32. Plate Tectonics: A Working Model for the Earth

So far we have established that seafloors spread and that continents move about like passengers on great plates of lithosphere, but a lot of questions remain. If there are places where the seafloor is separating, shouldn’t there also be places where something is coming together? What moves the plates? Why are earthquakes so much more abundant and severe along some plate boundaries than along others? Zones of abundant earthquakes also mark zones of violent volcanic activity along many plate boundaries—do the earthquakes cause volcanic eruptions, or the other way around, or are they connected at all? In this chapter we shall answer these and other questions as we investigate the details of the plate tectonic system.

Plate Motion

Some observations can be made that bear on the question of what moves the plates. First, despite the moving plates, we usually find it unnecessary to hold onto anything to keep our balance! The plates move very slowly indeed, but their velocities differ. The distance between North America and Europe, each riding on a different plate, increases about two centimeters every year. The African plate seems not to be moving at all, but the Indian-Australian plate races along at about 12 centimeters per year. These speeds may not impress you at first, but if you will consider how large the United States is and then realize that something is moving a slab of lithosphere several times larger than that at any speed, you will understand that some very powerful forces must be involved.

Second, whatever causes the plate motion originates within the earth. Wegener thought that it might have something to do with the rotation of the planet or with tides, but such forces were long ago shown to be inadequate. We can eliminate some forces we have learned about immediately. The strong (nuclear) force and the weak force are effective only at very small distances and, thus, cannot be responsible for moving tectonic plates. The long-range electromagnetic force acts only between charged objects, and certainly the plates are electrically neutral. This leaves only gravity and short-range (contact) electromagnetic forces to drive plate motion, and the theory favored by most geologists involves both.

The plates consist of lithosphere, the brittle outer shell of the earth made up of the crust and outermost mantle. The plates rest on the underlying asthenosphere, a zone in the upper mantle that is partially molten. The small amount of melt (probably only a few percent of the total volume) is generated by radiogenic heat from the decay of radioactive potassium, uranium, and thorium, and it renders the asthenosphere plastic under stresses that are applied slowly over long periods of time—that is, the asthenosphere behaves like a very, very viscous liquid. Because the top of the asthenosphere is cooler than the base, it is also denser and it tends to sink as the less dense partial melt underneath tends to rise. Thus, convection currents are generated, as depicted in Figure 32.1. This is the gravitational part of the model for plate motion. These convection currents convert gravitational potential energy into kinetic energy, and the friction of the currents along the bases of the lithospheric plates moves them—hence, the part

![Figure 32.1. Convection currents in the asthenosphere drag the plates about.](image-url)
of the model involving contact forces.

As you read the preceding paragraph you noticed our use of the word “model,” and you recognized that we have no way of actually going to the asthenosphere to see if the convection currents are present. We have previously built models for things we could not see—models of the nucleus of an atom, of electron waves, of the interior of a red-giant star, of the core of our planet. There were limits on what these models could be like (we say that they were “constrained”), and the constraints came largely from what we could observe and from the mathematics that governs the physical processes involved. It is so with the convection model for plate motion also, and one might wonder whether there will ever be a way to know what goes on beneath the crust. Some quite recent technological developments make us very optimistic about that.

Perhaps you have heard of a medical technique called x-ray tomography (used in CAT scans of internal organs, for example). It employs data from many crisscrossing x-ray paths to construct a picture of the inside of the body, based on the degree to which the x-rays are absorbed along each path. The very same principle has been applied to the earth, using seismic waves instead of x-rays, and is called seismic tomography. The required information is obtained from seismic waves generated by earthquakes all over the world and enables us to build a picture of the interior of the earth by comparing velocity (rather than absorption) variations for large numbers of crisscrossing waves. Because the waves travel faster in material of higher density (that is, colder rock) and slower in low-density (hotter) material, seismic tomography enables us to locate regions of hot and cold rock within the earth in three dimensions.

The technique is relatively new, and the results are not as refined as they will eventually be, but the early analyses suggest (not surprisingly) a more complex structure than had been envisioned. As expected, the upper mantle is hot just below the oceanic ridges, but the hot regions do not project vertically downward. Rather, the deep heat sources are somewhat offset from the surface features. It appears that we are seeing convection currents all right, but as they rise they are also carried horizontally and are not nearly as geometrically simple as suggested in Figure 32.1. Convection is thus still the best answer for what moves the plates, but the mechanism may turn out to be more complicated than our current notions.

**Divergent Plate Boundaries**

The oceanic ridges are known, in plate tectonic terminology, as *spreading centers.* They are *divergent plate boundaries,* because plates on either side of a ridge move away (diverge) from each other. It is here that new oceanic lithosphere is born as basaltic magma ascends to fill the void between the separating plates.

If there were no water in the oceans, the oceanic ridge system would constitute an impressive topographic feature of our planet, easily visible from the moon and not only high but also broad. The ridge stands above the surrounding ocean floor because the new lithosphere is hot and is therefore less dense than old lithosphere; it thus “floats” higher on the underlying asthenosphere. As it ages and cools, it spreads away from the ridge and subsides, forming the **abyssal hills** we discussed in Chapter 28. Eventually, parts of it are covered by sediment to become the **abyssal plains** (see Fig. 32.2).

![Figure 32.2](image-url)

**Figure 32.2.** An oceanic ridge is topographically high because it consists of hot lithosphere; but as the lithosphere spreads away from the ridge, it cools and subsides, giving rise to the abyssal hills and abyssal plains as it is slowly covered with marine sediment.
Not all spreading centers are underneath the oceans. If convection currents in the asthenosphere happen to ascend beneath a continent, they can create a **continental rift zone**, the continental equivalent of an oceanic ridge. Like their marine counterparts, continental rift zones are characterized by volcanic activity and shallow earthquakes.

Figure 32.3 shows schematically how a continental rift develops. The rising hot material in the asthenospheric convection currents underplates the lithosphere, not only heating it but also bulging it upward to create tensional forces near the surface. Additional tensional forces caused by the horizontal flow of asthenosphere thin and rupture the lithosphere, causing blocks to subside to form fault-bounded valleys. Eventually, if rifting is not stopped by shifts in the convection currents, the continental lithosphere can be completely severed, resulting in the transition from continental to oceanic lithosphere and the formation of an oceanic ridge. This scenario is being followed in east Africa right now. The East African Rift system, including the famous Olduvai Gorge, is the site of active continental rifting, and if it continues, it will eventually fragment the continent (see Fig. 32.4). A more advanced stage of rifting is seen in the Red Sea, where the Arabian plate has separated from the African plate, creating a new oceanic ridge. And, of course, this also happened to Pangaea as it broke apart during the Mesozoic Era.

**Convergent Plate Boundaries**

By now it has occurred to you that there must be more to plate tectonics than spreading centers. If lithosphere is slowly separating at ridges and rift zones, where does it go? Evidently, it does not stay around for long (from a geologic perspective), because the oldest ocean-floor rocks are only about 200 million years old, not quite 5 percent of the total age of the earth. If there were oceans for much of the earlier 95 percent of the earth’s history (and there were, because we have before us the sedimentary rocks that resulted from deposition in them), what has become of the rocks? The answer was suggested by Harry Hess and has already been introduced in Chapter 31.

The key comes in recognizing the correct interpretation of the deep ocean trenches, island arcs, and Benioff zones. **Benioff zones** (named for Hugo
Benioff, 1899-1968, the American seismologist who discovered them), are imaginary surfaces (almost planes) along which the hypocenters of earthquakes associated with island arcs occur. These planes begin near the surface at the deep ocean trenches and then slope downward underneath the island arcs, as illustrated in Figure 32.5. It is apparent that the further an epicenter is from the trench, the deeper its hypocenter is. This discovery was made before the plate tectonic theory developed, so the reason for the existence of Benioff zones was then unknown.

We now know that each Benioff zone marks the top of a cold, brittle, descending slab of lithosphere plunging into the asthenosphere as two plates converge. If both plates are oceanic, one will inevitably be the older—hence cooler and denser—and that is the plate that will founder and descend. The process is called subduction, a term invented from two Latin words meaning “to lead under,” and the Benioff zone with its associated trench is called a subduction zone. As the subducted plate descends, its temperature increases and, at some depth, it begins to melt. The magma produced from melting is less dense than its surroundings and rises buoyantly through fissures and cracks to eventual-
ly erupt at the surface, forming the volcanoes of the island arcs (see Fig. 32.6). Island arcs like the Aleutians, Japan, and the Marianas are good examples of the results of subduction involving two plates with oceanic leading edges. Sometimes slices of the down-going oceanic lithosphere are scraped off against the island arc, leaving a folded and deformed record above sea level of what the oceanic plate was like. (Conversely, some material derived from the overriding plate may be caught in the process of subduction and carried down into the asthenosphere.)

If the leading edge of one of the two convergent plates is oceanic, but the other leading edge is continental, there are a few differences from the description just given. First, the continental lithosphere is not dense enough to sink into the asthenosphere, so the oceanic plate is always the one subducted. Thus, instead of resulting in an island arc, subduction produces a volcanic mountain chain on the edge of the continent. Volcanoes in this sort of plate tectonic setting are generally quite violent because the interaction of the basaltic magma with the continental crust produces a very viscous fluid that is brought to the surface only by application of a great deal of force. The compression generated by the converging plates folds and deforms the sediment that has been shed from the continent, and faulting and

Figure 32.8. (a) A subduction zone in which the overriding plate has a continental leading edge and the subducted plate is carrying a continent. (b) Eventually this results in a continental collision and a mountain-building event.
folding of the continental margin itself produces a thickened continental edge that enhances the mountain range. The Andes of South America and the Cascades of the northwestern United States are good examples of this sort of tectonic relationship (see Fig. 32.7).

The last type of convergent plate boundary involves the collision of two continental masses. This is preceded, of course, by subduction of the second type (see Fig. 32.8); but as the continent on the subducted plate is slowly moved toward the subduction zone, the collision finally results. The continental mass on the descending slab begins to be subducted but, because in this case both leading edges are continental, neither is dense enough to be forced into the asthenosphere. The result is a collision that compresses and thickens the continental edges, uplifting the land to form fold mountain belts and welding the two continents together along an unusually thick band of continental lithosphere called a suture zone. The Appalachian Mountains in eastern North America are an ancient suture zone formed when North America and Africa met during the building of Pangaea. The Himalayas were produced as India moved north into Asia following the breakup of Pangaea, and the process continues there today as the Indian-Australian plate creeps northward at 12 centimeters per year.

**Transform Boundaries**

In many illustrations (such as Fig. 32.11 near the end of this chapter) the oceanic ridges are not shown as smooth continuous rifts but as relatively straight, short segments that are offset from one another by what appear to be cracks or faults. These are transform faults, and their function is to connect segments of spreading ridge. At first it might appear that the segments of ridge on either side of the fault are separating along it, as suggested by Figure 32.9a, but this is not the

![Figure 32.9](image)

**Figure 32.9.** (a) At first it may appear that segments of oceanic ridge separate from each other along a transform fault. This is not correct. (b) Actually, a transform fault is a boundary that separates two plates that are moving laterally past one another.

![Figure 32.10](image)

**Figure 32.10.** A linear chain of hot-spot volcanoes is formed as a plate moves over a mantle plume.
case. The correct nature of a transform fault is shown in Figure 32.9b, where we see that ridge segments are essentially stationary with respect to one another, and transform faults are just boundaries along which plates move past each other.

Not all transform faults are short. The famous San Andreas fault in California connects the segment of oceanic ridge that terminates in the Gulf of California with the segment at the south end of the Juan de Fuca plate. In doing so, it slices off a sliver of California that is several hundred kilometers in length. While most of the state is part of the North American plate, that sliver rides on the Pacific plate. As the two plates move past one another, strain builds up wherever the fault binds (see “elastic rebound” in Chapter 30) and is released in the earthquakes that are so common in that area.

Relative and Absolute Plate Motions—Hot-Spot Trails

The Hawaiian Islands and other linear island chains in the Pacific do not seem to fit into the plate tectonic picture anywhere so far. They are nearly parallel and seem straighter than coincidence would allow. Although they are volcanic in origin, none of them has a deep ocean trench or a Benioff zone nearby. In fact, they are nowhere near any plate boundaries, as are most of the plate tectonic features discussed so far.

The only currently active volcanoes in the Hawaiian Islands are on the island of Hawaii, at the southeast end of the chain. As one proceeds up the chain to the northwest, successive islands are progressively older, a fact inferred by geologists years ago from the states of erosion of the various islands and confirmed now by radiometric dating of the basalts. It appears that the same heat source has produced all the volcanoes in the chain either by migrating to the southeast or—more likely, given the several parallel island chains on the Pacific plate—by remaining stationary while the plate rode over it.

The nature of such heat sources is not well understood at present, but they obviously must originate beneath the lithosphere and probably far beneath it. They have been given the name mantle plumes to suggest columns of hot material rising convectively toward the lithospheric plate above (see Fig. 32.10). The volcanoes that result are called hot spots, to distinguish them from subduction-zone volcanoes. (Note that mantle plumes are inferred to exist, and their origin is unclear; hot spots are observed to exist.) Hot spots are not restricted to regions far from plate boundaries. Iceland is a hot spot, as are some other unusually prolific volcanic centers located on oceanic ridges. Hot spots can also be found on continents, and one of the

Figure 32.11. The plate tectonic system as we now envision it. Double lines represent spreading centers, single lines transform faults, and toothed lines subduction zones. Stars are the locations of some currently recognized hot spots. The arrows show directions of absolute plate motions, and their lengths indicate relative speeds.
classic examples is Yellowstone on the Idaho-Wyoming border. All told, there are probably at least a hundred hot spots distributed around the globe.

The trails of volcanism left on a plate as it moves over a mantle plume (hot-spot trails) provide us with information that would be very difficult to get in any other way—the absolute motion of that plate. As we stand on one plate and make any sort of observations or measurements to determine the motion of another plate, all we get is the relative motion between the two. It is as if we were stationary and only the other plate moved. What we need is a frame of reference that is stationary with respect to all of the plates, and the worldwide collection of mantle plumes appears to provide just that. Thus, hot-spot trails show the direction of absolute plate motion, and radiometric dating of the volcanic rocks can yield the rates of plate motion over the lifetime of the mantle plume. We have already seen in Chapter 31 that measurements obtained from light emitted by distant quasars has confirmed (by interferometry) the general directions and speeds of plate motion derived from hot-spot trails.

Figure 32.11 presents the global plate-tectonic picture.

The Plate-Tectonic Evolution of a Continent

As we look further and further back in time, the details that facilitate accurate reconstruction of plate motions and plate geometry become more and more obscure. The construction of Pangaea was a relatively recent major event, and all of the features we see on the ocean floors, as well as the present plate configuration, reflect post-Pangaea plate tectonics. Some of the geology on the continents, however, provides insight into pre-Pangaea plate tectonic activity. For example, ancient suture zones, such as the Ural Mountains between Europe and Asia, reveal collisions between early continents whose detailed geography we do not know. Paleomagnetic studies of the ancient rocks yield data on early geographic orientations, and radiometric dates help piece together the structural evolution of the present continents.

Naturally, each continent has followed a course of development that is unique and complex, but the broad outlines of the general evolution of a continent can be understood by focusing, as we have previously, on North America. Figure 32.12 is a map of North America showing generalized ranges of radiometric dates found for basement rocks in various parts of the continent. Basement rocks are those that underlie the younger sedimentary cover and are mostly Precambrian. A consistent pattern is clear: The most ancient rocks are in the shield, and the ages become younger toward the margins of the continent.

This age distribution suggests the following general history: The continent originated as a small landmass during Precambrian time (we shall give more precise statements at the end of Chapter 34 about how and when
it might have originated). Because the continental lithosphere was less dense than the oceanic lithosphere, subduction eventually began at one of its margins, adding new volcanic rocks from which sediment could be derived to extend the continental margins. Inevitable changes in the convection cells in the asthenosphere repeatedly shifted the location of subduction, adding new material on different sides. Island arcs may have been moved in by plate motion and plastered against the young continent. Other continents were, of course, in their own formative stages, and so continental collisions would likely have occurred also. These would have sutured “foreign” rocks onto North America—rocks that might have remained after subsequent continental rifting. For instance, there is good geologic evidence that much of the southeastern United States was part of the African continent before the assembly of Pangea. When the supercontinent rifted apart in the early Mesozoic Era, separation evidently occurred southeast of the old suture zone, leaving part of the African continent attached to North America.

The idea that continents have grown by addition of material at convergent boundaries is called continental accretion, and it seems to be supported by the age-distribution and the timing and styles of deformation of continental rocks. For North America, it yields a particularly straightforward scenario for everything east of the Rocky Mountains. The picture is a bit more complicated for the western part of the continent. Paleomagnetic and paleontological studies have revealed that rocks in some areas must have originated at very different latitudes than the rest of North America and evidently traveled a considerable distance to become part of the continent. Western North America appears to be made up of numerous blocks of lithosphere that are genetically unrelated. These may represent island arcs or microcontinental blocks that have been added to this continent as they rode in on subducting plates at its western edge, much as India has been added to Asia.

Figure 32.12 shows that the North America of Precambrian time was somewhat smaller than our present continent, lacking most of the eastern seaboard, the Gulf coast on the south, and essentially all of the far west. The continent consisted of what we identified in Chapter 28 as the shield and stable platform. By the end of the Precambrian, the continent had already been through several episodes of mountain building and erosion, had been involved in a major glaciation, and had drifted over much of the planet’s surface. After a quiet beginning, the Paleozoic Era saw three major episodes of mountain building in the east and at least one each at the southern, northern, and western edges of North America. These added the familiar eastern and southeastern parts of what would later be the United States.

During the Mesozoic Era, the eastern part of the continent was essentially passive as Pangea broke up and the fragments spread apart, but there were major mountain-building episodes in the west as the North American plate moved in that direction. From this time until late in the Cenozoic Era there was a subduction zone at the western margin of the continent, and several small blocks were added in the west (much like India being added to Asia), and large granitic igneous bodies such as the Sierra Nevada were emplaced. About 15 million years ago subduction in this area ceased and the present transform fault developed, yielding the configuration we see at the west edge of the North American plate today.

Summary

The earth’s lithosphere—the crust and uppermost mantle—is divided into about a dozen fragments of various sizes called plates, and these move in response to convection currents in the asthenosphere below them. Any given plate may consist of both continental and oceanic lithosphere, or of only one or the other. Divergence of plates occurs at spreading centers, which may be either ocean ridges or continental rifts, and is characterized by shallow earthquakes and volcanic activity; in such places, new lithosphere is created. Convergence of plates occurs at subduction zones (if at least one plate is oceanic at its leading edge), where intense earthquakes (with both shallow and deep hypocenters) and volcanism are produced and oceanic lithosphere is destroyed. When two continents collide, folding, faulting, metamorphism, and igneous activity result in the birth of fold mountain belts that parallel the convergent plate boundaries. Plates may slide past one another along transform faults, often accompanied by severe seismic activity. Mantle plumes, relatively stationary heat sources beneath the lithosphere, produce volcanic trails (hot spots) that enable us to determine absolute plate motions.

Continents evidently have grown by a process called continental accretion, in which material is added at convergent boundaries. At some convergent plate boundaries addition of new material has been largely through igneous activity, and at others it has been by addition of microcontinental blocks carried in by the subducting plate.

The crucial test of a scientific model is its ability to explain what is observed. Plate tectonics does very well. In Chapter 28, we observed the following facts that we were unable to explain at that point: A gigantic ocean ridge system circles the globe, flanked by the abyssal hills and abyssal plains, yet these features are made of rocks unlike those that constitute most features of similar appearance on the continents. Earthquakes tend to occur mostly in narrow bands spatially associated with volcanoes. Fold mountain systems also occur in narrow
belts, and some are associated with frequent seismic activity (the Himalayas, for instance), while others (for example, the Appalachians) are not. Around the margins of the Pacific Ocean and the Caribbean Sea are deep ocean trenches. Where they are adjacent to a continent, a chain of volcanic mountains is found on land, and if they are away from a continent, there is invariably a volcanic island arc parallel to them. The ocean floor is a geologically young feature of the planet. All continents contain vast areas, called shields, that consist of the ancient, eroded cores of old mountain belts, and the current mountain belts are always outside these.

All of these observations, and many more that have not been cited in this introduction, are explained by the Theory of Plate Tectonics. We would not mislead you into thinking that there is nothing left to do in this area, for there are yet significant unanswered questions concerning both the theory and its applications. However, plate tectonics has been for geology as the Periodic Table was for chemistry—not only filling gaps in our understanding but also pointing the direction to a new and unexpectedly rich level of perception.

STUDY GUIDE
Chapter 32: Plate Tectonics: A Working Model for the Earth

A. FUNDAMENTAL PRINCIPLES: No new fundamental principles.

B. MODELS, IDEAS, QUESTIONS, AND APPLICATIONS
1. The Theory (Model) of Plate Tectonics: See Chapter 31.
2. What geologic features occur at divergent plate boundaries? How does the model explain these features?
3. What geologic features occur at convergent plate boundaries? How does the model explain these features?
4. What geologic features occur at transform boundaries? How does the model explain these features?
5. What geologic features occur near mantle plumes? How does the model explain these features?
6. Describe the evolution of a continent according to the model. What role does Archimedes’ Principle play?

C. GLOSSARY
4. Basement Rocks: Primarily pre-Cambrian rocks (underlying the sedimentary layers) that form the shield of the continent.
5. Continental Accretion: The idea that continents grow by addition of material at convergent boundaries.
6. Continental Rift Zone: A zone where continental plates are moving away from each other in a manner similar to an oceanic spreading center.
7. Convection Current: Motion of matter as heated material becomes less dense than the surrounding material and begins to rise (or the corresponding sinking when material cools and becomes more dense than its surroundings). Convection currents are understood in terms of Archimedes’ Principle. See Chapter 6.
8. Convergent Plate Boundary: Where plates move toward each other and form such features as trenches, island arcs, suture zones, fold mountain belts, and volcanic mountain chains.
9. Divergent Plate Boundary: Where plates move away from each other, i.e., spreading centers or continental rift zones.
10. Hot Spot: Volcanoes which result from the lithosphere moving over a mantle plume. Hawaii is an example of an island formed at a hot spot. As the plate moves over the mantle plume, a line of volcanic structures (such as the Hawaiian chain of islands) marks the passage. The trail of volcanism is called a hot-spot trail.
11. Island Arc: Islands formed when two oceanic plates converge and the subducted plate melts as it descends. The magma from the melt rises to the surface to form volcanic islands such as Japan, the Aleutians, and the Marianas.
13. Mantle Plume: Columns of hot material rising convectively from the mantle toward the lithospheric plate above.
15. Spreading Center: A region where oceanic plates are moving away from each other. They are separated by an oceanic ridge where basaltic magma ascends to fill the void created between the separating plates.
16. Subduction: The process whereby, at a convergent plate boundary, the denser plate is pushed under the less dense plate and is reabsorbed into the mantle.
17. Subduction Zone: The trench, formed by subduction, and region of earthquakes associated with island arcs.
18. Suture Zone: An unusually thick band of continental lithosphere which formed from the collision of two continental masses. The Himalayas mark
the suture zone that joins Asia and India.

19. **Transform Boundary:** A plate boundary at which two plates move sideways past each other.

20. **Transform Fault:** The boundary along which plates move past each other. Examples include the San Andreas fault and the faults which join together segments of the oceanic ridge.

D. **FOCUS QUESTIONS**

1. Consider the plate tectonic model:
   a. Describe the basic elements of the model. How does it resolve the problems unexplained by the early ideas of continental drift and seafloor spreading?
   b. Describe the typical geologic features observed and explain why these features occur in terms of the plate tectonic model for
      (1) two categories of divergent plate boundaries.
      (2) three categories of convergent plate boundaries.
      (3) transform boundaries.
      (4) hot spots under oceanic plates.

E. **EXERCISES**

32.1. Convergent plate boundaries do not involve
   (a) subduction zones.
   (b) mountain-building events.
   (c) creation of new oceanic lithosphere.
   (d) deep ocean trenches.

32.2. Among the following choices, earthquakes would least likely occur
   (a) in a young fold mountain belt.
   (b) in a continental shield.
   (c) at a transform fault.
   (d) along the oceanic ridge system.

32.3. What is the origin of the abyssal hills and the abyssal plains?

32.4. The Theory of Plate Tectonics does not explain
   (a) where diverging convection currents will pull continents apart.
   (b) the location of most of the world’s active volcanoes.
   (c) the origin of fold mountain belts.
   (d) the association of deep ocean trenches and island arcs.

32.5. The least amount of plate tectonic activity would be found in which of these locations?
   (a) The California coastal area
   (b) The Canadian shield
   (c) Iceland
   (d) Japan

32.6. Explain why fold mountain belts are long, narrow features.