peli's pyroclastic cloud, and the Missouri River's almost yearly flooding, to give some diverse examples.

TSUNAMIS: Before we start, and just to sober you to the task, realize that the highest recorded wave wiped out whole forests to over 1700 ft above sea level, when an earthquake-generated landslide entered Litunya Bay, Alaska (fig.).

Fig. 21a. Simplified perspective diagram of the Litunya Bay Landslide and wave.

There's a fun barroom story goes with Litunya Bay - supposedly two guys, who had been drinking quite heavily, were fishing in a small boat on the bay. The wave carried them and their boat over the tops of a mature forest, that had been growing on the spit at the lower end of the bay, and deposited them in the open ocean, along with the forest. There the wave instantly dissipated, leaving them stranded in a forest of tangled debris in open ocean. Talk about two confused fisherman.

To call the Litunya Bay wave a tsunami is a stretch - it was an exceptional wave, caused by a local event, in a very small container. Classic tsunamis, on the other hand, are giant waves triggered by sea floor displacement during earthquakes, most often over subduction zones. The vast majority of subduction zones rim the Pacific and the vast majority of tsunami are confined to the Pacific Basin. But, as we saw in 2005, the short segment of subduction in the Indian Ocean in Indonesia is capable of a deadly tsunami. Because the Mediterranean Basin is a closing ocean that is tectonically active it, and to a lesser extent the Black and Caspian Seas, are also susceptible.

A ship in mid-ocean may not even know a tsunami is passing under them. Tsunamis may travel as much as 450 mph, but have wavelengths measured in hundreds of miles, and an amplitude of only a few feet - in mid ocean, so they are almost undetectable. But when they start to feel bottom, the water piles up into a monster that can be several tens of feet high. The runup of the wave can extend to over 100 ft above sea level (Fig.).

Fig. 21b Diagram showing how tsunamis act where they originate, in mid- ocean, and where they hit shore.

These waves are not unidirectional but do focus their destruction in a general direction, depending on the facing of the generating subduction zone. Alaska's Good Friday earthquake is a good example - because of the kink in Alaska, the generating sea floor faced almost directly toward the mega- headlands of British Columbia, Washington State and northern California, which sustained the greatest destruction.

Many Pacific beaches have tsunami warning systems. Another thing, that can give some needed time to evacuate to high ground, is the tendency of many tsunami waves (not all) to be proceeded by a withdrawal of water seaward - if the tide starts to go out abnormally fast, run for the highest ground you can find.

RIVER FLOODS: Because river floods are so common they cause huge damage and loss of life...most of which is preventable. Build high enough above rivers to avoid flooding - that means at least one <u>river terrace</u> up from the active flood plane. If there is a large beaver dam or old man-made dam upstream, add another 50 vertical feet. If their are glaciers or a large old man-made dam upstream, add another 100 vertical feet to that.

Look up the high-water mark of the greatest recorded local flood - there is a small plaque built into the masonry, at about the top of the restroom door, in a Montpelier, Vt. gas station near where I live - “Flood height - November 1927”. I found the precipitation contour map for that storm on the internet - ten inches in 24 hours - probably a stalled tropical hurricane. But the other reason for floods in northern latitudes is less spectacular but more common - ice dams during spring runoff can back up temporary lakes that cause severe, if temporary and local flooding.

I hope the above paragraph will give developers pause when they begin to lay out tracts on active flood planes - by far the easiest place to build houses. It isn’t a case that an active flood plane might flood, they <u>will</u> flood - that’s how they were built! There’s another factor - the flooding will get worse with time - every man-made structure, such as docks, retaining walls, levees, and bridge abutments confine a stream’s cross section, and make it less efficient at getting rid of flood water. Erosion and eutrafication - over-fertilization from agricultural runoff, both accelerated by man, add to this decrease in efficiency, and increase in severity of flooding with time. Erosion by silting the waterway, Eutrification by promoting too much aquatic plant growth, that traps the sediment.

MAN-MADE AND NATURAL TAMPORING WITH DERANGED GLACIAL DRAINAGE: Almost all places that have been glaciated have had their preglacial bedrock-dominated drainage rearranged by unconsolidated glacial deposits.

The West Wilson Spit: I learned my lesson as a kid: The Great Lake’s basins are tilting south because of accelerated glacial rebound to the north. Drainages on the south side of Lake Ontario, where I grew up, have drowned estuaries, usually dammed at their mouth by spits built through the drier season by wave action and long shore drift in the lake.

Through the drier months filtration through the sands of the spit took care of the excess water from a rain. In spring flood however, a few to several feet of water would back up and flood all the camps on the estuary. A crew of the hardiest men would dig a trench trough the spit.

Just before the last shovel full, the most athletic guy would rope up, and several others would get ready to haul him from harms way if he lost his footing. As he removed the last shovel full, the dammed estuary took over and dug a canyon full of spectacular whitewater through the spit in less than a half hour. Kids were strictly forbidden... but we watched from a distance.

The Glover-Barton Flood: About forty miles north of where I live, there was Long Pond (since known as Runaway Pond) that contained just under 2 billion gallons of water and was located right on the valley’s drainage divide. It either drained south or drained by subsurface filtration. In 1810, about fifty men decided to dig a new outlet to the north, probably to build a water-driven mill. It was just like the Wilson sand spit - it got away from them and the pond drained in about two hours, flooded Glover and Barton down stream, and raised the water level of the very large Lake Mephramagog, still farther down stream, by about a foot.

According to legend, a Guy by the name of Chamberline took off on a run warning of the impending flood. Probably others on horses took up the baton and, amazingly, there were no deaths. They still celebrate his heroism in a Chamberline appreciation run commemorating the event. (Google “Runaway Pond, Vermont” for more details.)

HUMMOCKY TOPOGRAPHY: Avoid hummocky topography with closed depressions that indicates Glacial kame and kettle, landslides, or karst.

Glacial Kame And Kettle Topography: Glacial kame and kettle topography is usually an area of glacial-fluvial sands and gravel, a kame terrace, shed into temporary lakes in the cleft between the edge of a glacier and the adjacent bedrock hill (Fig.).

Fig. 21c Diagram showing a common setting for kame and kettle topography.

It is unstable twice: Immediately after active glaciation, while buried giant ice blocks from the glacier are still melting and collapse is active into the forming kettle holes. It becomes unstable again, as any unlithified material would be, in meander bends of rivers eroding it and in the faces of the large pits dug to remove the excellent sand and gravel. It is important if you visit such pits, which show excellent sedimentary structures, that you do and go exactly where the owner says you can - they are attuned to the hazards because they work with it every day. If they have a sign, “No trespassing allowed”, they mean it - it isn’t safe!

Post glacial, kame and kettle terrain may actually be pleasant territory to build on, and can be very economic - providing some of the world’s best sand and gravel pits. You do have to avoid over-steepened slopes - next to an eroding river, on the banks of a kettle, or adjacent to a gravel pit. Other than that, it is well drained and a joy to put a foundation into - if its well engineered for the soft materials. The many small ponds do eventually fill in, but slowly because there is little surface drainage into them.

Latex Peels: This is a good place to digress to the fun and dangers of a latex peel. A latex peel is done by putting gauze on a vertical face of unlitified material and painting it with several coats of latex paint. The paint differentially seeps into the intricacies of bedding and structure and preserves them in minute detail when you pull the dried peel away on a piece of plywood. Latex peels decorate the walls of many executive suites in the extractive industries, and they have killed a good number of geologists - a vertical face in unlithified material is inherently unstable. A good rule of thumb is never take a latex peel from a face over navel high and always have helpers with shovels standing by.

Karst Terrain ; is an area of caves, sinkholes, collapsed cave systems and spectacular residual hills. It takes its name from the Karst region of Slovenia on the shores of the Adriatic Sea. There is no more classically spectacular karst than that around Goulin, China, (Fig.). Wikipedia provides a long list of karst areas of the world.

Fig. 21e Diagram of classic karst topography around Goulin China.

Karst is caused by dissolution of carbonate rocks in areas uplifted enough to lower the water table, and in a humid climate (or what was a humid climate during glacial intervals - ie. Carlsbad Caverns in semiarid New Mexico). In youth there are a few caves in an extensive limestone. In maturity many cave systems have collapsed, leaving a mix of spectacular carbonate remnants, resembling canine teeth, surrounded by valleys at or near the new water table, near the base of the dissolvable carbonate. In old age, only the occasional insoluble remnant stands above the now-extensive plane because most of the carbonate formation has been dissolved and eroded away (Fig.).

Fig. 21f. Diagram showing the youth, mature and old age stages of karst topography.

From a hazards point of view you don’t want to be collapsed on or under. Sink holes occasionally swallow houses or close roads, and water systems are often disrupted by changes in the plumbing as karstification advances. Some otherwise fertile areas can be unfarmable due to lack of surface water, other areas provide rich farm land. The latter are sometimes called karst windows, there the water table is at or near the surface. To paraphrase an old dictum - when in karst do as the karst dwellers do - they have a bred-in feel for the hazards and the specific areas of danger.

MASS WASTING: Mass wasting is the umbrella term for down-slope movement of material without the aid of a fluid medium. As desert flash floods and volcanic lahars prove, there is a continuum between dry mass wasting and stream transport with a heavy bedload. Though there are many variations in detail, mass wasting can be lumped into three big categories - rock falls, coherent landslides, and chaotic debris flows (Fig).

Fig. 21g. Four principle types of mass movement. Note that rock falls accelerate at the speed of gravity (32 ft/sec squared), slump and debris flows can be slow or fast, and creep/rock glaciers are slow slow slow. Note also that rotational slumps have an extensional upper part, and a contractional lower part. A clue to most mass wasting is hummocky topography.

Rock falls indicate at least a partial free fall of blocks. Collapse of the "Old-Man-Of-The-Mountain" profile in New Hampshire is a famous example, at least in New England. We saw a scary one on Svalbard - while walking on the flat between a big cliff and the fjord - we noticed erratic mega-worm tracks with a boulder at the fjord end of them, well down toward the fjord from where we were walking - freeze-thaw was wedging boulders from the cliff, they were bouncing off ledges, and way out on the flat before they hit - we got out of there in a hurry.

Landslides start as coherent rotational slump blocks, break up as they develop, and end up as chaotic debris flows, if they travel far enough (Fig.). So it kind of depends on what stage of development they are arrested at, or you see them at.

Landslides have a verity of causes, often with many factors acting together to cause the slide. Steep slopes, water saturation, undercutting of the base of the slope by man, rivers, or wave erosion, and earthquakes are just a few.

Mass wasting can be slow or catastrophic. It can be as slow and boring as watching paint dry - when the whole weathered regolith moves down hill imperceptibly slowly it is called side hill creep - no relation to the famous melodrama villein. Creep tries to tip trees over down hill. Trees try to straighten back up. This creates millions, maybe billions, of potential walking canes - great business opportunity!

Just up from creep in terms of excitement, are the rock glaciers of the mountain west - large areas that look hummocky and chaotic on the ground, are hard to walk over, and look like they are flowing downhill on aerial photos. Blame freeze-thaw - nightly freezes expand the regolith at right angles to the slope, daily thaws drop it back down vertically - the net movement being a saw-tooth ratchet down slope. In the arid west the greater diurnal change in temperature (often 50 degrees F) makes for more freeze-thaw cycles and better rock glaciers.

VOLCANOES Stay well away from volcanos, but if you must be near them be high above drainages that could funnel pyroclastic flows or lahars, and have a high hill or deep valley between you and the volcano, and upwind of the volcano is better.

Pyroclastic flows (Nuee ardents, glowing clouds) are gravity flows steered by the slope of the volcano and valleys below it- picture a bobsled run. The sled hugs the valley bottom on the straight stretches, but ramps up on edge as it banks into the turns. Pyroclastic flows do the same thing, but can actually top the ridge and spill into the next valley on a turn. Two of the world's most-experienced volcanic researchers were killed by misjudging the eruption and topography in such a setting.

Lahars are the bigger cousins of desert flash floods. With desert flash floods, scant vegetation holds the regolith down, and the seldom water that does come picks up soil and boulders and heads down valley like a freight train. Speaking of freight trains, one flash flood carried a steam locomotive down slope for the better part of a mile.

Figure 21h. Map of western Washington, State, between Mt. Rainier and Puget Sound. Volcanic mudflow (lahar) deposits within the last 5,600 years, from Mt. Rainier, shown shaded. Note that there are over a dozen towns shown within the mudflow deposits - mudflows and people both love valleys, there's the rub. Note also that the three major flow routes are over 50 miles long and hadn't expended their energy when they went into Puget Sound and continued on as turbidites. This is a very bad accident waiting to happen, especially if it is the middle of the night with everybody sleeping. From Session's 1995, USGS open file Report 95-642.

I got converted on flash floods the day we drove down Titus Canyon, an "hour-glass" canyon draining into the east side of Death Valley. Hour-glass because the canyon walls overhang until you can hardly see daylight. But enough daylight to see flood-born debris wedged in cracks 30-50 feet above the top of the vehicle. Needless to say, we were very thorough in checking the weather forecast, and looked around for any trace of a cloud just before we entered the canyon, which, is impossible to get out of except at the bottom on Death Valley's floor. In hindsight, we should have been even more apprehensive - had we encountered a debris dam, I'm not sure even a 4X4 could have made it back up the canyon in the soft gravel. Makes more sense to drive up such a canyon.

EARTHQUAKES: Earthquakes are concentrated at plate boundaries, but no place is immune - the very large Reelfoot Lake quake in the American mid continent in 1811 proved that. Earthquakes are caused by stick slip - stress builds up slowly (about the rate your fingernails grow) until faults finally snap, and then it starts to build up slowly again. The stronger the rock, the more stress can build up, and the bigger the quake, but the longer beween major quakes. The faster the plate movement, the more frequent the quakes. An excellent example of stick slip, that students just hate, is to screech a piece of chalk across the chalk board - the consistent periodicity of the dots is amazing, and the consistency of the pitch indicates that each "quake" was of the same magnitude.

The periodicity of quakes often exceeds both the historical record and our attention spans; The San Andreas pops off somewhere along its length about every 20 years - no problem there. Puget Sound, on the other hand, appears to have very large quakes (potentially like Alaska) but a periodicity of about 400 years, with a local written historical record of less than 200 years. Interestingly, the last big one around Seattle was recorded in Japan as a tsunami - their written history goes back much farther than that in the western U. S.

Earthquake-generated tsunamis are one of the main ways geologists date quakes in the geologic record. The tsunami sweeps all sorts of regolith into local depocenters, where it is preserved. The ample organic material swept in with it allows good carbon dating of the earthquake.

Earthquake intensity is measured by the Richter Scale, named after the US seismologist, Charles Richter, who devised it. It goes from 1 to 10, with each successive digit emitting ten times as much energy as its previous one (1=1, 2=10, 3=100, 4=1,000, 5=10,000, 6=100,000, 7=1,000,000, 8=10,000,000, 9=100,000,000, 10=1,000,000,000 units of energy). The biggest quakes yet measured are in the low nines, in Chile and Alaska. Fukushima's tsunami was caused by a 9.0, offshore.

Resources in an environment of falling (Post Peak Oil) energy availability: This logically leads to a discussion of what should happen to resource availability as oil peaks and energy availability begins to decline. I'm afraid the answer is disaster. We have too-late began too feebly to replace Oil with renewables and conservation.

You can't generate renewables, in the amount required, with energy from renewables - that would be like trying to construct the Eisenhower Interstate System with Mule teams - the energy just wouldn't be there. You can only do it with left over energy from pre-peak oil - a one-time gift that we have nearly squandered with excessively-high, and wasteful, living standards. Even the wars we wage to protect our access to these resources, in the long run are squandering the very resources they are (usually covertly) waged to protect.

We will basically be forced to run the movie backwards - exploiting only shallower and richer deposits as energy dwindles. But these were already used up in the early days of the Industrial Revolution? In combination with out of control population, the frightening inevitability is a free-fall in resource availability - driving us back toward the stone age.

We will have a few, but inadequate, cushions to ease the fall - re-mining our landfills, improvement in efficiency brought on by increases in technology, and a plummeting world population, be it by birth control or Malthusian disaster. As Hubbert pointed out to me in his one minute lecture, lemmings and locusts do finally have their population problem handled for them...but it isn't pretty.

The only humane alternative is massive conversion to renewables and efficiency, in combination with radical world-wide birth control. So far, the world, and especially America, give little indication that they are capable of handling (or even realizing) the massive sacrifices necessary for the good of our grandchildren. We have to convert, radically and rapidly, to a low-energy, high-efficiency, locally-dominated system to save humanity and its support systems.

EARTHQUAKES

Timber framing, (and log construction even worse), is ecologically wasteful. After the massive timber frame is complete, you still have to close in walls and partitions with stick construction. Add about another 10% to that stick construction, and you can frame the whole house with stick construction - timber framing wastes almost half of framing lumber. When timber framing was the best option 200 years ago they had virgin timber, were trying to clear fields to plant, and literally had premium wood to burn. And they overdid it - by the early 1800s Vermont, for example, was 80% denuded. It took 200 years and adverse conditions for the family farm to get it back to 80% timbered.

In summery, timber framing is a poor choice in the tropics, where the too-few critical pegs and braces can rot. It is a poor choice in earthquake country because it has unnecessary excessive mass, in combination with too few connections sharing potentially too much stress. It is a poor choice ecologically and socially, because you can build two stick frames with the same timber, and at almost half the price each. It is also a poor choice energy-wise, creating massive through-wall conduction, avoided by insulated stick framing - our ancestor's axiom was forty cords of wood per winter, and that was with closing off most of the upstairs rooms. But they had it to burn - we don't.

Try this mental exercise: A log cabin with 100 ft perimeter and 8 ft walls has about 800 ft. of logs. A stick frame has 6 inch walls about 1/10 wood = 40 ft. of wood. This leaves 760 ft. of wood to convert to cellulose insulation - about X10 lighter than wood = 7600 ft. of cellulose insulation from the same wood. The bays of a stick frame would be 40ft3 - 4ft3 = 36ft3. The insulation from the rest of the logs would insulate about 20 stick frames. Summary - the wood in a log cabin would build and insulate several stick frames the same size.

Now thermally - The above log cabin has 800 ft2 of interior side of exterior walls exposed to thermal conduction through solid wood and chinking. A stick frame with both interior and exterior strapping, at least one side of which is universal diagonal bracing, has almost no wall exposed to direct conduction through solid wood. 9/10 of the stick wall is exposed to conduction through cellulose insulation - 10X a better insulator than solid wood, but 1/2 as thick, so it passes 1/5 of the btus.

About 1/10 of the stick wall is exposed to conduction through paths with two thermal breaks filled with cellulose in the strapping bays. If one side of the stick wall is horizontally and the other diagonally strapped, there is almost no area where there isn't at least one thermal break filled with cellulose. This means that a 6 inch stick wall is at least X5 more thermally efficient than a 1 ft log wall, or will cause you to burn x5 less wood to stay warm.

The double offset stud variation of the stick wall, with three layers of strapping, ends up a foot thick, is 10x more thermally efficient, requires no drilling to run electric, and provides so many internal shoulders that there is no chance that dense-pack cellulose can sag, even a little. This "wave of the future" variation is probably 5x more thermally efficient than a straw bale wall twice as thick, and is near the ultimate in earthquake proof construction.

Bottom line - stick construction is several times more efficient thermally and materials-wise compared with log construction. As we transition into peak oil and global warming, log construction should be legislated out. Better still, fee-bate them - charge them 1$/ft.2 for the misguided privilege of being wasteful,and distribute this as a rebate to the ten stick frames that are several times more efficient and earthquake proof.

Stick construction: If I am being critical of other forms of construction, I had better lay out the details of stick construction, which I think are best. There are numerous reasons why stick construction makes up well over 90% of residential construction. It is the most frugal in materials and labor, among the best performing in earthquakes and good in hurricanes, is thermally efficient, and it is a renewable resource.

The variant promoted here - universally diagonally braced with locally-derived rough lumber, is probably the greenest of all construction. It has the capability of lasting 200+ years, thus avoiding the necessity of building several replacement houses built for planned-obsolescence with overly-frugal framing. It avoids petroleum based products, especially plywood, and expensive and dubiously-effective hi-tech metal and plastic fasteners, and long-range transportation. Structurally it is amazing - if the bases of studs in one corner rot out, adjacent walls pick up the load. If the bases of the studs on one wall rot out, the adjacent corners can pick up the load.

1.

EARTHQUAKE-PROOF CONSTRUCTION

Note: I am not a qualified structural engineer, though I had a 28 year career as a structural geologist. Rather, over and above that I have an atypical but extensive 65 year and continuing career in affordable housing. A low-tech and sometimes nearly homeless background in low-cost and small construction. From age 12 I worked construction whenever I wasn't actually in class. At 13 I mixed all the mortar for a small picture show by hand in a mortar box. This included one long wall that my father had to build twice - a flash thunderstorm flooded the foundation pit and pushed the green blocks over - he had not braced for it and lost his shirt.

By 14 I was a journeyman stone mason building fireplaces and also contracted to stucco a two story house - tended myself. At 15 my parents divorced and I began building a 20x24 house for my mother, sister and I. I still remember the figures - $500 for the lot and $1800 for all the materials. Through high school I went to school mornings, built fireplaces afternoons and saturdays, and built the house evenings and sundays. It took 4 years to get the $1800 for materials.

Since then, my wife of 53 years and I have renovated nearly that number of old houses. Correcting structural problems in old houses really teaches you how buildings fail. Along the way I have designed and built from scratch several utility buildings that have averaged about the size of typical dwellings in Haiti.

I don't preume to be smart enough to give a fool proof formula for building structures that will withstand all earthuakes. I hope I am giving advice that will improve the propability that humble structures, at the bottom of the economic ladder, will have a better chance.

Lessons from <u>Port au Prince, Haiti</u> and <u>Anchorage, Alaska;</u> These two cities are about the same size geographically, and are both in earthquake zones. At magnitude 9.2, (second largest ever recorded) the 64 Alaskan earthquake released more than 100 times more energy than the magnitude 7 Haitian earthquake. It caused considerably more ground breakage and elevation change, and was felt over a much greater area. It produced a tsunami that devastated Northern California thousands of miles away.

In fairness I should say that the the Port au Prince quake had a much shallower <u>focus</u> (depth of the initial break of the fault). This causes a sharper jolt, but in a more limited area.

Still, the Alaskan earthquake resulted in nearly 5 orders of magnitude less deaths (3 in Anchorage proper vs about 230,000 in Port Prince). Anchorage was back in business within a few days, you would have to look hard to see any scars within a few months, and they required little outside assistance to do it. Why?

1. In 1964, Anchorage had about 100,000 residents in a city with infrastructure designed for that number. Port au Prince has 2 million, with an infrastructure that, by the same standards, could minimally support 20,000. Port au Prince may be the largest city in the world to have no central sewage system. In other words, abject poverty, in combination with over population and poor education, were an overriding cause of the devastation in Haiti.

2. Anchorage women are educated and have small families, Port Prince women uneducated and have large families. There are two kinds of Anchorage women - White and Native American. White women tend to be well educated. Native American women are less well educated. But the Native American women are still in place and not kidnaped as slaves from their homeland. They still have the traditional support systems of their clan. Also, the dictates of the arctic winter are second nature to them - food will be scarce and there better not be too many mouths to divide it between.

World wide, there are several reasons for large families: A) Your country has no social safety net, infant mortality is high, and your only hope for security in your old age is a large family - China prior to Mao is classic; B) Your religion has a strict anti-birth control, pro large family bias; C) You have been displaced from your homeland as slaves; D) The interests or fortunes of your oppressors have changed with history and you have been abandoned. E) You have been ruled by a succession of despots with self aggrandizement as their main motive. In sharp contrast with Anchorage, Alaska, Haiti/Port au Prince suffers from all of these.

3. Anchorage people are vital, healthy, and resourceful - you don't move to or last there if you are a wimp. As recently as 1915 Anchorage was a vast tent city of prospectors heading for the gold fields. In Anchorage each few miners

brought and built their own tent because they wanted to be there. In Port au Prince the world is trying desperately to build a similar sized tent city for victims who don't want to be there, and have neither the physical, educational, or psychological resources to help themselves.

4. The Chugash Range, south east of Anchorage and the Island of Hispanola that Haiti sits on the western half of, have a lot in common. Anchorage is in a mild rain shadow, but Thompson Pass, on the other side of the Chugash Range, gets 900-1000 inches of snow a winter - the highest snowfall in North America. This is an extreme example of orographic control of precipitation. On Hispanola we see the same thing, though the prevailing winds are reversed because it is in the trade winds zone. There the east side of the island, the Dominican Republic, is well-watered, and Haiti is in the rain shadow.

Though Anchorage and Port au Prince are both in rain shadows, it helped Anchorage and hurt Port au Prince, largely because of latitude differences. The rain shadow is a major reason Anchorage is there - gray arctic climates combined with not much winter daylight are depressing, and a little bit of extra sunlight goes a long way. It doesn't take much rain to support forest cover around Anchorage because there is little evaporation. But the 18 plus hours of summer sunlight does wonders. The nearby Matanuska Valley is famous for bushel basket-sized cabbages. But the good transportation system from the lower 48, in combination with smaller population, makes it unnecessary to clear-cut forests for agriculture, houses, or firewood - the sustainability tipping points for these basic commodities have not been exceeded.

The combination of the rain shadow and good forest cover minimized land sliding in the 64 Alaskan quake, even though it was locally spectacular (Figures). In contrast, Haiti's combined rain shadow and over population have caused every aspect of their life support system to be exceeded, soil, forests and water supply among others. This combined with the abject poverty, minimal education, and lack of resources have resulted in rampant corruption and horrible construction standards. Lets now compare Anchorage and Port au Prince construction:

Figur 22a . This picture is characteristic of the business district in Anchorage: There is a one story high normal fault scarp in the foreground, and the whole row of buildings on the other side of the street, and the high rise in the background, are intact. There is not a single instance in this picture of a higher floor collapsing on a lower one.

Reasons are strait forward: The city is young and the population (especially the structural engineers that design the buildings) are educated. Design parameters are logical in principal, but have to be precise in detail - lots of rebar and portland cement in the concrete and lots of diagonal bracing - sometimes called “shear walls”. But above all, there must be adequate design and inspection, minimizing graft and corruption.

The next four pictures are of four different buildings in Port au Prince left in successively greater degrees of damage after the quake. To get a feel for how masonry/ concrete buildings collapse, consider them as a movie of the same building collapsing.

Figure 22b. A seismograph and a building have much in common. A seismograph has a suspended weight designed to stay stationary while the earth shakes under it. A pencil attached to the weight scratches a record on a paper disk attached to the earth. The paper disk is attached to a clock-like mechanism that moves or rotates it. The result is a timed record of the quake and its intensity. (The above is a metaphor - seismographs in use today are extremely high tech.)

A building, on the other hand, is forced to emulate the seismograph, but wasn't designed for it. The foundation moves with the earth, while the upper floors try, by inertia, to stay put. The result is extreme racking (shear) between the two. Allegorically - top of the building moving right, bottom moving left. Those Xs between windows are conjugate shears, and actually normal faults with the hanging wall moving downward. Combined they are trying to squash the building, but they are caused as the building racks first one way an then the other.

SideBar: I never realized what an authority I am - I've seen thousands of these shears and am the only person I know that claims to have seen a surface seismic wave (conventional wisdom says you can't - too fast and too long a wavelength). Not so. In the Air Force I was standing looking down a long central hall in a long wooden barracks drinking coffee at the machine at one end it. A 5.4 came through, the bottom of my feet were hit with a sledge hammer, and I spilled my coffee - small price to pay for such fame. The floor looked like a rug with a large rat under it running at me at fantastic speed. Actually, even my two buddies at the coffee machine never believed me - they weren't looking the right way. As for the thousand shears - they were all in concrete test cylinders - several to hundreds in every cylinder I tested - I was bottom man on the totem pole at a testing company branch office and had to bust a couple of dozen a day.

Figure 22c . Sometimes one set of shears dominates and the building begins to collapse sideways. Note the large intact segments of corner columns. They probably prevented, but barely, total collapse.

Figure 22d. Every thing bad shows here. The roof and floors are flat slabs instead of engineered designs with integrated beams to give it depth but not unneeded weight. Good floor designs look like a worms-eye view of a waffle from underneath. Sections of under-fit concrete block walls appear to have been the main vertical support. No rebar is showing.

At Pittsburgh testing we were asked by a structural engineer to do deflection tests on a suspect building designed like the one above in Port au Prince that collapsed. The floors sagged significantly when we sand bagged them, we were really glad to get out of there, and the building was condemned.

Figure 22e. Port au Prince. What a difference between this and the Anchorage school. This Port au Prince commercial building has gone past the stage of shear cracks, past the stage of floors collapsing on floors, and has disintegrated to rubble. No one could have lived through it.

Two salient reasons show clearly - the concrete floors are massive straight slabs, and there is almost no rebar showing. More subtly, there are both 4 and 8 inch concrete blocks in the rubble that could only have been used in walls. There are no intact segments of massive reinforced corners (see the second building back) and interior columns showing. In a well designed building these are the most massive and strongest structural features. They should have been the most recognizable unit in the rubble. There is no rebar showing - almost every linear feature is either downed electric wires or segments of railings.

Bottom line - the overly massive concrete floors and roof were supported by nothing but under-fit concrete blocks. They could (minimally) support a static load straight down. They were doomed to disintegrate the instant sideward shear stress from the earthquake hit them. This building is actually worse than classic old adobes, that are held up as the worst possible earthquake architecture. At least the old adobes were usually topped off with wood-framed roofs.

There is something even more spectacular about this picture - across the street is a block of buildings still intact, and the road between appears unbroken. This proves that the earthquake generated stresses were moderate and survivable, and that the fault lies with the building not the quake. I doubt that this street has ever seen a structural engineer or an inspector. The fate of each structure and the people in it depended strictly on the skill and integrity of the builder.

Skill and integrity of a builder doesn’t exist in a vacuum. They are strongly influenced by all the demons lurking in the background. Some of these might be the corruptness of local politics, financial constraints of the owner, availability of good help and/or materials, and time constraints - are there other clients wondering why he’s late starting their job.

Most of all is simply the chance for greed and corruption in an unregulated and uninspected environment. Strength of concrete is directly proportional to amount of cement and rebar - the most costly ingredients. No one is looking so you use half the cement and rebar and double your profit. And weak cement looks about as good without testing as good cement to the layman. There is a variation of Murphy's Law in a circumstance like this - The worse the builder, the more he is hassled and distracted and the less he is capable of doing even his best work, even if he has good intentions.

Figure 22f. An Anchorage area school cut in two by a fault scarp with offset equal to about one story of the school. The greatest loss of life in Port au Prince was when the floors of large public buildings collapsed in on each other. In contrast, this school is almost intact except right in the exact fault zone. Notice that almost all lines in the school are almost perfectly straight, including the roof line that has been sheared by the fault. This school in Anchorage performed superbly - kids would have been safe in the entire school except for about twenty feet right in the fault zone. (Photo from Wikipedia)

Lets take this to the other extreme, which unfortunately is Haiti's residential areas. About the only building materials these destitute people have are weathered and crumbling stone, usually laid up dry, or as inferior concrete. They dig it out of their poor soil that should have been left intact for a garden. That and a crude form of adobe made out of what's left of their garden mixed with water. With very low strength and very high mass, it is the worst af all building materials, and now the poorest of all gardens. The same goes for the commercial construction - its easy when no one really cares and things are corrupt to cut corners on quality of aggregate, rebar, structural design and inspection. This is what did in Port au Prince.

(Photos of Anchorage buildings are from Wikipedia, Photos of Port au Prince buildings are from Boston.com Google "earthquake building damage" for each city.)

I took a year off grad school to recoup finances. I worked in a branch office of Pittsburgh Testing Laboratories, a respected national outfit. Our bread and butter was concrete design and testing. I, being the new hire, got to check the mix at the batch plant, make the test cylinders at the jobsite, and break them in the carefully calibrated hydraulic machine. I also had the authority to shut the pour down if the slump was too great (too much water in the mix). Bottom line: there are rigidly followed procedures that must be followed for a good concrete building. Like a chain is only as strong as its weakest link, if any of these is inadequate the building can collapse. In Anchorage all of these procedures were apparently in place. In Port au Prince, apparently none of them.

Let's now turn to residential construction:

Figure 22g. Turnagain arm, an Anchorage residential area. At first it looks like utter chaos, but look again. Almost all the houses are intact, though tilted, even though the ground has been liquified by the shaking and is flowing toward the adjacent water. Those houses are performing superbly, acting like boats, intact, bobbing on a stormy sea.

Designed and done well, the combination of stick construction followed by a universal wrap of exterior plywood is about as strong as residential construction gets. It doesn't have the brute strength of reinforced concrete but it has something better - an even higher ratio of strength to weight than reinforced concrete on the commercial buildings. Concrete and traditional post and beam in wood both have the potential Achilles heal of too much stress on too few connections, In contrast, stick/plywood construction has the added advantage that resistance to shear is shared by hundreds of nails across the building, and not concentrated in one or a few hi-teck shear resisters.

Figure 22h. Chaos on a bedrock hill overlooking Port au Prince. The Bible, geologic and architectural conventional wisdom, and even common sense, suggests that “build ye not a house on sand, but on bedrock.” Here’s a bedrock side hill with no faulting and no indication that the regolith is sliding toward the ocean. There is apparently a complete spectrum of residential construction quality on this side hill. A significant minority of houses appear to be perfectly intact, proving intact was possible. A significant number are completely demolished, proving poor design, materials, or workmanship are at fault. Compare this picture with the Turnagain Heights residential area near Anchorage.

Bottom line: Good design, materials, builders, regulation, and inspection are necessary and, combined, Anchorage proves they really work. Flip side: These necessities are almost impossible to achieve in a socioeconomic setting like Port au Prince - that didn’t work.

A PLAN FOR PORT AU PRINCE:

20-30 years ago there was a write up in popular mechanics that a Russian engineer had done the impossible. Single handily he had figured out how to improve the efficiency of the steam engine several times more than the rest of the world’s engineers, combined, had been able to improve it in the previous 100 years. A Eureka moment? A true light bulb going on? Not in his view. In his view it was hard work. His bottom line:

1. Dream the utopian solution
2. list every possible obstacle to that solution
3. work doggedly to eliminate every obstacle

When the last obstacle was overcome he had his amazing improvement.
Thus the old cliché - progress is 1/10 inspiration and 9/10 perspiration.
Edison, with his hundreds of light bulbs that didn't work, would smile.

The utopian solution is important and has to come first. Hung above the work place where you stare at it every morning before you get started. Without it workers are adrift and will spend all their time chasing wild ideas down blind alleys. It may bear little relation to present conditions on the ground, just as heaven (a utopian solution) bears little relation to conditions on the ground. But, unlike heaven, in science it is constantly revisited, modified and improved as you get smarter.

Two is like a working grocery list, checking things off as they go in the cart and adding to the list as you think of them. You will never be smart enough to make this entire list at the start of a project.

Three is simply what you spend every day sweating at.

So there's an operating procedure, here's a list: Rebuild large buildings right, rebuild small building right, reforest to prevent landslides and gain lumber and a place to hike, rebuild the degraded soil for farming and food self support. Perhaps most important - educate the people to improve their lot so history will not repeat itself.

TO DO
universal diagonal bracing
during construction
retrofitted

San Migel de Alende indigenous concrete construction

THE BIG-BOX ROOF

In big-box stores roof structure is all alike, be it Walmart, Costco, Home Depot, Lowe's, etc. And it is fully exposed. It is made up of standardized trusses, capped by standardized decking, supported by standardized columns. It is rigidified by a combination of exterior reinforced concrete walls and corrugated metal roof decking that resist racking, and interior steel support columns anchored deeply in concrete below floor level. This is augmented by the largest support trusses being rigidly fastened to support columns at both their upper and lower chord.

This roofing system is almost infinitely adjustable to fit any size and configuration of floor plan. It is highly adaptable to earthqauke-prone areas - basically beef up the structural members and bracing relative to the size of the structure.

Big Box roofs have secondary aspects hard to beat. Welded and bolted connections are open for inspection, both during and after construction. In sum-total, the roof system is 9/10, maybe 99/100 air - extremely light for its structural rigidity. This contrasts starkly with the thick, massive, un-rebared concrete slabs that dominate Port au Prince rubble. The most frugal and effective business models wouldn't have all adapted this uniform and integrated construction system if it wasn't the best available.

Legislate (or make it a condition of aid) that replacement public buildings have the Big Box design. Also legislate against multiple floors - every big box store is single story, even though it may be more than thirty feet to the roof. Multi story buildings in and earthquake are accidents waiting to happen, both structurally and egress-wise. Though the roof system might be hidden by suspended ceilings, they must be panel-removable. The roof system must be open to inspection in detail through the full life cycle of the building.

Pick a handful of Haiti's most experienced builders and most experienced welders. Pay them masters wages and all expenses to apprentice to their peers in technologically advance earthquake prone areas, California and Japan being prime examples. After a thorough grounding and mentoring in their specialization, bring them home to become the master teachers to convey their knowledge, in hands-on job-site courses, to a larger working cadre that will oversee the reconstruction of Haiti.

In Haiti, graft, ignorance and poverty combined with a moderate earthquake to produce catastrophe. A most important part of reconstruction is to prevent the same old graft, ignorance and poverty from dominating the reconstruction. Reinforced concrete heavy construction, done right, is as earthquake safe as steel or wood. But the operative word is “done right”. There are too many places and too many steps along the way for inferior and graft-prone short cuts to be taken and go unnoticed in reinforced concrete construction. Too many hidden aspects can fail.

In contrast, with the Big Box Model, critical elements of the structure are open for inspection throughout the building’s whole life cycle. The Big Box store construction system is much more quality control and inspection prone. It is also much more correction friendly - a master welder can cut out and replace a flawed section of a structure with minimum disturbance. A good weld is often described as “110% strong.” Better than the original welded member. This can never be said of a “cold“ joint in reinforced concrete.

RESIDENTIAL CONSTRUCTION: I’ll start with some actual cases from my own background:

The Beaver Valley portable cabin: When we owned Beaver Valley campground, we built a 16x20 cabin, designed to be portable.

We bought out a small lumber co’s. entire stock of weathered rough 1x4s and used them for studs, plates, strapping and battens. It was framed 15 in. OC, to give a standard bay for batt insulation. Then we added universal diagonal 1x4 exterior strapping, 16 in. OC, in every plane.

To weather, with Tyvec behind it, we used rough 1/2x12 boards, sealed with 1x4 battens, for siding. This gave a structural wall thickness of 5 1/2 inches, stronger than the 4 inches of finished 2x4 studs sheathed with 1/2 in plywood. And at considerable less cost and, above all, less weight.

Rough full 1x4 studs and plates are actually stronger than finished 2x4 (1 1/2 x 3 1/2), in this structural setting. They make a thicker wall, and can’t fail sideways because of the diagonal bracing.

We also worked a deal on rough 1x10s that we used, 15 in OC, for floor joist and diagonal flooring. We also ripped these in half for 1x5 rafters, 15 in. OC, with a +12/12 pitched roof.

The resulting cabin was so rigid that if you jacked one corner, a second corner raised off its seating (scary actually). Before we lost track, it had been moved around the campground to several locations, sometimes dragged behind a tractor on skids, sometimes on a lowboy normally carrying a large back hoe. The only drawback of this amazing building was that it reverberated like a drum when someone walked in it - there was no structural give to dampen the sound.

The glued down Cheerios box experiment: We bought a property with a 2 car garage that was only 21 ft. wide. It had only three 1ft. wide. support columns, providing almost no diagonal bracing, in the plane of the two 9 ft. overhead doors - a classic achilles heel in garage construction. It leaned +2 inches toward the neighbors - so much so that both overhead doors were jammed. It had horizontal novelty siding and 1/2 in. plywood attic flooring.

We have a huge three-supporting-strand block-and-tackle we pull with a 32/1 mechanical advantage come-along, giving a mechanical advantage of 96. Minus friction, 1 pound of pull on the come-along handle should give 96 lbs. pull on the building. Thus, the 50 lbs. I am capable of should give 4,800 lbs.. of building straightening. This would not move the building until I loosened the screws in the plywood attic floor. Then it straightened it easily.

The problem now was how to keep it - keep the garage doors square and open, after removal of the block-and-tackle and come-along. I had the hunch, that if the sides, back and attic floor were diagonally braced, the door plane would, by default, also be braced. To prove it to myself I took a Cheerios box, with the top removed, and first racked it with the bottom corners free to lift off the table. The open side of the box warped out of square easily. Then I glued one wide side to the table. It was amazing - the empty “door-plane” of the Cheeries box was as structurally rigid as the other three planes.

So I diagonally braced both sides and the back wall of the garage and screwed the plywood back down in the attic - it worked, the doors stayed square, with the block and tackle removed. The bottom line from both the Beaver Valley cabin and the Cheerios box experiment is that universal diagonal bracing really works!

Application to Haiti: The perfect residence for Haiti would have these lightweight strength characteristics, while being well tied down into a concrete slab. Stick construction, universally diagonally braced in every plane, is the key. Universal diagonal strapping of an old building in every plane, can also increase its structural rigidity several times. The key is to let hundreds of fasteners share the racking stress evenly across the entire structure.

How to beef up walls in stick construction in primitive settings: Allegorically a back packing tent is best in an earthquake, but would blow away in a hurricane. Add to this, in the far north like Anchorage, you might have two feet of wet snow refrozen to the roof when the shake hit - one of Murphy’s unintended consequences you have to plan for in earthquake proof architecture.

(Note: This essay is focused on rebuilding Haiti, but also includes Alaska, and specifically the Anchorage area, as a point of comparison in an equally earthquake prone area.) Here is a way to beef up standard stick construction so that it should better withstand their combined threat. It is low-tech, simple, and inexpensive, though labor intensive:

Build these houses on a perimeter-thickened and rebar-reinforced slab with six inch steel mesh in the interior. Put double the number of J-bolts and/or galvanized plumbers strapping tie downs to hold the base plate to the concrete slab. If J-bolts, they have to “J” under and be wired to stay under the lowest of the two rebars under the outside perimeter. If of galvanized plumbers strapping, the bottom end of the strapping must wrap that same rebar.

Frame with rough full 2”x4” lumber, all nails hot-dip galvanized headed commons. Cedar is best for combined lightness and rot resistance but don’t use it. Cedars are small and inefficient to mill and can easily be logged unsustainably. Instead Use southern pine. It’s strong, long and strait grained, if heavy. We have just driven down from the Northeast and am writing this from northern Florida. Because of the downturn in housing starts, there are historically high reserves of these logs deteriorating in the log yards.

Load freighters with stacked and stickered piles of rough #2 2x4x16s, 2x6x16s and l2x10x16s. Let the lumber part-cure on the way to Haiti. On small primitive construction it is very reasonable to use green lumber - maybe even better. Southern pine nails better and splits less green, aging rock hard. With the suggested construction technique, individual boards will be nailed and braced so firmly in place before they dry that they will warp minimally after they dry.

In Haiti frame with single bottom plate, double top plate walls, with studs 16” on center. But spacing is not critical - no 4x8 sheets will be nailed to it. The double top plate is critical and should always be lapped and heavily through nailed at the corners. I take the extra precaution of nailing a 16p common through both 2x4s from each side several inches back from the corner. This acts as reinforcing to keep the plates from splitting at the corner nailing in a shake.

Don’t frame the corners conventionally, just with a single doubled 2x4 post. This is superior to a single 4x4 because the two 2x4s neutralize each other on twist and prevent single knots from causing excessive weakening. This corner post will be thoroughly tied to the upper and lower plates by the diagonal siding.

Windows and doors: Frame all windows and doors conventionally (old-time conventionally - current best practice takes too many shortcuts and uses too many hi tech metal fastenings). Support each end of all headers with a 2x4 jack stud, so every rough opening has double 2x4 sides extending all the way to the bottom plate. Add a third cripple to support the bottom horizontal 2x4 under windows, rather than cutting the jack stud supporting the header - a common bad practice in the US. Resist the trend in the US for hi-tech metal fasteners that produce hotspots of local stress, prone to fail in a shake. Substitute hundreds of nails distributed across the structure in universal diagonal bracing. Over nail everywhere - nails are the cheapest insurance policy you will ever buy. In the tropics, in quake/storm prone settings, all nails should be hot-dipped galvanized - the only concession to hi-tech.

Exterior siding: With wall framing plumbed and square and temporarily arrested with temporary single diagonal braces on the inside, begin sheathing the exterior with 45 degree diagonal full 1 inch thick shipload siding. People have the idea that the 45 degree end cuts are wasteful - only minimally. In the full course of the building, short pieces get used back at the corners. If you start with all 16 ft lumber waste will be minimal, and this is easy to do with southern pine lumber.

Shiplap siding should be in middle width ranges, 6 and 8 inch are best. 4s take too long and are too weak, 10s and 12s can't be forced to conform to their partners, shrink to produce larger cracks, and are therefore more leak prone. Cap the corners with 1x4 trim in both planes. Shiplap is the only siding that will provide both diagonal bracing and adequate weatherproofing in one operation (tongue and groove is an inferior alternative). Turnagain Subdivision in Anchorage proves that T-111 is a viable alternative in the short term, but I dislike it for environmental, energy, long-term stability, and construction ease, reasons. Workers with little skill and almost no power tools can deal with single boards much better.

At the bottom of the wall, this siding must be nailed thoroughly to the bottom plate and all studs and extend at least one inch below the top of the concrete to shed water, but not down into the dirt. At the top this siding must extend at least two inches above the top of the future roof rafters - it will tie the roof to the walls in a shake or blow. The roof-wall intersection is a classic achilles heal in residential construction. Slots for the rafters are cut in after the siding is in place. The bird-mouth in the rafters should swallow the siding.

This type of construction, if well nailed, will provide superior shear resistance and much better breathability, while remaining waterproof. It will perform better than plywood or strand board in the long term. Don't reverse the diagonal in mid wall for symmetry. In fact, go around the entire building with the diagonal the same way.

(**Note on economics:** Economics are turned on their ear right now because of the glut of building materials suppliers were caught with in the sudden collapse of the housing industry. Throughout much of 2009 finished lumber was less expensive than rough, and plywood cheaper than rough boards. That should be coming back to equilibrium as supply and demand get back in sync. Besides - my 18 years in oil company research convinced me that peak oil is real and upon us - I resist anything petrochemical. I also resist it because there are bad allergies to petrochemicals within my family. Also because I've seen million-dollar yachts, supposedly constructed of marine plywood, disintegrating in boat graveyards.

There is no real reason that any timber tree in America should burn or rot, as they are doing in the millions because of current government policy. Hundreds of times more timber trees are unnecessarily burning and rotting in our forests than it would take to completely rebuild Port au Prince. And that city is only a few hundreds of miles by freighter from one of our biggest supplies of timber in the southeast.)

Optionally wrap Haiti's houses with breathable house wrap under the siding. Plastic is not a good idea in the tropics. If you use house wrap it should go right over the window sash, and be nailed under the window sash's exterior trim. It is then neat-trimmed with a knife on the inside of the window casing, preventing both air and water intrusion around windows.

Inside strapping: On the inside of the building, strap walls horizontally with full 1x4 rough strapping, 16" OC. The strapping must continue right to the outside diagonal siding and be double nailed to the corner posts. This is why the corner posts have a simple 4x4 cross section. On alternate walls the strapping will be four inches higher so that strapping can also pass through the corner and dead end tight against the exterior siding. Optionally, put a full 1x12 at chair back height for a crude chair rail. I visualize this wall as all done and with strapping showing. The walls are now stronger than almost any residence in the US.

Finishing off: One of the pluses of this construction method is that the house is livable with just one layer of wood between you and weather. Alternatively, if the owner were to later have the means, the outside is ready to be finished with shingles clap boards, board and batten, or vinyl. Horizontal exterior sheathing has a triple achilles heal: it gives no rigidity to the structure, warps and deforms finished siding put over it, and is susceptible to having nailing of a whole course of finished siding occur in a crack in the sheathing. Diagonal sheathing/siding eliminates all of these problems.

On the interior, the horizontal strapping is ready for sheet rock. Though sheet rock is non structural, I resist interior plywood. It is highly flammable, out gasses long term, burns toxic, and kills many, especially in mobile home fires. (I had a friend who was a rural fire chief - he was most frightened of it and felt it should be outlawed.)

I also resist any kind of petrochemical insulation, regardless of its thermal efficiency and ease of installation. Besides the peak oil implications, it out gasses really bad stuff (Fig.).

Figure Aerial photo of part of 100,000 FIMA camp trailers used after Katrena, now abandoned in a huge field in Hope Ark. (photo by Evan Lewis, Texarkana Gazette). They have excessive formaldehyde contamination from their insulation. They were offered free to Haiti, and Haiti, rightfully, would not take them.

Insulating: This writing is focused on Haiti, but if necessary, this type of construction can be effectively insulated with blown in cellulose. The wall's cleated interior surface nearly preludes settling. For the far north, there is a double offset stud variation of this construction process that results in probably the most energy efficient, while earth quake safe, dwelling possible. Through-wall conduction is functionally eliminated, both at the plates and the corners. As a premium, there is universal access for electrical wiring without drilling.

Roof structure: I resist even the classic cape configuration in earthquake country and with a primitive population. All residences should be ranch-style and shed roof, both for instant egress, and to eliminate second floor weight. I strongly suggest simple shed roofs of modest but adequate pitch for drainage. If dwellings exceed about 14' parallel to rafters, rafters have to be overlapped and spliced, with the splice well nailed and fully supported by either a central wall or beam.

Trussed roofs with 4-6/12 pitch are probably second best - low enough to walk on but steep enough for drainage. Overhang should be 6 inches. Enough to keep most of the moisture off walls, but small enough that high winds don't catch it.

Cathedral ceilings are not good. The vertical acceleration in a quake is like a hammer blow to the ridge. Downward motion of the ridge will convert to an outward push on the walls, potentially destroying the building.

The bottom chord of the truss is all important. When building the trusses, lapped joints are best, plywood gussets second best. Gang nails, which can pop in an quake, are a poor third. At least one large-headed nail should pass through all wood at connections and have a half inch left over to clinch. But multiple nails are necessary to distribute stress.

Roof strapping should be nominal 45 degree diagonal, but not with conventional 16 or 24 inch spacing. Rather every strap should intersect the tip of every rafter so that the obtuse angle of the end cut falls right over the corner of all rafters. This gives a spacing of the 1x4s less than 16 OC and gives maximum good nailing at the rafter tips. Cap this with a 2x4, The 2x4s should be ripped on center from a 2x8, with the cut adjusted to the slope of the roof.

Cap it with wide drip edge, and roof with coarse corrugated metal roofing. It's a toss up - aluminum is better from an earthquake standpoint, steel from a Hurricane standpoint. Maybe the newer galv-aluminum is the best compromise.

Fasten only at the ridges of the corrugations. Use gusseted fasteners, long enough to extend right through the strapping. You may get a neater hole in the galv aluminum by pre drilling or punching with a fine-pointed nail set. It is a little more trouble to fasten to diagonal strapping, but the structural advantages are immense. Don't tack - completely fasten each sheet as you go. Use a fastener at every, at least every other, corrugation near the corners in hurricane country like Haiti.

(note: while I'm suggesting metal roofing, I actually feel that traditional cedar shingles on spaced strapping is superior. I've seen too many barn roofs, even in New England, where wind pressure blew entire roofing panels off, largely from the inside - though once loosened the exterior wind blew the panel off the roof. In contrast, traditional cedar on spaced strapping breaths between each shingle, precluding any pressure buildup on the inside of the building. Also, the biggest surface the wind can catch is a single shingle, not an entire roofing panel.)

The all-important wall to roof tie: Rip a 2x8 down center with the same pitch to the cut as the roof pitch. Cut them into blocks to match rafter spacing. Nail these thoroughly to both the inside and outside of the upward-extended wall sheathing. Nail them also to the diagonal roof strapping, and to the rafters. This roof-to-wall tie is much stronger than the small metal butterflies currently in vogue.

Beefing up stock W trusses: The prime rule in shake and blow country is to keep the roof light but strong. 2x4s are adequate for main members in the truss, but rough 1x4s make better small members in the classic “W” truss. I advocate a “crazy truss” in which the “W” made of 1x4s, side nailed to the top and bottom chords, is compacted on one side of the truss and extended on the other side. This distributes the strength across the truss better. Rafters or trusses should be gang cut and fabricated in a jig for uniformity. Rafters should be butted and gusseted at the ridge with no ridge beam. Since pitches are to be kept low and there is no need for a deep cavity for insulation, shed roof rafters, if used, should seldom exceed 2x8s.

Raising trusses without cranes: Cranes are so prevalent in the US that few remember the old fashion way of putting trusses up - by hand, preferably with a crew of four. (But a crew of one with a small block and tackle will work.) A ladder is leaned against each wall at the truss position. The truss is pushed “too far” up over the top of one wall, giving clearance for the other tail. The other tail is then pushed up over the wall, inverting the truss, and it is worked back to center inverted. With a pole for push and a rope for belay the center is raised through an arc to upright, and secured when spacing has been adjusted.

The first truss is a bear - better have a pole nailed to the exterior of the building to belay it against and keep it from flopping right out of the building. When it’s vertical, put diagonal braces from near-ridge to the wall plate well down the wall, one on either side of the ridge. Later trusses are rolled up under and secured to these diagonal braces (that finally become members of the diagonal roof strapping). Additional diagonal bracing is added as necessary as the trusses progress down the roof. The diagonal braces finally have to be unfastened from the plate, as the trusses approach them.

2.

Analize the Model:

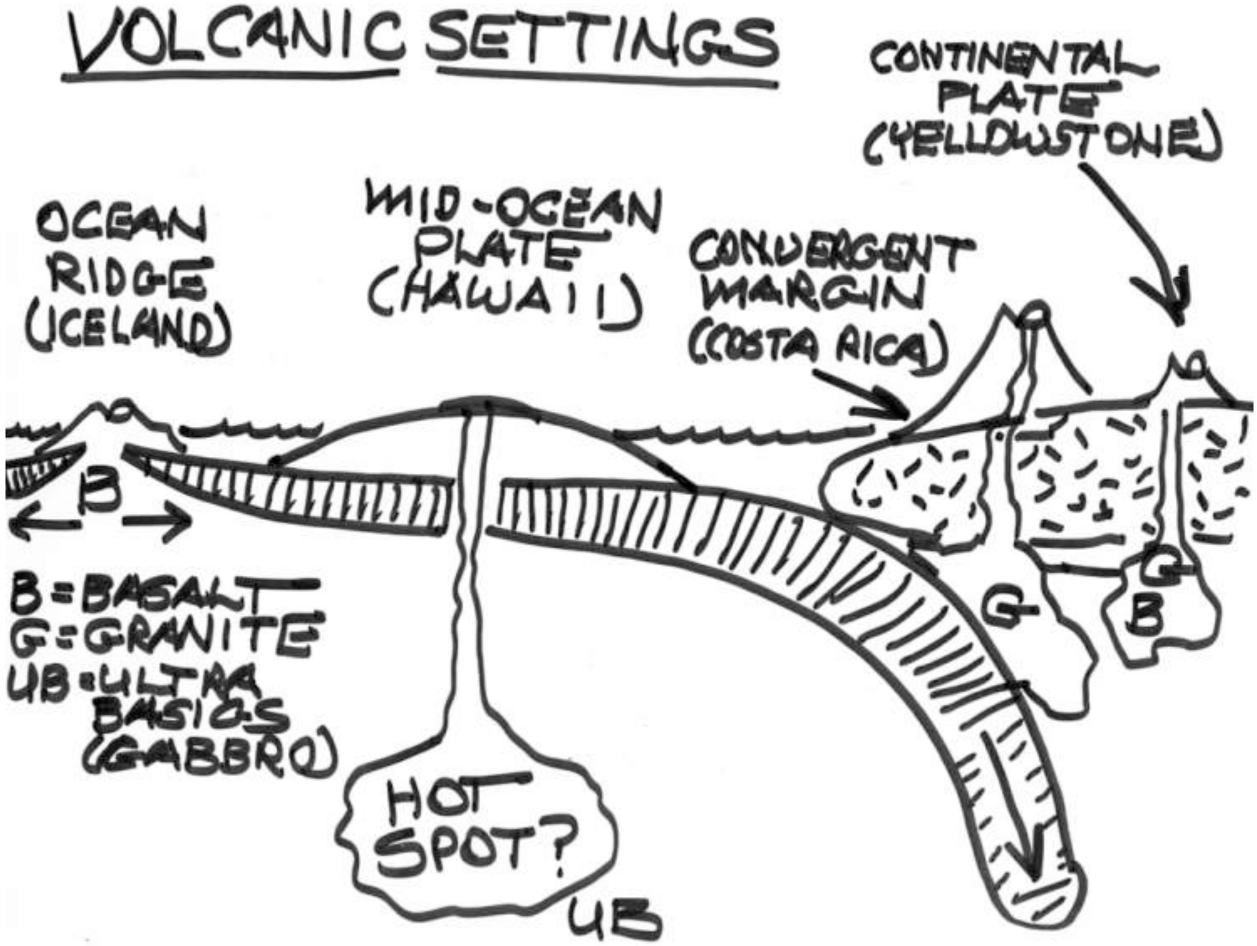


Figure 20b. The main styles of volcanoes. They boil down to two - broad and low shield volcanoes like Hawaii, and steeper and more explosive (strato or composite) volcanoes like Mts. Rainier or Fugiama.

(1) Flood Basalts: The world's most voluminous volcanics don't even come from volcanoes - they well up out of fissures as flood basalts - flow upon flow of fluid basaltic lavas. In oceanic settings they cause oceanic plateaus. In continental settings they "pond" and fill whole huge valleys, often forearc basins. Interestingly, on edges of continents they may drape over the edge and onto the sea floor as a huge one-sided fold or monocline. One of the reasons they don't make volcanoes is that they seldom use the same fissure twice - the congealing basalt chokes it and a crack opens somewhere else.

(2) Fissure ignimbrites are similar to flood basalts in their large volume and eruption from fissures along Basin and Range faults, rather than dominantly from central circular vents. A field of these ignimbrites, estimated at nearly 400,000 km cubed, coincides with the southern Basin and Range Province, from the southern margin of the Colorado Plateau in Arizona to the trans-Mexico volcanic belt, spanning over 10 degrees of latitude in the Sierra Madre Occidental of NW Mexico (Arguirre-Diaz, and Labarthe-Hernandez, 2003).

Note that though, like flood basalts, fissure ignymbrites aggregate as a huge thick sheet, the mechanism and chemistry are exactly opposite: the ignimbrites are silicic and explosive, while the flood basalts are mafic and dominated by passive lava flows with minimum explosive behavior. The Ignimbrites seem to have flared up when an intermediate to salicic batholith stoped it way close enough to the surface that overlying Basin Range faults could open in tension, allowing massive evacuation of the magma chamber. Alternatively it was when the East Pacific rise's mega slab window passed under the base of the then rapidly extending continental crust above. These two causes may not be mutually exclusive.

(3) Shield Volcanos: Hawaii is a cousin of flood basalts - think of it as a flood basalt confined to one central vent, even though the sea floor is moving slowly over it. (see "hot spots"). Because it is basaltic, lavas are so fluid the slopes of this, the world's largest and highest single mountain above its base (some 31,000 feet), are less than 5 degrees - thus the name "shield" volcano.

(4) Strato (composite) volcanos: These are the world's most numerous - almost all located over subducting slabs around the rim of the Pacific. They are constructed of alternating lava flows, mud flows, and ash falls, welded or not - thus the name stratovolcanos ("composite volcanoes" is a synonym).

(5) Calderas: are the hole left when a volcano either collapses into its emptying magma chamber, or blows its top off. If the former, huge blocks of country rock are engulfed and partially digested by the magma to form xenoliths, but few country rock fragments are scattered across the country side. If the latter, few blocks flounder back into the magma, but huge volumes are scattered across the countryside as tephra, or pulverized by the explosion as volcanic ash. Volcanic ash is called tuff after it has been lithified. The process may repeat to form resurgent domes in the caldera. Mt. Mazama collapsed to form Crater Lake, Oregon, a famous caldera.

(6) Volcanic necks (Devil's Tower, Shiprock) are the resistant conduit fillings of deeply eroded volcanoes.

(7) Sideward Collapsed Volcanoes: Many volcanos get so big so fast that their rock stength is exceeded by their mass, and they go into a state of continuous or sporadic collapse, sometimes called gravity flattening. Collapse morphology in the form of landslides is however continuously hidden by eruption of new volcanics that bury the scarps in a "growth relationship", not unlike that seen in deltas.

One of the most famous of these is the Sunlight Volcano in the Absoroka Range of N. W. Wyoming, where the extending flow in the base of the collapse dragged isolated Heart Mountain blocks apart over an area of hundreds of square miles (Figure).

GEOLOGIC HAZARDS:
AN OUNCE OF PREVENTION IS WORTH A POUND OF CURE

There are enough clues in the landscape, local history, in similar settings around the world, and in common sense, to let you make a valid judgment on most geologic hazards. And your homework is much easier, now that we have the internet. But what if a place is risky, yet you love it? A geologist can't help you there - that's psychological. Some avoid all risk with a ten-foot pole, others think it's the spice of life. For you, it may not make sense to avoid all risk, but it does make sense to understand the type and amount of risk, and how to minimize it. If you wish to avoid geologic hazards, an ounce of prevention is worth a pound of cure.

Geologic hazards have plagued us through the ages. For historic perspective, here is what Pliny the Elder, one of the world's first scientific observers, had to say about the Rhine Delta in the later Netherlands, after he had served there as a soldier in the first Century BC: "There lives a miserable people at the highest known levels of tide and here they have built their huts, living like sailers when the water covers their environment, and as if shipwrecked when the water has gone." (McQuaid and Schleifstein, 2006). Ironically these "miserable people", in the course of two thousand years, have evolved into those most technologically savy at dealing with sealevel rise due to global warming.

The Dutch, of course, have dealt with it by creating one of the engineering wonders of the world. But for every success story like the Netherlands there are hosts of horror stories: Haiti's quake, Katrina's hurricane, Indonesia and Japan's tsunamis, Mt. Peli's pyroclastic cloud, and the Missouri River's almost yearly flooding, to give some diverse examples.

TSUNAMIS: Before we start, and just to sober you to the task, realize that the highest recorded wave wiped out whole forests to over 1700 ft above sea level, when an earthquake-generated landslide entered Litunya Bay, Alaska (fig.).

Fig. 21a. Simplified perspective diagram of the Litunya Bay Landslide and wave.

There's a fun barroom story goes with Litunya Bay - supposedly two guys, who had been drinking quite heavily, were fishing in a small boat on the bay. The wave carried them and their boat over the tops of a mature forest, that had been growing on the spit at the lower end of the bay, and deposited them in the open ocean, along with the forest. There the wave instantly dissipated, leaving them stranded in a forest of tangled debris in open ocean. Talk about two confused fisherman.

To call the Litunya Bay wave a tsunami is a stretch - it was an exceptional wave, caused by a local event, in a very small container. Classic tsunamis, on the other hand, are giant waves triggered by sea floor displacement during earthquakes, most often over subduction zones. The vast majority of subduction zones rim the Pacific and the vast majority of tsunami are confined to the Pacific Basin. But, as we saw in 2005, the short segment of subduction in the Indian Ocean in Indonesia is capable of a deadly tsunami. Because the Mediterranean Basin is a closing ocean that is tectonically active it, and to a lesser extent the Black and Caspian Seas, are also susceptible.

A ship in mid-ocean may not even know a tsunami is passing under them. Tsunamis may travel as much as 450 mph, but have wavelengths measured in hundreds of miles, and an amplitude of only a few feet - in mid ocean, so they are almost undetectable. But when they start to feel bottom, the water piles up into a monster that can be several tens of feet high. The runup of the wave can extend to over 100 ft above sea level (Fig.).

Fig. 21b Diagram showing how tsunamis act where they originate, in mid- ocean, and where they hit shore.

These waves are not unidirectional but do focus their destruction in a general direction, depending on the facing of the generating subduction zone. Alaska's Good Friday earthquake is a good example - because of the kink in Alaska, the generating sea floor faced almost directly toward the mega- headlands of British Columbia, Washington State and northern California, which sustained the greatest destruction.

Many Pacific beaches have tsunami warning systems. Another thing, that can give some needed time to evacuate to high ground, is the tendency of many tsunami waves (not all) to be proceeded by a withdrawal of water seaward - if the tide starts to go out abnormally fast, run for the highest ground you can find.

RIVER FLOODS: Because river floods are so common they cause huge damage and loss of life...most of which is preventable. Build high enough above rivers to avoid flooding - that means at least one river terrace up from the active flood plane. If there is a large beaver dam or old man-made dam upstream, add another 50 vertical feet. If their are glaciers or a large old man-made dam upstream, add another 100 vertical feet to that.

Look up the high-water mark of the greatest recorded local flood - there is a small plaque built into the masonry, at about the top of the restroom door, in a Montpelier, Vt. gas station near where I live - "Flood height - November 1927". I found the precipitation contour map for that storm on the internet - ten inches in 24 hours - probably a stalled tropical hurricane. But the other reason for floods in northern latitudes is less spectacular but more common - ice dams during spring runoff can back up temporary lakes that cause severe, if temporary and local flooding.

I hope the above paragraph will give developers pause when they begin to lay out tracts on active flood planes - by far the easiest place to build houses. It isn't a case that an active flood plane might flood, they will flood - that's how they were built! There's another factor - the flooding will get worse with time - every man-made structure, such as docks, retaining walls, levees, and bridge abutments confine a stream's cross section, and make it less efficient at getting rid of flood water. Erosion and eutrafication - over-fertilization from agricultural runoff, both accelerated by man, add to this decrease in efficiency, and increase in severity of flooding with time. Erosion by silting the waterway, Eutrification by promoting too much aquatic plant growth, that traps the sediment.

MAN-MADE AND NATURAL TAMPORING WITH DERANGED GLACIAL DRAINAGE: Almost all places that have been glaciated have had their preglacial bedrock-dominated drainage rearranged by unconsolidated glacial deposits.

The West Wilson Spit: I learned my lesson as a kid: The Great Lake's basins are tilting south because of accelerated glacial rebound to the north. Drainages on the south side of Lake Ontario, where I grew up, have drowned estuaries, usually dammed at their mouth by spits built through the drier season by wave action and long shore drift in the lake.

Through the drier months filtration through the sands of the spit took care of the excess water from a rain. In spring flood however, a few to several feet of water would back up and flood all the camps on the estuary. A crew of the hardiest men would dig a trench trough the spit.

Just before the last shovel full, the most athletic guy would rope up, and several others would get ready to haul him from harms way if he lost his footing. As he removed the last shovel full, the dammed estuary took over and dug a canyon full of spectacular whitewater through the spit in less than a half hour. Kids were strictly forbidden... but we watched from a distance.

The Glover-Barton Flood: About forty miles north of where I live, there was Long Pond (since known as Runaway Pond) that contained just under 2 billion gallons of water and was located right on the valley's drainage divide. It either drained south or drained by subsurface filtration. In 1810, about fifty men decided to dig a new outlet to the north, probably to build a water-driven mill. It was just like the Wilson sand spit - it got away from them and the pond drained in about two hours, flooded Glover and Barton down stream, and raised the water level of the very large Lake Mephramagog, still farther down stream, by about a foot.

According to legend, a Guy by the name of Chamberline took off on a run warning of the impending flood. Probably others on horses took up the baton and, amazingly, there were no deaths. They still celebrate his heroism in a Chamberline appreciation run commemorating the event. (Google "Runaway Pond, Vermont" for more details.)

HUMMOCKY TOPOGRAPHY: Avoid hummocky topography with closed depressions that indicates Glacial kame and kettle, landslides, or karst.

Glacial Kame And Kettle Topography: Glacial kame and kettle topography is usually an area of glacial-fluvial sands and gravel, a kame terrace, shed into temporary lakes in the cleft between the edge of a glacier and the adjacent bedrock hill (Fig.).

Fig. 21c Diagram showing a common setting for kame and kettle topography.

It is unstable twice: Immediately after active glaciation, while buried giant ice blocks from the glacier are still melting and collapse is active into the forming kettle holes. It becomes unstable again, as any unlithified material would be, in meander bends of rivers eroding it and in the faces of the large pits dug to remove the excellent sand and gravel. It is important if you visit such pits, which show excellent sedimentary structures, that you do and go exactly where the owner says you can - they are attuned to the hazards because they work with it every day. If they have a sign, "No trespassing allowed", they mean it - it isn't safe!

Post glacial, kame and kettle terrain may actually be pleasant territory to build on, and can be very economic - providing some of the world's best sand and gravel pits. You do have to avoid over-steepened slopes - next to an eroding river, on the banks of a kettle, or adjacent to a gravel pit. Other than that, it is well drained and a joy to put a foundation into - if its well engineered for the soft materials. The many small ponds do eventually fill in, but slowly because there is little surface drainage into them.

Latex Peels: This is a good place to digress to the fun and dangers of a latex peel. A latex peel is done by putting gauze on a vertical face of unlitified material and painting it with several coats of latex paint. The paint differentially seeps into the intricacies of bedding and structure and preserves them in minute detail when you pull the dried peel away on a piece of plywood. Latex peels decorate the walls of many executive suites in the extractive industries, and they have killed a good number of geologists - a vertical face in unlithified material is inherently unstable. A good rule of thumb is never take a latex peel from a face over navel high and always have helpers with shovels standing by.

Karst Terrain ; is an area of caves, sinkholes, collapsed cave systems and spectacular residual hills. It takes its name from the Karst region of Slovenia on the shores of the Adriatic Sea. There is no more classically spectacular karst than that around Goulin, China, (Fig.). Wikipedia provides a long list of karst areas of the world.

Fig. 21e Diagram of classic karst topography around Goulin China.

Karst is caused by dissolution of carbonate rocks in areas uplifted enough to lower the water table, and in a humid climate (or what was a humid climate during glacial intervals - ie. Carlsbad Caverns in semiarid New Mexico). In youth there are a few caves in an extensive limestone. In maturity many cave systems have collapsed, leaving a mix of spectacular carbonate remnants, resembling canine teeth, surrounded by valleys at or near the new water table, near the base of the dissolvable carbonate. In old age, only the occasional insoluble remnant stands above the now-extensive plane because most of the carbonate formation has been dissolved and eroded away (Fig.).

Fig. 21f. Diagram showing the youth, mature and old age stages of karst topography.

From a hazards point of view you don't want to be collapsed on or under. Sink holes occasionally swallow houses or close roads, and water systems are often disrupted by changes in the plumbing as karstification advances. Some otherwise fertile areas can be unfarmable due to lack of surface water, other areas provide rich farm land. The latter are sometimes called karst windows, there the water table is at or near the surface. To paraphrase an old dictum - when in karst do as the karst dwellers do - they have a bred-in feel for the hazards and the specific areas of danger.

MASS WASTING: Mass wasting is the umbrella term for down-slope movement of material without the aid of a fluid medium. As desert flash floods and volcanic lahars prove, there is a continuum between dry mass wasting and stream transport with a heavy bedload. Though there are many variations in detail, mass wasting can be lumped into three big categories - rock falls, coherent landslides, and chaotic debris flows (Fig).

Fig. 21g. Four principle types of mass movement. Note that rock falls accelerate at the speed of gravity (32 ft/sec squared), slump and debris flows can be slow or fast, and creep/rock glaciers are slow slow slow. Note also that rotational slumps have an extensional upper part, and a contractional lower part. A clue to most mass wasting is hummocky topography.

Rock falls indicate at least a partial free fall of blocks. Collapse of the "Old-Man-Of-The-Mountain" profile in New Hampshire is a famous example, at least in New England. We saw a scary one on Svalbard - while walking on the flat between a big cliff and the fjord - we noticed erratic mega-worm tracks with a boulder at the fjord end of them, well down toward the fjord from where we were walking - freeze-thaw was wedging boulders from the cliff, they were bouncing off ledges, and way out on the flat before they hit - we got out of there in a hurry.

Landslides start as coherent rotational slump blocks, break up as they develop, and end up as chaotic debris flows, if they travel far enough (Fig.). So it kind of depends on what stage of development they are arrested at, or you see them at.

Landslides have a verity of causes, often with many factors acting together to cause the slide. Steep slopes, water saturation, undercutting of the base of the slope by man, rivers, or wave erosion, and earthquakes are just a few.

Mass wasting can be slow or catastrophic. It can be as slow and boring as watching paint dry - when the whole weathered regolith moves down hill imperceptibly slowly it is called side hill creep - no relation to the famous melodrama villein. Creep tries to tip trees over down hill. Trees try to straighten back up. This creates millions, maybe billions, of potential walking canes - great business opportunity!

Just up from creep in terms of excitement, are the rock glaciers of the mountain west - large areas that look hummocky and chaotic on the ground, are hard to walk over, and look like they are flowing downhill on aerial photos. Blame freeze-thaw - nightly freezes expand the regolith at right angles to the slope, daily thaws drop it back down vertically - the net movement being a saw-tooth ratchet down slope. In the arid west the greater diurnal change in temperature (often 50 degrees F) makes for more freeze-thaw cycles and better rock glaciers.

VOLCANOES Stay well away from volcanos, but if you must be near them be high above drainages that could funnel pyroclastic flows or lahars, and have a high hill or deep valley between you and the volcano, and upwind of the volcano is better.

Pyroclastic flows (Nuee ardents, glowing clouds) are gravity flows steered by the slope of the volcano and valleys below it- picture a bobsled run. The sled hugs the valley bottom on the straight stretches, but ramps up on edge as it banks into the turns. Pyroclastic flows do the same thing, but can actually top the ridge and spill into the next valley on a turn. Two of the world's most-experienced volcanic researchers were killed by misjudging the eruption and topography in such a setting.

Lahars are the bigger cousins of desert flash floods. With desert flash floods, scant vegetation holds the regolith down, and the seldom water that does come picks up soil and boulders and heads down valley like a freight train. Speaking of freight trains, one flash flood carried a steam locomotive down slope for the better part of a mile.

Figure 21h. Map of western Washington, State, between Mt. Rainier and Puget Sound. Volcanic mudflow (lahar) deposits within the last 5,600 years, from Mt. Rainier, shown shaded. Note that there are over a dozen towns shown within the mudflow deposits - mudflows and people both love valleys, there's the rub. Note also that the three major flow routes are over 50 miles long and hadn't expended their energy when they went into Puget Sound and continued on as turbidites. This is a very bad accident waiting to happen, especially if it is the middle of the night with everybody sleeping. From Session's 1995, USGS open file Report 95-642.

I got converted on flash floods the day we drove down Titus Canyon, an "hour-glass" canyon draining into the east side of Death Valley. Hour-glass because the canyon walls overhang until you can hardly see daylight. But enough daylight to see flood-born debris wedged in cracks 30-50 feet above the top of the vehicle. Needless to say, we were very thorough in checking the weather forecast, and looked around for any trace of a cloud just before we entered the canyon, which, is impossible to get out of except at the bottom on Death Valley's floor. In hindsight, we should have been even more apprehensive - had we encountered a debris dam, I'm not sure even a 4X4 could have made it back up the canyon in the soft gravel. Makes more sense to drive up such a canyon.

EARTHQUAKES: Earthquakes are concentrated at plate boundaries, but no place is immune - the very large Reelfoot Lake quake in the American mid continent in 1811 proved that. Earthquakes are caused by stick slip - stress builds up slowly (about the rate your fingernails grow) until faults finally snap, and then it starts to build up slowly again. The stronger the rock, the more stress can build up, and the bigger the quake, but the longer beween major quakes. The faster the plate movement, the more frequent the quakes. An excellent example of stick slip, that students just hate, is to screech a piece of chalk across the chalk board - the consistent periodicity of the dots is amazing, and the consistency of the pitch indicates that each "quake" was of the same magnitude.

The periodicity of quakes often exceeds both the historical record and our attention spans; The San Andreas pops off somewhere along its length about every 20 years - no problem there. Puget Sound, on the other hand, appears to have very large quakes (potentially like Alaska) but a periodicity of about 400 years, with a local written historical record of less than 200 years. Interestingly, the last big one around Seattle was recorded in Japan as a tsunami - their written history goes back much farther than that in the western U. S.

Earthquake-generated tsunamis are one of the main ways geologists date quakes in the geologic record. The tsunami sweeps all sorts of regolith into local depocenters, where it is preserved. The ample organic material swept in with it allows good carbon dating of the earthquake.

Earthquake intensity is measured by the Richter Scale, named after the US seismologist, Charles Richter, who devised it. It goes from 1 to 10, with each successive digit emitting ten times as much energy as its previous one (1=1, 2=10, 3=100, 4=1,000, 5=10,000, 6=100,000, 7=1,000,000, 8=10,000,000, 9=100,000,000, 10=1,000,000,000 units of energy). The biggest quakes yet measured are in the low nines, in Chile and Alaska. Fukushima's tsunami was caused by a 9.0, offshore.

GEOLOGIC HAZARDS USING COSTA RICA AS A LABORATORY

Geologic hazards include earthquakes, volcanic eruptions, tsunamis, landslides/mud flows, floods, etc. They are the aspects of the science that most directly affect people's lives. It is a topic that forces you to grapple with the geologic vs the human time scale and analyze acceptable risk. For example, Costa Rica's high Central Valley, centered on the Capitol, San Jose, is cool, beautiful, and home to over half of Costa Rica's population...and right below active volcanoes (active in a geologic time frame, sleeping peacefully in a human time frame). To the natives it's paradise. To a geologist it is like playing Russian-roulette with three guns.

Minimizing risk from geologic hazards boils down to good choices on the location and construction of your home. A Costa Rican can decrease volcanic risk probably by a factor of 100, just by moving from the east side to the high west side of the Central Valley. The risk from collapse in earthquakes is minimized by good home construction - both well diagonally braced wood construction and well done reinforced concrete construction fare well in earthquakes.

ARENAL'S SOBERING AND INSTRUCTIVE HISTORY
(abbreviated mostly from Soto and Alvarado, 2006):

<u>How do geologists figure this out anyway?</u> Good old-fashion field work - getting down on your hands and knees and measuring, sampling and recording the data - dominates in providing our understanding of volcanos. But before you even do that you walk all around the outcrop to make sure you are looking at the best exposed part of it. Nature of the eruption is clued by the event's lithology, volume by its isopach thickness determined at multiple outcrops, and age usually by carbon dating of wood fragments from these outcrops. We rely heavily on the "uniformatarian principle", the present is the key to the past, by comparing ancient deposits to those of historic eruptions that have been witnessed.)

<u>Summary of Arenal's eruption history:</u> Arenal is considered the western hemisphere's most currently active volcano, with basically continuous nonviolent eruption since the destructive eruption of 1968). But there have been 22 mappable and dateable events (numbered oldest to youngest from the bottom up) since Arenal's inception 7000 bp. All 22 of these have been larger and more violent than present activity. Since man has been in this hemisphere more than 20,000 years, he likely witnessed Arenal's first eruption.

Based on nature and size of the deposits, Arenal had four violent plinian eruptions at 700-1000 yr. intervals. It also had 8 sub-plianian, 7 violent strombolian and 2 volcanian eruptions. (listed in an order from most to least violent - see glossary for definitions of eruption types.)

<u>What Arenal sits on:</u> Arenal's oldest deposits sit on deposits of the Monte Verde and Aguacate volcanic groups to the west, that are older than 20,000 bp, that have isopachs unrelated to Arenal - from different, long dead and eroded volcanos. Arenal's deposits are separated by a well-developed paleo-sol (ancient buried soil) from these older units (Fig.).

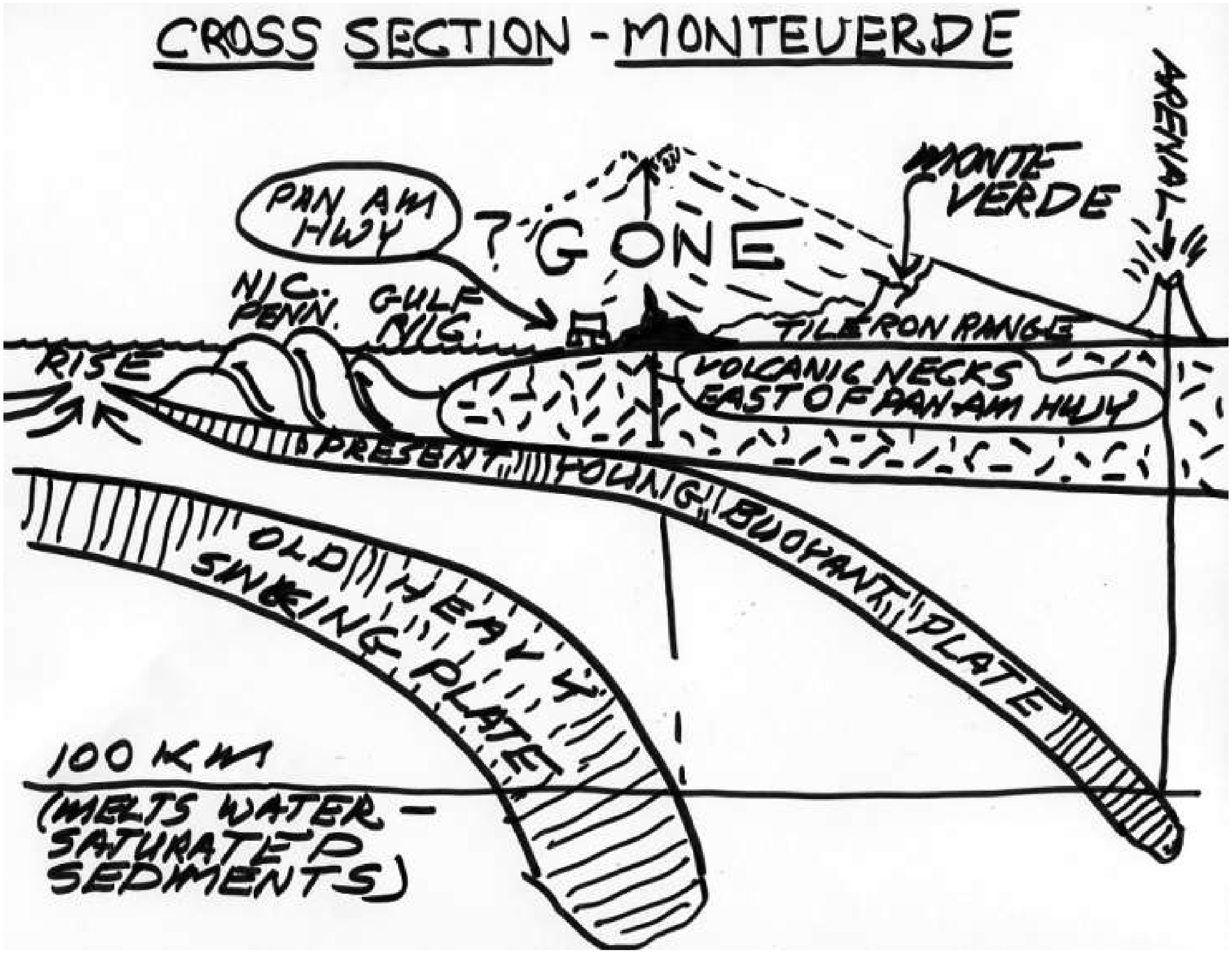


Figure Crossection looking north between Arenal volcano and a styalized East Pacific Rise to the west of the Nicoya Penninsula. When the East Pacific Rise was farther off shore to the west, a heavier plate on its east side subducted more steeply causing the axis of the older Monteverdi group volcanics to be well to the west of active Arenal. Some volcanic necks that cored these older volcanoes can still be seen in the topography east of the Pan American Highway. With migration of the East Pacific Rise toward the west coast of Costa Rica, subduction shallowed causing volcanism to migrate east. There was at least a 13 thousand year time gap between the two volcanoes in which a well established paleo sol formed.

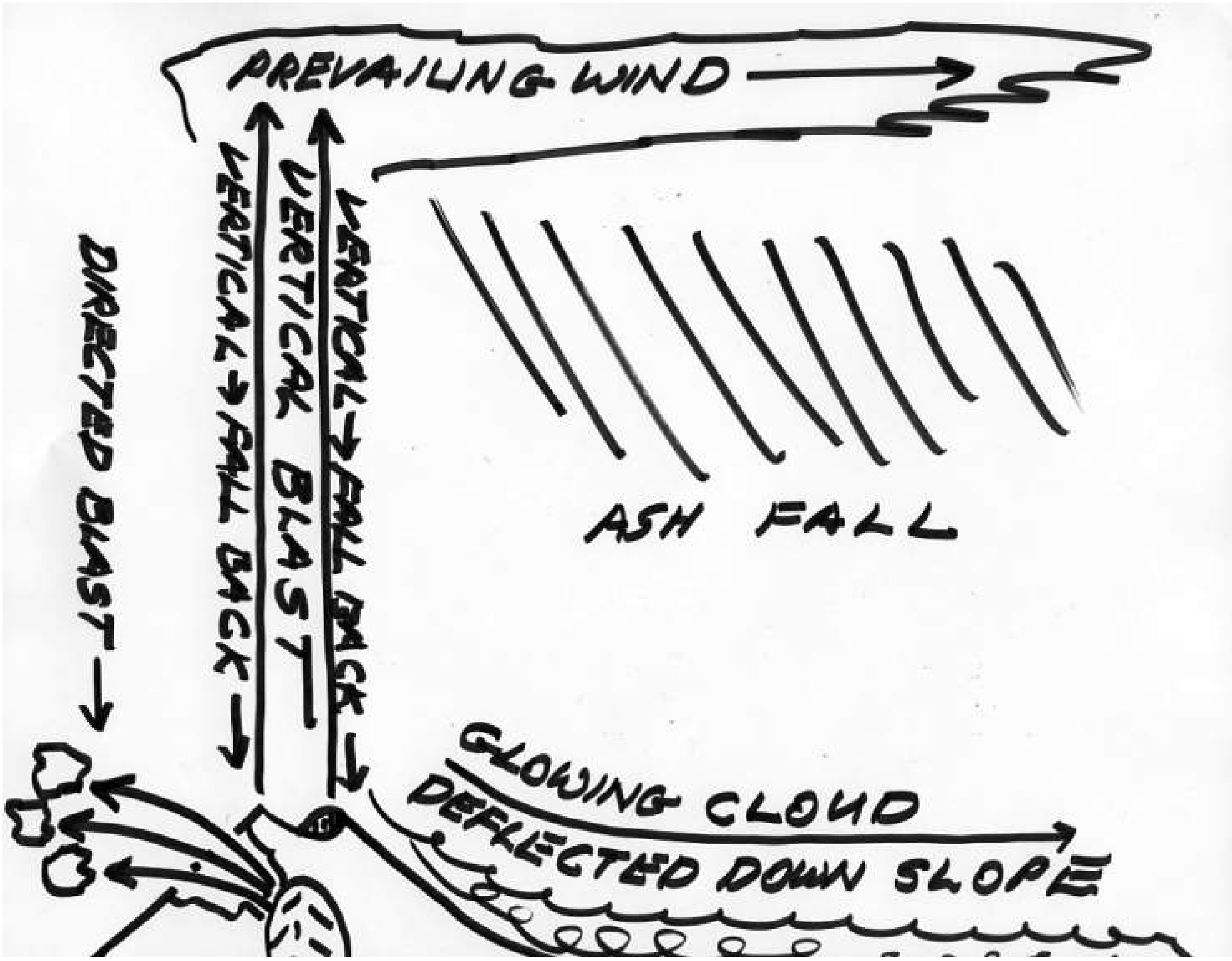


Figure   Cross section showing the principle types of volcanic deposits related to a violent explosion:

The main blast shoots hot pulverized rock and expanding gas vertically, often 50,000-100,000 feet - about twice as high as thunderheads. As they lose momentum, they fall back vertically and are diverted down the slopes of the volcanoe as pyroclastic flows.

Another more steady-state source of pyroclastic flows is merely that overtopping the lowest point on the volcanoes rim and heading down slope - kind of like a pot boiling over.

The weakest part of a volcano, especially when its throat clogs with cooling magma, is often its flank, with pressure buildiup causing a sideward dirceted blast - like huge chunks of rocks shot from a cannon.

Meanwhile there is a continuous rain of cool fine particles from the highest parts of the cloud as volcanic ash, with the greatest thickness forced to the lee side of the volcnoe by the prevailing winds. Early ash will predate the main pyrclastic flows, later ash will post date them.

<u>Arenal's 1968 disaster in perspective:</u> The disastrous 1968 directed-blast eruption (A 22) erupted about .003 cubic km of ejecta, an amount so small as to be normally undetectable in older eruptions of its size. Ironically, even though the 1968 eruption was one of Arenal's smallest from a geologic perspective, it was Arenal's most disastrous from a human historical perspective. The last mappable eruption before that (A 21) was 510 bp, before either much recorded history or population, and was only about its size. But Arenal's most violent eruption (A 20), judged by eruption ejecta type and volume, was only 40 years before that (550 bp). It erupted .44 cubic km of ejecta - 147 times larger

volumetrically than A 22. Arenal's largest eruption was 930 bp and erupted .90 cubic km of ejecta - it was 300 times larger volumetrically than the 1968 eruption, but of a type slightly less violent than A 20.

Arenal in repose? The repose period of a volcano is the quiet time between major eruptions when the magma chamber is refilling and pressurizing for the next major eruption. Relative to its major eruptive events, Arenal is in a "repose" period right now, even though it is considered the hemisphere's most "active" volcano. Unfortunately, the repose periods for Arenal vary between 0 and 1000 years, with duration's scattered seemingly randomly between these extremes. Not much security in that set of data.

Thus, nearly continuous non-explosive eruption since 1968 gives a false sense of security. This is important because conventional wisdom has it that a volcano that is continuously active like Arenal is "safe" because it can't build up pressure for a catastrophic eruption. The detailed history of Arenal indicates otherwise.

Arenal's next great eruption? Even though Arenal's repose periods vary erratically between 0 and 1000 years, the last four major plinian eruptions, the most violent kind, show a periodicity, with 1080, 820 and 750 years between them, getting slightly closer together toward the present. Continuing this tend, if A20 was at 550 bp we might expect a major violent plinian eruption, exceeding the 1968 eruption by orders of magnitude, in about 700 years from A 20, somewhere between 2100 and 2200 - our grandchildren might be alive to see it.

Climate change at 3200 bp: 3200 bp seems to record an initiation of the more humid present climate. No paleo-sols have been found between eruption deposits prior to that date, but good ones occur between most deposits younger than that. This is presumably because of an increase in rate of weathering and soil formation caused by the more-humid, present-day, climate starting 3200 bp. (Note that we don't count the well-developed paleo-sol under the Arenal deposits, because it appears to have had one or two orders of magnitude more time to form than those between Arenal eruptions.)

It is interesting that paleo-anthropologists suggest that man, in Costa Rica, converted from a nomadic to an agrarian life style at about this same time, presumably because he could now grow better crops. Its neat when independent lines of research converge on the same conclusion.

ARENAL'S GEOLOGIC HAZARDS: Arenal provides a good place to talk about geologic hazards, both from a physical and psychological point of view.

First the psychology: Man, by his very nature, is a risk taker. "Nothing ventured, nothing gained" and we as a species have gained a lot. All of us drive cars almost every day and think nothing of it, even though cars are statistically very risky. Also, risk taking has, in one sense, become more pervasive as we have grown more mobile. We all figure we will be somewhere else before it happens. Besides, risk taking adds spice to life - witness the popularity of gambling.

I like an example from Dallas, Texas, where I lived - every traditional farmstead prior to about mid 20th century had a tornado celler, exterior of the house, dug by hand with a huge commitment of time and sweat. Now millions there live in housing with no tornado cellars. When you ask they reply, "oh we are on bedrock, it would be much to costly to dig a tornado cellar." But these same millions all have pools, holes several times larger than the traditional tornado cellar, dug with a few scoops of a mighty backhoe. They falsely assume they will have moved somewhere else before the tornado hits...and besides, tornados are statistically less dangerous than driving a car.

Man's history - too brief a sample: When it comes to volcanic hazards, man's recorded history is too short to adequately sample a volcano's activity - Arenal's almost 1000 year periodicity between major eruptions is nearly twice as long as recorded history - Arenal hasn't outgrown its violent eruption stage, its just between two violent eruptions.

Arenal vs tourists - a show and a threat: Arenal is the top tourist attraction in Costa Rica. Starring at a slumbering volcano is about as exciting as watching paint dry, but Arenal gives you a dependable show whenever the weather lets you see the upper part of the mountain. And the risk - it's like gambling, it adds spice to the adventure - tourists love it. The only other contenders are the great surfing beaches of the Nicoya Peninsula and the rainforest ecological preserves, and they are each, even in aggregate, in second place, compared with Arenal.

Yet, potential loss of life wise, Arenal itself is definitely in second place to the the three big volcanos above the populated Central Valley that contains the capitol, San Jose, and several other large cities - most of its 2.4 million residents are in potential harm's way there, compared with probably less than a thousand around the more sparsely settled, and smaller, Arenal.

Never-the-less, Arenal has two examples of volcanic hazard that are significant and need to be discussed - The Tabacon Hot springs Resort, and the prime viewing area on the facing hills to the southwest of the volcano. These hazards are mitigated somewhat by ever-improving monitoring and communication, but they are still safety concerns:

Tabacon Hot springs Resort: Tabacon Hot Springs Resort is the largest and most popular tourist attraction at Arenal, right beside the main road, and close to the northwestern base of the volcano. The problem is that it sits in the lower end of one of the best developed valleys on the most active side of the volcano. Nuee ardantes (glowing clouds), lahars (volcanic mud flows), lava flows, and directed blasts, like the 1968 eruption, all tend to follow, or be triggered by, such valleys.

Nuee ardantes, one of which killed nearly 30,000 at the Mt Pelee eruption on Martinique, East indies in 1904, can travel over 100 mph down such a steep valley.

Lahars, in aggregate, kill more people than any other type of volcanic hazard because they are so frequent, silent, often arrive in the night, and can travel up to 50 miles (100 km) from the volcano, at up to 10 mph.

Lava flows seldom travel over 1 mph, but the lower limit of a very recent one is less than a tenth of a mile up valley from Tabacon's hot springs.

A directed blast is like firing a huge cannon full of hot rocks sideways, with the fragments traveling up to a mile or two from the blast site at velocities during the 1968 eruption calculated at 400+ km/ sec. Tabicon is just to the north of the fringe of the 1968 directed-blast deposits, but a slightly more northerly oriented blast of similar extent could overwhelm it. Such a valley can actually cause such a blast - the valley is like scratching a hole through one of the plys in the sidewall of a tire, causing the weakest place for the pressure to vent.

Tabacan in perspective: Actually, even though Tabacon is a classic volcanic accident waiting to happen, I wasn't too intimidated by it, soaked in its great hot springs, and did live to tell about it, just like thousands of other tourists. It at least has a main-road escape route in two directions, and at right angles to the valley. If you even drove a quarter of a mile up the hill in either direction from the valley bottom you would probably be cutting your risk by an order of magnitude. But you better keep right on going - significant risk extends considerably farther than that. Tabacon also, presumably, is well connected with the volcano's monitoring and warning systems. In summary, Tabacon is a classic example of volcanic risk, but I guess I would rate it as a risk worth taking. Plumbing probably won't allow moving the hot springs up out of the valley bottom, but any additional building should be done well up out of the valley bottom, if possible.

Main volcano viewing hills south of El Castillo - inadequate escape routes: Of the two, the situation with the most popular side hill for viewing the volcano, on the hills south of El Castillo, is more subtle, easier to overlook, and possibly more threatening. This area faces the most active side of Arenal and provides many resorts for viewing. Ironically the volcano's main research station and largest entrapenurial venture, a large new gondola for viewing, share this hazard.

The resorts all have rooms with picture windows facing the volcano and beds arranged so you an can prop up in bed and watch it. This partially makes up for viewing's two Achilles heels - the summit tends to be cloud covered during the day, but clearer at night and the cascading hot rockfalls are barely hot enough to see their pale red glow during the day, but they show up clearly and brightly at night. The night we stayed there it did clear and Arenal put on quite a show.

(Here it should be said that you should not expect to see the spectacular displays shown in tourist brochures - these are done with long time exposures, a month or more of eruption captured in one picture. You won't see that all in one night - still the night display is very impressive).

No way out in a crunch: Realize that the great majority of tourist vehicles that use this area are two-wheel drive sedans and not four-wheel drive off-road vehicles. The geologic hazard related to this prime viewing area is that, because of Lake Arenal, you have to drive toward and under the volcano to get away from it. Indeed, you have to drive right through the area covered with the lethal blast deposits of the 1968 eruption that killed scores of people.

This is because the two other possible escape routes, over the shoulder of Chato volcano and northward up the west side of the lake, are too primitively developed.

Though it still has a small lake in its crater, the small Chato volcano is effectively dormant, the last eruption being over 3000 bp. The escape route over its west shoulder toward Fortuna, however, shows as a primitive trail, at least on the 1:50,000 1944 topographic map which is the best that I have available - I stand corrected if that has been adequately improved.

The other escape route, to the north along the west side of Lake Arenal, I'm sure is inadequate because we tried it and failed. And we tried it with a Toyota Forerunner with extra large tires, a vehicle better off-road than probably 95% of the tourist vehicles. The hang-up is a primitive ford where the road crosses the Cano Negro River. We even attempted to wade the ford to check it out and it wasn't even borderline passable for the Forerunner.

How to fix the situation: These two under-developed escape routes could force maybe a few hundred people right back under the base of the volcano to escape it during an eruption. The obvious solution is to improve them. The state should build a permanent bridge at the Cano Negro ford, and a decent two-cars-passable gravel road over the west shoulder of Chato and down to Fortuna. I would suggest that the State foot the entire bill and get it done immediately. Then they might recoup 1/3 from tourists via a toll booth, and 1/3 from the local entrepreneurs via a special tax. Spread the cost equitably among the three groups (the country, local businesses, and tourists) that benefit most from Arenal's appeal as a tourist attraction.

Costa Rica's Central Valley's immense volcanic hazard in perspective: Costa Rica's high cool Central Valley is a tropical paradise, compared to the sweltering mosquito and malaria ridden jungles down on the coast. It is home to nearly 2.4 million, half of Costa Rica's population, including San Jose, the capitol and largest city. It is dominated on the east by very large volcanos. The summit crater of Irazu (the second highest mountain in Central America) is only 17 km from the center of the city of Cartigo.

While there are many other eruption deposits, almost the entire Central Valley is underlain by a single giant pyroclastic deposit, the Tiribi Tuff (322 ka) that varies from 20 to 100 feet thick. It covered 820 sq. km and erupted from Brava Caldera, only 25 km north of San Jose. To put this pyroclastic deposit in perspective, the ashfall that buried Pompeii was about 3 meters thick (10 feet) and the one that killed everybody in St. Pierre below Mt. Pelee was about 0.5 m (call it two feet) thick. In summary, there is no reason it couldn't happen again and if it did the potential disaster might be huge.

How Explosive Plinian Eruptions and Nuee Ardentes Work: To have a possible evacuation plan we must first have a grasp of how an explosive plinian eruption works (fig.). First a giant mushroom cloud, very dense with pulverized solids and buoyed by hot expanding gasses, is propelled to about twice the height of the highest thunder heads (50 to 100,000 feet). While the majority of material is still going up, the first, lower, ash rains down around the volcano vertically, though its isopach may be skewed strongly downwind, in this case by the Southeast Trade Winds. Then the huge mass of debris looses momentum and falls. As it hits the volcano it is deflected sideways down the volcano's slopes at speeds that can exceed 100 mph, as the radially-moving pyroclastic surge deposit. Sometimes the surge deposits from the first giant blast are augmented by continuing fountains of ash, like something boiling over out of a sauce pan, all around, or from one collapsed side of the volcano, as in Mount St., Helen's eruptions In the western U.S. in the 80s.

Modeling These Eruptions: The sideward and down slope deflected surges that do so much damage are gravity flows of hot pulverized rock and gasses in hot expanding air that can't easily be modeled in air. However, they are beautifully and easily modeled in turbidite experiments that substitute water rather than air as the fluid medium. All you do is mix and pour a cup of half and half plaster and water into one end of a glass-sided tank of water. If you previously build a topography out of plaster or modeling clay you can see how effectively these are "steered" down valleys and deflected around and away from highs. Pour several turbidites in succession, each with a different colored powdered tempra pigment and the resulting model is spectacular. This ability of gravity flows to be "steered" by topography is the key to survival in Costa Rica's Central Valley.

Visualizing the Geometry: Costa Rica's great Central Valley can be best visualized as a western saddle, with one of the great volcanos on the northeast as the saddlehorn (Fig).

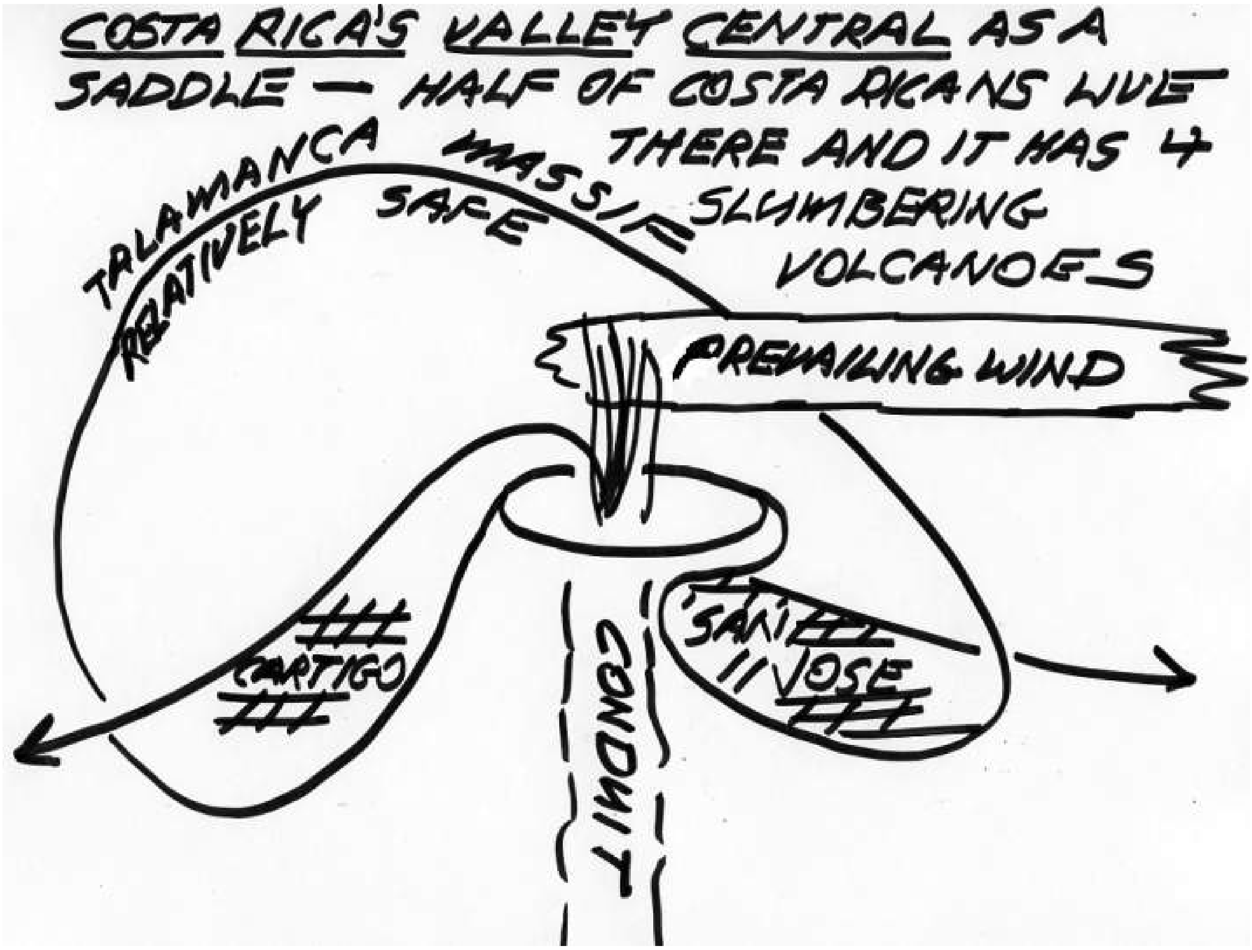


Fig. Volcanic hazzards of Costa Rica's Central Valley simplified as a western saddle: The seat is the Central Valley. Where the stirrups attach are the sloping valley bottoms down toward the Pacific on the northwest and down towards the Caribbean on the southeast. The Talamenca Massif to the southwest is like the high back (cantle) of the saddle, and it is non volcanic - or more accurately, is a batholith that is the roots of long-dead volcanos, now eroded away. the saddle horn represents the several active (on a geologic time scale) volcanos on the northeast side of the valley. The main potential hazard is from purocalstic flows - one of the large pyroclastric flow deposits Costa ricas two largest cities are built on is ten to fifty times as tick as theone that did in Pompee.

<u>Crux of a Plan:</u> Deadly pyroclastic surge deposits are sensitive to topography, they will flow off the volcano (saddle horn) into the Central Valley (seat) and be deflected down toward the stirrups by the high back of the saddle. The best place to head is up the back of the saddle onto the Talamanca Massif. The worst way to evacuate is down-valley toward the Pacific, via the Pan-American Highway to the northwest - the prevailing trade winds are likely to blow the majority of ash in that direction.

<u>What the government should do</u> is beef up and augment the first 1-2 thousand vertical feet of all highways heading up onto the Talamanca Massif, and also feeders into them from the bottom and away from them at the top. This on top of continuing to improve early warning and educating the public.

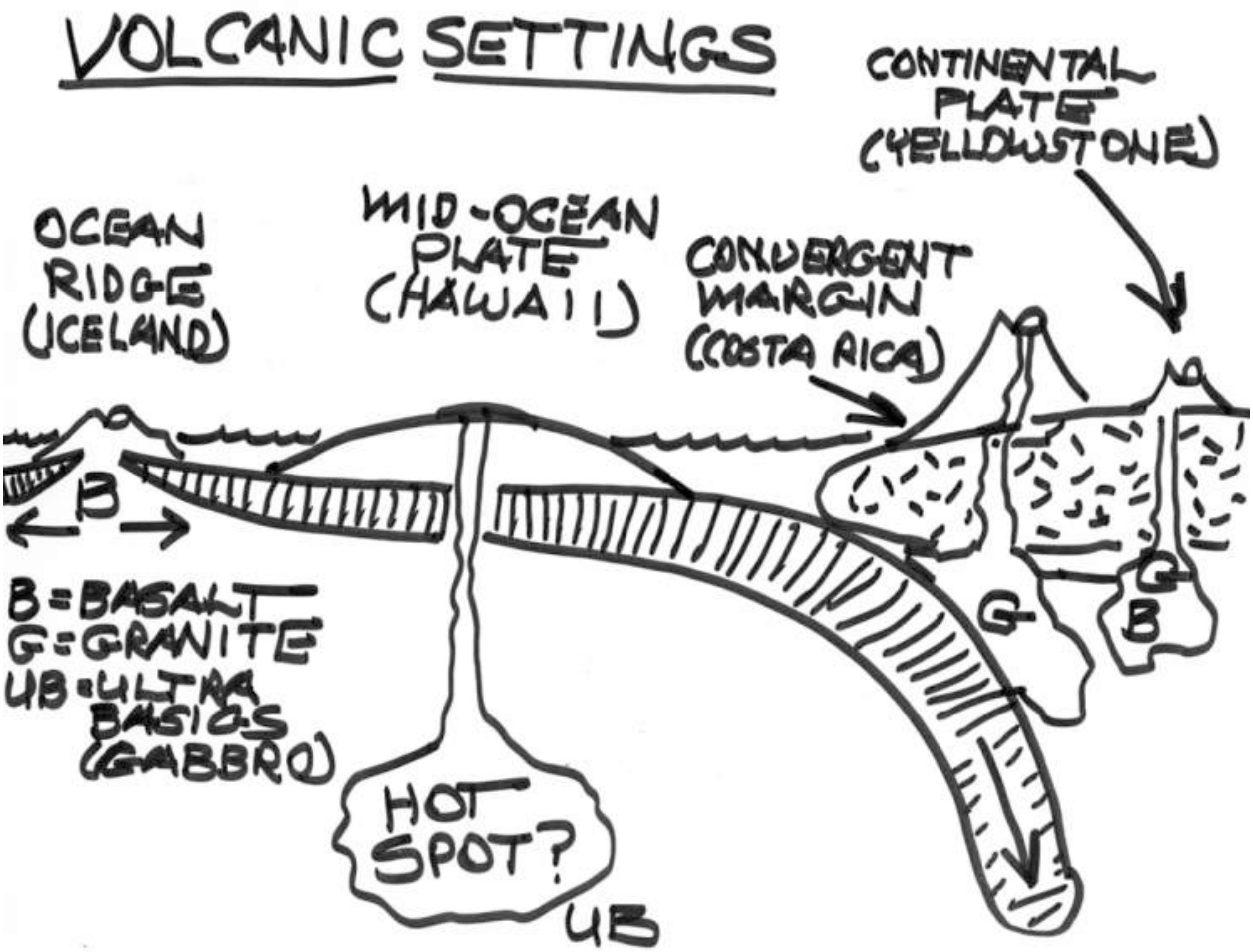
They might also pass a <u>volcanic feebate</u> - charge a hazard fee to those that build under the volcanos and use that money to give a rebate to those that build on the nearly volcanic hazard-free high west slope of the valley - don't draw a simplistic single boundary between hazard and no hazard zones - the people will be hassling the authorities forever to get it redrawn in their favor. Instead draw a hazard-potential contour map - 10 contours - +5 up under the volcanos, 0 at the base of the Talamanca Massif, and -5 at about 2,000 vertical feet up that side of the valley. Base the feebate system on that map. This will put a premium on real estate that is safe, a drag on real estate that is hazardous. (One of the towns high on the west side of the Central Valley has been written up as one of the notable longevity pockets in the world - that's a great place to live!)

Summery: We have to be pragmatic - if any of us put our feet in the shoes of our ancestors, prior to knowledge of volcanology and when malaria down in the sweltering jungle would likely kill you at an early age, and after a sweltering miserable life, we would all head for the Central Valley. Even now, knowing there will likely be a catastrophic eruption sometime between tomorrow and thousands of years from now we would still head for the Central Valley. The best we can do is understand the hazard, monitor the volcanos, and have a plan.

Avoiding Costa Rican Volcanic Hazard Entirely: Actually, fully a half of Costa Rica is almost devoid of volcanic hazard. This includes the entire Talamanca Massif that dominates the southern third of the country, and the entire Pacific Coast sheltered by it. The Nicoya Peninsula is sheltered by the forearc depression behind it, and the west side of the Tileran Range is nicely sheltered from Arenal by its high crest - and it is cool like the Central Valley. The entire Caribbean coast is volcanic hazard free , but both hot and humid. The northern Pacific coast is impinged on by the northern most volcanos - call it moderate volcanic risk, and still hot, but dry.

Why are Costa Rican volcanos so unpredictable and dangerous? Actually they are not any worse than other subduction-generated stratovolcanos. In total these represent maybe 90% of the world's volcanos and they are both the most catastrophic and least predictable.

Lets start by figuring out the dependable ones - the mid-ocean volcanos.



Hawaii chugs away millennia after millennia without much loss of life: 1) It has access only to oceanic basalt for magma, and basalt is so fluid, gasses bubble right out of it and can't build up pressure. 2) Hawaii has nothing to build a volcano out of but basalt that hardens into a good hard rock, with only minor pyroclastics. This, combined with fluidity, forces it to build a low-profile "shield" that is very strong compared with the towering stratovolcanos. 3) All volcanos have a tendency to bust out there side if they get high enough. The higher the summit crater, and the more fluid and dense the magma, the more magmastatic pressure to do this. Hawaii did this to form Kilauea and abandon the Mona Loa summit crater. Not a big deal - the side of the mountain cracked, the plumbing rearranged to flow out the lower end of the crack, and probably into the sea. There were probably spectacular phreatic (steam) explosions. Blacksmiths get this all the time when they stick hot iron into water to temper it. But then the down-slope lava flows dammed it up and made the pit of boiling bubbling and nearly harmless basalt we see today.

Soda pop analogy: Thus, Hawaii acts like a completely dead bottle of soda pop the top has been off of a week. Poke a hole in the side of it and you'll have to mop up a puddle on the counter but not much else. Not so the stratovolcanos, they act like a still capped fresh bottle of soda pop you just shook up. Poke a hole in the side of it and you'll have to clean up the whole kitchen. Its even worse than that. Stratovolcanos have magma so heterogeneous and unpredictable that, metaphorically, at any one volcano and moment in time, you don't know which kind of soda pop can you are dealing with. Here are some of the reasons stratovolcanos over subduction zones are so heterogeneous:

1) In contrast to mid-ocean volcanos, they have access to multiple source materials to melt magma from - from the most silica-poor basalt and mantle ultramafics to the most silica-rich and water-saturated sediments dragged down the subduction zone. These sediments can be carbonate banks, quartz-poor turbidites or silica-rich ooze off the deep sea floor, among many others.

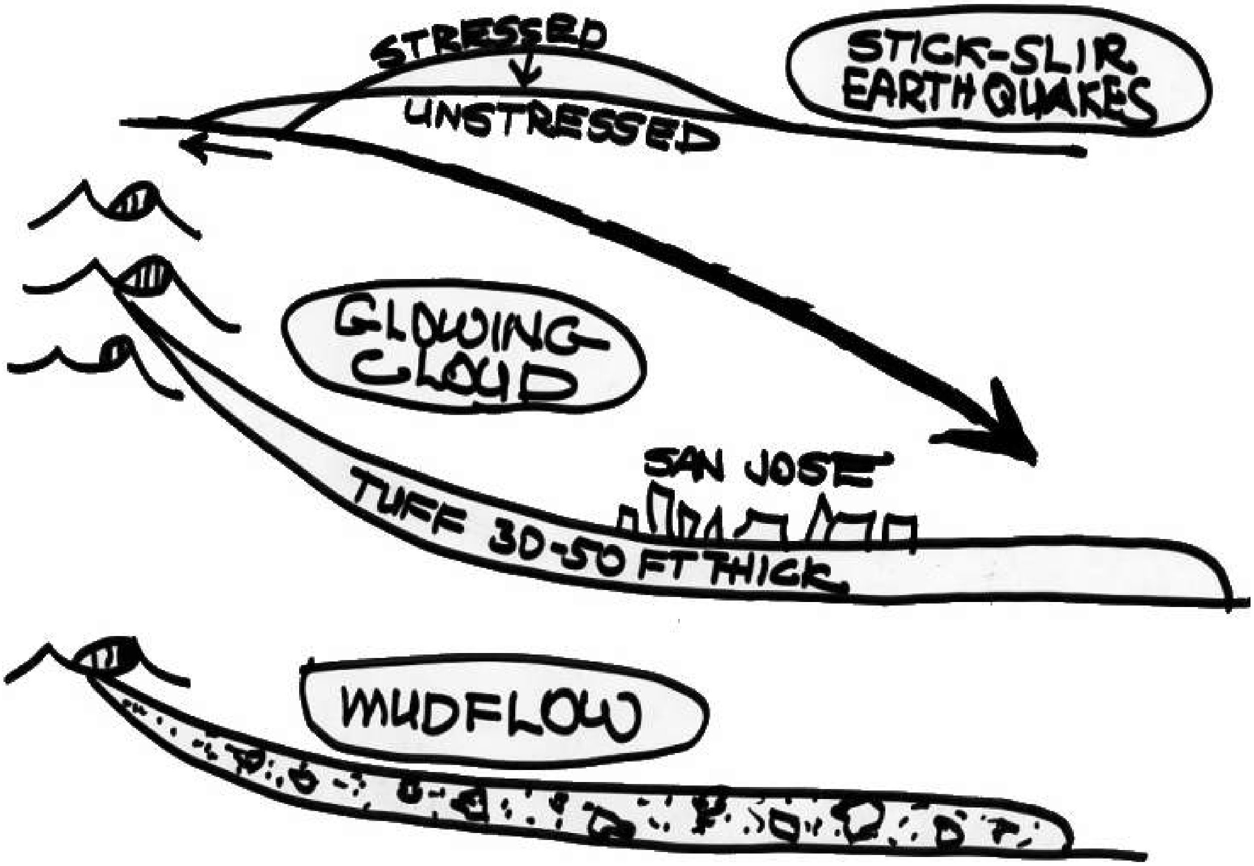
2) There is another, mechanical, reason for this diversity of magma - metaphorically, how the blade of the bulldozer is set. At one extreme (blade set high) everything dragged in off the ocean floor or eroded down off the continent, or brought along sideways by strike-slip, can be dragged down the subduction zone to form magma. At the other extreme, the blade can be set low and scrape everything off the top of the basalt ocean crust and plaster it against the edge of the blade as the accretionary prism. In this mode the ocean crust is scraped clean before it goes down the subduction zone and there is nothing but oceanic basalt to make magma out of.

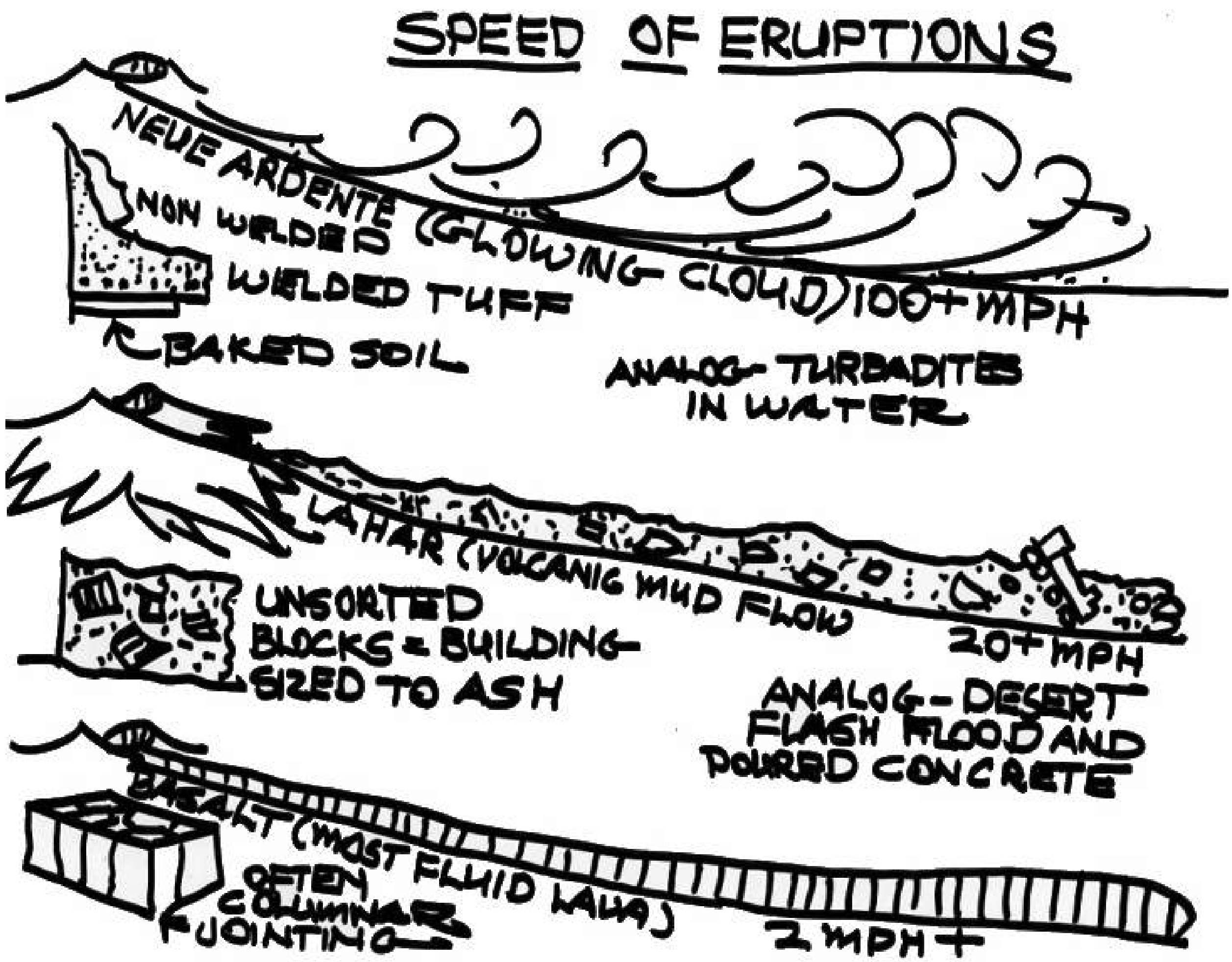
The "wild card" in magma is water - it both lowers melting temperatures and increases explosive potential of the eruption. In mid-ocean volcanos water tends to be both scarce and steady, because the magma comes straight up out of the mantle. In strato volcanos it varies radically from volcano to volcano, and even eruption to eruption. Strato volcano's water is dragged down the subduction zone with saturated sediments that can be both abundant and highly variable.

Above, we have also touched on the reason that most stratovolcanos are made of andesite and most batholiths that feed them, granodiorite - both of intermediate composition. The extremes, basalt and rhyolite lavas, and diorite and granite batholiths are less common - mixing of materials brought down the subduction zone from multiple sources enhances the center and represses the extremes, composition-wise.

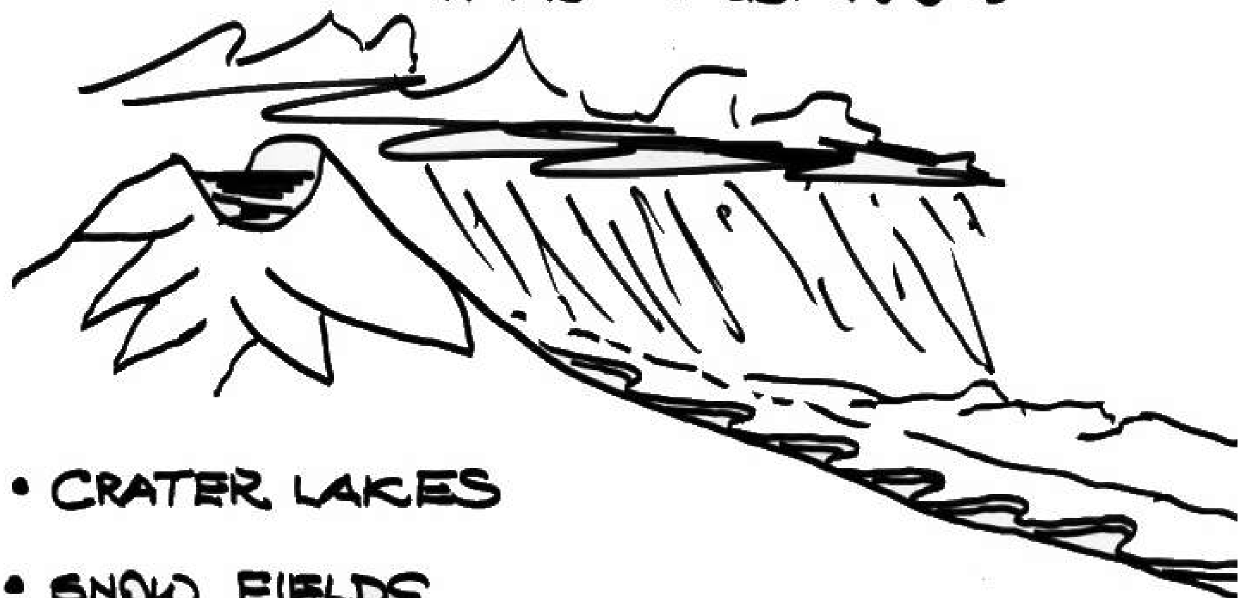
In summery, subduction zones swallow a verity of source material and mix it into andesite of average composition. But significant clots (metaphorically) of prunes (basalt or water-saturated anything) or cheese (dry rhyolite) don't get mixed. When they work their way up through the digestive tract of the volcano, they radically change both the composition of the magma and the character of the volcanic activity. That's why stratovolcanos are so diverse and unpredictable.

GEOLOGIC HAZARDS

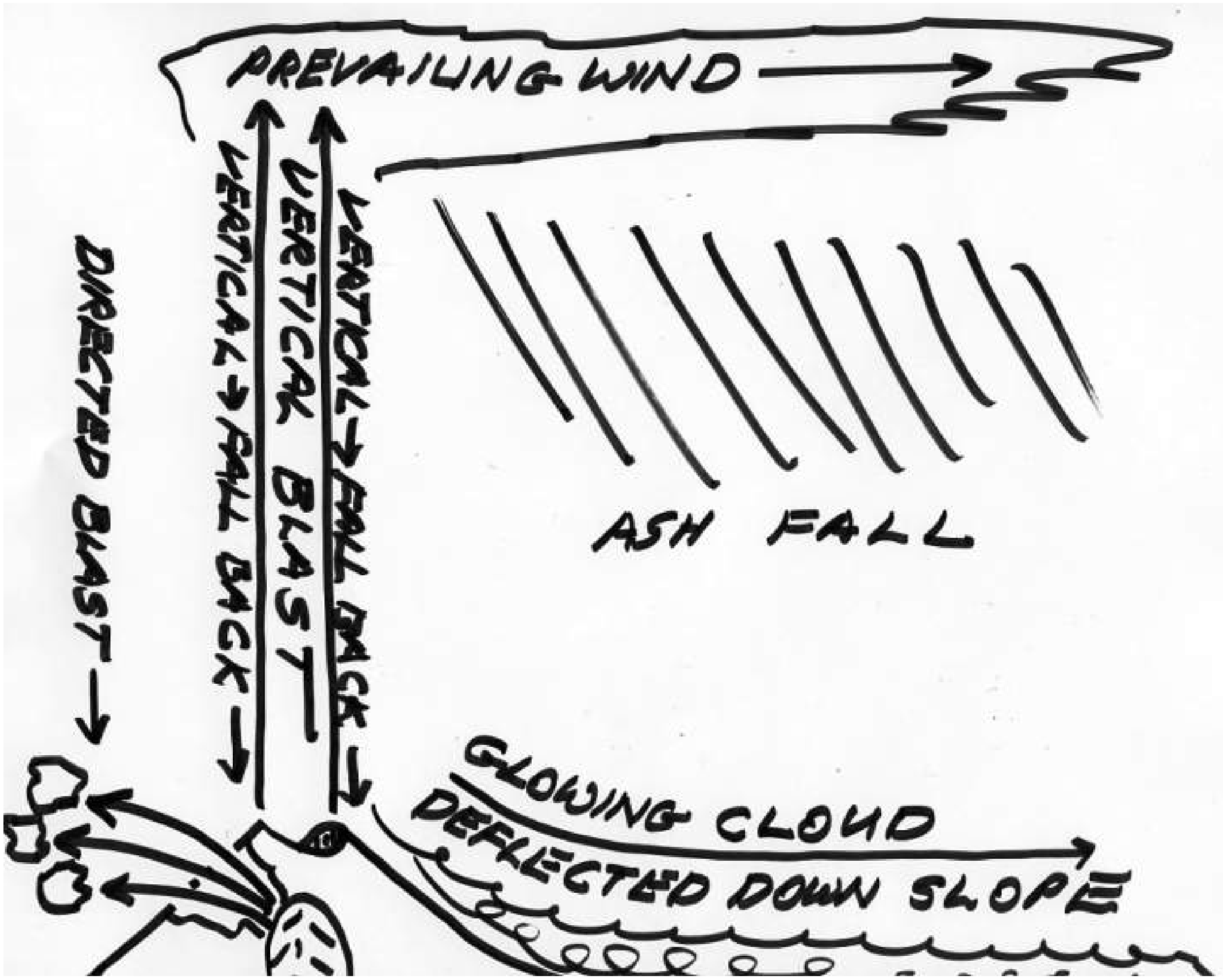



SPEED OF ERUPTIONS
NEUE ARDENTE (GLOWING CLOUD) 100+ MPH
NON WELDED
WELDED TUFF
BAKED SOIL
ANALOG - TURBADITES IN WATER
LAHAR (VOLCANIC MUD FLOW
20+ MPH
UNSORTED BLOCKS = BUILDING SIZED TO ASH
ANALOG - DESERT FLASH FLOOD AND POURED CONCRETE
BASALT (MOST FLUID LAVA)
OFTEN COLUMNAR JOINTING
2 MPH +

WHERE WATER COMES FROM FOR LAHARS (MUDFLOWS)



- CRATER LAKES
- SNOW FIELDS
- ERUPTION MAKES ITS OWN RAIN
- FLOWS INTO EXISTING DRAINAGE



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(Note: both “Suspect Terranes” and “Metamorphic Core Complexes” were seminal papers in launching these respective concepts.)

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(Note: I'm prejudice because this is the text I grew up on, but I feel it is still the best physical geology text ever written - late in his life Gilluly gave a talk at a big Boston meeting that basically said "you young whipper snappers think you're so smart, but here's a few things you can't solve with your new fangled plate tectonics" - and one was Wyoming. I walked up to him in the hall and begged to differ - he chewed me up one side and down the other and told me to go home and do my homework - from the vantage of being the same age now that he was then, I can see his point of view.)

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