CHAPTER I

THE OCEAN PLANET

A. Coverage

One would think that a marine biologist–or any other scientist whose research requires that they know scientific facts about the ocean–would have a thorough understanding of the ocean's vastness–that he or she would know the average depth of the ocean, the percentage of the earth that is covered by water, and the relative size of the major ocean basins. And, yes, these scientists do, in fact, learn the basic facts about the ocean's size and, in doing so, develop an appreciation for its enormity.

But to see our planet from the eyes of the astronauts onboard the Space Shuttle Discovery, even after having studied the ocean for many years, brings any scientist to the realization that knowledge gained from a textbook, or from onboard scientific research vessels, has its limitations. Seeing our planet as the astronauts have seen it from space is to see our planet in a different dimension–a kind of seventh sense that cannot be learned through any classroom textbook, instinct, or through the many scientific voyages or research projects that have been conducted over millennia. Because only when you see the earth through the eyes of the astronauts do you truly realize that you live on an Ocean Planet.

The astronauts have seen the Ocean Planet in its simple, naked form. They have seen a small, beautiful electric-blue sphere suspended by nothing at all in the black void of space. Streaks of white, which we call clouds, lightly brush the Ocean Planet's surface, while small, muted-green and dull-gold land masses appear to float on top of the electric-blue ocean. The edges of the Ocean Planet glow brilliantly as the sun rises, while the violent lightning bolts of thunderstorms act out their eerie, yet very fascinating, light show for those in space. And if you look very closely, you can see tiny lights shining on the muted-green and dull-gold land masses–the only evidence of human life on the Ocean Planet.

The Ocean Planet differs from all other planets in our solar system in several ways—the most significant of which is that the majority of its surface is covered by a layer of water known as the hydrosphere. Although scientists have found water ice on Mars and an ice crust has been discovered on Jupiter's moon Europa, it is no surprise that the Ocean Planet is the only planet presently known to mankind that is capable of supporting life—and it has continued to do so for over 3 billion years. Over 71 percent of the Ocean Planet is covered by water, 98 percent of which is oceanic.

The remaining two percent is fresh water, existing either in the form of freshwater lakes and streams, groundwater underlying the surface, or fresh water locked in the polar ice caps. Oceanic water is ultimately the source of fresh water on land, as oceanic water is cycled back onto the Ocean Planet's land surface through a process called the hydrologic cycle, which we will discuss in greater detail at the end of this chapter.

B. The Major Ocean Basins

The global ocean is geologically divided into four major ocean basins: the Atlantic, the Pacific, the Indian, and the Arctic Basins (Fig. 1-1). Although each of these ocean basins is consolidated into one global ocean, each differs in ways that make it a very distinct body of

Figure 1-1.
Four major ocean basins of the world.
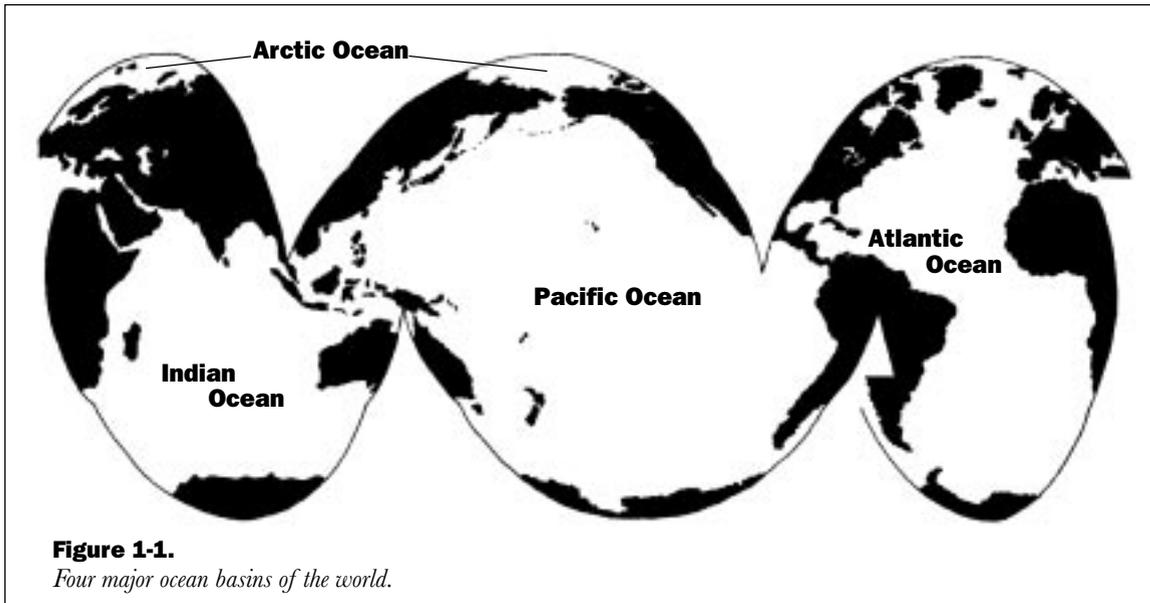
water. They not only differ in surface area and depth, but they also differ in physical, chemical, and biological properties, such as temperature, chemical composition, and the types of living organisms they support. Around the margins of some major ocean basins are semi-enclosed bodies of salt water, referred to as seas.

The Pacific Ocean contains most of the water on earth, with about half of the earth's water located in this one basin (Table 1). The Pacific Ocean not only contains the most water, but it is followed in surface area by the Atlantic and the Indian Ocean, with the Arctic Ocean being the smallest of the four ocean basins. The Pacific Ocean is also the deepest of all the major ocean basins, with an average depth of 4,282 meters (14,049 feet). The Indian Ocean has an average depth of 3,963 meters (13,003 feet), and the average depth of the Atlantic Ocean is 3,926 meters (12,881 feet). The Arctic Ocean is the shallowest of all the major ocean basins, with an average depth of 1,205 meters (3,954 feet).

Because the major ocean basins differ in their physical, chemical, and biological properties, there are a variety of habitats found throughout

Table 1-1. Comparison of ocean basins.

Ocean	Mean Depth (m)	Area (km²)
Atlantic	3,332	106.4 x 10⁶
Pacific	4,028	179.7 x 10⁶
Indian	3,897	74.0 x 10⁶
All	**3,795**	**361.0 x 10⁶**

them. Some of these habitats, or specialized places where organisms live, are similar among the ocean basins, while others are quite different. These habitats, some of which will be discussed in detail in Chapter 4, support wonderfully diverse assemblages of marine organisms. Just as habitats may be similar, or quite different, among ocean basins, the organisms living in these habitats may also exhibit similarities to, or striking differences from, the organisms inhabiting other ocean basins. Even though each major ocean basin has its unique characteristics, remember that each basin, along with its inhabitants, is part of one global ocean.

The coastline of the Southeastern United States abuts the western edge of the Atlantic Ocean. The Atlantic Ocean is very productive and teams with marine life of all forms, from

the smallest phytoplankton (small plants that float with the currents at or near the ocean's surface) and zooplankton (small animals that float with the currents at the ocean's surface) to very large fishes and mammals. This productivity is evidenced by the greenish-blue hue that is characteristic of coastal waters and continues toward the deep ocean. The coloration is due to tiny, microscopic marine organisms that so abound in these waters because of the nutrients that are available to them. Productivity is discussed in detail in Chapter 5.

In the following section, you will learn more about how the major ocean basins are further divided into "zones." In Chapter 4 you will learn about the types of organisms inhabiting these zones.

C. Zones of the Ocean

Ocean systems are complex and scientists have developed methods by which to classify major sections, or zones, of ocean basins. Methods of classification are generally based on the following factors:

- Exposure to tides;
- Vertical position (depth) in the water column;
- Distance from shore;
- Amount of sunlight penetrating the ocean depths; and
- Regions of the ocean floor.

1. Tidal Zones

Zones of the ocean that are influenced by the tides, or the periodic rise and fall of the ocean's surface, are the splash zone, the intertidal zone, and the subtidal zone. The splash zone is rarely submerged with water and typically receives only salt spray from the ocean. Periodic submergence of the splash zone occurs during storms and occasional extreme high tides accompanied with high winds.

The intertidal zone experiences the full effect of a tidal range, or the difference in the height the water between high tide and low tide, as it is completely submerged at high tide and completely exposed at low tide. The intertidal zone is also frequently called the littoral zone. Saltwater marshes, beaches, tidal rivers, creeks, sounds, and bays that are submerged during high tides and exposed during low tides occupy the intertidal zone.

The subtidal zone remains submerged all of the time, with possible exceptions occurring during times of extremely low tides. Portions of saltwater marshes, beaches, saltwater rivers, sounds, bays, and tidal creeks that are submerged at low tide are located in the subtidal zone.

2. Pelagic Zone: the Water Column

The pelagic zone extends from the ocean surface to just above the ocean floor (Fig. 1-2). In other words, it is the water column itself. This zone is sub-divided into the neritic and oceanic zones, based on the relative distance from shore. The neritic zone may be considered the "nearshore" portion of the pelagic zone. Its boundaries are from the shoreline's high tide mark to the point offshore where the water depth is 200 m (656 feet) (Fig. 1-2). The oceanic zone is that part of the pelagic zone that extends seaward of the neritic zone to the open ocean waters.

3. Benthic Zone: the Bottom of the Ocean

The ocean floor is also called the benthic zone. Even though some areas of the benthic zone appear to be devoid of life, many species have successfully made themselves at home in or on the seafloor sediments. Off the coasts of North Carolina, South Carolina, Georgia, and parts of Florida, the benthic zone may only consist of large expanses of sand, sparsely littered with brittle stars, sea stars, sea cucumbers, or an occasional lizard fish.
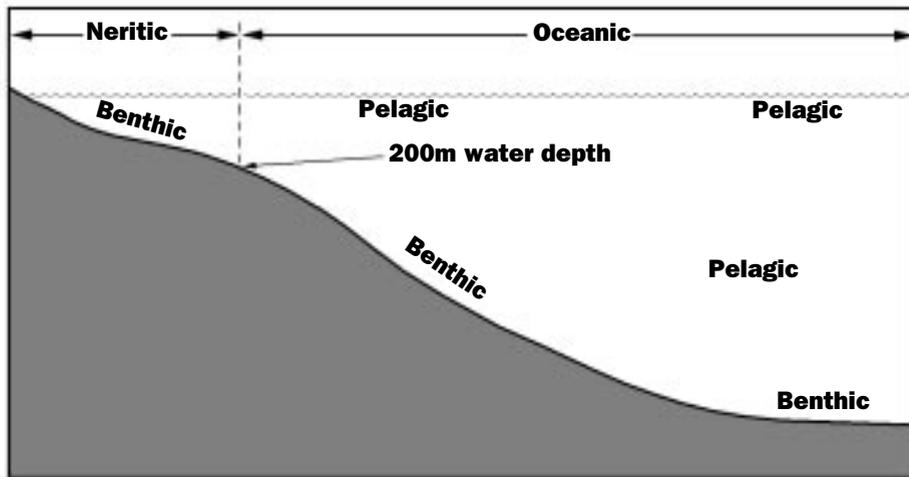
Figure 1-2.
Pelagic and benthic zones of the ocean. The pelagic zone is further subdivided into a nearshore (neritic) and offshore (oceanic) zone.

But there are rocky outcrops off the Southeastern U.S. coast that break the monotonous pattern of the sandy benthic zone. These rocky outcrops and overhanging ledges support beautiful gardens of soft coral, sponges, and tropical fishes, including brightly-colored butterfly fishes that are so characteristic of clear tropical waters. In section D that follows, you will learn more about the benthic zone. Specifically, you will learn about the shape, or bathymetry, of the ocean floor.

4. Zones of Sunlight Penetration

The area of the ocean where light penetration is great enough to support plant growth is called the photic zone. This zone extends to a wide range of depths in different ocean basins. The photic zone typically extends from 50 to 100 meters (164 to 328 feet), depending on the productivity and/or clarity of the water. Water clarity is related to the concentrations of tiny plants, animals, and/or other particles suspended in a body of water. The photic zone reaches to much greater depths in tropical

waters. A good example is the crystal clear Caribbean Sea. Along portions of the Southeastern U.S. coast, the depth of the photic zone is about 50 meters (164 feet), an indication that the Atlantic Ocean is very productive, and sometimes is very turbid, or "cloudy," due to the amount of suspended material in the water column. The disphotic zone is that area of the ocean where light levels are too low to support plant growth. The aphotic zone is the zone of no light penetration, generally below 1000 meters depth.

D. The Ocean Floor

The ocean floor is not simply a featureless, vast receptacle for sediment that has been eroded from the earth's surface and transported seaward by rivers and streams. In fact, you will find many of the same topographic features seen on land located at the bottom of the ocean. Mountainous ridges, trenches, and undersea volcanoes called seamounts occur on the ocean floor. Some oceanic mountains

extend above the ocean's surface to form oceanic islands. The Hawaiian Islands are seamounts which have grown above sea level. When measured from its base on the seafloor, Moana Loa on the Island of Hawaii is actually one of the largest mountains on earth, comparable in size to Mt. Everest.
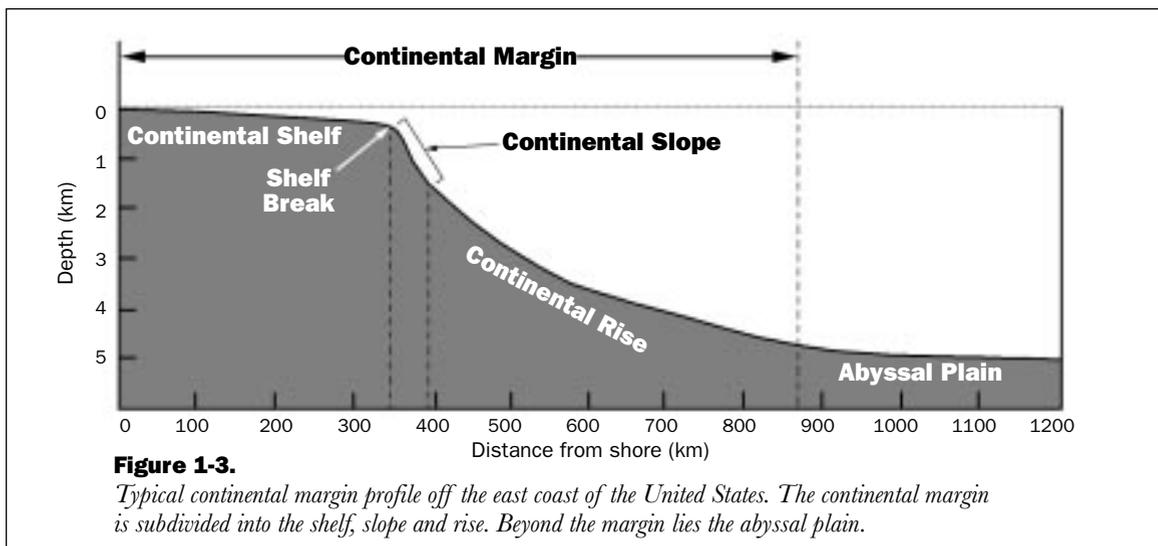
Just as the ocean has been divided into various zones for ease of classification and study, scientists have also divided the ocean floor into various sections. Submerged edges of continents are called continental margins. During the Ice Age over 18,000 years ago, the uppermost part of the margins, the continental shelves, were exposed to air. At that time, large amounts of ocean water that today cover the shelves were locked in the polar ice caps and sea level was much lower. Sea level may have been approximately 120 meters (394 feet) below the present level! Ancient rivers carved deep valleys into the exposed shelves. These valleys are now submerged and are known as submarine canyons. They are found on many of the world's continental shelves.

Continental shelves vary in width. Off South Carolina and Georgia, the shelf is relatively wide (as much as 130 kilometers, or 80 miles)

and dips very gently seaward to depths of 50 to 200 meters (164 to 656 feet). Off the coast of Cape Hatteras, N.C., however, the continental shelf is much narrower, extending only 50 kilometers (approximately 30 miles) offshore; and the shelf is less than 10 kilometers (6 miles) wide along the southern Florida coast. Worldwide, continental shelves extend to an average depth of 130 meters (426 feet).

The gentle slope of the continental shelf becomes more pronounced, or steeper with distance from shore. This area of the ocean floor is known as the continental shelf break (Fig. 1-3). The continental shelf break meets an area of the ocean floor where the gradient, or slope, increases, referred to as the continental slope. Most continental slopes are found at water depths from 3,000 to 4,000 meters (9,843 to 13,124 feet) in depth and continue seaward until the gradient becomes less pronounced. This area seaward of the slope is known as the continental rise, even though the ocean floor continues to drop, or increase in depth.

The continental rise continues seaward to large expanses of broad and virtually flat abyssal plains, at depths of 3,000 to 5,000

Figure 1-3.
Typical continental margin profile off the east coast of the United States. The continental margin is subdivided into the shelf, slope and rise. Beyond the margin lies the abyssal plain.

meters (9,843 to 16,405 feet). Abyssal plains are interrupted by ridges, trenches, and volcanoes. Ridges are comprised of long chains of underwater mountains, ranging from 1,000 to 4,000 kilometers (621 to 2,486 miles) in width. The Mid-Atlantic Ridge, which is located near the center of the Atlantic Ocean Basin, is the longest mountain chain in the world, extending from north of Iceland to the southern tip of Africa.
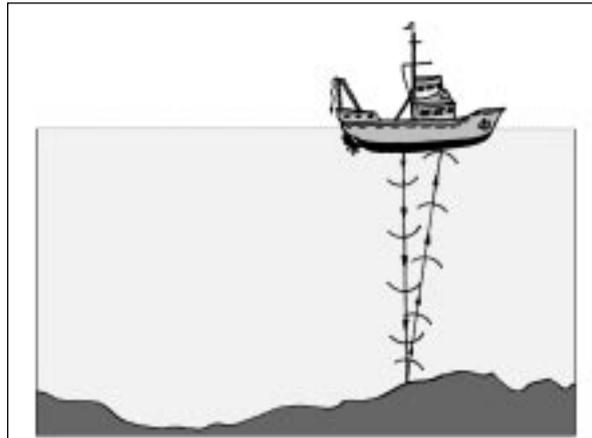
Figure 1-4.
Because we know how fast sound travels in seawater (1,463 m/sec), we can measure the amount of time a sound wave takes to travel from a ship to the sea floor and back to the ship to determine the water depth. This "bouncing" of sound waves off the seafloor is called echo sounding.

equipment has allowed us to easily "see" the surface of the ocean floor. Pulsing sound waves emitted from a ship bounce off the sea floor and return to the ship (Fig. 1-4). The travel time for the sound wave to reach the ocean floor and return to the ship is measured and used to determine the depth of the ocean floor. Additionally, deep-sea submersibles and robotic vehicles have just recently revolutionized how humans explore the depths of the ocean floor. Many discoveries lie ahead!

E. Mapping the Ocean Floor

We have learned much of what we know today about the ocean floor within the last 50 years. Variation in the depth of the ocean floor is referred to as bathymetry, which is analogous to underwater topography. Deep sea bathymetry is determined by measuring ocean depths, using a variety of mapping techniques. Some of these techniques use highly advanced technological inventions that have only recently been developed.

Sounding lines were probably the first "instruments" used by scientists to record bathymetry at different locations around the world. These sounding lines were nothing more than hemp ropes with lead weights attached and lowered over the sides of ships to the bottom of the ocean. The length of rope was then recorded at each location. Piano wires and bowling balls replaced the earliest sounding lines! Today, echo sounding and other state-of-the-art sonar

F. Plate Tectonics

At the beginning of this chapter, we discussed why the earth is called the Ocean Planet. From the eyes of astronauts "muted-green and dull-gold land masses" were viewed "floating on top of the electric-blue ocean." Land masses only seem to "float" because they are above sea level.

In the early 1900's the German meteorologist Alfred Wegener first theorized that over 240 million years ago, the continents were once part of one large super-continent called Pangaea (also spelled Pangea) (Fig. 1-5). Wegener also theorized that Pangea broke apart and the segmented continents shifted and moved apart until they reached their present-day locations. He believed that continents drifted across the oceans, bulldozing sediments before them. Wegener's idea, known as the Continental Drift Hypothesis, is

not accepted today in part because there was no evidence of bulldozed sediments and Wegener could not explain the *mechanism* that caused the continents to move. The existence of Pangaea, however, is supported by a great deal of geological evidence and is to this day considered to be a plausible concept.
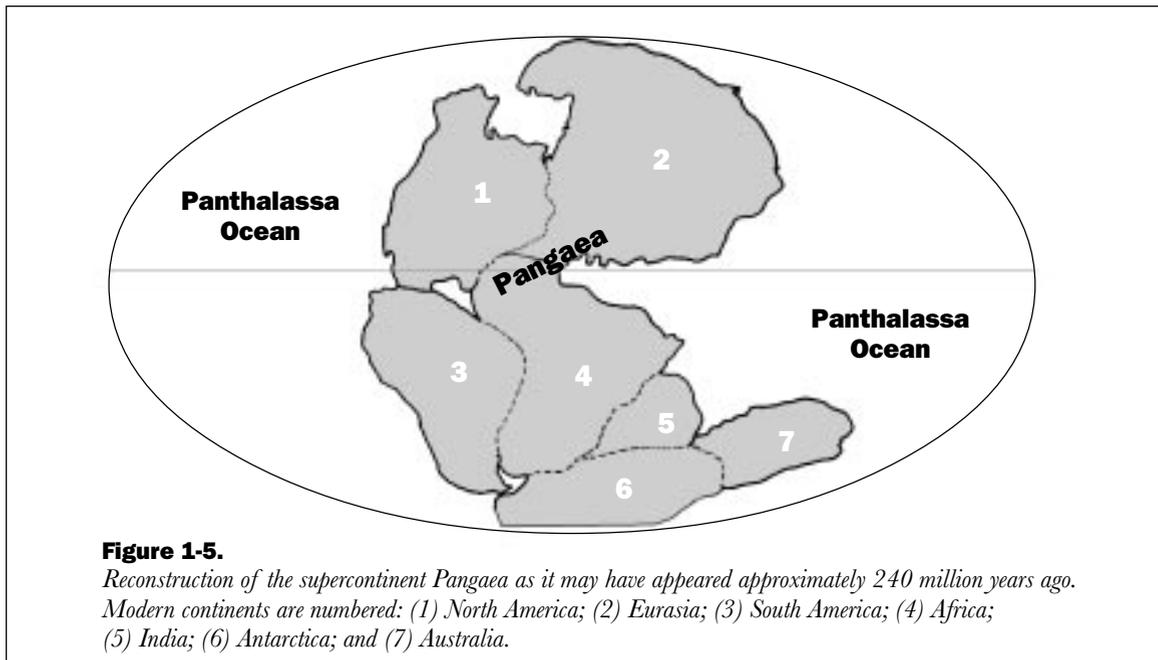
Since the 1950s we have learned much about the structure of the outer layers of the earth. We have determined that the outer layer, or crust, is strongly coupled with the uppermost portion of the mantle and, together, they comprise the lithosphere (Fig. 1-6). The lithosphere is characteristically brittle, or rigid. Crustal material within the lithosphere may be either continental crust or oceanic crust, depending on its origin, composition, and location.
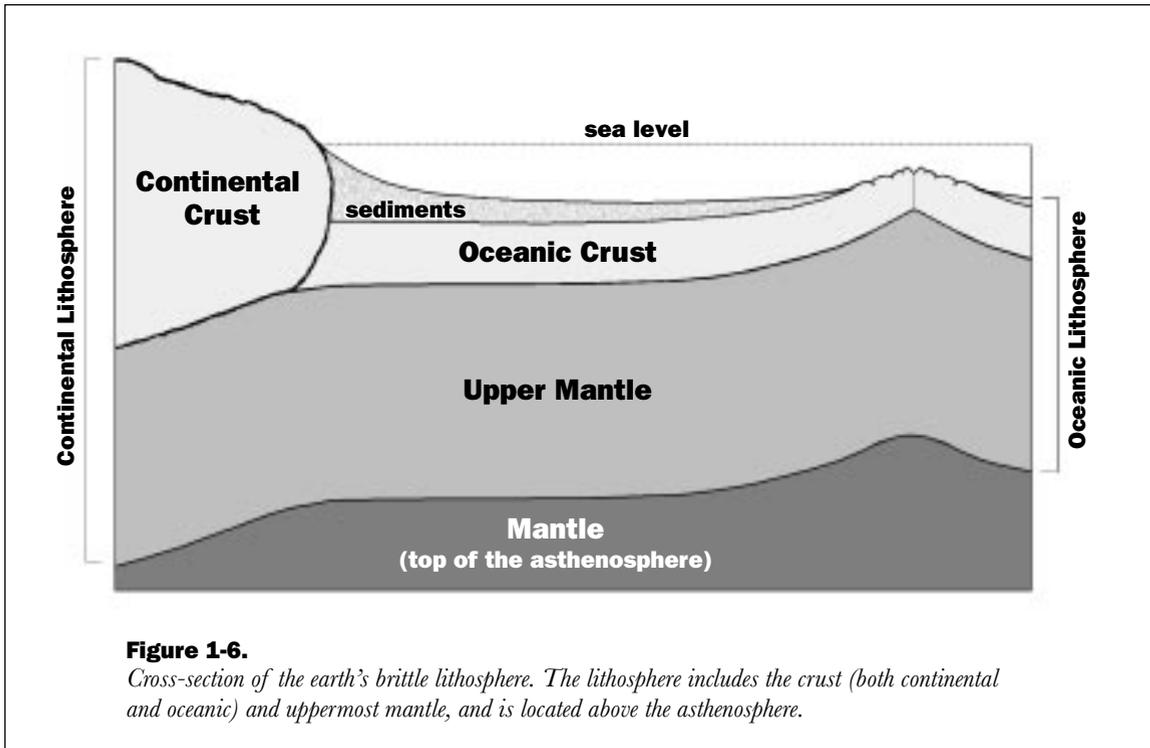
Because of the lithosphere's rigid nature, earth movements often cause it to break. The result is that lithospheric plates are formed. The surface of these plates, viewed on a map, includes oceanic floor *and* continental land masses (Fig. 1-7). Therefore, a continent is only part of a larger piece of lithosphere.

The occurrence of earthquakes and volcanic eruptions along the edges of lithospheric plates is evidence that plates are in continual motion. Volcanoes are very common along these plate boundaries where molten, or melted, rock makes its way to the surface through cracks and faults. Movement and friction along the plate boundaries frequently cause large amounts of energy to be released in the form of earthquakes. Scientists are able to measure the minute movements of plates with very sensitive instruments, and have shown that plates move very slowly around the earth. In fact, most plates are presently moving at a rate of 1 to 4 centimeters (0.4 to 1.6 inches) per year, yet some exceed 10 centimeters (3.9 inches) in a year. Compare these rates to the rate of your fingernail's growth which is approximately 2 centimeters (0.8 inches) per year!

The study of the earth's lithospheric plates involves investigation of their formation, interactions and destruction through time and

Figure 1-5.
Reconstruction of the supercontinent Pangaea as it may have appeared approximately 240 million years ago. Modern continents are numbered: (1) North America; (2) Eurasia; (3) South America; (4) Africa; (5) India; (6) Antarctica; and (7) Australia.

Figure 1-6.
Cross-section of the earth's brittle lithosphere. The lithosphere includes the crust (both continental and oceanic) and uppermost mantle, and is located above the asthenosphere.

helps us to understand the mechanisms for plate motions. The theory of how and why plates move is known as the Theory of Plate Tectonics. It has only been in the last four decades that we have compiled enough information on the earth's lithosphere to piece together like a puzzle the complex processes involved with plate motions and interactions. In the 1960's, Tuzo Wilson and numerous other scientists were able to utilize advanced technology and drilling ships to verify the movement of plates through time.

Wegener's concept of Continental Drift differs from the Theory of Plate Tectonics because Wegener believed that continents behaved independently from the ocean floor. We now understand that there are many lithospheric plates that contain both continental crust and oceanic crust which travel as a unit. Continents do not float or "drift" across the ocean floor. The Continental Drift Hypothesis is sometimes referred to synonymously with the

Plate Tectonics Theory, but they are different concepts. Without question, the theory of Plate Tectonics developed as a result of Wegener's early ideas regarding Pangaea's existence.

Plate Tectonics is a very complex subject and much is still unknown about the mechanisms of plate motion. New evidence is uncovered continually. Thus, Plate Tectonics remains a theory. To understand the physical processes of Plate Tectonics and the resultant crustal features that are produced, we will focus on the plate boundary interactions and one of the current hypotheses as to *why and how* the plates move.

There are several types of interactions between plates at the plate boundaries. Two plates may be moving in opposite directions away from one another, resulting in a divergent boundary. Or, they may be on a collision course with one another, creating a convergent boundary. Also, two plates may slide past each

other, as each moves in an opposite direction. This last example is referred to as a transform boundary. Different topographic and bathymetric features, both above and below sea level result from these three major boundary types.

1. Divergent Boundaries

In many areas, the earth's plates are being pulled apart by tensional forces. Enormous elongate cracks, or fissures, in the lithosphere allow molten rock from deep within the earth to rise and escape as lava. If a fissure occurs in oceanic lithosphere, the lava will erupt under water and cool very rapidly. The solid rock that is formed (called basalt) is oriented in elongate bands parallel to the fissure. Repeated events of tensional forces and escaped fissure lava continually add material to the plates being pulled apart. The result is that at divergent bound-

aries new lithosphere is produced and lithospheric plates "grow."

In regions of extensive and repeated fissure eruptions, ridges are formed (Fig. 1-8). Often these underwater ridges have substantial height (as much as 2,000 to 3,000 meters) and are considered to include the longest mountain chains in the world. As new oceanic crust forms at the ridges, older crust is progressively moved farther and farther from the ridge, creeping along at a rate of a few centimeters per year. This process is referred to as seafloor spreading. For this reason, we often refer to divergent boundaries as spreading boundaries. As the new oceanic crustal rock moves away from the heated ridge, it cools and contracts, decreasing the ridge height (i.e., increasing the water depth) of the ridge flanks.

Recently, the use of undersea submersibles has provided a window to view the mid-ocean
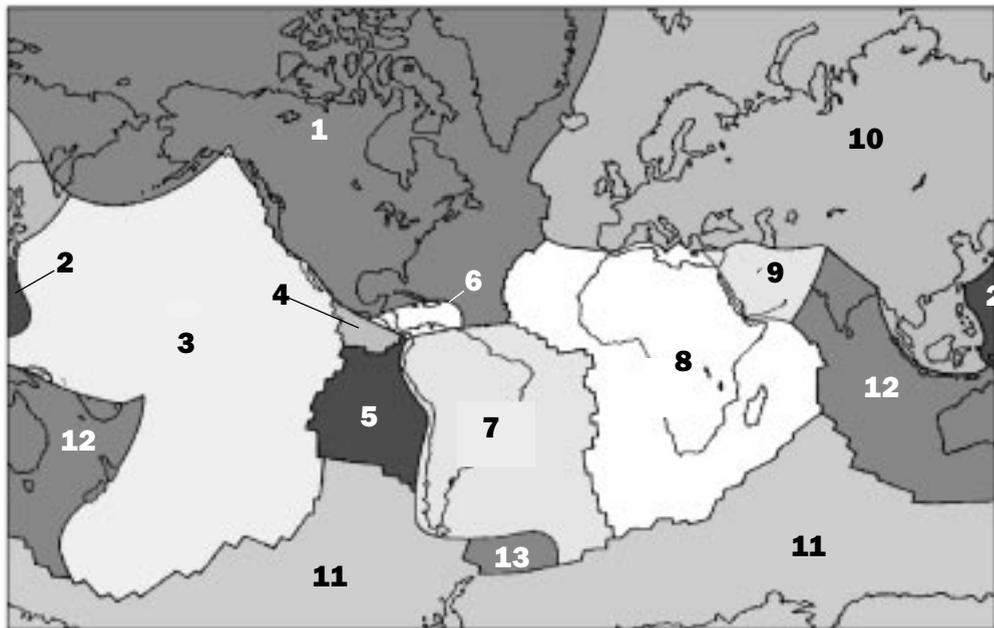
Figure 1-7.
The major lithospheric plates of the earth. Plates are numbered: (1) North American Plate; (2) Philippine Plate; (3) Pacific Plate; (4) Cocos Plate; (5) Nazca Plate; (6) Caribbean Plate; (7) South American Plate; (8) African Plate; (9) Arabian Plate; (10) Eurasian Plate; (11) Antarctic Plate; (12) India-Australia Plate; (13) Scotia Plate.

ridges. Scientists have actually observed new ocean floor being produced as red-hot lava flows from active fissures, instantly "freezing," or cooling, in the 2°C bottom water. Associated with the ridges are hydrothermal vents, where super-heated gases and minerals escape from deep within the earth.

The process of seafloor spreading not only forms ocean ridges, but over millions of years of seafloor spreading creates entire ocean basins. The modern oceans have all been formed by the divergence of two plates and the creation of newer oceanic crustal material. Examination of a map of the sea floor reveals a crooked but continuous mountain chain that divides the Atlantic Ocean, known as the Mid-Atlantic Ridge. Like the seams of a baseball, the ridge system continues around the globe, connecting with the Indian Ocean ridge system. Eventually the "seam" travels across the southern Pacific and appears to end as it runs into Central America. There it is actually broken into small segments in the Gulf of California. In fact, the Gulf of California is an excellent example of a young ocean being born. The Red Sea is another example. Investigation of a map of the seafloor will reveal a small, young divergent ridge system within the centers of both the Gulf of California and the Red Sea.
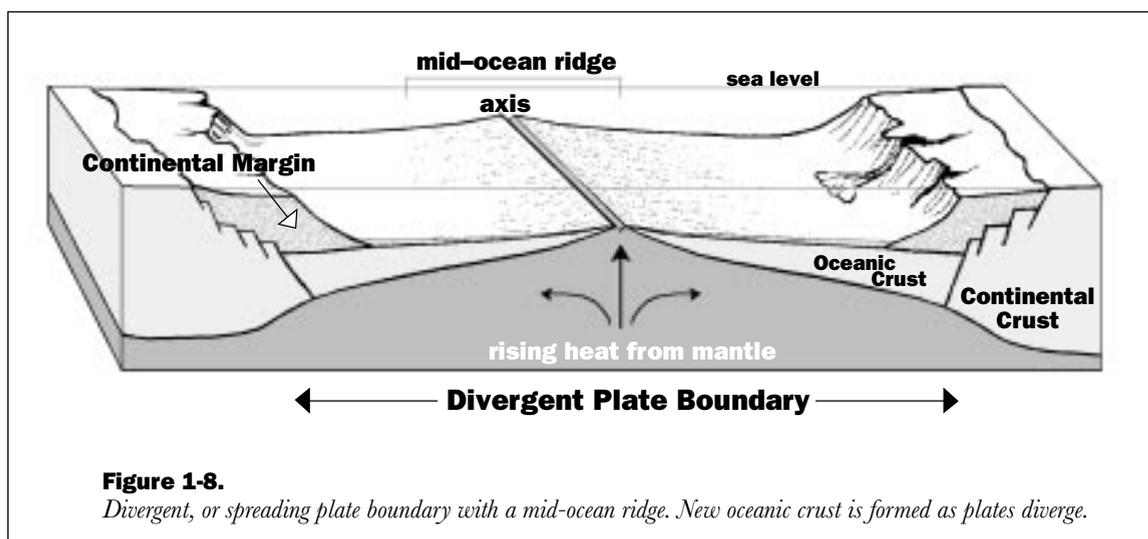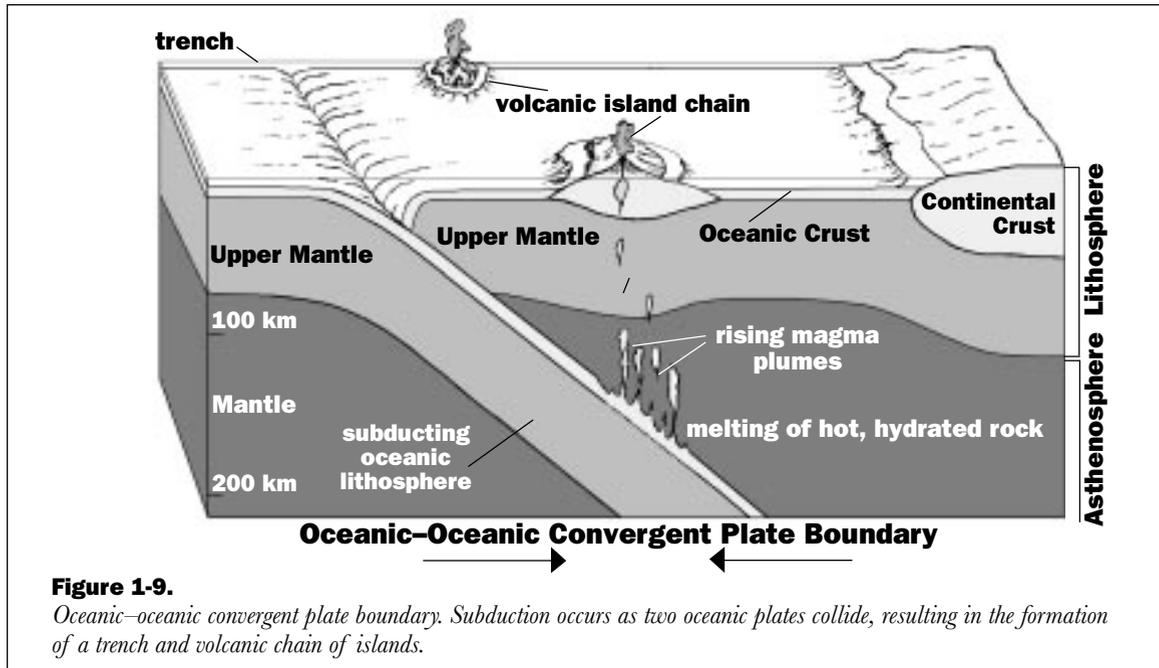
2. Convergent Boundaries

As you have seen, divergence and spreading cause the surface areas of the plates on either side of the ridge ultimately to increase. If all plate boundaries were divergent, the earth would be expanding! To compensate for the continual addition of plate surface area from divergence, plate material must be destroyed or consumed elsewhere. Because the edge of a plate may be composed of either oceanic crust *or* continental crust, and because two plates are involved in any one collision, there are *three* types of plate collisions: (1) when both plates have oceanic crust along their boundaries; (2) when one plate has an oceanic crust boundary and the other has a continental crust boundary; and (3) when both plates have continental crust boundaries.

a. Oceanic-Oceanic Collisions

The collision of two plates with oceanic crust edges causes one of the plates to slide under the other (Fig. 1-9). This process is referred to as subduction, and the area where the plate is subducting is called the subduction zone. As

Figure 1-8.
Divergent, or spreading plate boundary with a mid-ocean ridge. New oceanic crust is formed as plates diverge.

Figure 1-9.

Oceanic–oceanic convergent plate boundary. Subduction occurs as two oceanic plates collide, resulting in the formation of a trench and volcanic chain of islands.
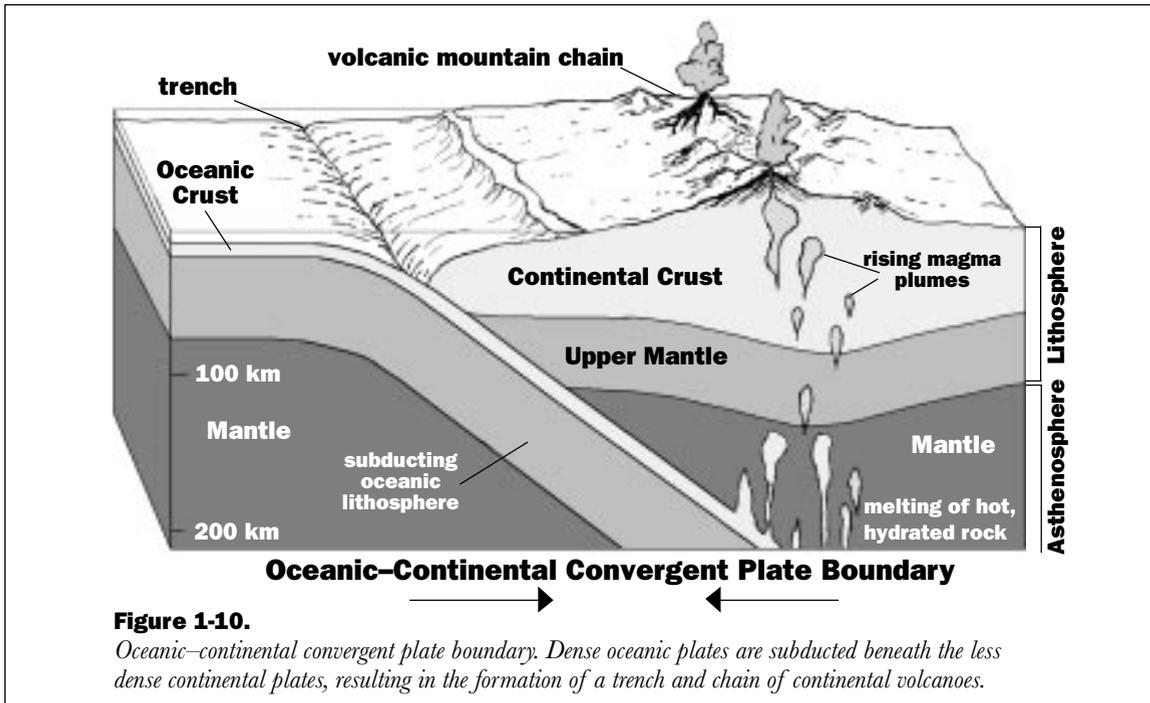
the oceanic plate descends, it produces numerous earthquakes from the release of frictional and heat energy. A deep and elongate trench on the seafloor marks the top of the subduction zone and the boundary between the two plates. As subduction continues, the subducted plate's temperature increases and vaporized water within the plate may cause partial melting of the mantle rock above it. The molten rock material, referred to as magma, rises because of its lowered density. If the molten material reaches the surface of the lithosphere, a volcano is born. This type of volcano is initially built under the sea, but may grow and, eventually, reach above sea level, producing a volcanic island.

Because plate boundaries are often long and nearly linear features, the volcanic islands produced from subduction most often occur as a chain parallel to the plate boundary and trench. These volcanic island chains and associated trenches mark the locations where two oceanic plate edges have collided. Japan and the Aleutian Islands of Alaska are

examples of volcanic island chains produced from oceanic-oceanic plate collisions.

b. Oceanic-Continental Collisions

Because oceanic crust is composed of denser material than continental crust, when the collision of two plates involves an oceanic plate edge and a continental plate edge, the oceanic plate slides, or subducts, underneath the continental plate. As with oceanic-oceanic collisions described above, this type of collision produces an elongate trench as well as a subduction zone with earthquakes (Fig. 1-10). The heated subducted plate may cause partial melt of the mantle, allowing plumes of molten rock to rise through the cracks and faults in the overlying continental crust. A chain of continental volcanoes often results. The Cascade Mountains in the northwest corner of the U.S. is actually a chain of volcanoes produced from the subduction of a small plate beneath Oregon and Washington. As evidenced by the eruption of Mount St. Helens in 1980, this is an active subduction zone! The

Figure 1-10.

Oceanic–continental convergent plate boundary. Dense oceanic plates are subducted beneath the less dense continental plates, resulting in the formation of a trench and chain of continental volcanoes.

Andes Mountains of South America are the result of the Nazca Plate's subduction beneath the South American Plate. Deep trenches and volcanic mountain chains are common features of oceanic-continental plate collisions.

If one examines a map of seafloor features, numerous trenches can be found along much of the Pacific Ocean's perimeter. Some of these trenches are the result of oceanic-oceanic plate collisions (northern and western Pacific), while the rest are from oceanic-continental plate collisions (along the coast of South America). A map of the globe showing locations of earthquakes and volcanoes reveals that the highest concentrations of each are found in a ring around the Pacific. Consequently, this ring is known as the Ring of Fire (Fig. 1-11).

c. Continental-Continental Collisions

When two continents collide, tremendous compressional and frictional forces are at play. These forces cause solid rock to bend, fold and fault, or break. Over the course of millions of years, enormous continental mountain belts are formed and uplifted as the land "wrinkles" from the continuous and extreme pressures (Fig. 1-12). A modern day example is the Himalayan Mountains that have been under construction for the past 40 million years, ever since the small plate on which India was originally located first collided with the Eurasian Plate. This collision is ongoing and has produced Mt. Everest, the tallest continental mountain on earth.

Closer to home in the Southeastern U.S., the Appalachian Mountains are remnants of a mountain belt formed when ancient plates collided over 250 million years ago during the construction of Pangaea! The Appalachians are no longer growing, but instead have been exposed to the natural forces of weathering and erosion for the past 200 million years, since the break-up of Pangaea.

3. Transform Boundaries

If one were to draw directional arrows on a map showing plate movement, arrows would be placed on either side of every mid-ocean ridge, with the arrows pointing away from one another. Because ridges are segmented on the curved earth, there are regions *between* the ridge segments where the motion is in opposite directions, and the edges of the plates are *sliding past* each other, rather than away from each other (Fig. 1-13). This is actually another type of plate boundary, referred to as a transform boundary. Because of the intense friction that results from the sliding motion of one plate past another, transform boundaries also have high occurrences of earthquakes.

Transform boundaries can be found connecting all the broken and offset segments of the mid-ocean ridge systems. They also connect segments of ridges that are quite distant from one another. For example, the ridge just east of Baja in the Gulf of California is actually
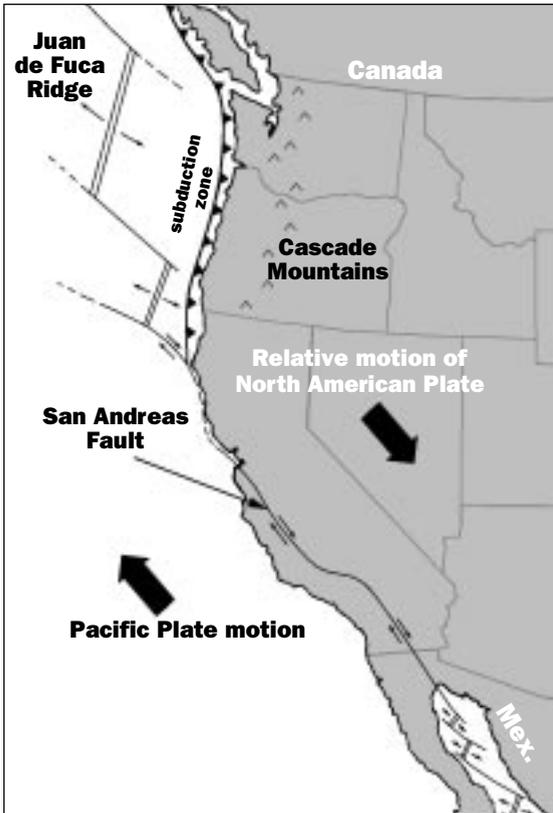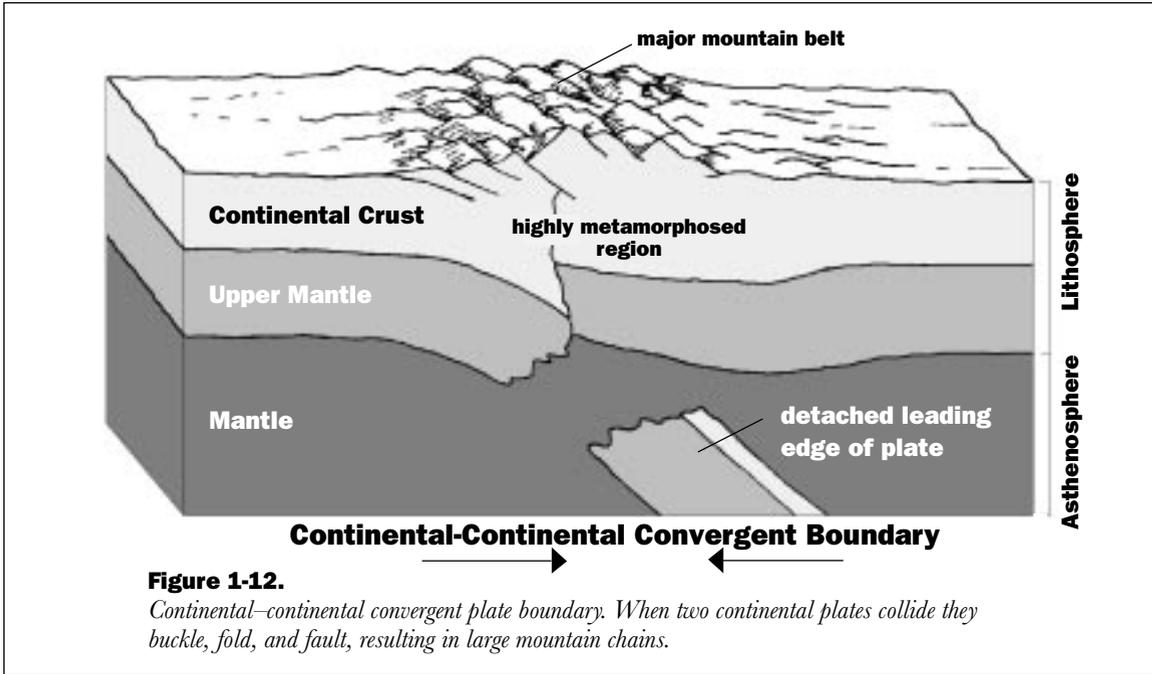
connected to a small ridge off the coast of Washington and Oregon (the Juan de Fuca Ridge) by a long transform boundary between the North American Plate and the Pacific Plate (Fig. 1-13). This boundary passes through San Francisco and just east of Los Angeles. Divergence from the Juan de Fuca Ridge is in part causing the western edge of the North American Plate to move in a southeast direction. Divergence from the ridge in the Gulf of California is causing Baja and the rest of the Pacific Plate to move in a northwest direction, opposite to the North American Plate.

Intense frictional forces prevent the Pacific Plate from gliding easily past the North American Plate. Instead the plates are temporarily locked in position until the forces of movement overcome the frictional forces, resulting in an enormous release of locked-up energy: a California earthquake. Sunny California has the great misfortune of being situated astride the transform plate boundary, known as the San Andreas Fault.
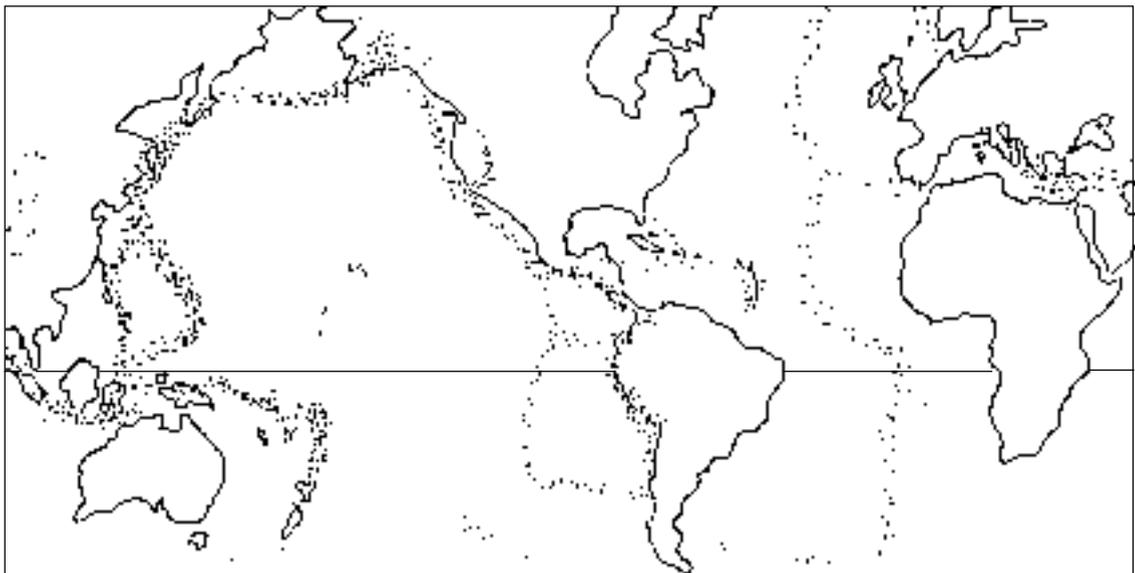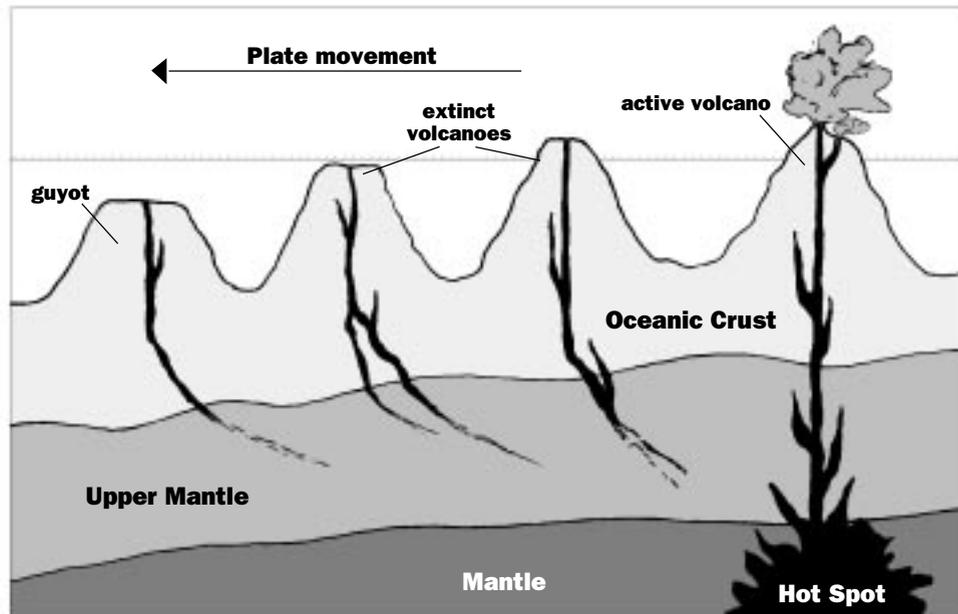

Figure 1-11.
Global distribution of earthquakes. Active volcanoes are closely associated with this same pattern. The high concentration of volcanoes and earthquakes around the edge of the Pacific Ocean is referred to as the Ring of Fire.

major mountain belt

Continental Crust

highly metamorphosed region

Upper Mantle

Lithosphere

Mantle

detached leading edge of plate

Asthenosphere

Continental-Continental Convergent Boundary

Figure 1-12.
Continental–continental convergent plate boundary. When two continental plates collide they buckle, fold, and fault, resulting in large mountain chains.

Juan de Fuca Ridge

Canada

subduction zone

Cascade Mountains

Relative motion of North American Plate

San Andreas Fault

Pacific Plate motion

Mex.

Figure 1-13.
The San Andreas Fault is a transform boundary between the Pacific Plate and the North American Plate. Motion along the plate boundary is in opposite directions, as shown by the arrows.

4. Hot Spots

Not all volcanoes and earthquakes are associated with plate boundaries. The Hawaiian Island chain of seamounts is located near the center of the Pacific Plate, without a spreading ridge or a convergent trench in sight! The Hawaiian volcanoes have been formed as the Pacific Plate has moved across an area known as a "hot spot" (Fig. 1-14). A hot spot is where a huge chamber of melted rock is located deep within the mantle, providing a tremendous source of molten material to the earth's surface. Scientists are still uncertain why hot spots occur, but the Hawaiian Island chain provides an excellent and active study site!

Figure 1-14.
The Hawaiian Island chain of volcanoes was formed by the Pacific Plate passing over a "hot spot" of magma located within the mantle.

The ages of the Hawaiian Islands are progressively older with increasing distance from the "Big Island" of Hawaii. On Hawaii, which is less than 2 million years old, the volcanoes Kilauea and Moana Loa today periodically erupt fountains and rivers of lava, ever increasing the mass and volume of this phenomenal lava-rock island that extends to the seafloor 9 km (nearly 6 miles) below its summit. Older islands house extinct volcanoes, quiet now after their own episodes of eruptive activity millions of years ago when they were created.

As the Pacific Plate passes over the hot spot a volcano is "born" directly above and is active for several million years. With time and movement of the plate, the volcano is carried far enough past the hot spot location to cause its dormancy and extinction. As it moves

away from its position above the hot spot, the volcanic island cools and contracts, eventually sinking below the ocean waves. The result is a chain of volcanoes where increasingly older and smaller (from contraction) volcanoes can be found with increasing distance from the hot spot that created them.

5. What Drives the Plates?

Scientists have several ideas of the mechanisms that cause plate movements. Most agree that the earth's internal heat plays the most significant role. Beneath the rigid lithosphere tremendous heat causes solid rock to flow very slowly. This mobile rock is located within the asthenosphere, simply defined as the interior of the earth below the lithosphere. Because lithospheric plates are more rigid and do not flow internally, their
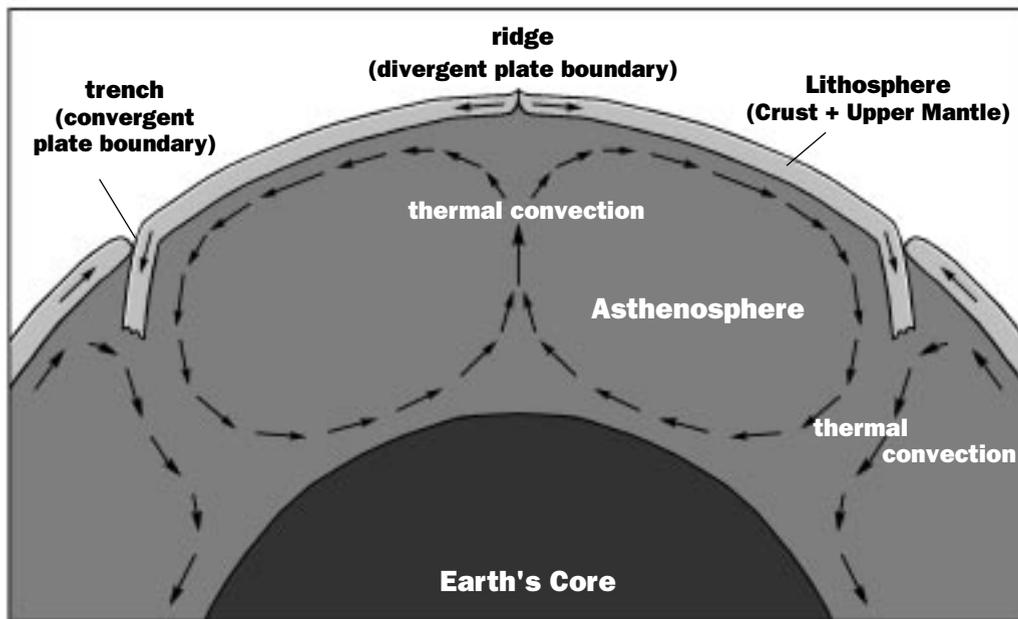
Figure 1-15.
Thermal convection within the earth's mantle may drive the motion of the lithospheric plates. The actual depth of the convection is not known.

movements as plates are most likely aided by the mobility of the upper asthenosphere on which they rest. But how does heat drive the lithospheric movement?

Consider a large pan of water on a stove burner. As heat is applied to the center of the pan's bottom, the warm water expands and rises because of its lowered density. As the warm water reaches the surface it is cooled and becomes more dense. Eventually the cooled water sinks because of its increased density. With a continuous source of heat applied to the center of the pan's base, a circular motion of rising heated water and descending cooled water is created. This circular motion is known as a thermal convection cell. Scientists believe that rising heat from the mantle causes overlying lithosphere to expand and may be the initial cause of breaking the lithosphere into plates. In areas where thermal convec-

tion cells diverge, divergent plate boundaries are found (Fig. 1-15). This idea is referred to as the Thermal Convection Hypothesis. The details of the depth of circulation are still unknown, but are being studied by geologists around the world.

There are still many unanswered questions of how and why lithospheric plates move. Certainly, heat alone does not move the plates, but without heat rising from within the earth, most scientists believe there would be no plate motion. Elevated ridges are formed where the lithosphere has expanded from the heat and new oceanic crust is being produced. Gravity may actually cause the plates on either side of the ridge to slide away from the fractured boundary, initiating plate motion. As scientists learn more about the structure of the earth and the internal flow of heat, many of the pieces of the plate tectonics puzzle will fall together.

G. The Hydrologic Cycle

The hydrologic cycle, or water cycle, is a very complex transport mechanism through which water moves from the oceans onto land and then back to the oceans again. This cycle, though complex, is quite simple to understand (Fig. 1-16). The entire system is continuously driven by energy from the sun, with no net loss or gain of water to the system. Water from the ocean is evaporated into the atmosphere as the sun heats the ocean's surface. Ocean salts are left behind as this fresh evaporated water condenses and forms clouds. Clouds produce rain, or other forms of precipitation, such as snow, sleet, or hail. This precipitation then falls back to the earth's surface. Precipitation continually supplies fresh water to the land, rivers, streams, and the ocean. As we already know, freshwater rivers and streams flow to meet the ocean. Plants also play an important part in the hydrologic cycle, as their roots take up water from the soil. This water is then actively transported, or transpired, through their leaves back into the atmosphere.

There are over 1,360 million cubic meters $(3.59 \times 10^{11}$ gallons) of fresh water on earth. Rivers, streams, and groundwater are also the reservoirs that serve as sources of fresh water. Other sources of fresh water are the polar ice caps, glaciers, lakes, and moisture present in the soils. But the ocean is, by far, the largest reservoir of water on earth, comprising 97.2% of all the water available to the hydrologic cycle.
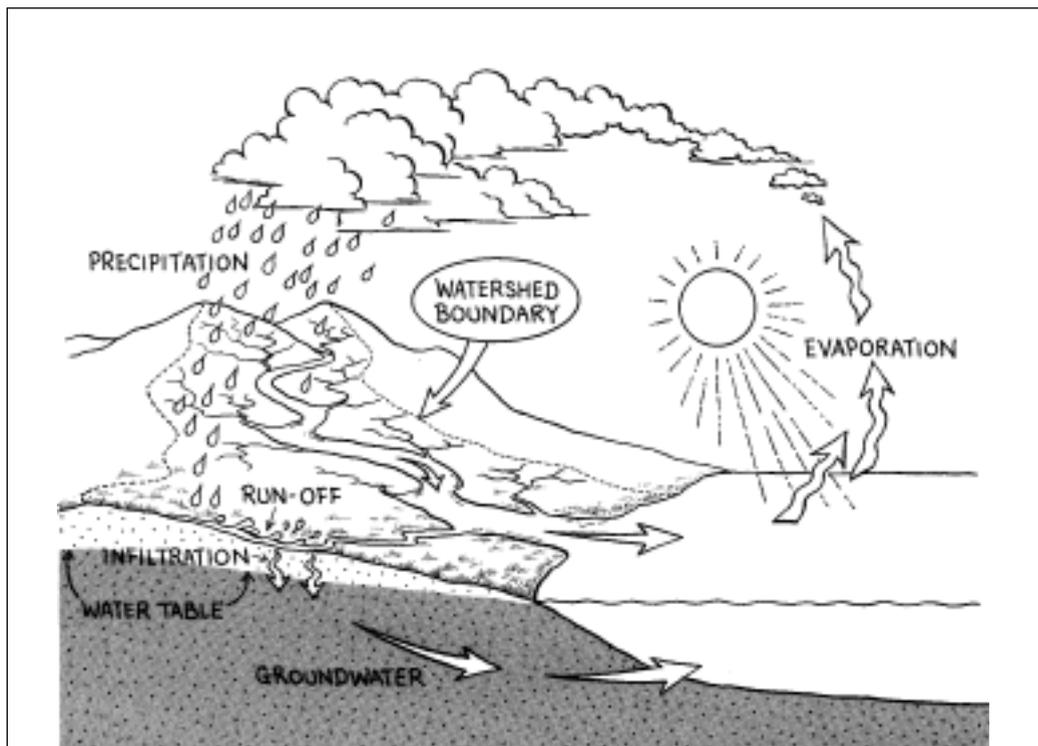
Figure 1-16.
A simplified hydrologic cycle.

Illustration by JOHN NORTON