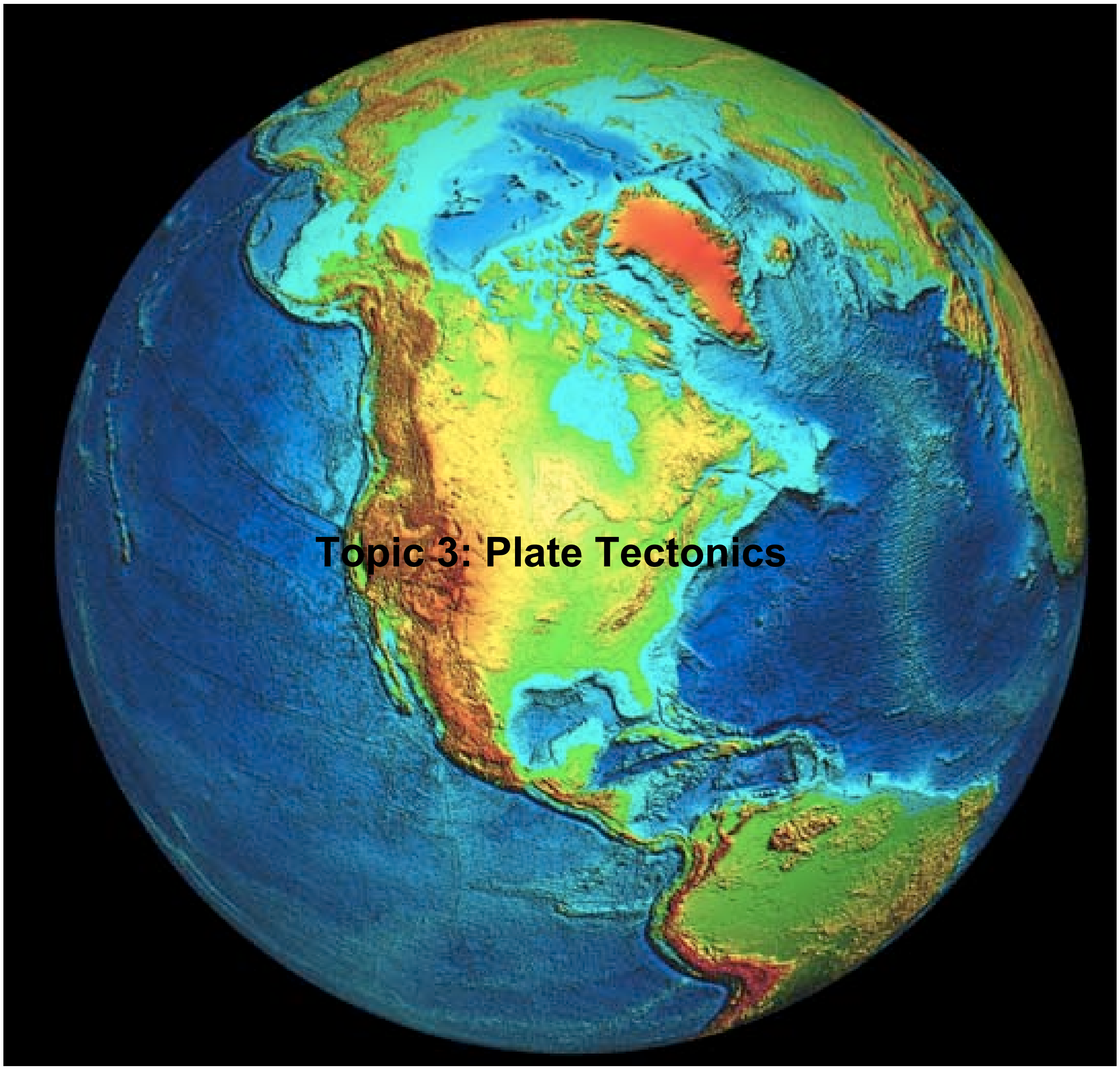
Planet Earth:
An Introduction to
Earth Sciences



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Planet Earth Topic 3: Plate Tectonics

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The mid-ocean spreading centers that host the hydrothermal vents and chemosynthetic organisms consist of a continuous string of volcanoes that encircle the globe (Figure 3-1). This mid-ocean ridge system produces new sea floor when the volcanoes erupt. Lava pours onto the sea floor, cools and spreads away from the ridge crest to become the conveyor belt upon which the continents ride, hence the name sea-floor spreading. This process forms new ocean floor, then moves this new lava away from the mountain crest as ever newer lava replaces it.

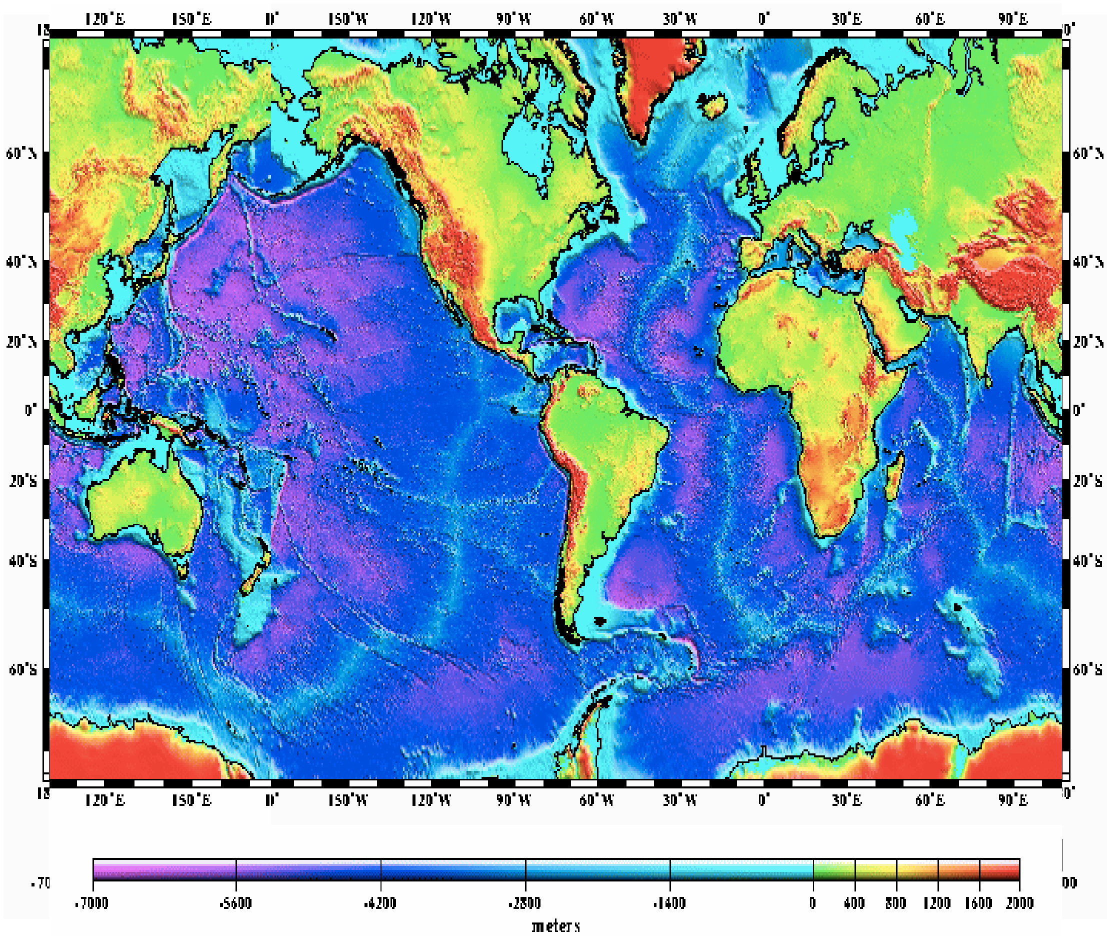

Figure 3-1. The global mid-ocean ridge system as seen on this bathymetry map created by scientists from Lamont Doherty Earth Observatory of Columbia. The topography of the ocean basins was determined from satellite measurements of the ocean surface, that is deflected slightly to mirror the sea floor topography.

The mid-ocean ridge spreading centers form the extensional component of the theory of Plate Tectonics. But how is new sea floor continuously formed at the mid-ocean spreading centers such as at the Mid-Atlantic Ridge, that grows the Atlantic Ocean and separates North and South America farther and farther from Europe and Africa without expanding the Earth?

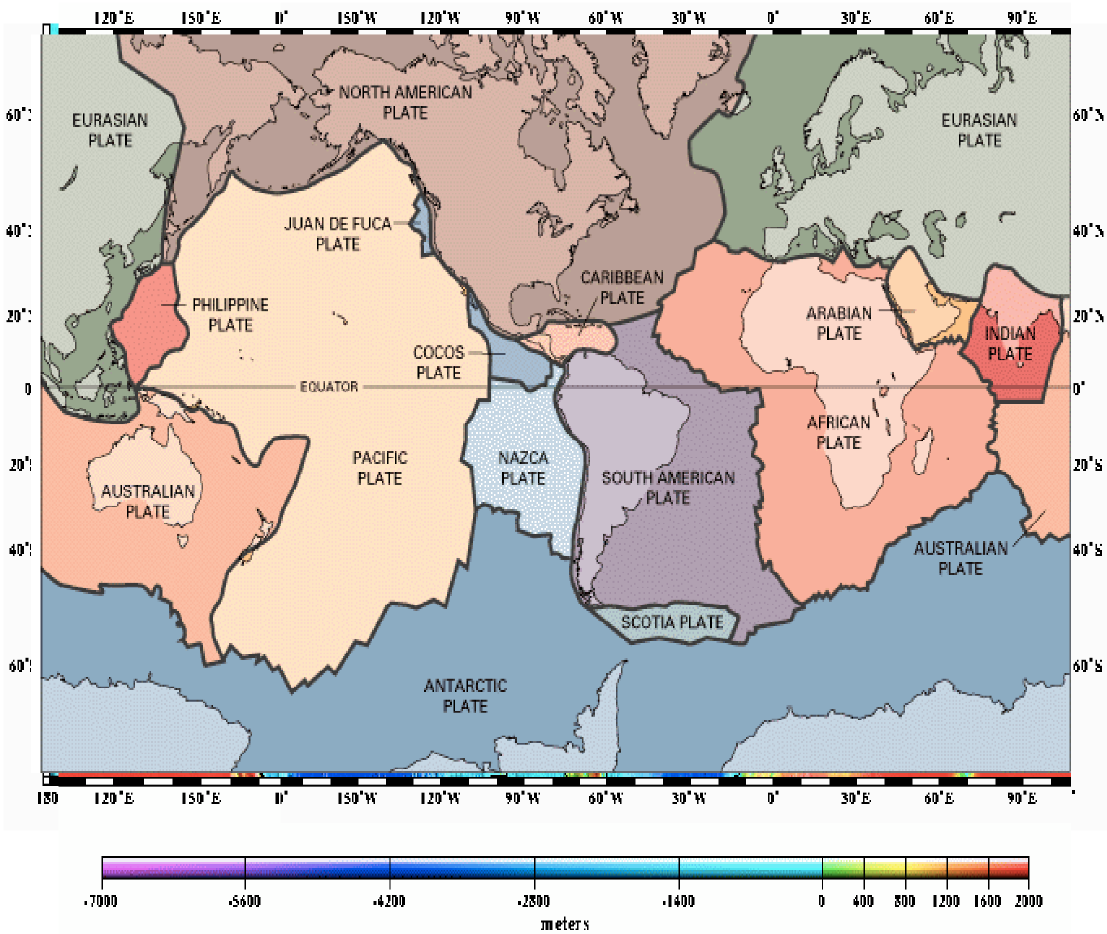

Figure 3-2. The Lithospheric Plates that define the surface dynamics of Planet Earth.

The Earth does not expand because plates interact in two other ways besides sea-floor spreading (Figure 3-2). At the opposite end of the conveyor belt, deep-sea trenches such as that off the west coast of South America are the locations where old rock from the surface “subducts” or plunges downward, back into the mantle. Subduction zones mark the collision of two plates, the opposite of the extension occurring at mid-ocean spreading centers. At subduction zones, one lithospheric plate rides over the other, forcing the downgoing plate back into the mantle and the overriding plate up into the air to form the great mountain ranges of the continents. There are mountain ranges of similar size at both of these boundaries, but the ocean ridges begin miles beneath the sea surface and rarely grow high enough to break through (like Iceland).

A third type of lithospheric plate interaction occurs in Plate Tectonics when two plates slide past each other. A long linear fracture in the earth called a transform fault is formed, such as the San Andreas Fault in California. There, the Pacific lithospheric plate is sliding to the northwest across the North American lithospheric plate.

The theory of Plate Tectonics proposes that the Earth's surface is broken into a large mosaic of lithospheric plates that continuously move relative to each other in a precisely determined way. Geometry explains the motion; mantle convection, the push of mid-ocean ridge topography, and the pull of subduction zones control the speed, timing, and directions of plate movements.

Each of these three plate boundaries is characterized by a different kind of force: tension from extension at mid-ocean ridge spreading center boundaries; compression from collision at subduction zones; and shearing from tearing at transform faults (figure 3-3).

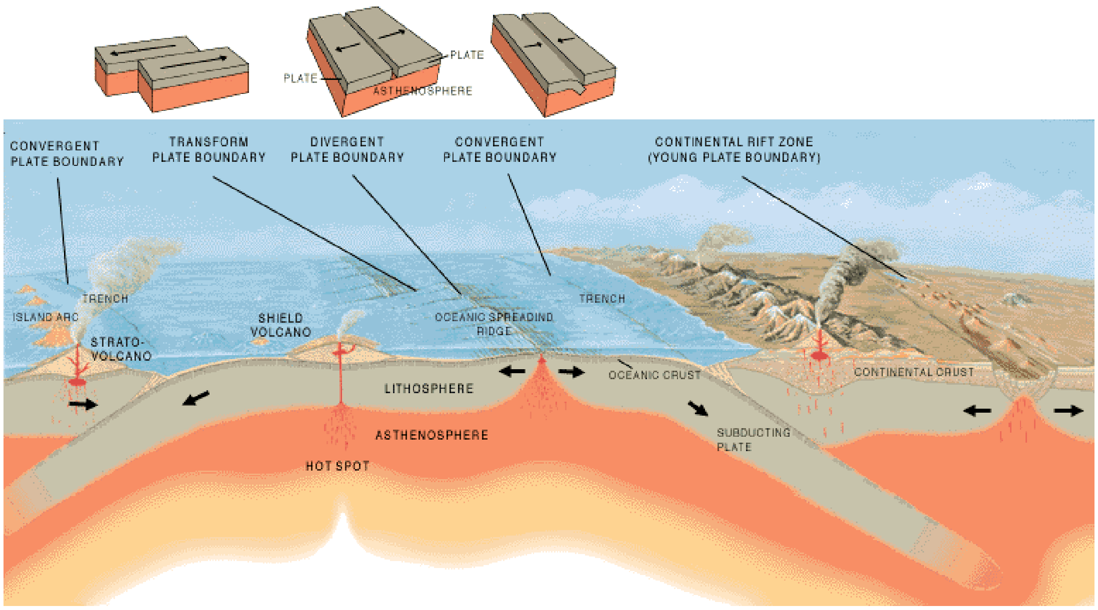

Figure 3-3. The three types of Plate boundaries are shown at top, and where they occur within a cross section of the Nazca and Pacific Plates sliced open from South America on the right to Tahiti on the left.

Evidence for Plate Tectonics

How is it that we know that the Earth is covered with a mosaic of rigid plates, and that these plates interact with each other only at their common boundaries. The discovery at the foundation of Plate Tectonics is that the surface of the Earth is capped by rigid outer or lithospheric plates that are only a hundred kilometers or so thick. These plates "float" on a softer, partially liquid upper mantle.

Seismology provides the most compelling evidence for the existence of these lithospheric plates. Earthquakes predominantly occur only along plate boundaries (shallow earthquakes in black in figure 3-4), and not inside the interior of the plates. Simply observing where the earthquakes are delineates the plate boundaries. Deep (in red, Figure 3-4) and intermediate depth earthquakes (green in Figure 3-4) define the subduction back into the mantle shown in Figure 3-3.

The seismic data to prove the plate tectonic theory was provided to the geological community beginning in the 1950s, when the United States was preoccupied with the detection of Soviet nuclear bomb tests. The Eisenhower administration built a worldwide network of 125 seismic stations to record ground shaking from nuclear tests, and this network also recorded every large earthquake that happened anywhere in the world. By the late 1960s the network had accumulated enough earthquake locations to plot them on a world map. It became clear that earthquakes do not occur randomly on the surface, but in linear belts that wrap around the Earth. This remarkable fact had escaped detection until the seismic network was constructed.

But what controls earthquakes so precisely as to align them into belts? Moreover, when the locations of all known volcanoes are added to the same world map, they fall along the same belts as the earthquakes, so much so that it is difficult to distinguish between the earthquakes (circles in Figure 3-4) and volcanoes (solid dots in Figure 3-4). It took a simple but elegant intellectual leap for geologists to recognize that these belts of seismic (earthquake) and volcanic activity are the boundaries of interaction among a few large and rigid plates that cover the surface of the Earth.

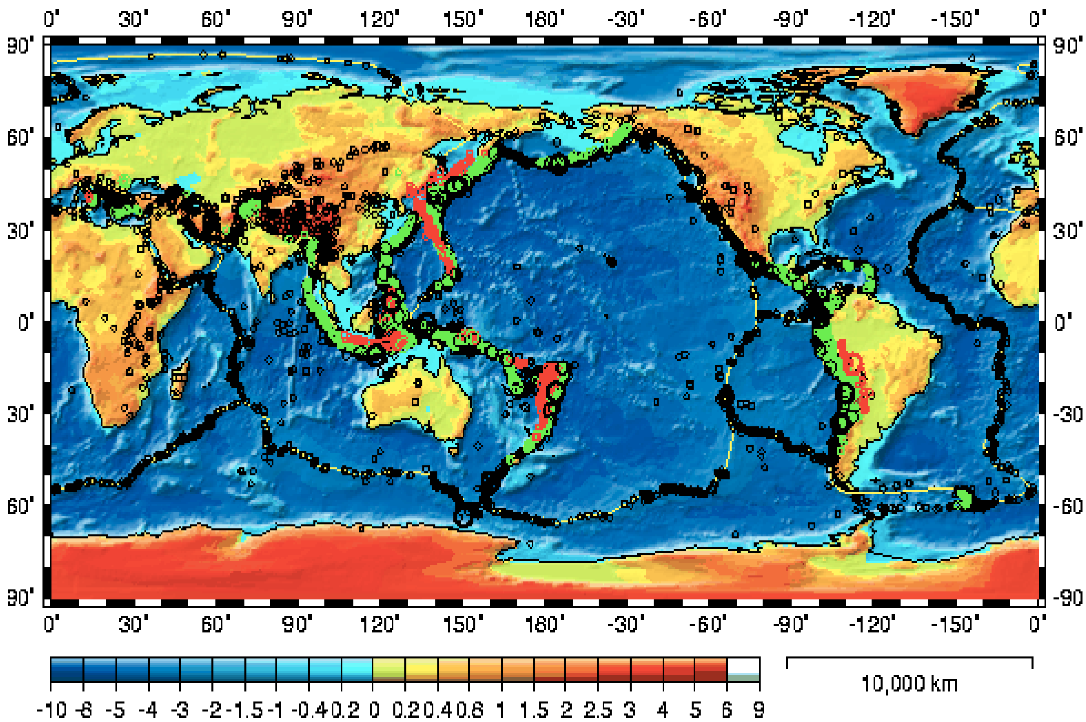

Figure 3-4. Earthquakes from 1977 to 1992 broken into categories determined by their focal depth, with black circles indicating depths from the surface to 70 km, green circles are earthquakes occurring from 70 to 300km depth, and red circles are from 300 to 700 km. Over 10,000 large earthquakes with magnitude greater than 5.5 are plotted. Notice that majority of the large earthquakes occurs at or close to major plate boundaries, at the same locations as the active volcanoes (solid black dots) (see Figure3-2).

The surface motions of those conveyor belts are governed by very precise laws because the lithosphere is made up of rigid, solid plates constrained to move on the sphere that is the Earth's surface. Plates were discovered because they are so rigid that they obey these strict rules of geometric motion. These patterns were noticed only after observations of the sea floor we complete enough to map the shape and form of the sea floor – only in the 1960's as part of the cold war's anti-submarine defenses.

Geometry of Plate Tectonics

Two solids on a sphere can do only one of three things and remain rigid: pull apart from each other, collide, or slide across each other. Tear a sheet of paper in two, then hold one piece in each hand. Any motion of the left- hand piece relative to the right can be described by one of these three motions *if and only if they remain on the same plane of motion.* Sound familiar? Substitute the surface of a sphere, and these are the three forms of plate boundaries described in the last section. The plates interact only at their edges, not within their solid interiors.

Plate Tectonics describes the relative motion of surface plates but does not deal directly with the forces within the mantle that push and pull the plates and create the motion in the first place. This will come later.

The Earth is covered by 12 large, stable lithospheric plates. They move relative to each other causing tectonic activity only at their boundaries where interactions with other plates occur. Almost all the earthquakes and volcanoes on the surface of the earth happen at these precisely defined boundaries.

The elegance of plate tectonics goes far beyond just describing where earthquakes and volcanoes occur. There are processes occurring at these boundaries that allow us to determine the direction of motion of plates on the surface. For example, we can predict that if the Pacific plate continues to move to the northwest relative to the North American plate as defined by the San Andreas Fault (Figure 3-5), San Francisco will collide with Alaska in 40 million years. You might say that this information is not of much use, but plate tectonics also allows us to infer that San Francisco used to be attached to Sonora, Mexico, and that gold mines found there might "have brothers" ripped off Sonora and carried a thousand miles to the north.

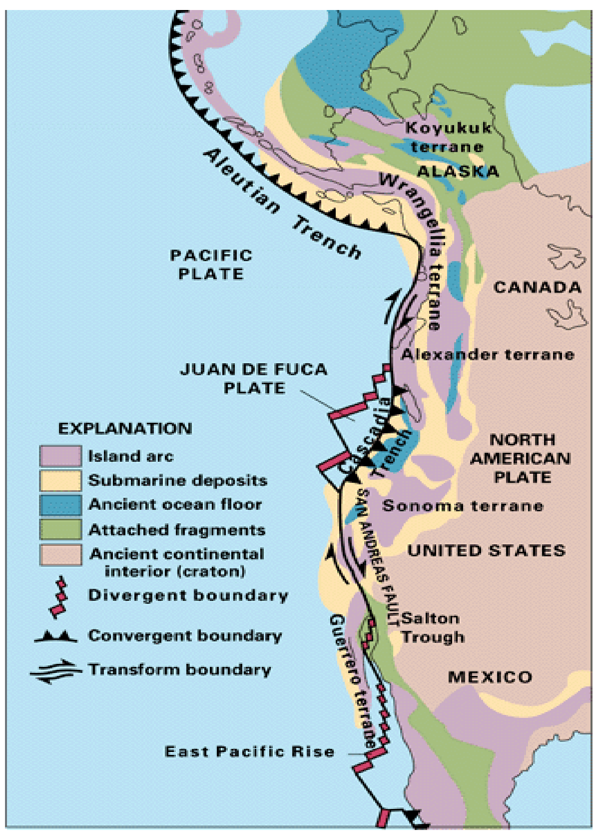

Figure 3-5. Plate boundaries along the western margin of North America show that if motions continue, about 50 million years from now, southern California will collide with Alaska.

Plates that move apart have transform fault “scratched” into their surface (Figure 3-6). These always point in the direction of the relative motion of the two plates involved because they are accommodations for the plate to conform to the spherical surface of the Earth. If we can map the direction of these transform faults, we can determine a pole of rotation because they are latitudes about that pole.

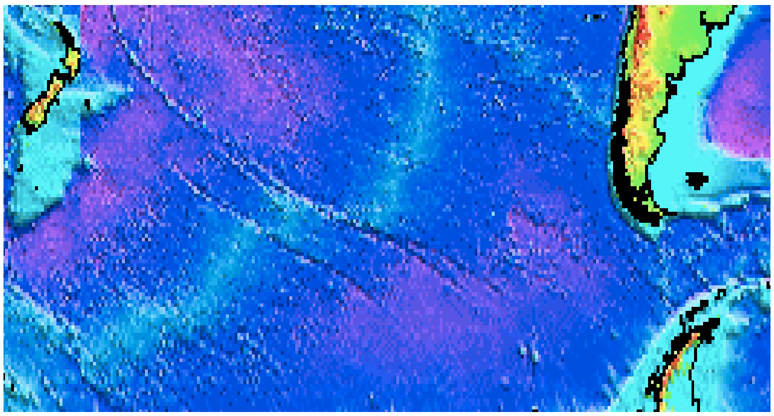

Figure 3-6. Transform faults also form along the mid-ocean ridge system accommodating the “stretching” to fit the plates onto the spherical Earth as spreading occurs. These transform faults “scratch” into the ocean floor arcs that are latitudes about the pole-of-rotation between the two plates involved. As can be seen here, the Pacific Antarctic Plate pole has moved, producing the swoop in the fracture zone scars.

Eighteenth-century Swiss mathematician Leonhard Euler showed that two rigid bodies moving on a sphere can only rotate about a single pole. Thus, we can exactly describe the motion of any two plates relative to each other by some angular rotation velocity about a pole located somewhere on the Earth. This pole is not tied to the Earth's pole of rotation. That is, the rotation of two plates is relative only to each other; it is not related to a fixed reference frame within the Earth, such as the Earth's rotation axis. We can prove that Eulerian geometry holds for the motion of, for example, North America versus Africa. First we locate the direction of transform faults marking the sea-floor spreading motion of Africa away from North America. These will define latitudes, or small circles about the pole of rotation. Then we draw longitudes, or great circles perpendicular to these lines of latitude. Euler predicts that these great circles intersect at two and only two points on the globe, the poles of rotation for the two plates. Sure enough, the real data converge upon a point just south of Greenland. There is another pole on the exact opposite side of the Earth. Euler further predicts that the velocity of separation wil1 vary with angular distance from the pole, and this turns out also to be true.

The same test can be applied to every plate with a sea-floor spreading or transform-fault boundary with another plate. But Eulerian geometry also predicts that three plates must be in contact many places in the world. Similar geometric laws allow us to vector sum around such “triple junctions” to determine the relative motion of three plates in contact. Consider the easiest of such junctions: where three spreading centers intersect. If we know the direction and velocity of opening of any two of them, we can uniquely determine the velocity and direction of motion of the third relative to the other two.

But what if a spreading center does not separate two or three plates? How do we determine relative motion, or even more interestingly, how do we know what kind of motion is occurring along that boundary at all?

It is possible to define the boundaries of plates by the type of tectonic activity associated with each. But it is important to realize that the continent- ocean transition is an insignificant barrier compared to the thickness of a lithospheric plate. Therefore, a continent-ocean boundary can occur well within any single plate, and in general such edges of continents have little to do with plate boundaries! The continents are, however, large enough to weigh down plates that contain significant surface area of continent, but the continental crust is insignificant compared to the dimensions of a plate (greater than 100 km thick and often several thousand kilometers across). That is, plates with continents appear to move more slowly than those without, such as the Pacific plate; but they still move by the same geometric laws.

Plate tectonics is a powerful geological tool because it is predictive. One can determine the type of plate boundary interactions by studying the focal mechanisms of earthquakes, for example. North American-Pacific plate interaction can be determined by studying the orientation of the fault planes along this boundary (Figure 3-7). These earthquake mechanisms have distinct orientations that tell in what direction the plates are converging or diverging. They are of different form, depending upon whether the fault motion causing the earthquake was tensional (a gravity, or normal, fault in which the motion is in the same direction as gravity's pull), compressional (a thrust fault caused by collision where motion appears to be against gravity), or strike-slip (as the name implies, one plate slides across the other). Sound familiar (Figure 3-3)? Earthquake focal mechanisms can be used equally well to determine the pole of rotation of Pacific-North America motion, as transform faults determined North America-African plate motion in the previous example.

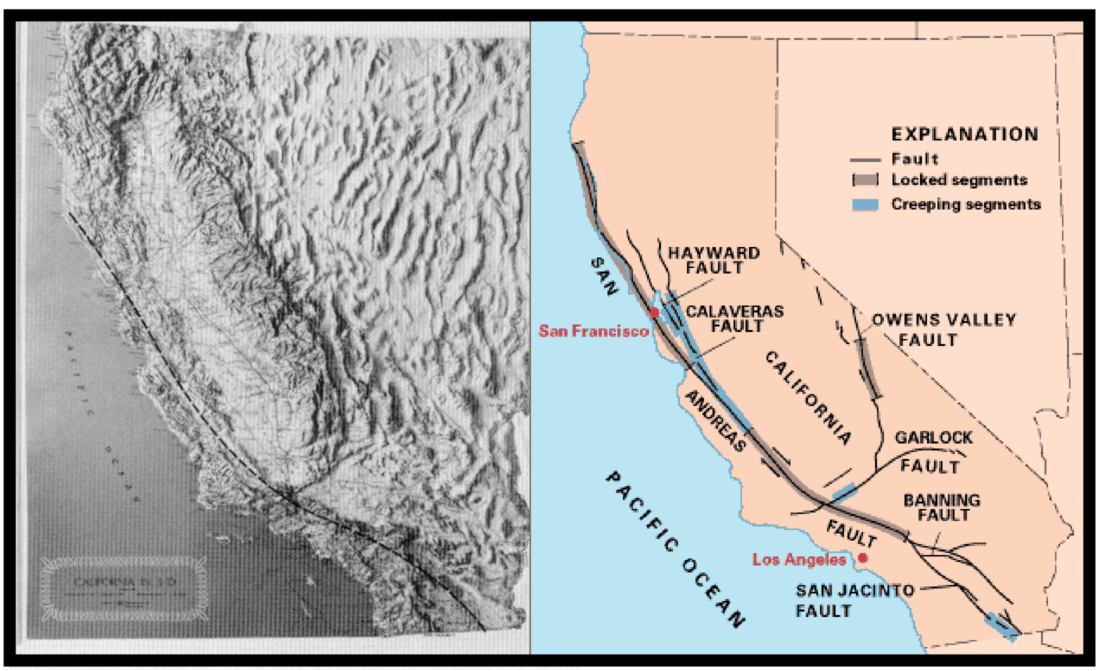

Figure 3-7. The topography of California is explained by the plate tectonic boundaries, but that of Nevada must await further discussion of how continents work in the next chapter.

Seismology and Plate Tectonics

When an earthquake happens, the Earth shakes with a precise pattern to its vibrations – a pattern controlled by the type of earthquake that it is. The initial, outgoing wave of energy from the break along a fault is called a compressional wave (also called the primary or P-wave) because the particles in the Earth push and pull each other as the vibration passes directly away from the break (think of it as shaking exactly away from, then toward, the location of the earthquake like ripples on a pond moving away from a pebble-impact). The second form of vibration is a shear wave (also known as the secondary or S-wave), so called because the Earth transmits the shear vibrations by a sideways motion, moving perpendicular to the expanding shear waves. This wave is important because solid must be in contact with solid for a shear wave to pass. If liquid exists anywhere within the Earth, shear waves will be absent for the portion of the wave's path that crosses through that region.

Waves going directly through the center of the Earth have very slow velocities as they pass through the outer core because part of that path is through the liquid iron core. Not only do shear waves disappear there, but compressional waves are slowed by the "softness" of the liquid as well. That is, the time it takes for the P-wave to pass through the Earth appears to be slow because the liquid outer core absorbs all shear and some compressional energy and thus slows down even the P-wave. But it then speeds up again in the solid iron inner core, before slowing again thru the outer liquid core on its way back to the earths surface on the other side of the planet.

The lithospheric plates that form surface layer of the Earth are fast transmitters of shear waves, and thus rigid and solid. However, only a few hundred kilometers below the surface, a slow velocity is observed everywhere from the partially liquid upper mantle. Lithospheric plates vary in thickness with their oceanic portions sometimes less than 100 km thick and continental segments sometimes over 300 km thick.

Low velocity seismic waves are found wherever there is molten rock, but not much is required – even 1 percent melt and 99% solid rock . Even that scant amount is enough to eliminate shear waves and slow down P-waves. It is this upper mantle of partially molten magma "slush" that provides lava to the surface at mid-ocean ridge spreading centers whenever extension pulls two plates apart and a crack appears in the lithosphere. The partially molten upper mantle is called the asthenosphere. The lithosphere, made up of cold, completely solidified rock, is gravitationally unstable in that it is heavier than the asthenosphere below. In fact, plate tectonics is often described as a set of large conveyor belts, with new rock moving upward at mid-ocean ridges, outward and along the ocean basins and downward, back into the asthenosphere at subduction zones.

Seismologists use visual displays of earthquake focal mechanisms, called balloons, that are really the simplest information one can get from an earthquake. An earthquake literally shakes the entire Earth. But as we saw above, there is logic and a pattern to this shaking. As the compressional wave passes any given location on the Earth, the ground either heaves up or sinks down as its first-motion response to the passing compressional energy. But the earth moves either up or down in four quadrants, not in halves as one might expect.

The planet cannot move only in two halves like an orange sliced along the fault that caused the earthquake in the first place. Consider the San Andreas Fault: If half the globe west of California heaved up and slid to the north after the San Francisco earthquake in 1906 and the other half of the planet east of California sank and moved to the south, the rotation of the Earth would be disrupted. It would be as if one were to slice a tennis ball in half, then glue it back together with the two halves offset. Throwing the tennis ball would cause it to carom wildly off to one side. The Earth cannot do the same. It must spin smoothly in its orbit. The secret of how the Earth accommodates the splitting motion of an earthquake is found in that familiar axiom: For every force in one direction, there must be an equal force in the opposite direction (one of Newton's laws of motion). If the Pacific moves to the north, then the Indian Ocean on the opposite quadrant of the globe must move counter to it to balance the net force on the Earth. Otherwise, our rotation would be disrupted. This means that the Earth must move in *quadrants* during an earthquake, rather than in halves, and this is just what we observe when studying the first motions of all earthquakes.

Consider a gravity, or normal, fault where the Earth breaks along a slope and the rock slides downhill in the direction of the gravitational pull. Tensional forces cause such faulting. Somewhere on the opposite side of the globe, the Earth must move in the opposite direction to counteract this force. There are now many thousand more than the original 125 seismographic stations around the world that have instruments that record the motion of earthquakes. By recording whether the first motion of the ground was either up or down after an earthquake, the mechanism or type of earthquake can be determined, even if the earthquake happened hundreds of miles underground. A normal fault will cause all stations near the downthrown side of the fault to record downward first motions. Stations on the other side of the fault will record upward first motions. By examining enough seismograms from the four quadrants of the planet centered on the location, or epicenter of the earthquake, the two regions that moved up can be mapped. Ninety degrees from these quadrants will be two regions that moved down. By projecting the spherical earth onto a plane, a balloon, or focal mechanism can be drawn. The pattern of the balloon allows one to determine the type of earthquake that occurred, even if the event was located thousands of miles to sea under the ocean.

What if a mysterious earthquake occurred last night in the center of the Indian Ocean? Visual inspection of the fault is impossible, yet we can determine not only what type of event it was, but also the orientation of the quadrant boundaries will show the type of plate boundary on which the earthquake occurred.

By determining the focal mechanism “balloons” from the earthquakes occurring under Japan, we can describe the physical processes occurring during subduction. Not only do we see the Pacific plate hanging beneath Japan, as outlined in the locations of the earthquakes themselves, but the focal mechanisms on the upper plane of the plate are all compressional or thrust earthquake balloons. Those on the bottom plane are all normal fault balloons (Figure 3-8). The plate is first bending under Japan, then unbending again after passing into the mantle. Such forces can be replicated by sliding a sheet of paper over the edge of a table. Because the paper is elastic, first it bends then unbends as it passes over the edge of the table. The balloons have allowed us to see not only the forces present for hundreds of miles beneath Japan, but the elasticity of the solid lithospheric plates as well.

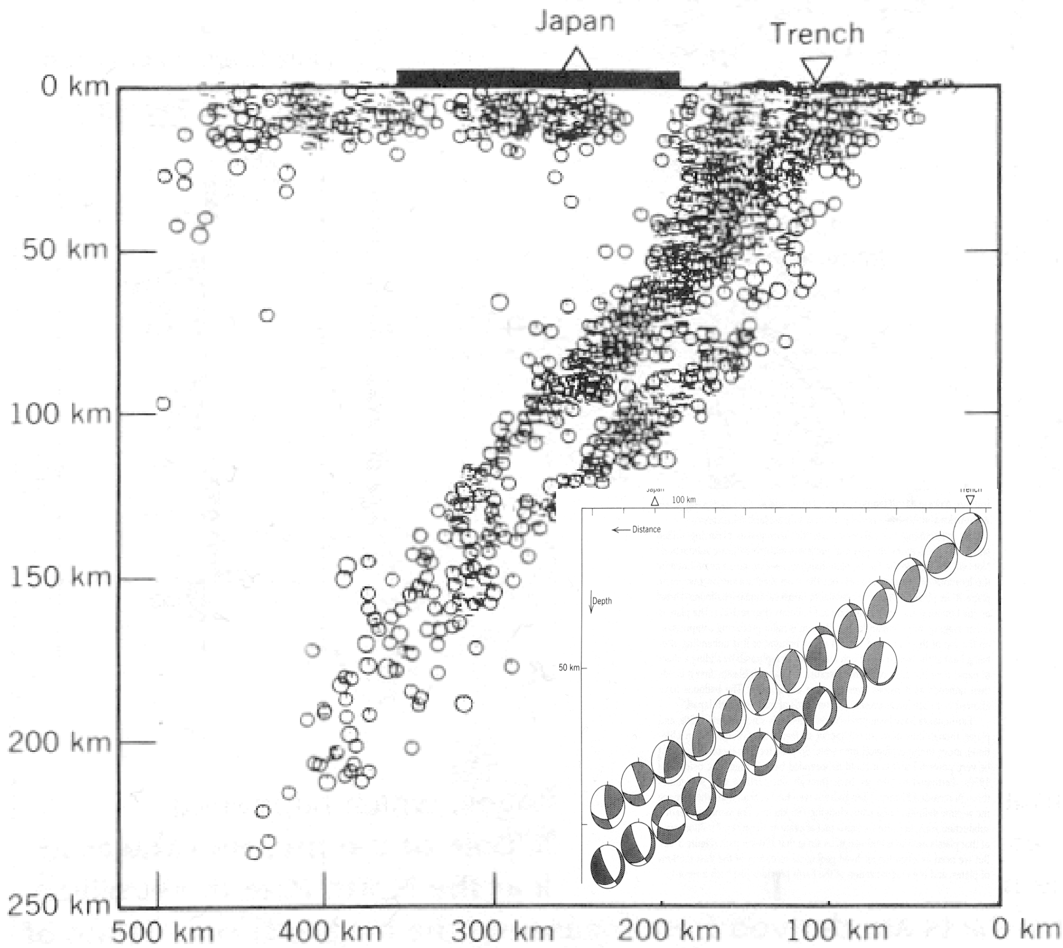

Figure 3-8. Small circles are all the earthquakes to occur beneath Japan (marked by the black bar at the surface) between 1970 and 1990. In the lower right are the composite focal mechanism balloons for all the earthquakes that occurred along the two bands marking the upper and lower boundaries of the subducting Pacific plate. A black center indicates compressional or thrust earthquakes. A white center indicates extensional or normal earthquakes. The plate is unbending!

Earthquakes have been precisely recorded only since the late 1950s, and plates, though they move slowly: a few centimeters per year or about six feet in the average person's lifetime. So plate tectonic theory would not be very powerful unless it could be extended back in time long before the 1950's. Earthquakes recorded in human history take us back sometimes thousands of years. They go back even further than that when we see the seismic definition of a plate plunging 250 km or more into the mantle beneath a subduction zone like Japan though, because we know that at a rate of 10 cm/yr, 2.5 million years of that plate's motion is outlined to us along that path (Figure 3-8). But we need an even longer-lived geological recording of the past motions of plates, and the magnetization of the Earth provides just such a record.

Magnetism and Plate Tectonics

The dilemma of how to extend the geological record far into the past is solved partially on the ocean floor, which provides us with the history up to about 160 million years ago. We will have to turn to the continents and its mountain ranges and sedimentary basins to “see” from then till when the record disappears at about 3.7 billion years. The plates are indeed geologically young, because subduction carries the oceanic lithosphere back into the mantle whenever collision with another plate occurs. Continents are the rock “scraped-off ” from more than 20 successive generations of lithospheric plates, born at the mid-ocean ridges and successively subducted back into the mantle. The ocean itself has been deep and blue for the all that 3.7 billion years, resting on this restless conveyor belt of ever changing rock. Amazing.

Fortunately, sea-floor spreading has recorded this most recent sea floor progression with the precision of a map -- and a magnetic map at that. The Earth's magnetic field originates in the liquid outer core. Convection currents are again responsible, this time for moving electrons in the slowly churning iron liquid. This motion results in an electrical field, and as Maxwell's equations tell us, a magnetic field is therefore present as well. Because of the still poorly understood “instability” in these convection currents in the outer core, a unique phenomenon has occurred randomly throughout the history of the Earth -- polarity reversals. The north magnetic pole flips from attractive to repulsive and the south pole does the opposite (Figure 3-9). That is, the repellent “North” magnetic pole suddenly flips to become the attractant “South” pole. To observe rocks with reversed magnetic poles is easy (one need only use a compass), but the explanation of why the Earth's magnetic field reverses randomly is mostly unknown. Still, one can begin to appreciate the joy of the founders of plate tectonics to recognize so simple yet so bizarre a phenomenon as magnetic pole reversals. They must have initially wondered whether anyone would believe such an outlandish concept.

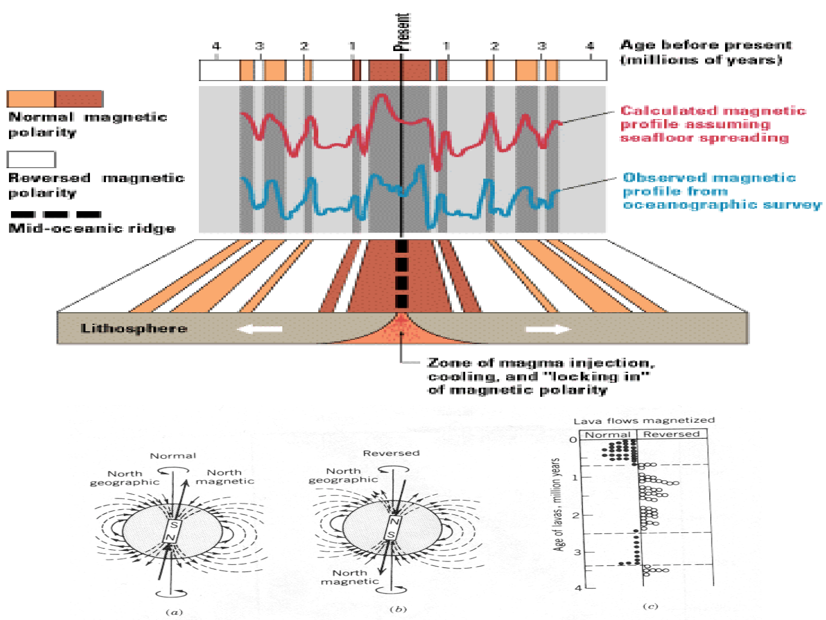

Figure 3-9. Magnetic reversals are recorded by cooling magma at mid-ocean spreading centers producing stripes that can be mapped to date the age of the sea floor.

The Earth's magnetic field works as if a large bar magnet or dipole were at the center of the Earth. Of course, there is no such magnet down there. The convection just makes the magnetic field look that way. The present configuration of north and south is called *normal.* It was *reversed* 700,000 years ago. If you go to a volcano in Iceland, at the center of the Mid-Atlantic Ridge, and pick up a newly solidified piece of lava, its magnetic memory will be frozen in the instant it cools (slows its vibration state) just enough to solidify into rock -- that field that existed on Earth when it cooled down past that crystallization temperature -- will tell you that the north pole is up towards the present pole. If, however, you drive a few miles down the flank of the volcano, toward the eastern or western shores of Iceland, and pick up a volcanic rock that crystallized 701,000 years ago, it will show the incredible fact that the south pole of the rock faces up toward the present north pole. A compass needle will point toward the young rock and away from the older rock. The Earth’s magnetic field reversed itself., and as the volcano continued to spew out new lava, a compass of the earth's past magnetic field was recorded within the successively younger rocks (Figure 3-10).

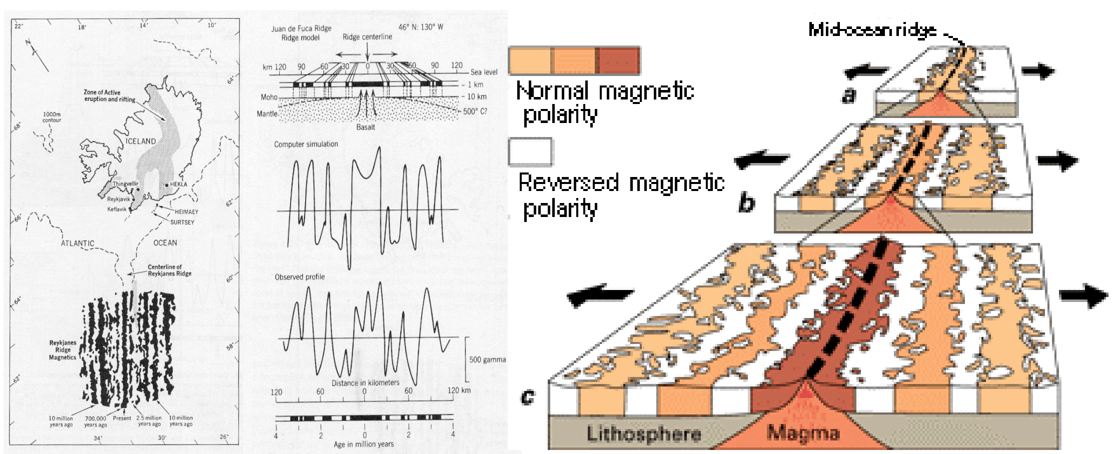

Figure 3-10. Magnetic stripes of successively normal and reversed rock cooled on the mid-ocean ridges as sea-floor spreading has proceeded since long ago in the geologic past.

If you take a ship and steam east to west several times across the Reykjanes Ridge, the portion of the Mid-Atlantic Ridge just south of Iceland with a magnetometer trailing behind the boat, stripes will appear on your shipboard magnetic field recording device (Figure 3-10). These stripes are parallel to the mid-Atlantic ridge and to the coasts of Europe and North America. They represent successively older rock as one goes away from the Mid-Atlantic Ridge crest towards the continents. The pattern of normal (brown-striped) and reversed (white-striped) magnetic anomalies is as distinctive as a fingerprint, telling the age of the sea floor in Figure 3-10.

The earth's magnetic field reversed scores of times during the formation and cooling of successive segments of the Reykjanes ridge sea-floor. As the North American plate spread away from the European plate, these stripes of younger and younger lava cooled onto the edges of the receding plates, only to record permanently the compass direction of their age.

The validity of this "fingerprint" was proved by the deep-sea drilling vessel *Glomar Challenger.* Named for the first purely scientific oceanographic vessel, the HMS *Challenger* of the 19th century, the *Glomar Challenger* has proved to be the most powerful tool ever devised for obtaining scientific information about the sea floor (Figure 3-11). Over 1000 holes have been drilled into the oceanic lithosphere by the *Glomar Challenger* and its successor, the *JOIDES Resolution* since its first hole in 1969. Yet a third generation of ocean floor drilling is scheduled to commence with a brand new, state-of-the-art drilling ship in 2005.

The rock and sediments at all these sites are dated, and have proved beyond a shadow of a doubt that the sea floor spreads, that the continents ride on lithospheric plates, and that magnetic-reversal stripes have accurately recorded the history of that movement (Figure 3-11). Since the late 1960s, hundreds of oceanographic ships from more than 50 nations have scoured the oceans recording the magnetic anomalies of the ocean floor, and consequently, the age of the sea floor has been determined virtually everywhere. Yet we would surely still be arguing about such an outlandish theory that the magnetic poles have reversed if the drill bit had not actually returned specimens to the laboratory to prove it.

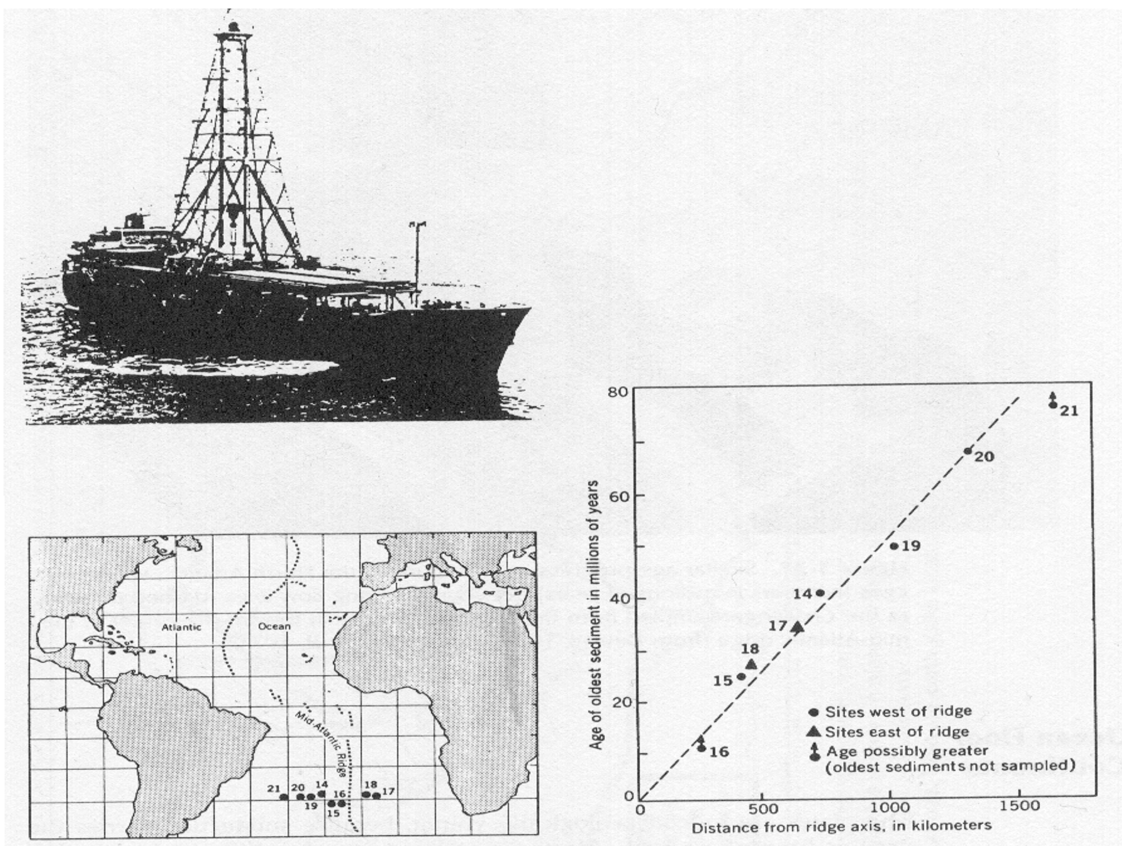

Figure 3-11. Sediment cores recovered from the deep sea floor are age-dated to show the age progression away from the mid-Atlantic ridge to validate Plate Tectonics.

Volcanoes and Plate Tectonics

The continents grow by this same collision process because they are made up of rock that is lighter than oceanic rock and thus more difficult to subduct. Some of this light rock is “scraped-off”. Also, at subduction zones, the oceanic plate is melted back into the mantle and the lightest and most buoyant of this magma escapes back to the surface forming volcanoes. This combination creates the largest mountain ranges on Earth, such as the Andes, the Sierra Nevadas, and the Himalayas (Figure 3-12). These mountain ranges are the predominant mechanism by which the continents grow new rock. This subduction process is also one of the reasons why earthquakes and volcanoes occur at the same places on the planet.

The sea floor is relatively simple geologically because it is never at the surface to suffer erosion. All sea floor older than 160 million years has been subducted back into the mantle. Complexity is bred by multiple overprinting events through a long geological history. The longer a feature remains on the surface, the more complex and more difficult to decipher it becomes. Thus, plate tectonics was not discovered until the simplicity of the ocean floor was realized. The continents are light, and they float like blocks of wood in the bathtub of the heavy ocean-floor rock. They float because they are made of some of the lightest rock on the planet. Continents are hard to force down a subduction zone because they are so light. Therefore, continents have grown throughout geological time and so are much more complex than the oceans. More on that in Topic 4.

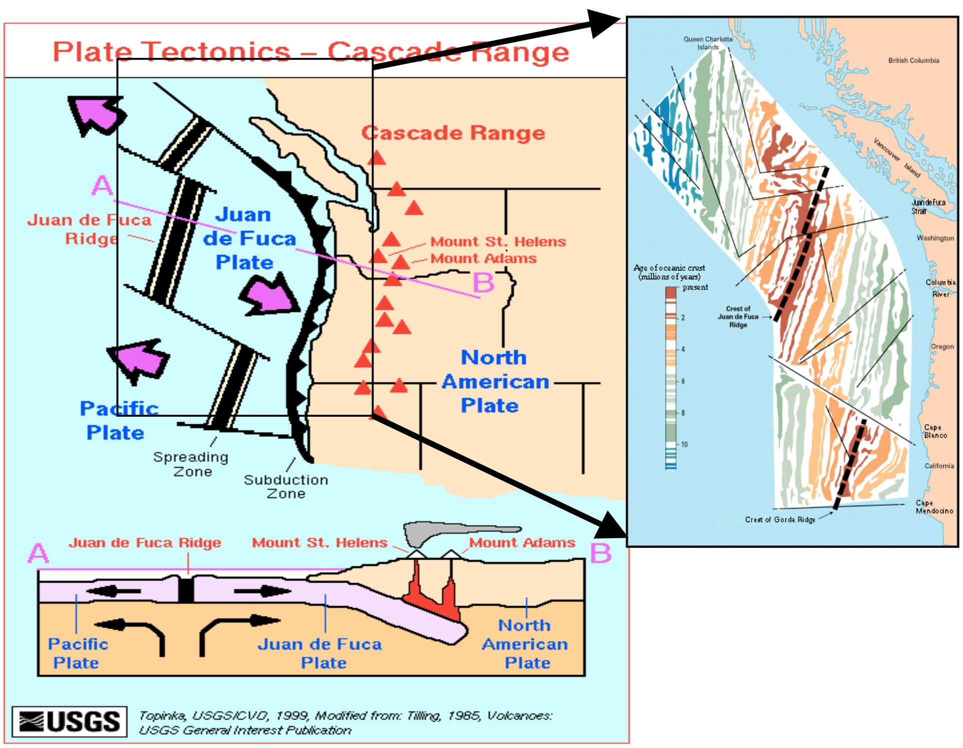

Figure 3-12. The magnetic stripes off the western U.S.show sea floor about to be subducted beneath Washington, Oregon, and Northern California resulting in volcanoes like Mts. Ranier, Hood, and St. Helens.

Surrounding the Pacific Ocean is a line of dangerous volcanoes often called the "Ring-of-Fire." Not coincidentally, most of the violent earthquakes occurring in the Pacific region are also located along this Ring-of-Fire. Why is there so much geological danger along the boundaries of the Pacific Ocean? A visual inspection of the distribution of earthquakes around the margins of the Pacific hints at the explanation.

From the Aleutians in the north to Kamchatka, Japan, and the Marianas on the west to New Guinea, the New Hebrides, and Tonga in the south, and Peru and Chile, Central America, and the Cascades in the East, the Pacific Ocean is rimmed by subduction zones. For some yet unexplained reason, most of the plates surrounding the Pacific Ocean are subducting on its borders. The result is that oceanic lithosphere under the Pacific Ocean is being overridden by the surrounding plates at its edges, forcing lithosphere downward, deep into the mantle. Edges of the Pacific oceanic plates are literally hanging beneath Alaska, Japan, the Andes, and the western United States (Figure 3-12).

Why are subduction zones located where they are and how do they start in the first place? Our interest in this phenomenal event is required, however, because most of the geological violence that affects our daily lives occurs along these subduction zones. The evidence is incontrovertible that this subduction definitely causes catastrophic volcanic eruptions and earthquakes periodically. Until we understand subduction better, we stand little chance of successfully predicting their fickle outbursts.

Because of human curiosity, it is very difficult to keep scientists who spend their lives studying volcanos away from erupting volcanoes. Consequently, it is a risky profession. The geological news magazine *Geotimes* recently ran an advertisement for a job as “chief volcanologist” for the government of New Guinea: excellent pay, good fringe benefits, liberal vacation time, etc. On the back page to this ad was the obituary for the last chief volcanologist of New Guinea. He had ventured too close to an eruption trying to sample the gases and volatiles from an erupting volcano!

Yet we are entertained often by beautiful pictures of lava flowing as rivers down the slopes of Kilauea Volcano in Hawaii. There has even been a tourist hotel right on the caldera crest, Volcano House, that has looked outs on the National Volcano Observatory on the big island of Hawaii since 1856. Mark Twain once stayed there and wrote about it. Needless to say, eruptions there can be witnessed first-hand without too much danger there. The same cannot be said for Mt. St. Helens and other “Ring-of-Fire” volcanoes, which killed volcanologists along with a lot of other people each year.

Understanding the dangers involved in some but not all volcanoes gives us a grand hint at processes that are active beneath volcanoes in subduction zones. What makes volcanoes like Mt. St. Helen's or those on New Guinea so dangerous compared to passive eruptions such as on Hawaii, or Iceland or the Galapagos, for that matter?

The Japanese classify their volcanoes according to what they call the E- factor, which rates the likely violence of the Eruption. For a high E-factor volcano, consider Vesuvius, which erupted killing the residents of Pompeii as they slept. They did not even have time to be awakened by the incredible noise of the eruption!How can this be? How can a volcano kill so quickly? Here is an eye-witness account from a ships-log of the eruption in 1902 of Mt. Pelee on Martinique (above a subduction zone in the Carribean):

I saw St. Pierre destroyed. The city was blotted out by one great flash of fire. Nearly 40,000 people were killed at once. Of eighteen vessels lying in the roads, (harbor) only one, the British steamer, Roddam escaped and she, I hear, lost more than half of those on board. It was a dying crew that took her out. Our boat, the Roraima, arrived at St. Pierre early that morning. For hours before entering the roadstead we could see flames and smoke rising from Mt. Pelle. No one on board had any idea of danger. Captain Muggah was on the bridge, and all hands got on deck to see the show. The spectacle was magnificent. As we approached St. Pierre we could distinguish the rolling and leaping of red flames that belched from the mountain in huge volumes and gushed into the sky. Enormous clouds of black smoke hung over the volcano. There was a constant muffled roar. It was like the biggest oil refinery in the world burning up on the mountain top.

There was a tremendous explosion about 0745, soon after we got in. The mountain was blown to pieces. There was no warning. The side of the volcano was ripped out and there was hurled straight toward us a solid wall of flame. It sounded like a thousand cannons. The wave of fire was on us and over us like a flash of lightning. It was like a hurricane of fire. I saw it strike the cable steamship Grappler broadside, and capsize her. From end to end she burst into flames and then sank. The fire rolled in mass straight down upon St. Pierre and the roads. The town vanished before our eyes.

The air grew stifling hot and we were in the thick of it. Wherever the mass of fire struck the sea, the water boiled and sent up vast columns of steam. The sea was torn into huge whirlpools that careened toward the open sea. One of these horrible, hot whirlpools swung under the Roraima and pulled her down on her beam end with the suction. She careened way over to port, and then the fire hurricane from the volcano smashed her, and over she went on the opposite side. The fire wave swept off the masts and smokestacks as if they were cut by a knife.

Captain Muggah was the only one on the deck not killed outright. he was caught by the fire wave and was terribly burned. He yelled to get up the anchor, but before two fathoms were heaved-in, the Roraima was almost upset by another boiling whirlpool and the fire wave threw her down on her beam ends to starboard. Captain Muggah was overcome by the flames. He fell unconscious from the bridge and overboard. The blast of fire from the volcano lasted only a few minutes. It shriveled and set fire to everything it touched. Thousands of casks of rum were stored in St. Pierre, and these were exploded by the terrific heat. The burning rum ran in streams down every street and out into the sea. This blazing rum set fire to the Roraima several times.

Before the volcano burst, the landings of St. Pierre were covered with people. After the explosion, not one living soul was seen on the land. Only twenty-five of those on board the Roraima were left after the first blast. The French cruiser Suchet came in and took us off at 1400. She remained near by, helping all she could, until 1700, then went to Port de France with all the people she had rescued. At the time it looked as if the entire north end of the island was on fire.

On the other hand, the entire country of Iceland lives on active volcanoes. Icelanders even produce their electricity and heat their homes from hot springs on the flanks of these volcanoes. An occasional eruption threatens to direct rivers of lava into one of their towns, but only rarely is anyone killed by an eruption.

What is different about Iceland that allows townspeople to sit calmly and watch lava bubble down the road in Iceland, or Mark Twain to cross the erupting caldera at night in Hawaii, whereas their colleagues risk instant and unpredictable death by even approaching an eruption in Japan , Indonesia, Washington, or New Guinea (Figure 11-13).

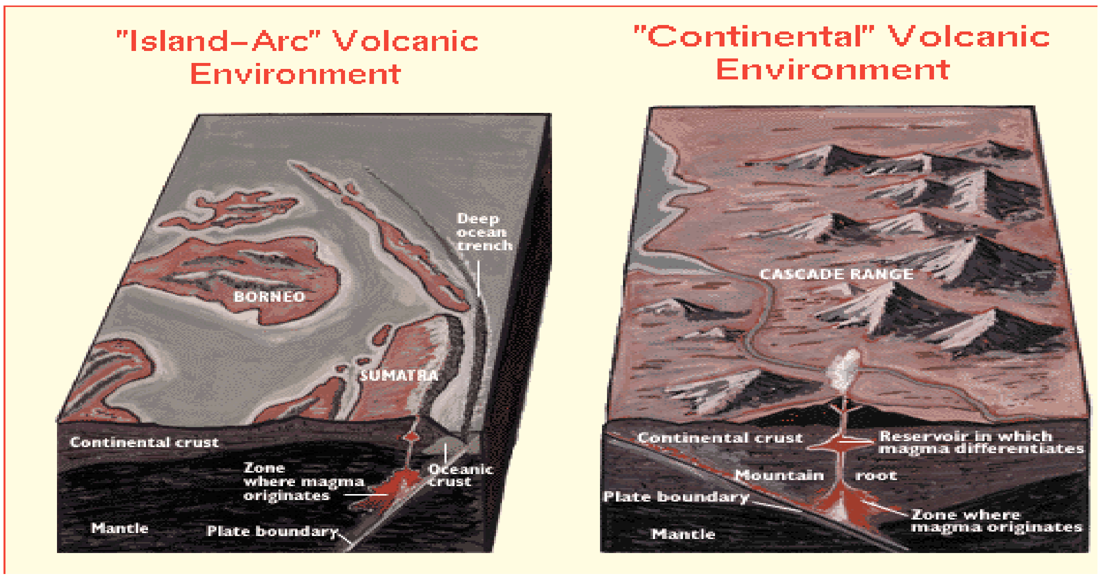

Figure 3-13. Volcanoes above subduction zones like in Indonesia (left) or the western United States (right) contain steam and other dangerous gases like hydrogen sulfide from dehydration as the oceanic lithosphere reheats and assimilates back into the mantle.

Plate tectonics provides an answer to this important question. Explosive volcanoes erupt above subduction zones, whereas passive volcanoes are located great distances from subduction zones above what are called “Hot Spots”. Iceland is on the crest of the Mid-Atlantic Ridge, for example, and Hawaii is an isolated hot-spot tapping deep mantle magmas far from any plate boundary.

The volcanoes above subduction zones are explosive because they contain large quantities of volatile gases such as steam, carbon dioxide, and hydrogen sulfide. These do not come from the mantle directly, or all volcanoes would be explosive. Most of the mantle's gases have been long ago lost to the oceans and atmosphere. Explosions occur when volatiles such as water come up entrapped in lava melted from the dehydration of subducting ocean lithosphere. As the water approaches the surface, it flashes to steam, and we have a natural pressure cooker. Any small breach of the cooker walls and the steam explodes out, often taking entire sides of the volcano with it.

The subducted oceanic crust is the source of the water and other volatiles. Here is a case where, if it were not for ridge-axis black smokers and the pervasive hydrothermal circulation of seawater into spreading centers that gave us tube-worms, giant clams and chemosynthetic bacteria, subduction zones thousands of miles away would be a whole lot safer places. Notice how plate tectonics has a way of tying world-encompassing events together to make sense of how the Earth works. The steam from these explosive volcanoes had become locked into newly forming ocean crust millions of years before, at the start of the plate's long traverse across the conveyor belt. The water was captured in the structure of alteration minerals within the new rock forming the oceanic plate. Perhaps 5 percent by weight of the rock of the upper 2 or 3 km of the oceanic plates is water locked into the mineral structure of hydrous clays and other minerals. This altered rock passively rides the plates until the "kiln" is re-fired during subduction and the water is again released.

Sound familiar? Here again we encounter the rock kiln. As the oceanic rock is heated by friction and the heat flow from the surrounding hot mantle, dehydration eventually occurs. The water is suddenly freed. This newly freed water is restored to a buoyant fluid. This time though, it is deep within the mantle. As it forces itself into the overlying mantle, melting occurs in rock that would not ordinarily melt at those temperatures. Water acts as a catalyst, allowing rock to melt at cooler temperatures than normally would be possible. and it explodes toward the surface as part of the magma making up subduction zone volcanos (Figure 3-14).

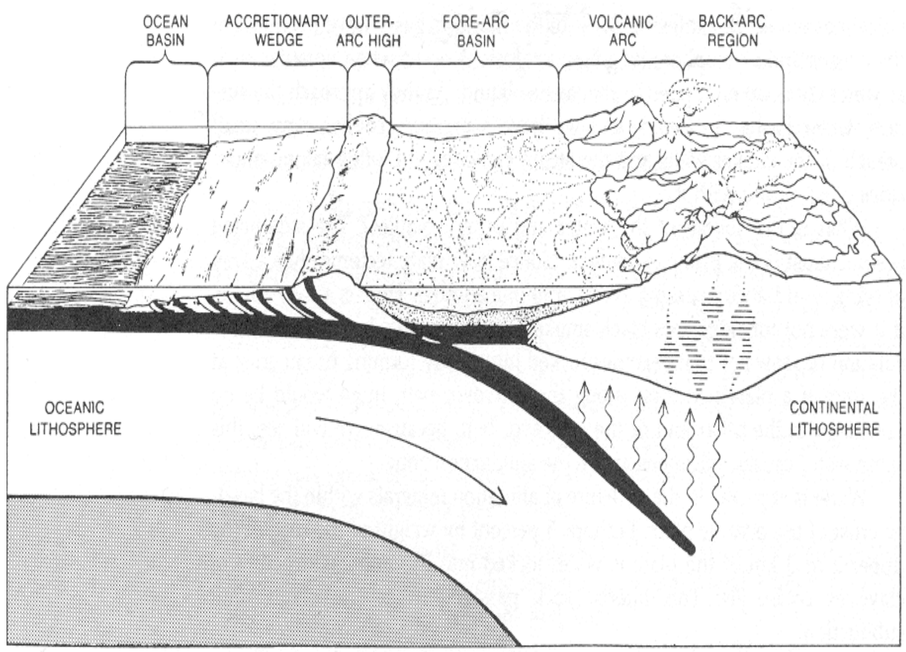

Figure 3-14. Dehydration of the subducting oceanic lithosphere provides the water that flashes to steam in volcanic arcs to form explosive eruptions.

Melting is the breakdown of the rigid lattice structure of solid rock. It requires heat because this breakdown is caused by increased vibration of the molecules. Water acts as a catalyst to melting because it is highly soluble and "seeps" in the solid structure of the rock. It penetrates between individual crystals and separates them. Remember that water is incompressible. Less energy is then required to raise each individual molecule to the vibration state required to breakdown the structural bonds from crystalline into liquid. Being less tightly interconnected, individual vibration states are lower and closer to breakdown; that is, the melting temperature is lower in wet mantle than in dry mantle.

Earthquakes give us direct, observational proof that the dehydration is producing mantle melting in subduction zones. Probably the single easiest observation to make about earthquakes is the ”b-value”. A histogram of the number of earthquakes occurring at each magnitude shows an interesting, trend – a straight, linear line on a logarithmic plot of the number of earthquakes occurring at each magnitude or size. Such “fractal distributions” are abundant on the Earth. Put simply, there are always many more small earthquakes than medium ones than large ones that very large ones, and so on. The slope of such a fractal line is called the b-value of a group of earthquakes, and it varies from locale to locale. Some places have many large earthquakes; others have only a few large earthquakes and many more small ones. California, for example, has about the same total number of earthquakes as Japan, but the b-value is smaller and therefore many more of them are small. While we do not fully understand the physical basis of why earthquakes are always distributed linearly, or fractally, on such a plot, we can still use such an observation to classify different earthquake provinces. The name “b-value” by the way comes from the equation of any line: $y = a + bx,$ where b is the slope of the line. What would you guess the effects of water would be on the b-value?

Water lubricates a fault and makes it break and slide more easily, so there are more, but smaller, earthquakes in a wet rock environment than in one that is dry. The slope of the line tracing the population of big versus small earthquakes then steepens at the small end and the “b-value” increases if water is present along a fault zone. This observation has been proved in cases where humans have altered the water pressure inside the earth artificially. Near Rangely, Colorado, in 1967, a large volume of water was pumped into deep oil wells to try to get more out of the ground – called a “water flood” when suddenly earthquakes began to occur beneath nearby Denver. Since no previous earthquake activity had been recorded in the Denver area, the pumping was stopped. The earthquakes immediately stopped also. A series of pumping tests then established that the “b-value” beneath Rangely could be controlled by the volume of water pumped into the wells. The larger the water volume, the larger the number of small earthquakes recorded. The good news for Denver was that when pumping was stopped completely, the earthquakes stopped. The bad news is that the “b-value” returned to its natural, lower value, indicating that there will be many fewer earthquakes, but when they come, they will be larger in magnitude than if pumping had continued.

While this is an unfortunate design problem for enhanced oil recovery, it provides an excellent empirical framework with which to test for water release beneath Japan and along other subduction zone. We can actually see the increased occurrence of small earthquakes beneath Japan as water is being released by dehydration as the kiln is activated in the subducting oceanic crust. Looking down the upper plane of seismic activity along the subducted plate beneath Japan, we first see high b-values from the escape of free water in the shallow accretionary wedge near the trench (Figure 11-15). Surprisingly, it appears to take 50 km or more of subduction to squeeze all the free water out of the subduction zone. Then a dry zone is encountered from 50 to about 100 km as seen from low b-values. A dramatic increase in “b-value” occurs at the proper depth for dehydration reactions to be occurring in the upper seismic plane directly below explosive volcanos like Mt. Fuji in Japan (Figure 11-15).

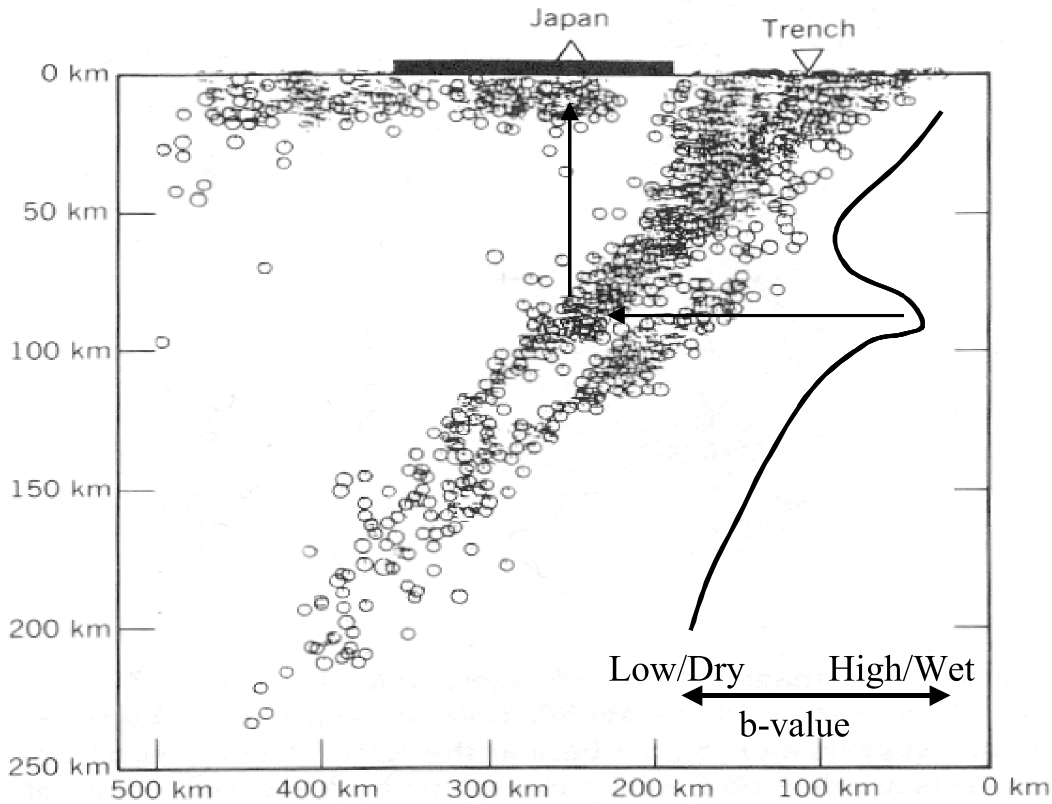

Figure 3-15. The "b-value" of earthquakes along the upper earthquake plane of the subduction zone beneath Japan shows that first free water is squeezed out of the plate by 50 km depth, then earthquakes occur in a relatively dry top to the subducting Pacific plate to about 75 km, where the "kiln" fires-up and dehydration produces the characteristic high b-values from wet conditions along fault zones to deeper than 100 km. By then, all of the water from the downgoing plate has been driven into volcanic magmas that rush to the surface. The rest of the subduction zone gets dryer and dryer with depth.

Water is not the only thing freed to make its way to the surface at subduction zones. Shallow dipping faults scrape mud and sediments from the oceanic lithosphere as it bends down in the first place to form "Accretionary Wedges" that gloms onto the landward plate (Figure 3-14). The combination of soft mud and buoyant water trying to escape provides liquid surfaces for the sediments to scrape off the down-going oceanic lithosphere and accrete onto the overlying plate. Similar decollement surfaces are sometimes accreted high into the mountains as nappe structures in old collision zones. That is the origin of the Alps.

The *Glomar Challenger* drilled into such a fault zone off Barbados and accidentally provided graphic proof of the existence of free water along such decollement faults in accretionary wedges. The drill string became stuck in the fault zone. When that occurs, dynamite must be used to shoot-off the stuck pipe, thus freeing the boat itself from the anchorage in the rock. During the 12 hours it took to dynamite off the pipe, water began backflowing onto the rig floor at rates of hundreds of gallons an hour. In order to push water in a reverse direction to gravity and up the pipe, pressures in the fault zone must overcome the hydrostatic weight of the entire column of water standing in the mineral lattices.

Most of the activity that affects man in a subduction zone occurs landward of the Accretionary wedge and trench axis. Volcanoes made from dewatering of the downgoing slab come to the surface in either continental mountains or in island arcs, but always on the landward side. Whether the volcanoes form islands or become part of a large mountain range has to do with the previous geological history of the plate margin colliding with the subducting plate. If it is continental, a mountain range will be formed because all the volcanic activity from subduction will be piled on top of an already emergent coastline. Examples are the Andes of South America and the volcanoes of Central America. If however, the overriding plate is oceanic, new volcanoes must begin by piling lavas onto the sea floor. They emerge as islands only after they have flowed enough magma to build a pyramid tall enough to break the sea surface. Examples are Guam in the west Pacific where the Pacific plate is subducting beneath the Philippine plate and the Sandwich Islands between South America and Antarctica where the Atlantic plate is subducting beneath the Scotia plate (Figure 3-16).

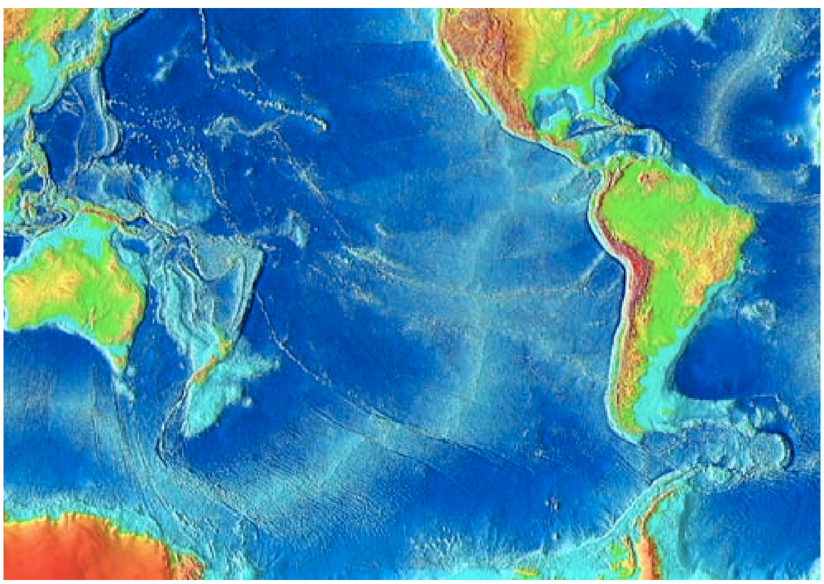

Figure 3-16. Island arcs can be seen in the western Pacific (upper left) and the southern Atlantic (lower right) where subduction is of an oceanic plate beneath another oceanic plate.

Island arcs are the early beginnings of new continents. They are arcuate (curved) because the subducting slab is a plane penetrating into a sphere. The surface expressions of volcanic plumes moving directly to the surface from such a plane define an arc. Volcanoes appear at the surface spaced about 100 km apart. That is the segregation distance for the production of enough magma along the slab to produce individual magma diapirs, which then congeal and move upward to the surface. If volcanism continues, enough rock is extruded to completely fill all the space between individual volcanoes to the point that sea level is exceeded even between volcanoes and a new continent appears.

There are other processes active above the subduction zone that add rock onto the island arc to fatten it into a small continent. A remarkable phenomenon often occurs even farther landward from the trench than the volcanic arc. Sea-floor spreading begins landward of the volcanic arc and is called back-arc spreading (Figure 3-14). The forces involved must be extensional since the process is virtually identical to mid-ocean ridge volcanism. They also must be related to the slabs interaction with the overriding plate. But we often call the subduction process collision, so how can tension result in the back arc? One possible explanation is that the subducting plate “falls” into the mantle like a wet towel laid onto the surface of a full tub of water. This results in a trench that migrates seaward with time, pulling the volcanic arc away from the overriding plate. Whenever tension opens rifts in the surface of the planet, mantle magma comes passively to the surface and a sea-floor spreading system begins.

Examples of back-arc spreading are the Mariana Trough behind Guam in the western Pacific, and closer to home, the Basin-and-Range province of the western United States. Finally, we have the beginnings of an explanation for the topography in Figure 3-7 above. Here, tension within the continent is from the Pacific plate's subduction beneath the Sierra Nevada range. This tension is pulling California to the west relative to Colorado. The result is faulting, which produces a series of north-south-aligned basins separated by ridges; thus the name Basin and Range. Extension inside continents only occurs along faults; that is, no actual gaps have appeared along which mantle lavas can reach the surface in large quantities. The whole basin is hot, with high heat flow at the surface indicating that the molten mantle is working its way closer and closer to the surface. Eventually, the continent could split apart, separating California from the eastern United States. This is one example of how we are beginning to understand more and more of the continent.