Background Reading for Instructor

Much of the following information, including most Visuals, was reproduced from the online version of *This Dynamic Earth: The Story of Plate Tectonics*, by W.A. Kious and R. I. Tilling. The online version can be obtained from the US Geological Survey at: http://pubs.usgs.gov/publications/text/dynamic.html#anchor19309449
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Causes of Earthquakes:

In the early 1960s, the emergence of the *theory of plate tectonics* started a revolution in the earth sciences. Since then, scientists have verified and refined this theory, and now have a much better understanding of how our planet has been shaped by plate-tectonic processes. We now know that, directly or indirectly, plate tectonics theory influences nearly all geologic processes, past and present. Indeed, the notion that the entire Earth's surface is continually shifting has profoundly changed the way we view our world.

People benefit from, and are at the mercy of, the forces and consequences of plate tectonics. With little or no warning, an earthquake or volcanic eruption can unleash bursts of energy far more powerful than anything we can generate. While we have no control over plate-tectonic processes, we now have the knowledge to learn from them. The more we know about plate tectonics, the better we can appreciate the grandeur and beauty of the land upon which we live, as well as the occasional violent displays of the Earth's awesome power.

Wegener, Alfred Lothar

Alfred L. Wegener (1880-1930) was a German geologist, meteorologist, and Arctic explorer. He is known for his theory of continental drift, as presented in *Die Entstehung der Kontinente und Ozeane* (1915; tr. *The Origin of Continents and Oceans,* 1924). According to Wegener, the present continents on earth were originally one large landmass he called Pangaea that gradually separated and drifted apart. He argued that the continents were still in the process of change and are still changing. His evidence included the jigsaw lineup of certain continents including the coast of Brazil and Africa's Gulf of Guinea, and paleontological similarities on either side of the Atlantic Ocean. His ideas were supported by some, including A. L. Dutoit, but rejected by most scientists until the early 1960s when scientists found more definitive evidence of continental drift (i.e., paleomagnetic evidence). He is also known for his expeditions to Greenland (on the last of which he lost his life) to establish meteorological stations and to ascertain the thickness of the icecap and the rate of drift of Greenland

Earthquake Frequency and Plate Boundaries

The USGS typically reports 2000 earthquakes per month, for an average of about 70

earthquakes per day. There are actually many more quakes than this, but we are limited in our ability to detect small earthquakes that occur far away from seismic observing stations.

Due to measuring limitations, a plot of known seismicity worldwide includes some spatial bias. For example, the southern hemisphere is almost entirely ocean, and much of the land there is inhospitable, so there are more seismometers deployed in the northern hemisphere. Therefore a plot of one month's earthquakes shows more events in the northern hemisphere simply because smaller events in the southern hemisphere are not detected. In addition, very dense networks of seismometers are arrayed in certain regions of the developed world with high seismic risk, such as Japan and California, which means that disproportionately many small earthquakes are detected in these regions.

Concentration of Earthquakes

During the 20th century, improvements in seismic instrumentation and greater use of earthquake-recording instruments *(seismographs)* worldwide enabled scientists to learn that earthquakes tend to be concentrated in certain areas, most notably along the oceanic trenches and spreading ridges. By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40-60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as *Wadati-Benioff zones,* or simply *Benioff zones,* in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States. The study of global seismicity greatly advanced in the 1960s with the establishment of the Worldwide Standardized Seismograph Network (WWSSN) to monitor the compliance of the 1963 treaty banning above-ground testing of nuclear weapons. The much-improved data from the WWSSN instruments allowed seismologists to map precisely the zones of earthquake concentration worldwide.

1. Earthquakes Delineate the Earth's Tectonic Plates

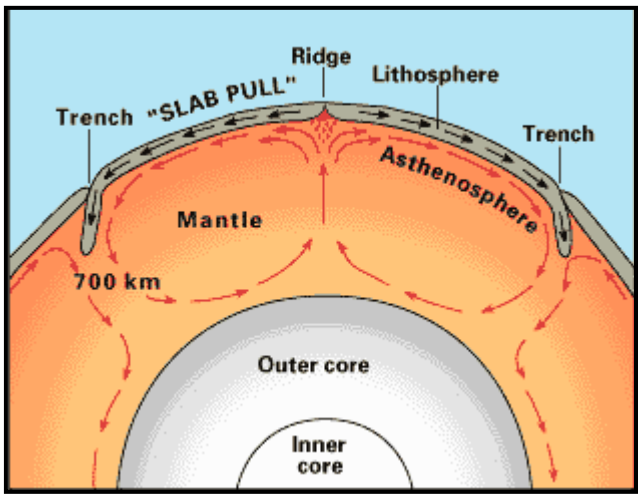
Because of the large number of earthquakes that occur on a daily basis, we can see a nearly complete set of plate boundaries with as little as 3-4 months of data. Six months' worth of data allows us to map the boundaries with a high degree of accuracy. The narrow bands of seismicity outline seven large plates and several smaller ones. The largest plate is the Pacific plate, followed by the African plate, Eurasian plate, Australian-Indian plate, Antarctic plate, North American plate, and South American plate. Smaller plates include the Nazca plate, Philippine plate, Caribbean plate, Cocos plate, and Juan de Fuca plate

2. Lithospheric Plates

Most continental shorelines do not coincide with plate boundaries (one important exception is the west coast of South America). Nor are most shorelines zones of earthquake activity. For this reason, continental shorelines are referred to as "passive margins," places that may have been plate boundaries in the past, but are

no longer active. The east coast of North America is a passive margin, as are the east, south and west coasts of Africa, northern and western Europe, and others. The eastern boundary of the North American plate is in the middle of the Atlantic Ocean, where there is a belt of active seismicity. Thus the North American plate is made up of both continent and ocean. In fact, most plates consist of both continental and oceanic material. There are several entirely oceanic plates (e.g., Nazca, Cocos), but no entirely continental plates (with the possible exception of the Arabian peninsula; it depends on the criteria one uses to define individual plates and how much ocean is required to be considered "ocean"). The fact that continents are included as part of plates made of both continent and ocean suggests that the continents do not move independently of the oceans as Wegener envisioned, but rather that continent and ocean move together as part of a single plate. Thus from a geodynamical perspective, a "plate" appears to be a more fundamental unit than a continent or ocean.

The tectonic plates do not randomly drift or wander about the Earth's surface; they are driven by definite yet unseen forces. Although scientists can neither precisely describe nor fully understand the forces, most believe that the relatively shallow forces driving the lithospheric plates are coupled with forces originating much deeper in the Earth.

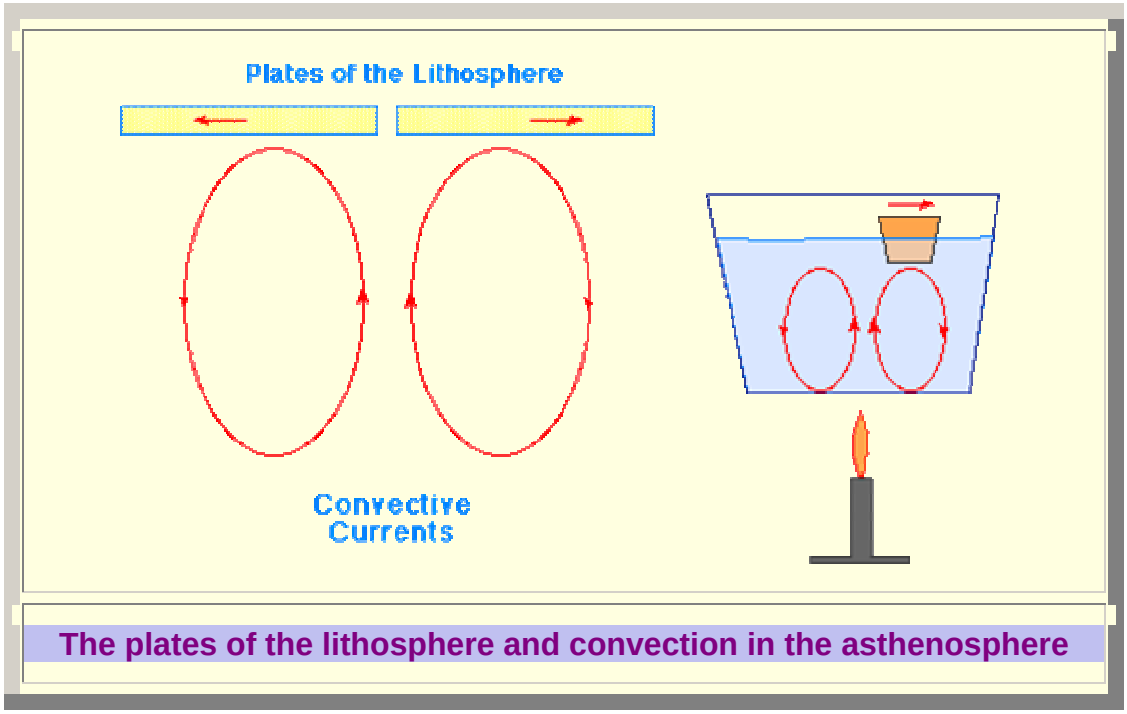


Visual 1. Diagram that illustrates the mechanism for plate movement. Very slow convection currents flow in the Asthenosphere, and these currents provide horizontal forces on the plates of the Lithosphere (much as convection in a pan of boiling water; see example below).

What Drives the Plates?

From seismic and other geophysical evidence and laboratory experiments, scientists generally agree with Harry Hess' theory that the plate-driving force is the slow movement of hot, softened mantle that lies below the rigid plates. This idea was first considered in

the 1930s by Arthur Holmes, the English geologist who later influenced Harry Hess' thinking about seafloor spreading. Holmes speculated that the circular motion of the mantle carried the continents along in much the same way as a conveyor belt. However, at the time that Wegener proposed his theory of continental drift, most scientists still believed the Earth was a solid, motionless body. We now know better. As J. Tuzo Wilson eloquently stated in 1968, "The earth, instead of appearing as an inert statue, is a living, mobile thing." Both the Earth's surface and its interior are in motion. Below the lithospheric plates, at some depth the mantle is partially molten and can flow, albeit slowly, in response to steady forces applied for long periods of time. Just as a solid metal like steel, when exposed to heat and pressure, can be softened and take different shapes, so too can solid rock in the mantle when subjected to heat and pressure in the Earth's interior over millions of years.



Visual 2. Diagram that illustrates the mechanism for plate movement. Very slow convection currents flow in this plastic layer, and these currents provide horizontal forces on the plates of the lithosphere much as convection in a pan of boiling water causes a piece of cork on the surface of the water to be pushed sideways). Of course, the timescale for convection in the pan is seconds and for plate tectonics is 10-100 million years, but the principles are similar. Credit: USGS.

The mobile rock beneath the rigid plates is believed to be moving in a circular manner somewhat like a pot of thick soup when heated to boiling. The heated soup rises to the surface, spreads and begins to cool, and then sinks back to the bottom of the pot where it is reheated and rises again. This cycle is repeated over and over to generate what scientists call a *convection cell* or *convective flow*. While convective flow can be

observed easily in a pot of boiling soup, the idea of such a process stirring up the Earth's interior is much more difficult to grasp. While we know that convective motion in the Earth is much, much slower than that of boiling soup, many unanswered questions remain: How many convection cells exist? Where and how do they originate? What is their structure?

Convection cannot take place without a source of heat. Heat within the Earth comes from two main sources: *radioactive decay* and *residual heat.* Radioactive decay, a spontaneous process that is the basis of "isotopic clocks" used to date rocks, involves the loss of particles from the nucleus of an isotope (the *parent*) to form an isotope of a new element (the *daughter*). The radioactive decay of naturally occurring chemical elements – most notably uranium, thorium, and potassium – releases energy in the form of heat, which slowly migrates toward the Earth's surface. Residual heat is gravitational energy left over from the formation of the Earth – 4.6 billion years ago – by the "falling together" and compression of cosmic debris. How and why the escape of interior heat becomes concentrated in certain regions to form convection cells remains a mystery.
Until the 1990s, prevailing explanations about what drives plate tectonics have emphasized mantle convection, and most earth scientists believed that seafloor spreading was the primary mechanism. Cold, denser material convects downward and hotter, lighter material rises because of gravity; this movement of material is an essential part of convection. In addition to the convective forces, some geologists argue that the intrusion of magma into the spreading ridge provides an additional force (called "ridge push") to propel and maintain plate movement. Thus, subduction processes are considered to be secondary, a logical but largely passive consequence of seafloor spreading. In recent years however, the tide has turned. Most scientists now favor the notion that forces associated with subduction are more important than seafloor spreading. Professor Seiya Uyeda (Tokai University, Japan), a world-renowned expert in plate tectonics, concluded in his keynote address at a major scientific conference on subduction processes in June 1994 that "subduction . . . plays a more fundamental role than seafloor spreading in shaping the earth's surface features" and "running the plate tectonic machinery." The gravity-controlled sinking of a cold, denser oceanic slab into the subduction zone (called "slab pull") – dragging the rest of the plate along with it – is now considered to be the driving force of plate tectonics.

We know that forces at work deep within the Earth's interior drive plate motion, but we may never fully understand the details. At present, none of the proposed mechanisms can explain all the facets of plate movement; because these forces are buried so deeply, no mechanism can be tested directly and proven beyond reasonable doubt. The fact that the tectonic plates have moved in the past and are still moving today is beyond dispute, but the details of why and how they move will challenge scientists far into the future.

Rates of Plate Motion

We can measure how fast tectonic plates are moving today, but how do scientists know what the rates of plate movement have been over geologic time? The oceans hold one of

the key pieces to the puzzle. Because the ocean-floor magnetic striping records the flip-flops in the Earth's magnetic field, scientists, knowing the approximate duration of the reversal, can calculate the average rate of plate movement during a given time span. These average rates of plate separations can range widely. The Arctic Ridge has the slowest rate (less than 2.5 cm/yr), and the East Pacific Rise near Easter Island, in the South Pacific about 3,400 km west of Chile, has the fastest rate (more than 15 cm/yr). Evidence of past rates of plate movement also can be obtained from geologic mapping studies. If a rock formation of known age (with distinctive composition, structure, or fossils) mapped on one side of a plate boundary can be matched with the same formation on the other side of the boundary, then measuring the distance that the formation has been offset can give an estimate of the average rate of plate motion. This simple technique has been used to determine the rates of plate motion at divergent boundaries, for example the Mid-Atlantic Ridge, and transform boundaries, such as the San Andreas Fault.

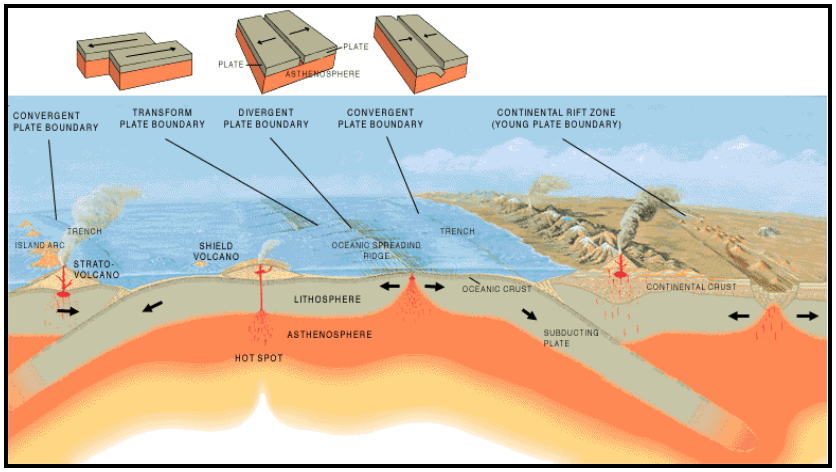
Current plate movement can be tracked directly by means of ground-based or space-based *geodetic* measurements; *geodesy* is the science of the size and shape of the Earth. Ground-based measurements are taken with conventional but very precise ground-surveying techniques, using laser-electronic instruments. However, because plate motions are global in scale, they are best measured by satellite-based methods. The late 1970s witnessed the rapid growth of *space geodesy*, a term applied to space-based techniques for taking precise, repeated measurements of carefully chosen points on the Earth's surface separated by 100’s to 1000’s of kilometers. The three most commonly used space-geodetic techniques, very long baseline interferometry (VLBI), satellite laser ranging (SLR), and the Global Positioning System (GPS), are based mainly on radio astronomy and satellite tracking.

3. Three Types of Plate Boundaries:

As it was established in the earlier reading that earthquakes are generated by the interaction of lithospheric plates, the interaction among plates can be grouped into three main categories:

- **Divergent boundaries** – where plates move away from each other.
- **Convergent boundaries** – where two plates move toward each other.
- **Transform boundaries** – where plates slide horizontally past each other.

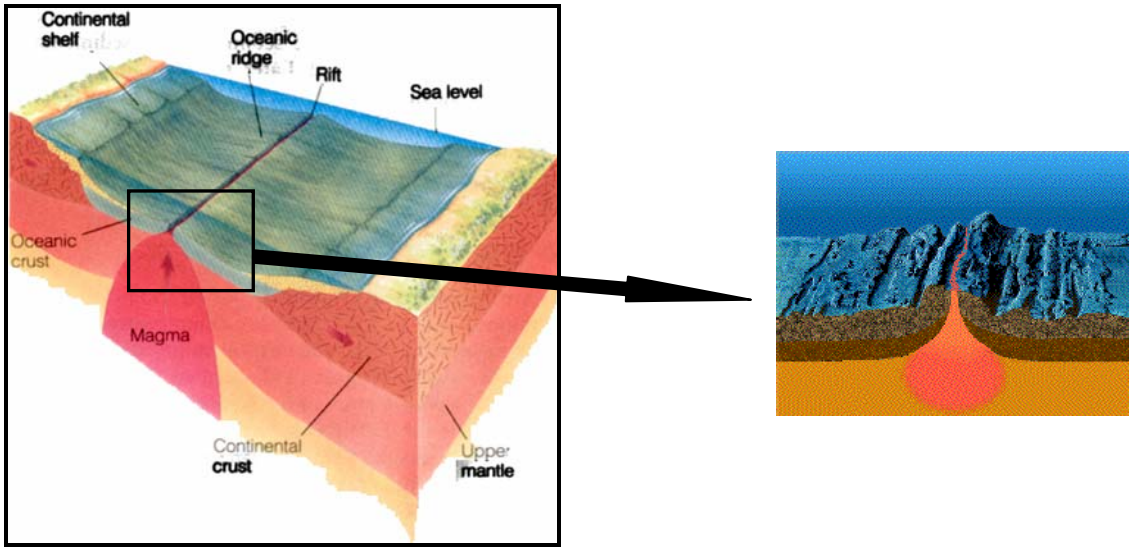
In addition to these zones, there are other plate boundary zones in which the boundaries are not well defined and the effects of plate interaction are unclear.



Visual 3: Sketch showing various types of plate interactions. Credit: USGS.

Divergent Boundaries:

- Divergent boundaries occur along spreading centers where plates are moving apart and new crust is created by magma pushing up from the mantle.
- Perhaps the best known of the divergent boundaries is the Mid-Atlantic Ridge.
- This submerged mountain range, which extends from the Arctic Ocean to beyond the southern tip of Africa, is but one segment of the global mid-ocean ridge system that encircles the Earth.
- The rate of spreading along the Mid-Atlantic Ridge averages about 2.5 centimeters per year (cm/yr), or 25 km in a million years
- Seafloor spreading over the past 100 to 200 million years has caused the Atlantic Ocean to grow from a tiny inlet of water between the continents of Europe, Africa, and the Americas into the vast ocean that exists today.



Visual 4: Diagram showing type of plate behavior at divergent boundaries such as the Mid-Atlantic Ridge. Credit: USGS

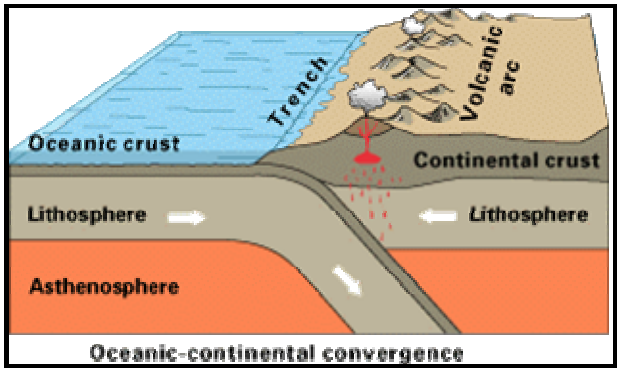
Convergent Boundaries:

The size of the Earth has not changed significantly during the past 600 million years, and very likely not since shortly after its formation 4.6 billion years ago. The Earth's unchanging size implies that the crust must be destroyed at about the same rate as it is being created, as Harry Hess surmised. Such destruction (recycling) of crust takes place along convergent boundaries where plates are moving toward each other, and sometimes one plate sinks (is subducted) under another. The location where one plate sinks beneath another occurs is called a subduction zone.

The type of convergence – called by some a very slow "collision" – that takes place between plates depends on the kind of lithosphere involved. Convergence can occur between an oceanic and a largely continental plate, between two largely oceanic plates, or between two largely continental plates.

<u>Oceanic-Continental Convergence</u>

If by magic we could pull a plug and drain the Pacific Ocean, we would see a most amazing sight –a number of long narrow, curving trenches thousands of kilometers long and 8 to 10 km deep cutting into the ocean floor. Trenches are the deepest parts of the ocean floor and are created by subduction.



Visual 5: Diagram showing subduction of one plate beneath another at an oceanic-continental convergent plate boundary. The Cascadia subduction zone in the Pacific Northwest region of the U.S. is an example of this type of plate boundary. Credit: USGS

Off the coast of South America along the Peru-Chile trench, the oceanic Nazca Plate is pushing into and being subducted under the continental part of the South American Plate. In turn, the overriding South American Plate is being lifted up, creating the towering Andes mountains, the backbone of the continent. Strong, destructive earthquakes and the rapid uplift of mountain ranges are common in this region. Even though the Nazca Plate as a whole is sinking smoothly and continuously into the trench, the deepest part of the subducting plate breaks into smaller pieces that become locked in place for long periods of time before suddenly moving to generate large earthquakes. Such earthquakes are often accompanied by uplift of the land by as much as a few meters.

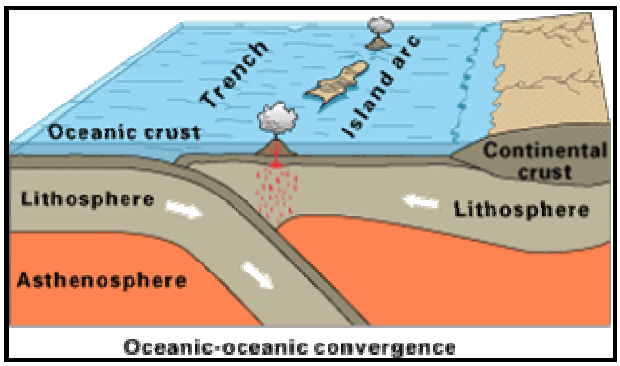
On 9 June 1994, a magnitude-8.3 earthquake struck about 320 km northeast of La Paz, Bolivia, at a depth of 636 km. This earthquake, within the subduction zone between the Nazca Plate and the South American Plate, was one of deepest and largest subduction earthquakes recorded in South America. Fortunately, even though this powerful earthquake was felt as far away as Minnesota and Toronto, Canada, it caused no major damage because of its great depth.

Oceanic-continental convergence also sustains many of the Earth's active volcanoes, such as those in the Andes and the Cascade Range in the Pacific Northwest. The eruptive activity is clearly associated with subduction, but scientists vigorously debate the possible sources of magma: Is magma generated by the partial melting of the subducted oceanic slab, by the overlying continental lithosphere, or both?

Oceanic-Oceanic Convergence

As with oceanic-continental convergence, when two oceanic plates converge, one is usually subducted under the other, and in the process a trench is formed. The Marianas Trench (paralleling the Mariana Islands), for example, marks where the fast-moving Pacific Plate converges against the slower moving Philippine Plate. The Challenger

Deep, at the southern end of the Marianas Trench, plunges deeper into the Earth's interior (nearly 11,000 m) than Mount Everest, the world's tallest mountain, rises above sea level (about 8,854 m).

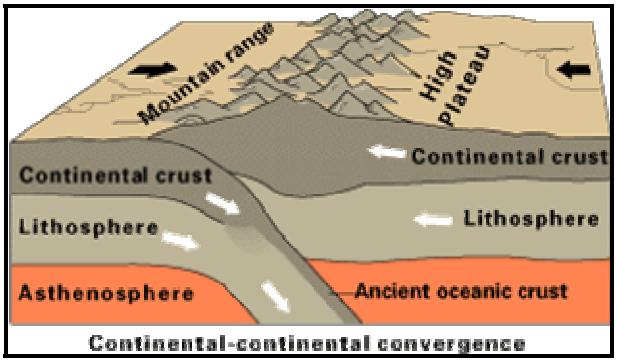


Visual 6: Diagram showing subduction of one plate beneath another at a convergent divergent plate boundary. Credit: USGS

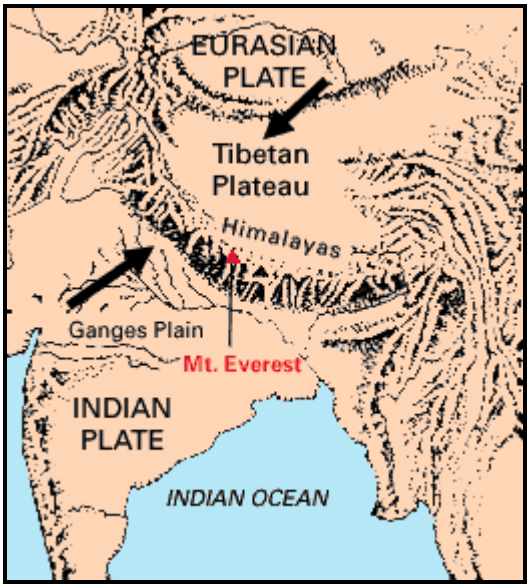
Subduction processes in oceanic-oceanic plate convergence also result in the formation of volcanoes. Over millions of years, the erupted lava and volcanic debris pile up on the ocean floor until a submarine volcano rises above sea level to form an island volcano. Such volcanoes are typically strung out in chains called island arcs. As the name implies, volcanic island arcs, which closely parallel the trenches, are generally curved. The trenches are the key to understanding how island arcs such as the Marianas and the Aleutian Islands have formed and why they experience numerous strong earthquakes. Magmas that form island arcs are produced by the partial melting of the descending plate and/or the overlying oceanic lithosphere. The descending plate also provides a source of stress as the two plates interact, leading to frequent moderate to strong earthquakes.

Continental-Continental Convergence

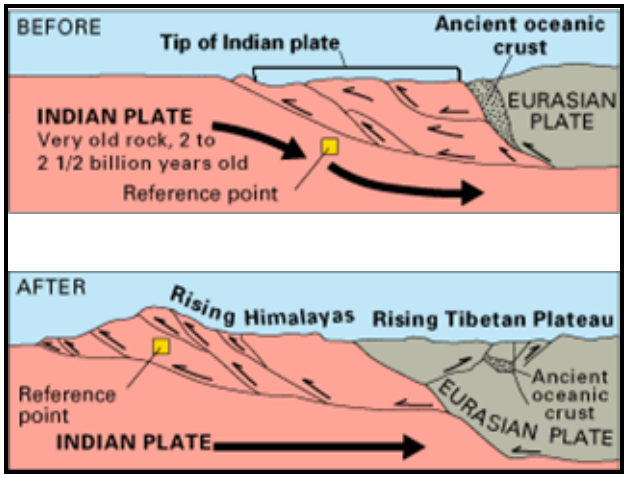
The Himalayan mountain range dramatically demonstrates one of the most visible and spectacular consequences of plate tectonics. When two continents meet head-on, neither is subducted because the continental rocks are relatively light and, like two colliding icebergs, resist downward motion. Instead, the crust tends to buckle and be pushed upward or sideways. The collision of India into Asia 50 million years ago caused the Eurasian Plate to crumple up and override the Indian Plate. After the collision, the slow continuous convergence of the two plates over millions of years pushed up the Himalayas and the Tibetan Plateau to their present heights. Most of this growth occurred during the past 10 million years. The Himalayas, towering as high as 8,854 m above sea level, form the highest continental mountains in the world. Moreover, the neighboring Tibetan Plateau, at an average elevation of about 4,600 m, is higher than all the peaks in the Alps except for Mont Blanc and Monte Rosa, and is well above the summits of most mountains in the United States.



Visual 7: Diagram showing subduction of one plate beneath another at a continental-continental plate boundary. The Himalayas were created due to this type of plate interaction. Credit: USGS



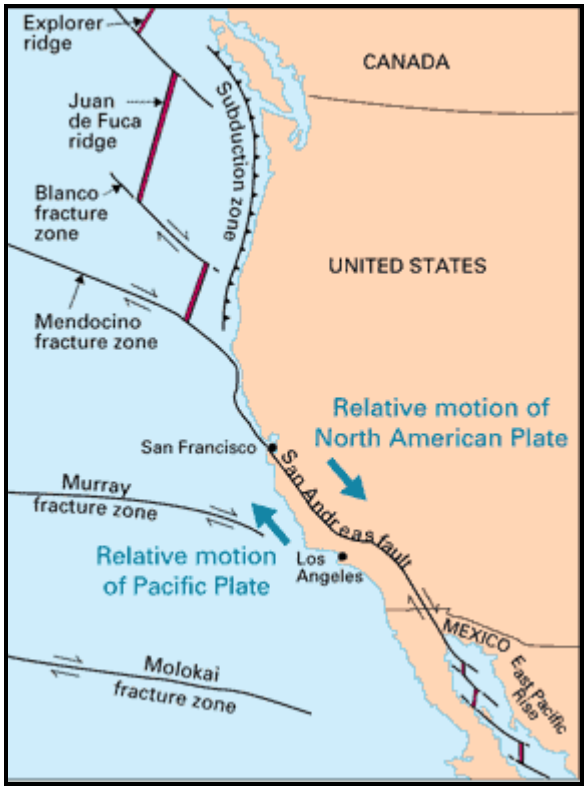
Visual 8: The collision between the Indian and Eurasian plates has pushed up the Himalayas and the Tibetan Plateau. Credit: USGS



Visual 9: Cartoon cross sections showing the meeting of these two plates before and after their collision. The reference points (small squares) show the amount of uplift of an imaginary point in the Earth's crust during this mountain-building process. Credit: USGS.

Transform Boundaries:

The zone between two plates sliding horizontally past one another is called a *transform-fault boundary,* or simply a *transform boundary.* The concept of transform faults originated with Canadian geophysicist J. Tuzo Wilson, who proposed that these large faults or *fracture zones* connect two spreading centers (divergent plate boundaries) or, less commonly, trenches (convergent plate boundaries). Most transform faults are found on the ocean floor. They commonly offset the active spreading ridges, producing zigzag plate margins, and are generally defined by shallow earthquakes. However, a few occur on land, for example the San Andreas fault zone in California. This transform fault connects the East Pacific Rise, a divergent boundary to the south, with the South Gorda – Juan de Fuca – Explorer Ridge, another divergent boundary to the north.



Visual 10: Map showing the Blanco, Mendocino, Murray, and Molokai fracture zones are some of the many fracture zones (transform faults) that scar the ocean floor and offset ridges (see text). The San Andreas is one of the few transform faults exposed on land. Credit: USGS.

The San Andreas fault zone, which is about 1,300 km long and in places tens of kilometers wide, slices through two thirds of the length of California. Along it, the Pacific Plate has been grinding horizontally past the North American Plate for 10 million years, at an average rate of about 5 cm/yr. Land on the west side of the fault zone (on the Pacific Plate) is moving in a northwesterly direction relative to the land on the east side of the fault zone (on the North American Plate).

Oceanic fracture zones are ocean-floor valleys that horizontally offset spreading ridges; some of these zones are hundreds to thousands of kilometers long and as much as 8 km deep. Examples of these large scars include the Clarion, Molokai, and Pioneer fracture zones in the Northeast Pacific off the coast of California and Mexico. These zones are presently inactive, but the offsets of the patterns of magnetic striping provide evidence of their previous transform-fault activity.

Other Plate-Boundary Zones:

Not all plate boundaries are as simple as the main types discussed above. In some regions, the boundaries are not well defined because the plate-movement deformation

occurring there extends over a broad belt (called a *plate-boundary zone*). One of these zones marks the Mediterranean-Alpine region between the Eurasian and African Plates, within which several smaller fragments of plates *(microplates)* have been recognized. Because plate-boundary zones involve at least two large plates and one or more microplates caught up between them, they tend to have complicated geological structures and earthquake patterns.

Elastic Rebound Theory:

(see http://www.crustal.ucsb.edu/ics/understanding/elastic/intro-rebound.html)

After the 1906 San Francisco, California earthquake, a fault trace that could be followed along the ground in a more or less straight line for 270 miles was discovered. The earth on one side of the fault had slipped by up to 21 feet (7 m) compared to the earth on the other side of the fault. This fault trace drew the curiosity of a number of scientists, especially since nobody had yet been able to explain what was happening within the earth to cause earthquakes. Up until this earthquake, it had generally been assumed that the forces leading to the occurrence of earthquakes must be close to the locations of the earthquakes themselves.

Harry Fielding Reid, after studying the fault trace of the 1906 earthquake, postulated that the forces causing earthquakes were not close to the earthquake source but very distant. Reid's idea was that these distant forces cause a gradual buildup of stress in the earth over tens or hundreds or thousands of years, slowly distorting the earth underneath our feet. Eventually, a pre-existing weakness in the earth – called a fault or a fault zone – can not resist the strain any longer and fails catastrophically. This is something like pulling a rubber band gradually until the band snaps. This theory is known as the "elastic rebound theory."

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