THE EARTH IN MOTION: PLATE TECTONICS, THE EARTH'S INTERIOR, AND GEOLOGIC HAZARDS

As you have learned in the previous chapter, the careful and continuous application of science can lead to new ideas. When enough evidence is collected for these ideas through rigorous observation, experimentation, testing, and debate, that idea becomes a theory.

There have been many theories that have completely redefined how we view ourselves, our planet, and our universe. There is Charles Darwin's Theory of Evolution, or the Big Bang Theory, which states the Universe formed an astonishing 13.8 billion years ago, and Einstein's Theory of General Relativity. You don't have to understand every detail of these theories to know that they have changed our world and society.

The groundbreaking theory that revolutionized geosciences was the understanding that our continents were once in a far different place than they are on today's world map. This realization came with a lot of controversy and debate until we arrived at a theory that could neatly explain many geological processes, including why volcanoes and earthquakes happen where they do–we call this the theory of Plate Tectonics.

Image of the world map appearance over the past 250 million years.

Figure 2.1. These globes display what we now think the world looked like over the past 250 million years. What caused the continents to move?

LEARNING OBJECTIVES

After reading this chapter, you should be able to…

Describe the physical and chemical properties of the layers in Earth's interior.
Explain the current theory of plate tectonics and provide supporting scientific evidence for this concept.
Describe the plate boundary types and how each shape distinct landforms.
Identify real-world examples of plate boundaries.
Explain how plate boundaries connect to the distribution of geologic hazards.

2.1 Alfred Wegener and the Strange Idea of Drifting Continents

CHARLENE ESTRADA

Our “Contracting Earth”?
How can we explain the movement of land around us over long periods of time? Sometimes volcanoes spring up when there were previously none. Other times, the ground shakes in certain places. Some areas, like Arizona, are home to amazing mountain ranges and valleys, and others are island destinations. How did we make sense of any of this?

Science is an evolving thing, which means that scientists don’t always get it right. Case in point: until the mid-1900s we believed our planet formed all its breath-taking features by “squeezing” them out! These scientists rightly believed that Earth was a ball of hot, molten material when it first formed in space. Where they went wrong, however, is the belief that the cooling outer shell contracted like a dried-out raisin [1].

Video 2.1.1 Visualize how the contracting Earth hypothesis would explain mountains and valleys on Earth (1:22).

Furthermore, these scientists thought new landscapes formed through a process called isostasy. This process involved the continents and ocean basins sinking and rising up as they experienced changes in density [1].

Video 2.1.2. Isostasy, how does it work? (5:22) Professor Wheeler uses a big aquarium full of water as an analog (model) for the Earth’s mantle and boxes for the Earth’s continental crust.

Continental Drift
Image of Alfred Wegener
Figure 2.1.1. A young Alfred Wegener.

Alfred Wegener (1880-1930) was a German scientist who specialized in meteorology and climatology. He enjoyed fieldwork in Greenland to establish weather monitoring stations and made substantial contributions to climatology. However, as an avid explorer of the planet, he had something to say about how it operated. In 1910, he publicly disagreed with the extent that the role of isostasy played in the Contracting Earth hypothesis. He furthermore noticed some patterns in our world map that led him to propose a radical counter-hypothesis: the concept of Continental Drift. [2].

Video 2.1.3. Evidence supporting the Continental Drift hypothesis (3:48).

Ever since the first world map, people have noticed the similarities between the coastlines of South America and Africa. Would it be such a stretch to imagine these continents being pushed together like two pieces of a jigsaw puzzle? Indeed, what if all the continents were once merged together at one point as a single landmass, and they broke apart for some reason?

The idea that South America and Africa were once attached as a single landmass was not a new one; Antonio Snider-Pellegrini even did preliminary work on continental separation and matched fossils between the two continents in 1858 [2]. But Wegener's contribution to this idea was new and interesting in that he collected a tremendous amount of data on these two continents. Let's review some of this evidence below!

Fossils
A map of the distribution of fossils that are spread across continents which are now oceans apart.
Figure 2.1.2. One powerful line of evidence that the continents were once together is that ancient fossils of animals and plants spread across regions that are now oceans apart.
The fossils of the ancient life that existed hundreds of millions of years ago have been found along the separate coastlines of not just Africa and South America, but also India, Australia, and Antarctica (see left figure)! These organisms appeared to be exactly the same, but how could they have lived on separate continents? For example, neither the reptile Mesosaurus nor Cynognathus, which were found in South America and Africa, could live in salty ocean water. Therefore, Wegener argued, these animals could not have crossed the ocean to live on the continents if they were always separated. That meant that at one time, the continents had to have been merged as a single landmass!

Those that disagreed with Wegener's hypothesis made this counterargument: perhaps the continents were in the same configurations hundreds of millions of years ago as they are today. Instead of swimming across deep oceans, these ancient reptiles might have traveled between the continents on narrow land bridges that stretched across the oceans [1]. The only reason we don't see these land bridges today is because they have sunk down or eroded away.

Which idea makes more sense to you: the continents once being merged together OR the idea of ancient land bridges? Science is about a healthy debate given data and evidence, but Wegener was not done!

Geologic Evidence
Even if ancient reptiles and animals crossed the oceans on land bridges, as Wegener's opponents argued, there was something that they could not explain: the Geologic Record.

Think of a volcanic eruption, a landslide, a winding river, or a sandy beach. When a layer of rock is deposited, it reflects an environment or event that has happened in the area. Each layer of rock is like a page in a book that each of us can learn to read. Therefore, if one area has a distinct sequence of layers, a trained geologist can tell you that region's unique history. Let's keep this "book" metaphor in mind.

Layers of books stacked one on top of another (left) are not so different from layers of rock deposited over time. The oldest layer is on the bottom, and the youngest is on the top.
Figure 2.1.3. Layers of books stacked one on top of another (left) are not so different from layers of rock deposited over time. The oldest layer is on the bottom, and the youngest is on the top.
When Wegener examined the layers of rock between two separate continents, he found something exciting. Places an ocean apart from each other, such as the Appalachians in the United States and the mountains extending through Greenland, Ireland, the United Kingdom, and Norway, had the same sequence of rocks. That is essentially finding the same book two continents apart.

What would a reasonable person conclude when finding the same book with two different covers? The same author wrote it. Much in the same spirit, Wegener concluded that these two mountain ranges in North America and Europe actually formed as one chain hundreds of millions of years ago when these two continents were merged. North America and Europe then drifted apart to the place we see them now on the world map.

Climatic Evidence
Let's not forget that Wegener was a climatologist, and as he traveled the continents, he began to notice some strange patterns in the geologic record. Wegener found indications that places like southern Africa, India, Australia, and the Arabian subcontinent were once glaciated about 250 million years ago. He also discovered fossils of tropical plants in areas north of the Arctic Circle. In short, the rocks and fossils Wegener observed were telling him that places that we know today are cold were once hot, and places that are hot were once cold.

Map of ancient Earth with Pangaea supercontinent assembled with a lot of land localized over the Southern hemisphere. There, the Karoo ice age caused glaciation to cover a significant portion of the landmass.

Figure 2.1.4. The Karoo ice age affected Pangaea in the southern hemisphere (shaded blue), and glaciated areas such as India and South America.

Wegener used these observations to further conclude that the continents must have moved. For example, Wegener knew that glaciers only formed near the poles in the modern-day climate; therefore, he argued that to have glaciers, India, Australia, and Africa must have once been centered on the South Pole. Similarly, today's Arctic Circle must have once been around the tropics – approximately 23 °N and S along Earth's latitude to host tropical plant life [3].

Putting the Puzzle Together

After gathering a significant amount of evidence across the world, Alfred Wegener took the bold step of publishing his Continental Drift hypothesis in 1915 in a book entitled Die Entstehung der Kontinente und Ozeane or "The Origin of Continents and Oceans". In this book, Wegener presents all of his evidence, and asserts that the continents must have once been together in a single landmass called "Ur kontinent" (supercontinent) or "Pangäa" (entire earth). Over large timescales of millions of years, this landmass broke apart, and the continents shifted into the configuration as we know them today.

Video 2.1.4. Recent evidence (post-Wegener) supporting the Continental Drift hypothesis (3:00).

In order to successfully argue for Continental Drift, Wegener also had the monumental task of dismantling the case for the Contracting Earth hypothesis and the popular idea that all ancient life moved across separate continents using narrow land bridges. In his book, Wegener makes the following appeal:

"…where does the truth lie? The Earth at any one time can only have had one configuration. Were there land bridges then, or were the continents separated by broad stretches of ocean, as today? It is impossible to deny the postulate of former land bridges if we do not want to abandon wholly the attempt to understand the evolution of life on earth. But it is also impossible to overlook the grounds on which the exponents of permanence deny the existence of sunken intermediate continents. There clearly remains but one possibility: there must be a hidden error in the assumptions alleged to be obvious." – Alfred Wegener, The Origin of Continents and Oceans, translated from the Fourth and Revised German Edition by John Biram [4]

Backlash and Legacy

Wegener had no trouble collecting interesting evidence for his idea of continental drift, but his hypothesis had a weak point. In the early 1900s, he and his contemporaries did not understand the Earth's interior and the structure of the oceans nearly as well as we do today. The mechanism by which he assumed the continents moved was flawed.

Wegener thought that the continents quite literally "drifted" atop the oceans very slowly over periods of millions of years. We might think of each landmass like a boat or iceberg slowly moving across the seas until they collide with another large mass. He proposed the continents might have moved due to the Earth's rotation, or centrifugal forces. Opposing scientists rightly pointed out that this type of mechanism was improbable; not only would the continents be deformed beyond all recognition from dragging across the ocean floor, but the timeframes he originally proposed were much too short given the age of the fossils.

Unfortunately, the response to Wegener's hypothesis was vicious. Although some of the backlash was well-founded by the weak mechanism for continental drift, much of it was also biased and xenophobic; American geologists, in particular, often pointed out Wegener's German nationality and training in climatology.

How Bad Was the Criticism Against Wegener?

"delirious ravings"

"moving crust disease and wandering pole plague."

"Germanic pseudo-science"

"wrong for a stranger to the facts he handles to generalize from them"

"utter damned rot"

Wegener did not back down in this overwhelming criticism, and he never abandoned his idea of continental drift. However, he never did see it receive its due credit by the scientific community. It was not until decades after his death in 1930 that geologists began to truly understand Earth's oceans and interiors, and realize – perhaps sheepishly – that Wegener was onto something transformative [5,6].

Alfred Wegener's Final Expedition

The last known image of Alfred Wegener in Greenland before his death. He is in a winter tundra in heavy coats.

Figure 2.1.5. The last known image of Alfred Wegener (pictured left) in Greenland before his death.

Wegener's scientific contributions were not only in the field of geology. As a climatologist, one of his passions was exploring the north of Greenland, which in the early 1900s had not been completely mapped. Wegener helped establish weather-monitoring stations on Greenland that took many readings of its brutal winter weather. This project became a lifelong love for Wegener despite the deadly risks each expedition posed. In 1928, even though Wegener was approaching his 50s, he departed again to explore northern Greenland. The weather was bad (-76 degrees F) and one of the nearby camps was running low on food. He managed to travel through the terrible weather to resupply the camp on dog sleds, but the success was short-lived. Even with supplies, it was clear that the food would not last long enough for everyone. Therefore, he and another colleague volunteered to go back into the weather in the hopes of traveling to another camp. Wegener died on the journey from a heart attack, and his grave was marked with skis. His brother eventually discovered his body, but the family agreed that Wegener belonged in the field he so loved, and his final resting place has since remained in Greenland. [5,6]

2.2 Journey to the Center of the Earth

Alfred Wegener's Continental Drift hypothesis faced some major problems. One was that scientists of the early 1900s thought that the ocean floor was one uniformly flat basin like a cement pool. Such a flat surface beneath the ocean would not bear any evidence of past moving continents. The next chapter will address how this idea significantly changed in the scientific community. The other problem with Continental Drift was that Wegener could not convincingly explain why the continents would move.

To satisfy this issue, geologists needed to think beyond the Earth's surface. In Wegener's time, scientists knew some of the necessary information about the Earth's interior; there was a crust, a mantle, and core. The key to the movement of the continents was not something happening to the crust – it was a process operating within the Earth's interior in the mantle and the engine driving it within the core! Before we discuss these processes, it is important to understand the differences between each layer in our planet.

Layers of the Earth
In Ancient Greece, they believed that all the matter in the Universe was made up of the four basic elements: Water, Air, Earth, and Fire. Today, we have refined our understanding of the Universe: there are 118 known elements (94 of which are naturally occurring), and there are still four states of matter: solid, liquid, gas, and plasma.

The Periodic Table of Elements
Figure 2.2.1. The Periodic Table of Elements
This is all-important in how we describe the interior of our planet. Our Earth is geologically active, and a big reason for that is the fact that the inside of the Earth is composed of different layers. These layers differ chemically – the bulk makeup of elements – and physically – with differences in their states of matter. All of this is a fancy way of saying that the inside of Earth is not the same as the outside!

The structure of Earth and its interior.
Figure 2.2.2. The structure of Earth and its interior, drawn to scale.
Crust, Mantle, and Core. Most of you have probably heard of the three main layers of Earth before in school, media, or elsewhere. We live on the crust. Beneath it is a hot mantle, and at the very center of the planet is a very hot core. Even if you aren't already familiar with this basic description, there's a good deal more to the composition of our planet. Let's take a journey to the center of our Earth!

Video 2.2.1. Layers of the Earth mini-lecture, by Khan academy (9:32).

Or take your own journey right here!!

Stop 1: The Crust
PASSPORT TO THE CRUST
Physical State: Solid

Chemical Composition: O, Si, Al, Fe,

Depth: 0 – 70 km (variable depending on crust type)

Temperature: 0 – 500 °C

Video 2.2.2. How much do you have to dig to reach the Earth's core? Take a trip through markers in buried layers until you reach the center? (3:05)

The crust is where we and every known organism on the planet lives. It may be pretty important to us, but it only makes up a measly 1% of Earth's total mass! Even if it is a very thin layer on Earth, the majority of geologic hazards we will be studying occur on the crust.

The crust is mainly composed of 4 elements: 46.6% Oxygen, 27.7% Silicon, 8.1%, Aluminum, and 5.1% Iron [7]. These elements mostly form igneous rocks in the crust, although a smaller percentage of the crust is also made of the two remaining rock types, sedimentary and metamorphic rocks. Physically, the crust is solid and pretty brittle at the uppermost regions on the surface. However, we draw some distinctions between two types of crust: oceanic and continental.

Continental crust is a lot thicker and more elevated than the oceanic crust.
Figure 2.2.3 The continental crust is much thicker than the oceanic crust, which means that continental lithosphere is also thicker than oceanic lithosphere.
As the name implies, oceanic crust can be found underneath the world's oceans. It is the denser of the two crust types because it contains more rocks and minerals with heavier elements such as iron (Fe). Basalt and gabbro are very common rock types found here. Oceanic crust is typically thin, about 5 km, or sometimes at maximum, 10 km, but there is another intriguing property about the crust beneath the oceans: it's young. Although our planet is 4.54 billion years old, the oldest oceanic crust is typically about 200-300 million years old. Why is there such a disconnect? We will explore this further as we investigate plate tectonics!

The continental crust is the material that makes up the large landmasses of our world. It is lighter than oceanic crust because it contains rocks and minerals with lighter elements, such as those with more silicon and alkali elements. Some rocks that you would typically find on continental crust would be granite, rhyolite, andesite, and diorite. Unlike oceanic crust, continental crust is very thick: in some areas it can be between 40 – 70 km in depth! Continental crust can sometimes be billions of years old, and it can hold clues for the oldest events in Earth's history.

Stop 2: The Upper Mantle
PASSPORT TO THE UPPER MANTLE

Physical State: Solid

Chemical Composition: O, Si, Mg

Depth: ~70 – 410 km

Temperature: 500 – 900 °C

An image of Earth cut in half
Figure 2.2.4 An artist's view of the layers of the Earth.
We've now arrived at the Earth's mantle, which makes up over 80% of Earth's total volume – don't get lost! Because of its great volume and variation with increasing depth, it is more accurate to think of the mantle as being separated into two distinct zones: an upper and lower mantle. Here, we will begin with the upper mantle.

At the upper mantle, we see a distinct change in chemical composition from the crust. The mantle is much denser with an elemental breakdown of 44.8% oxygen, 22.8% magnesium, and 21.5% silicon [8]. Silicate rocks and oxide minerals often form here, but many of them would not be as common on the surface: peridotites, spinels, garnets, and olivine are all prime examples.

If you were to do a quick search for the depth of the upper mantle, you won't get a consensus between different sources; the depth, pressure, and temperature of the upper mantle vary! The exact transition point to the lower mantle is a matter of debate because we cannot directly observe it. So, what do we know?

From the crust-mantle boundary down to about 100 km beneath the Earth's surface, the upper mantle is rigid. This means that even though it is hotter and chemically different than the crust, this section of the mantle will tend to break and rupture when it is subjected to stress. This section of the mantle belongs to what we call the "lithosphere", and we will discuss what that means later in the chapter.

A pie slice of Earth's interior demonstrating that the crust is very thin in comparison to the lower mantle and core which make up the majority of the interior.
Figure 2.2.5. Earth's layers from right to left: crust is pink, mantle is green, core is blue.
Between 100 – 410 km deep, the upper mantle becomes hotter and begins to flow and stretch easier; we call this reaction ductility or plastic flow. Nevertheless, this section of rock is still solid.

This part of the mantle is called the “asthenosphere“, but don’t worry about this term and its implications just yet – all you need to know now is that with depth, the upper mantle is beginning to act differently!

Backyard Geology: San Carlos, Arizona.
A peridotite xenolith is a rock with bright green coarse crystals that are embedded in a very smooth, fine-grained gray rock matrix.
Figure 2.2.6. A mantle xenolith of peridotite with green olivine.
The San Carlos Apache Reservation is located east of Phoenix in Gila County. This region is a rich source of the gem peridot, which originates from the igneous rock peridotite. Peridotite is an intrusive, ultramafic rock. What makes the occurrence of peridotite and the resulting olivine/peridot unusual is that ultramafic rocks only tend to form at the mantle; we rarely find them on Earth’s surface. How did the peridotite end up at San Carlos? Up to 4 million years ago, a volcano erupted basaltic lava; however, in that eruption, it carried hardened peridotite rocks up to the surface in the process. The mafic magma would not melt the peridotite, because it originally crystallized at higher temperatures deeper in the mantle. Mantle rocks that are brought up to the surface with a volcanic eruption are called xenoliths, which imply that they did not form within or on the crust. The peridotite at San Carlos remains a literal “piece” of our upper mantle that we can physically examine – as it turns out, the mantle is actually green, not hot red or orange as most diagrams of the Earth’s interior might suggest [9]!

Pit-Stop: The Transition Zone
Around 410 – 660 km deep, we enter the transition zone. This area is wide boundary between the upper mantle and the lower mantle. There’s a lot of pressure in the transition zone, which causes the rocks there to become very dense. However, what has really fascinated scientists in recent years has been the discovery of water stored in solid minerals like ringwoodite (Mg2SiO4). We currently estimate that there’s just as much stored water in the transition zone as in our oceans [8]!

A diagram of the upper mantle, transition zone, then lower mantle with increasing depth.
Figure 2.2.7 The transition zone is about 410 – 660 km in depth.
Stop 3: The Lower Mantle
PASSPORT TO THE LOWER MANTLE

Physical State: Solid

Chemical Composition: Mg, Fe, Si, O

Depth: 660 – 2900 km

Temperature: 900 – 3500 °C

The lower mantle is HUGE! It spans from 660 to 2900 km in depth, and it easily makes up the majority of the whole mantle. At up to 3500 °C, the lower mantle is very hot, but there is also plenty of pressure from the overlying layers of rocks (think over ONE MILLION TIMES the pressure we have on the surface of Earth!). Some websites and sources might claim that because of the high temperatures, the lower mantle is liquid, but this is not true! The high pressures experienced at the lower mantle keep the materials in the solid phase [8].

There's still a lot that we don't know about the lower mantle. It is generally agreed that because of the pressure, the rocks in this layer do not flow and stretch with ductile deformation as much as they might in the upper mantle. A lot of the lower mantle is also composed of Mg, Si, and O, but the main minerals are made of Mg, Si, and Ca, which are squeezed together in an atomic structure called the perovskite group.

Diagram of the perovskite atomic structure, which appears as a repetitive pattern of spheres, found in the lower mantle.
Figure 2.2.8 Atomic structure of perovskite. Small red spheres are oxygen; medium blue spheres are metallic ions (e.g., Ti^{4+}) and the large green spheres alkali metals ions (e.g., Mg^{2+}, Ca^{2+}).

Stop 4: The Outer Core
PASSPORT TO THE OUTER CORE

Physical State: Liquid

Chemical Composition: Fe, Ni

Depth: 2890 – 5150 km

Temperature: 4,500 – 5,500 °C

Welcome to the core – it's getting hot! At a devilish 4,500 to 5,500 °C, the material in the outer core cannot remain solid. The outer core is the only liquid layer in the Earth's interior [10]. Just imagine – molten, liquid iron and nickel swirling around under tremendous pressures and temperatures! The outer core is not only fascinating; it is responsible for making life far more tolerable here on Earth's surface. But how?

Iron and nickel are both metallic elements that also hold some magnetic properties – think about a refrigerator magnet attracting iron shavings, for example. When these elements move around in liquid form, they actually generate electric currents! When these currents are combined with the way the Earth is tilted slightly on its axis and rotates, a magnetic field is established.

Video 2.2.3 Why does Earth have a magnetic field? And what is the purpose that it serves? (2:04)

Why should we care about a magnetic field? Our Sun emits electromagnetic radiation that can disrupt electronics as well as destroy living tissues. These come in the form of solar flares and coronal mass ejections. Be glad we have a magnetic field around to keep us protected!

Stop 5: The Inner Core
PASSPORT TO THE INNER CORE

Physical State: Solid

Chemical Composition: Fe, Ni (possible other elements Si, C, S, ???)

Depth: 5,150 – 6370 km

Temperature: 5,200 – 6,000 °C

Cross-Section of Earth, focused on core
Figure 2.2.9. Cross-section of the Earth down to the inner core.
We've made it quite literally to the center of the Earth! Our final stop is the inner core, which is a solid sphere composed of iron and nickel. The inner core's composition is very similar to the outer core; however, unlike our previous stop, it has remained solid! Why does the inner core remain solid while the outer core is liquid? The temperature of outer core is not much different at nearly 6000 °C, so heat is not the reason [10]. Instead, think about the other process occurring at the inner core: pressure.

To arrive at the inner core, it is necessary to travel to a depth of 5,150 km or about 3,200 miles. Under all of that densely packed rock, the inner core is subjected to at least 3.6 MILLION times the pressure we would experience at the Earth's surface [10]! That's enough to keep molten hot iron and nickel in solid form!

Besides iron and nickel, scientists believe that there are trace amounts of other elements in the Earth's core. The identity of these elements has not been well agreed upon yet – they could be anything from sulfur (S) to silicon (Si) or even carbon (C)! Another strange property of the inner core is that it might even be divided further into an inner-inner core. Geologists suggest that the crystals making up the iron in the outer shell are oriented North and South, whereas those in the inner-inner core are oriented East and West (Stephenson, Tkalčić and Sambridge 2015). This idea of two layers being present within the inner core has been gaining wider acceptance as of 2015, which shows us how much we are constantly learning about Earth's interior!

2.3 From Junk Science to Theory

Alfred Wegener died in 1930 on an expedition in Greenland. His ideas of moving continents seemed destined to be lost to history as a fringe idea. As discussed in the previous chapter, Continental Drift suffered from two major flaws: a lack of a convincing mechanism and scientists did not understand the seafloor between the continents. However, these issues would soon change. In the 1950s, the world had found itself with new technologies developed from the World War II era that could now open fascinating new possibilities for exploration and science. The scientific community would soon be surprised to learn that much of Wegener's "pseudoscience" actually had a sound basis!

Mapping the Ocean Floors
Using submarines and sonar particularly redefined how we thought of our ocean floor. Beginning in 1947, researchers adapted sonar to map the ocean floor, which was very poorly understood. With the new advances in this technology, it was possible to determine the bathymetry, or three-dimensional rises and falls in elevation of the seafloor.

How It Works: Sonar. Echo sounders on a submarine or ship produce sound waves that travel outward in all directions and bounce off the nearest object. These sound waves will then return to the vessel. By knowing the sound of speed in seawater, scientists calculate the distance to the object based on the time it takes for the wave to make a round trip. This animation shows how sound waves are used to create pictures of the seafloor and ocean crust.
Marie Tharp was the first to make a detailed map of the ocean floor. This map revealed the Mid-Atlantic Ridge, a basaltic feature in the middle of the Atlantic Ocean. This underwater feature is actually the longest mountain chain on our Earth, measuring around 10,000 miles! In addition to its astonishing length, there were several other strange features discovered about the Mid-Atlantic Ridge: it had relatively little sediment, which indicated it was younger than the surrounding oceanic crust, and most underwater earthquakes originated along the ridge [2]. What was happening here?

MARIE THARP: THE WOMAN WHO MAPPED OCEANS

Photograph of Marie Tharp
Figure 2.3.1. Photograph of Marie Tharp.
In the 1940s, women were commonly excluded from science, but the absence of men in academia during World War II opened a path forward for one woman who would fundamentally change how we thought about our planet. Marie Tharp earned a Masters degree in Geology during the war, but could not find many job opportunities similar to her male counterparts. Nonetheless, in the early 1950s, she volunteered to take on the tedious and painstaking task of

drafting maps of the Atlantic ocean from sonar data collected aboard research vessels. Tharp herself could not go on these expeditions as people believed that women brought bad luck along sea voyages, but she created the maps at the famed Lamont-Dohert Observatory at Columbia University, where she worked for her colleague Bruce Heezen [11]. Early in this process, she noticed that the feature called the Mid-Atlantic Ridge actually appeared to have all the features of a deep, rifting valley:

“When I showed what I found to Bruce, he groaned and said, ‘It cannot be.It looks too much like continental drift.’ At the time, believing in the theory of continental drift was almost a form of scientific heresy. Almost everyone in the United States thought continental drift was impossible. Bruce initially dismissed my interpretation of the profiles as ‘girl talk.’” (Tharp, 1999 [12])

Nevertheless, Tharp persisted in collecting evidence for her hypothesis, and she eventually convinced Heezen, who soon after championed the idea that the Mid-Atlantic Ridge was firm evidence that seafloor spreading was occurring. When her maps were published, they played a key role in shifting the attitudes of the scientific community toward accepting seafloor spreading as scientific fact. For decades, scientists did not acknowledge that Marie Tharp authored the seafloor maps as Bruce Heezen published their work under his name only. But she still enjoyed a lifelong friendship with him. Since their initial publication in 1957, Marie Tharp’s maps are still regarded today as being extraordinarily sophisticated [11,12]. View a brief video displaying those maps below!

Video 2.3.1. Observe the amount of detail in the first maps models of the ocean floor (2:07)

In the 1960s, scientists were able to make magnetic measurements of the seafloor. The basaltic rock in the oceanic crust contains iron-rich minerals such as magnetite, and once iron cools as a solid, it aligns with the Earth’s magnetic field toward the North Pole. The Earth’s magnetic field creates flux lines surrounding the magnetic North and South Poles (like a bar magnet), which are both close to the Earth’s rotational North and South Poles. Our planet’s magnetic poles will reverse every couple hundred thousand years (and don’t worry, it is unlikely to harm us!). As a result, the Earth’s magnetic North sometimes becomes the South Pole. Rocks rich in iron record these changes! For example, iron-rich crust produced continuously for a million years will indicate the poles flipping back and forth when carefully measured. These are often represented as alternating stripes.

A simplified image of Earth's magnetic field. Earth has a magnetic in its core which generates the surrounding field lines.
Figure 2.3.2. We can think the iron core of Earth as a magnet, which generates a magnetic field, shown with flux lines.
A record of geomagnetic reversals over the past 169 million years.
Figure 2.3.3. A record of reversals in the Earth’s magnetic field over the past 169 million years (Ma). White bars indicate a reversed magnetic field relative to today.

Scientists knew all of this already by the 1960s, but when they measured the magnetic anomalies at the Mid-Atlantic Ridge, they found something strange – instead of finding one set of stripes showing pole reversals in the rocks, they found two nearly identical sets of symmetrical stripes!

Seafloor Spreading

Together with previous observations of the Mid-Atlantic Ridge, these symmetrical magnetic stripes were interpreted as evidence for a new idea called seafloor spreading, which was first proposed by the geophysicist Harry Hess in 1960. The basic idea behind seafloor spreading was that regions such as the Mid-Atlantic Ridge were areas where brand new oceanic crust was created. Magma from the Earth's mantle would push upward to the crust and surface, where it would cool. Once cooled, that new crust would displace the older crust by pushing it outward and to the side – new oceanic crust would spread from these locations.

Animation showing the oceanic spreading center.
Figure 2.3.4. The spreading center "conveyer belt" at mid-ocean ridges.
If brand new crust was being formed at the Mid-Atlantic Ridge, it explained why there was no sediment at the location, and earthquakes would also be expected because the region would be a place of active geologic activity. Moreover, this idea addressed the magnetic striping anomalies. Cooling iron minerals would orient toward the geomagnetic North Pole as the brand new crust formed at opposite sides of a spreading center; hence, two sets of magnetic stripes would also be expected (see Fig. 2.3.5).

Magnetic alignment of rocks switches back and forth with switching magnetic poles over time. At spreading centers, these anomalies appear as a symmetrical set of bands.
Figure 2.3.5. Magnetic North Pole reverses (white) and goes back to normal (red/orange) during Earth history. The alignment of iron minerals in new crust at spreading centers records this anomaly as a set of symmetrical bands.
But what happens when Earth keeps growing new crust? Surely this process can't occur indefinitely! The seafloor spreading hypothesis found an answer for this problem as well. In mapping the seafloor for the past decade, trenches extending miles deep were found bordering some continents. Therefore, it made sense that old crust might be pushed far toward these trenches, where it would eventually descend back into the mantle. It turned out that the Seafloor Spreading hypothesis was the missing puzzle piece that had eluded Alfred Wegener a generation earlier. Wegener's Continental Drift hypothesis did not have a realistic mechanism in which the continents might move, but Wegener was looking at the wrong thing!

Active Planet

Shortly after convincing evidence for seafloor spreading was brought to light, the scientific community realized that it had made some serious misassumptions about the planet. Wegener's Continental Drift hypothesis saw a revival, this time with seafloor spreading as the primary mechanism to explain the movement of our continents over millions upon hundreds of millions of years.

Image of J. Tuzo Wilson
Figure 2.3.6. J. Tuzo Wilson.
The synthesis of these two ideas together transformed into the theory of plate tectonics, which was put forward by the Canadian Geophysicist John Tuzo Wilson in 1966. This theory states that the Earth's solid crust is divided into multiple parts, some large and some small. These parts slowly ride over the more pliable mantle, and geological features and hazards result when they interact with one another.

Plate tectonics was a unifying theory in that it not only explained the movement of continents, the formation of deep ocean trenches and long ocean ridges, but it also could tell us why we observe volcanoes and mountains and feel earthquakes. It was a fundamental paradigm shift in how large-scale processes on the planet can cause very small-scale effects!

Wegener did not get all of plate tectonics correct. Besides proposing the wrong mechanism for this process, he believed that only the continents moved on the planet while the oceans remained in place. But both oceans and continents move, transported by plates. A plate can include both oceanic and continental crust or either. The rigid material makes up what we call the lithosphere. As shown below, we divide the lithosphere into a dozen major and several minor tectonic plates across the world.

World map divided into lithospheric plates.
Figure 2.3.7. Our modern world map divided into the major lithospheric plates.
Not to be confused with the Earth's crust layer, the lithosphere is composed of the crust AND a small amount of rigid upper mantle. On average, the lithosphere is 100 km thick.

Video 2.3.2. reviews plate tectonics and the layers of the Earth. How does everything connect? (8:00).

The tectonic plates on Earth move over the something called the asthenosphere. The asthenosphere roughly makes up the remaining portion of the upper mantle down to the transition zone. The temperatures within the asthenosphere are very hot and can exceed 1000-1300 ºC! Such high temperatures cause the rock of the asthenosphere to be nearly molten, and the solid rock will flow like silly putty. This movement of the asthenosphere alone, however, is not why the lithospheric plates on our surface move according to plate tectonics!

The beauty of plate tectonics is that it is a whole Earth theory. That means it considers the processes that occur within the Earth besides those on the Earth's surface, to explain our observations. One of these processes is something called convection. Convection occurs within the mantle when it is supplied with fresh heat from the core. The heat in the mantle rises toward the Earth's surface, while the colder materials sink toward the bottom. This process creates convection cells, which when illustrated, appear as circular patterns of heat movement (see below image).

Mantle Convection cells driving movement of tectonic plates
Figure 2.3.8. Convection cells drive the movement of mantle material, which forces the overlying lithosphere plates to push apart at spreading ridges and pull downward at trenches.
Video 2.3.3. Using home supplies, you can observe how convection cells move material floating on a hot liquid. The second experiment would be better performed at a lab but you can also see how temperature drives the flow of fluids.

It is the movement of solid, hot material within the mantle that causes the rigid plates above it to move. Plates move at a rate of a few centimeters a year, about the same rate fingernails grow [13]. These movements come as rifting, colliding, and shearing, which we will learn about in the next chapter.

2.4 Convergent Boundaries

CHARLENE ESTRADA

Across our Earth, different plates collide with one another, move past one another, and pull away from one another. These movements between plates result in a wide variety of different plate boundaries, amazing landscapes, and dangerous hazards. Very broadly, plate interaction can be placed in one of three categories. Below, we will explore the first of these: convergent boundaries.

Schematic showing transform, divergent, and convergent plate boundaries above asthenosphere.
Figure 2.4.1. Cross-section of the lithosphere and asthenosphere showing Transform, divergent, and convergent plate boundaries on Earth.
Convergent boundaries are places where two or more tectonic plates move toward each other. The process of convergence relies on compressional stress, which squeezes or pushes the two tectonic plates together. Convergent boundaries, more than any other, are known for building mountain chains. It is because tectonic plates collide with one another that Earth has seen periods of supercontinent formation, in which the continents as we know them today were once merged together into one landmass. The ancient continent of Pangaea is a well-known example of a supercontinent that once existed over 250 million years ago!

The key to predicting what will happen at a convergent boundary is understanding the density of each plate involved in the movement. You may tend to think of density, mass, and weight as all being similar. Whereas weight is the heaviness of an object relative to the planet's gravitational field, mass is the amount of matter that object contains. Density is different; it is a measure of how tightly packed matter is within a given volume of a material, and it is usually measured in units of "mass per volume".

Digging Deeper: Weight, Mass, and Density

We just read through a verbal description of weight, mass, and density, but what do they really mean? Notice that the description of weight is "relative to a planet's gravitational field". Earth is the only home we know, so we are a bit biased in assuming weight and mass tend to be the same thing in our daily lives, but that wouldn't be helpful for an astronaut walking on the Moon!

Buzz Aldrin on the Moon
Figure 2.4.2 Buzz Aldrin working on the Moon.
Example: Astronaut Buzz Aldrin takes his first step on the Moon! A spacesuit tends to weigh a whopping 280 lbs, plus let's assume Buzz was about 150 lbs at the time for a total weight of 430 lbs on Earth. The Moon's gravity is only one-sixth of the Earth's! So how much does Buzz weigh on the Moon?

430 lbs / 6 = 71.7 lbs   No wonder Buzz is feeling light!

However, Buzz's mass on Earth with the spacesuit is about 195 kg. This remains the same on the Moon, in space, and wherever he may go – he just may experience "heaviness" differently in those places!

Let's assume the volume of Buzz with the spacesuit on is roughly 90 L, or 90,000 cm3. The density of our astronaut (in grams/cm3) is:

Density = 195,000 g / 90,000 cm3 = 2.2 g/cm3

That is pretty dense. Humans without spacesuits are mostly water, and that's a density of around 1 g/cm3 for comparison.

How does density affect plate motions at convergent boundaries? View the different types of plate collisions below to find out!

Oceanic-Continental Convergent Boundary
Block diagram of oceanic lithosphere colliding and subducting beneath continental lithosphere.
Figure 2.4.3. At a convergent boundary between oceanic and continental lithosphere, the oceanic plate will always subduct, which will cause earthquakes and form volcanic arcs.
Oceanic-continental convergent boundaries occur when a tectonic plate primarily composed of oceanic lithosphere collides with a plate with continental lithosphere. As mentioned in a previous chapter, oceanic lithosphere, or crust, contains more iron- and magnesium-rich minerals, and it is therefore denser than continental lithosphere. When these very different plates converge, the plate with oceanic lithosphere will buckle beneath the continental plate, and sink into the hot asthenosphere. This process is called subduction [14].

When the subducting plate, which is also known as a slab, is subjected to the high temperatures of the asthenosphere, surface materials that were trapped in its rocks, such as hydrated minerals, undergo alteration and water vapor escapes. That water vapor lowers the melting temperature of the surrounding rock, and it produces magma. The magma rises and forms volcanic arcs in the mountains along the overlying continental crust.

Video 2.4.1. The convergence between oceanic and continental crust in a subduction zone produces a volcanic arc on the continental plate. Identify the processes occurring in this short animation (0:11).

What Happens to the Subducting Slab?
As the dense oceanic lithosphere begins to subduct down into the mantle, it continues this journey at an average rate of 25 miles per million years, or a half inch per year. This slab also pulls the neighboring ocean floor down into a trench. On average, the ocean floor is around 3-4 km deep. In trenches, the ocean can be more than twice as deep, with the Mariana Trench approaching a staggering 11 km!

Over tens of millions of years, the descending slab will eventually be destroyed in the Earth's internal heat, although in some cases it will journey far into the mesophere in the lower mantle before this occurs. Today geophysicists image our mantle to find the remains of ancient slabs that were once part of Earth's surface. All of this is proof that plate tectonics has been operating for billions of years, and it has enabled the Earth to become an efficient recycler!

PLATE TECTONICS IN ACTION: Oceanic-Continental Convergent Boundaries
The landscapes resulting from oceanic-continental convergent boundaries are all around us! Some well-known examples of this type of convergent plate boundary on our planet include:

The Cascades (Western North America)
The Andes: (Western South America)
Oceanic-Oceanic Convergent Boundary
Block diagram of oceanic lithosphere colliding and subducting beneath another plate of oceanic lithosphere.
Figure 2.4.4. At a convergent boundary between two plates of oceanic lithosphere, the older, denser oceanic plate will always subduct, which will cause earthquakes and form volcanic isles.
An oceanic-oceanic convergent boundary describes a collision between two plates composed of oceanic lithosphere. Even though this boundary involves the same type of lithosphere, one of the plates will still subduct beneath the other. Oceanic lithosphere is notoriously dense; in some cases it is even denser than the asthenosphere, which means it never has trouble sinking into the mantle once the subduction process begins!

When two plates made of oceanic lithosphere meet, how can we predict which of the two will subduct? It almost always depends on age. With increasing age, the oceanic lithosphere becomes colder and denser. The oceanic lithosphere becomes systematically older as it moves away from the spreading centers at mid-ocean ridges, as you can see in the heat map below:

heat map of the oceanic crust, where the youngest crust is at the mid-ocean ridges and the oldest crust is near the trenches
Figure 2.4.5. Age distribution of the oceanic lithosphere.
All of this means that the older, denser, and colder plate at an oceanic-oceanic convergent boundary will always subduct into the mantle!

Video 2.4.2. Short animation of a convergent boundary between two oceanic crusts. Observe the volcanic island arc. What is different and similar between this video and the previous one? (0:15)

PLATE TECTONICS IN ACTION: Oceanic-Oceanic Convergent Boundaries
The features at or resulting from oceanic-oceanic convergent boundaries are pretty well known! Some notable examples of this type of convergent plate boundary on our planet include:

The Marianas trench
The Japanese island arc
Continental-Continental Convergent Boundary
Two plates of continental lithosphere collide to build a mountain range
Figure 2.4.6. At a convergent boundary with two plates of continental lithosphere, no subduction occurs, and a large mountain range forms with associated earthquakes.
A continental-continental convergent boundary describes the collision of two tectonic plates composed of continental lithosphere. Just like an oceanic-oceanic convergent boundary, this type of boundary involves the compression of the same type of lithosphere. However, there is one key difference; subduction never takes place at these boundaries.

The continental lithosphere is not very dense. In fact, compared to the underlying asthenosphere it is buoyant! This means that if a force were to push continental lithosphere down into the mantle, the low-density lithosphere would push itself back up like a cork in a glass of water.

What happens at these convergent boundaries? Any underlying, dense oceanic lithosphere attached to the plate might sink, but the two plates of continental lithosphere will collide with one another. Within these collision zones, the lithosphere will deform, thicken, and events of extreme mountain-building will occur. Some of our most famous mountain ranges have been formed as a result of continental-continental convergence! For example, watch the Himalayan mountain range (which contains Mt. Everest) form in the video below (0:39 to end).

Video 2.4.3. Animation of paleogeography showing the evolution of the continents over time (0:56).

Because the continental lithosphere never subducts, very little of it is destroyed in the mantle. Although continental crust can slowly become weathered down and eroded away by Earth's atmosphere and hydrosphere, some of it has persisted for billions of years! As a result, geoscientists can piece together the early history of our planet using clues from rocks on our continents.

PLATE TECTONICS IN ACTION: Continental-Continental Convergent Boundaries
There are some famous mountain ranges that have formed as a result of Continental-Continental convergent boundaries! These include:

The Himalayas (India, China, Tibet)
The Alps (France, Switzerland, Italy, Austria, Slovenia)
Zagros (Iran, Iraq, Syria, Turkey)
The Appalachians (The United States)
Something important to keep in mind is that Continental-Continental convergent boundaries do not "just" form! When the plates first collide, at least one of them typically contains oceanic crust. This is because over 70% of our planet's surface is covered by oceanic lithosphere. As a result, the convergent boundary will first form a subduction zone, but after all the oceanic lithosphere has finished subducting, the boundary becomes Continental-Continental. This is how supercontinents form!

Video 2.4.4. This short animation shows what happens when two continental crust collide. Compare and contrast this video with the two before (0:22).

2.5 Divergent Boundaries
CHARLENE ESTRADA

Divergent boundaries are places where two or more plates move away from each other. These boundaries can be found on continental or oceanic lithosphere. Tensional stress operates between the tectonic plates at a divergent boundary, which causes the lithosphere at these locations to stretch and pull apart. Divergent boundaries slowly grow ocean basins within continental lithosphere.

The process of divergence breaks up continental landmasses and supercontinents. This boundary type is the reason why early generations of scientists noticed the apparent fit between the coastlines of South America and Africa. Indeed, it is the reason that the world map appears the way it does today!

Block diagram of divergent boundary forming continental rift
Figure 2.5.1. A divergent boundary may form beneath the continental lithosphere, where mantle convection cells cause the plates to push apart and form a Rift Valley.
Continental Rift Valleys
How does a continent, or even a supercontinent, break apart? At first glance, such a task seems difficult considering continental lithosphere can be up to 20 times thicker than oceanic

lithosphere due to billions of years of mountain-building. However, the insulation from that thick lithosphere will eventually allow a hot plume of magma from the mantle to rise toward the Earth's surface. That mantle plume will weaken the continental lithosphere, and eventually the convection cells within the mantle will be able to push the continent apart.

The an artificial rendering of the East African rift valley, seen from space.
Figure 2.5.2. The East African rift valley is an example of an active continental rift valley.

A continental rift valley is a region where the continental lithosphere is weakening and stretching apart. It is an observable divergent boundary and a sign that a continent is breaking apart. Given enough time, the rifting will continue to a point in which the continental lithosphere will become so thin, it will become predominantly enriched in the mantle plume materials. At that point, the rift will have created brand new oceanic crust, and a newborn ocean basin will open between the continental fragments.

This process of continental rifting has taken place about 250 million years ago between South America and Africa, as well as North America and Eurasia during the breakup of the supercontinent Pangaea. From a single landmass, the Earth saw many new continents form and a narrow sea that would one day widen to become our Atlantic Ocean.

Video 2.5.1. Tension precedes the opening of the crust in divergent boundaries. Observe what else happens (0:20)

PLATE TECTONICS IN ACTION: Continental Rift Valleys
Some of the world's continents are breaking apart as we speak! Here are some examples of regions undergoing continental rifting:

The East African Rift Valley (Djibouti, Ethiopia, Uganda, Kenya, Tanzania)
The Red Sea (Egypt, Sudan, Eritrea, Djibouti, Saudi Arabia, Yemen)
Lake Baikal (Russia)
Mid-Oceanic Ridges
Block diagram of divergent boundary forming mid-ocean ridge
Figure 2.5.3. A divergent boundary may also form beneath the oceanic lithosphere, where mantle convection cells cause the plates to push apart and form a mid-ocean ridge.
We have previously discussed the discovery of mid-ocean ridges as a key piece of evidence for the theory of plate tectonics. The reason these spreading centers along the ocean floor are essential for plate tectonics is that they represent a simple example of a divergent boundary.

Mid-ocean ridges typically follow the long process of continental rifting. Once continental lithosphere has thinned and become mafic, upwelling magma produces new oceanic lithosphere and a narrow ocean basin forms between the rifted continents (review video in previous sections). As this process evolves, a mid-ocean ridge forms above the rift on the floor of the new ocean because the cooling lava is hot and less dense (i.e., it takes up more space than cold material).

The places where we find mid-ocean ridges are called spreading centers. These are sometimes characterized as “conveyor-belts” because they are the one site on the planet where new oceanic lithosphere is constantly created. These spreading centers are volcanoes; molten magma from the asthenosphere erupts underwater as lava and rapidly cools as new oceanic lithosphere. The material near the spreading centers is relatively hot and less dense, and therefore it has a higher elevation. Mid-ocean ridges often form long, high-elevation mountain chains because of their underwater volcanism.

Some Like It Boiling: Life at Hydrothermal Vents
Mid-ocean ridges also are home to some of the unique ecosystems discovered, found around hydrothermal vents that circulate ocean water through the shallow oceanic crust, and send it back out as rich chemical compounds and heat. While it was known for some time that hot fluids could be found on the ocean floor, it was only in 1977 when a team of scientists using the Diving Support Vehicle Alvin discovered a thriving community of organisms, including tubeworms bigger than people!

Video 2.5.2. Footage of the mid-oceanic ridge from the DSV Alvin (2:37).

This group of organisms is not dependent on the sun and photosynthesis but instead relies on chemical reactions with sulfur compounds and heat from within the Earth, a process known as chemosynthesis. Before this discovery, the thought in biology was that the Sun was the ultimate source of energy in all ecosystems; now, we know this to be false. Not only that, but some have also suggested that life could have started around hydrothermal vents on Earth, and these type of chemosynthesis have become a target for extraterrestrial life (e.g., Jupiter’s moon, Europa).

Continued volcanism will cause the new oceanic lithosphere to move away from the mid-ocean ridges, and that lithosphere will cool and sink deeper along the ocean floor. Because new oceanic lithosphere is always produced at a spreading center, the age of the seafloor is predictably younger near a mid-ocean ridge and older as it moves farther away.

Divergent plate motion at a Mid-Ocean Ridge occurs at different rates, depending on the location. Spreading can be as fast as 20 cm/year or as slow as 1 cm/year. At these rates over hundreds of millions of years, it is not a surprise that the continents have moved so far apart.

Figure 2.5.4. The age of the oceanic lithosphere.
PLATE TECTONICS IN ACTION: Mid-Oceanic Ridges

Although they are sometimes deep underwater, we have known about mid-ocean ridges for decades! Here are some good examples of this type of divergent boundary:

The Mid-Atlantic Ridge
The East Pacific Rise
The Gakkel Ridge/ Mid-Arctic Ridge
2.6 Transform Boundaries
CHARLENE ESTRADA

Block diagram of transform boundary sliding two plates of continental lithosphere past one another
Figure 2.6.1. A transform boundary causes a fault between two plates of the lithosphere, which will slide past one another. This motion does not create or destroy crust and will cause earthquakes, but no volcanoes.
A transform boundary occurs when two tectonic plates move past one another. Shear stress operates at transform boundaries, which involves sliding motion. No lithosphere is destroyed or created, and mountain chains are not built at transform boundaries. Although none of these events occur at transform boundaries, they are far from boring; the continuous stress that builds within the lithosphere from the sliding motion causes faulting and earthquakes.

Most transform boundaries are associated with the spreading spreading centers at mid-ocean ridges. They occur near these divergent boundaries because the spreading rate changes along a ridge. Because the surrounding rock along the ridge is hard and brittle, it accommodates these shifts in spreading rates with sliding motions. Perhaps the most famous transform boundaries, however, are those on the continental lithosphere with effects that are directly felt by nearby cities and towns.

Transform boundaries can cause both large faults and a series of smaller associated faults. Transform faults refer to the lateral displacement of large rock units due to the shearing motion caused by a transform boundary. The motion at a transform fault is classified into two categories: right-lateral and left-lateral. However, these categories are not determined by the composition of the lithosphere. An examination of the two transform faults below demonstrates that they are very similar. Can you notice the difference?

Right lateral fault, where the block on the right appears to be moving toward you if you were looking down the fault line.
Figure 2.6.2. Block diagram and horizontal view of a transform fault. The different colors represent rock layers. The scale is at the bottom.
Left lateral fault, where the block on the left appears to be moving toward you if you are looking down the fault line.
Figure 2.6.3 Block diagram and horizontal view of a transform fault. The different colors represent rock layers. The scale is at the bottom. How are these diagram different from the ones on Figure 2.6.2?

A type of transform plate motion can be identified by examining the two tectonic plates from a bird's-eye view. For example, below is the Piqiang fault from China:

Piqiang fault in China where one set of layers on the left appear to be displaced at least 2km above the others along the fault line.
Figure 2.6.4. Google Earth imagery showing the transform Piqiang fault in China.
To determine what type of transform fault it is, follow these steps:

Identify the boundary between the two rock units.
Same image of the Piqiang fault as above, but with a red line superimposed over the fault line.
Figure 2.6.5. The red color traces the fault line between rock units.
Find features that have been displaced apart from one another due to the sliding motion of the plates or rock units.
Piqiang fault image with red fault line drawn and blue circles indicating layers of rocks that appear to be displaced from one another.
Figure 2.6.6. Blue circles indicate distinctive rock units that have been displaced from one another by the fault.
Based upon those displaced features, decide which rock unit appears to be moving toward you. Which side is it on?
Piqiang fault with purple arrows indicating the direction of displacement for each rock unit along the fault.
Figure 2.6.7. Purple arrows show the direction the rock units (blue circles) are moving relative to a person looking down the red fault line.
If the plate moving toward you is on the right side, the motion is right-lateral. If it is on the left side, it is left-lateral. This method always works, no matter from which direction you are looking at the boundary!
Piqiang fault with purple arrows indicating direction of rock displacement on each side of the fault line. On the left side, the rocks are moving toward the viewer. On the right side, the rocks are moving away from the viewer.
Figure 2.6.8. The unit of rock layers that moves toward the viewer relative to the red fault line is on the left. The Piqiang Fault is a left-lateral fault.

2.7 Hot Spots
CHARLENE ESTRADA

One key to unravelling the Theory of Plate Tectonics was J. Tuzo Wilson's investigation of the Hawaiian islands. Volcanic activity has formed these islands in the middle of the Pacific Plate with no apparent plate boundaries for hundreds of miles. However, a close examination of each of the islands reveals something interesting: the big island of Hawaii is the youngest of the chain and the age of the islands steadily increases to the northwest.

A map of the Hawaiian-Emperor Seamount Chain
Figure 2.7.1. Map of the Hawaiian Emperor Seamount Chain, in which the colors demonstrate differences in land elevation.

What does this progression in age tell us? Unlike most volcanism on our planet, the volcanic activity at Hawaii occurs from a hot spot. A hot spot begins deep in the lower mantle when hot molten material melts and begins to move upward through the lower and upper mantle toward the crust. Eventually, this material may erupt at the surface as a volcano without the need of any plate boundaries; it is an isolated spot of volcanic activity.

Video 2.7.1. The hotspot under Hawaii has been creating islands in linear fashion as the Pacific plate moves. But this process is not a calm one! Watch this clip that unravels a violent explosion 2 million years ago (3:05).

Hot spots that erupt in the middle of oceanic lithosphere do create brand new crust. In the case of the hot spot in the middle of the Pacific Ocean, it creates a volcanic mountain that rises enough in elevation to potentially become a brand new island. This first happened about 81-85 million years ago to form the first guyot in what is now known within the Emperor Seamount Chain.

Today, we can see hundreds of islands, seamounts, and guyots making up a V-shaped chain in the Pacific ocean in what we call the Hawaiian-Emperor Seamount Chain. How did so many islands form from a single source of magma? Did the hot spot move over time? J. Tuzo Wilson thought about plate motion and reasoned that the Pacific Plate must be drifting slowly over tens of millions of years, while the hot spot remained relatively stationary. Thus, as the Pacific Plate moved, and even changed directions (causing the bend in the V), multiple new islands were created to form the Emperor Seamounts and the Hawaiian Islands.

We can find the proof of this systematic process in the ages determined in each of the islands themselves. The Big Island of Hawaii, where the hot spot is currently located, is approximately 400,000 years old [15]. Below is a table that shows the increase of age for some of the major landforms in the island and seamount chains.

Table 2.7.1 Distance from hotspot and age of formation of the Hawaiian islands

Landform Name	Approximate Age [15] (My)	Distance from Hotspot (km)
Hawai'i	0-0.4	0-54
Maui	0.8 – 1.3	182-221
O'ahu	2.6 – 3.7	339 – 374
Kaua'i	5.1	519
Nihoa	7.2	780
Necker	10.3	1058
Gardner	12.3	1435
Laysan	19.9	1818
Midway	27.7	2432
Abbott Seamount	38.7	3280
Koko Seamount	48.1	3758

Jingu Seamount	55.4	4175
Suiko Seamount	59.6 – 64.7	4794 – 4860

Calculating Relative Plate Motion from Hotspots

The approximate age of the island of Hawaii is 0.4 million years, and it is at maximum 54 kilometers from the active hotspot. To determine the average motion of the Pacific Plate over this time, let us consider the following equation:

Movement Rate = Distance / Time

54,000 m / 400,000 years = 0.135 m / year

On average, the Pacific Plate moved about 0.135 meters (or 13.5 centimeters) each year over the past 54 million years. That means that it moved an average of half a foot each year!

Go to Google Earth

Backyard Geology: The San Francisco Volcanic Field

Hot spots are not restricted to island chains in the middle of the ocean. They are also very close to home, in what is called the San Francisco Volcanic Field. This region covers about 5000 square kilometers of Northern Arizona, and in this relatively small portion of the state there are approximately 600 volcanoes. The majority of these are mafic cinder cone volcanoes that have deposited basaltic lavas over the past 6 million years. However, scientists have noticed that the ages of these volcanoes decrease moving to the east. Because the North American Plate steadily moves to the west, it is likely that the volcanoes in this region have formed from a hot spot. Among the youngest of these can be found at Sunset Crater National Monument, where the namesake volcano last erupted just 900 years ago [16].

Map of San Francisco volcanic field in Northern Arizona, where the hotspot has migrated causing volcanoes first in the west and moved toward the East.

Figure 2.7.2. The San Francisco Volcanic Field of Northern Arizona is a local example of a continental hot spot.

2.8 Predicting Geologic Hazards at Tectonic Boundaries

CHARLENE ESTRADA

Plate tectonics explains why our oceans open and continents move throughout Earth’s history. This theory also explains why we have tall mountain ranges, valleys, and deep ocean trenches. However, what does all of this have to do with the geologic hazards and disasters that impact our society daily? In this section, we will explore how we can predict, and even come to expect, certain types of disasters near plate boundaries.

The Ring of Fire

The Pacific Ring of Fire can be found from S. New Zealand, North of Australia, Japan, Java, the coast of Eurasia, across the Aleutian trench to Alaska, along the Western U.S. down to the southern tip of Southern America.
Figure 2.8.1. Map displaying the Pacific Ring of Fire (shaded red regions).
If you have ever had a unit on earthquakes and volcanoes in school or watched a documentary on the subject, chances are good that you may have heard of a region called the "Ring of Fire." Not to be confused with the Johnny Cash song, the Ring of Fire is enormous! It extends for around 40,000 km around the coasts that border the Pacific Ocean – from New Zealand to the Philippines, Japan, Alaska, the western coast of the United States, Mexico, and all the Western Coast of South America. The Ring of Fire is infamous for having heightened volcanic and earthquake activity, and that is a direct consequence of tectonic activity.

Convergent plate boundaries involving subduction primarily occur throughout the Ring of Fire. The release of volatiles, such as water, from the subducting slab enables the overriding lithosphere to melt easier, and volcanic arcs form.

Diagram of a subduction zone at convergent plate boundary. These cause volcanoes, earthquakes, and associated tsunamis.
Figure 2.8.2. At a subduction zone associated with a convergent boundary, melting of the lithosphere by released water will cause volcanism, and the movement of the slab will cause earthquakes and possibly tsunamis.
Volcanoes are not the only consequence of subduction zones. When cold, the rigid lithosphere sinks into the asthenosphere, stress from that movement will build up in the rocks over long periods of time. There is a limit to the amount of stress a rigid object, such as a rock, can tolerate before it breaks. Once the rock does rupture under the stress, it releases the energy it built up over those many years in the form of a seismic wave – an earthquake occurs.

Because this energy is released from a plate that underwent tremendous stress deep beneath the Earth's surface, the earthquakes at subduction zones can be as devastating as 9.0 in magnitude. Some of these earthquakes originate under seawater, which can result in giant tsunamis, such as the 2004 Indian Ocean Earthquake and the 2011 Tōhoku Earthquake in Japan.

KEY TAKEAWAY: SUBDUCTION ZONES
The process of subduction at convergent boundaries will produce volcanoes and moderate to severe earthquakes!

Gigantic Mountain Ranges
Aerial view of snow-covered Mt. Everest among the Himalayan mountain range.
Figure 2.8.3. Mount Everest and the Himalayas have formed by mountain-building at a convergent boundary between the Indian and the Eurasian Plates.
Subduction is not the only tectonic process responsible for the world's geologic hazards! When two continental plates collide at a convergent boundary, the lithosphere is too buoyant to subduct, and large mountain chains build upward toward the sky. We know that Mount Everest

is the Earth's tallest mountain (above water, that is), and as part of the Himalayas, a convergent plate boundary between the Indian and Eurasian Plates has built it.

Because there is no subduction at this type of boundary, however, the continental lithosphere does not melt easily. There is almost no volcanic activity around continental-continental convergent boundaries. Nevertheless, there are still the same compressional stresses acting between the plates, and those stresses will slowly build upon rigid rocks in the lithosphere until they break and release seismic waves. That means that like the other convergent boundaries, regions such as the Himalayas experience earthquakes. The lack of subduction may not allow these earthquakes to originate as deeply, but these earthquakes are often moderate, and sometimes severe, in magnitude.

KEY TAKEAWAY: CONTINENTAL-CONTINENTAL CONVERGENT PLATE BOUNDARIES
The process of mountain-building at continental-continental convergent plate boundaries will produce little to no volcanism, but moderate to severe earthquakes!

Map highlighting the Mid-Atlantic Ridge, which is in the middle of North America, South American AND Europe, Africa.
Figure 2.8.4. The Mid-Atlantic Ridge highlighted in light-blue on the bathymetric map of the Atlantic.
A far greater mountain range than the Himalayas can be found underwater, and it is produced by a different tectonic process. The Mid-Atlantic Ridge was the first example of a Mid-Ocean Ridge discovered by scientists, and is 16,000 km (10,000 miles) long. Divergent boundaries are sites of magma upwelling from the mantle because the tensional stress has thinned the lithosphere enough to allow the molten plume to penetrate the surface.

New oceanic crust forms at Mid-Ocean ridges from rising magma at a seafloor spreading center, then spreads away from the magma to allow more new crust to form like a continuous conveyer belt.
Figure 2.8.5. The spreading center "conveyer belt" at mid-ocean ridges.
A divergent boundary, such as a rift or a spreading center at the Mid-Atlantic Ridge, hosts active volcanism on the axis of the ridge. Furthermore, new lithosphere is always being formed at a divergent boundary and pushing the old crust aside. This motion causes the older crust to fracture and rupture, which will produce earthquakes. The lithosphere at divergent boundaries is not very thick, and the earthquakes at these locations are shallow (< 30 km), but the magnitude can vary from low to moderate.

KEY TAKEAWAY: DIVERGENT PLATE BOUNDARIES

The process of continental rifting and mountain-building at mid-ocean ridges will produce volcanism and mild to moderate earthquakes!

Shifting Ground

Transform boundaries will slide one segment of the lithosphere relative to another, with results that are observable in our lifetime. However, most of that sliding motion is not something that happens on a day-to-day basis! As stress builds up at the plate boundary, these large units of rock will resist moving. Therefore, that stress will build over many years. Once the plates cannot tolerate any more stress, their rocks fracture, and the plate releases the energy by snapping past one another. Two things happen:

The two tectonic plates move past one another in large amounts

The energy previously stored within two plates is released as a shallow, but moderately powerful earthquake.

Video 2.8.1. How does shear break the ground? (0:10).

Video Player

00:00

00:10

Keep in mind that there is no subduction at transform boundaries, and there are also no lithosphere creation/destruction processes. Because there is no opportunity for the lithosphere to melt from transform plate motion, there are few, if any, active volcanoes along a transform plate boundary.

KEY TAKEAWAY: TRANSFORM BOUNDARIES

The slipping motion at transform plate boundaries and their related faults will produce mild to moderate earthquakes but no volcanism.

2.9 The Great Cycle

CHARLENE ESTRADA

The supercontinent of Pangaea, shown with today's continental borders, assembled 300 - 180 million years ago.

Figure 2.9.1. The supercontinent of Pangaea, shown with today's continental borders, assembled 300 – 180 million years ago.

Our world map has inspired human imagination for centuries. Alfred Wegener was not the first to notice that the South American and African coastlines could align together like puzzle pieces or conclude that they might have once been connected as one mass. However, in his book over a century ago, Wegener was the first to publish the words “Ur-Kontinent” and “Pangäa”, which we now popularly refer to as a supercontinent or Pangaea.

When the ideas of seafloor spreading and continental drift were unified into the theory of plate tectonics by J. Tuzo Wilson in the late 1960s, questions remained over how Earth's appearance evolved over its 4.54 billion-year history. If the oceans and continents shifted and change configuration as a result of tectonic forces, then what might our world map looked like millions or billions of years ago and what will it look like in the future?

In the decades following the acceptance of plate tectonics until present, geologists have examined the rock and fossil record for clues to describe the appearance of Earth throughout the eons. Many of these techniques were similar to those used by Alfred Wegener, Marie Tharp, and Harry Hess. Today, there are still many questions about the processes behind plate tectonics and Earth's history, but we have pieced together paleomaps that illustrate Earth's past appearance.

Video 2.9.1. Paleogeography and ice ages. Christopher Scotese has worked for decades reconstructing paleomaps and the evolution of the continents (1:39).

Throughout Earth's history, there have been several episodes of supercontinent assembly and breakup. The last supercontinent on Earth was called Pangaea, and it existed around 300 million to 180 million years ago. The formation of a supercontinent is driven by convergent boundaries. However, the breakup of these landmasses requires a more complicated mechanism. The extremely thick crust from the convergence of land will insulate the lithosphere and eventually allow magma to rise from the mantle; thus, divergent boundaries will form throughout the supercontinent. It took approximately 250 million years for our world map to arrive at its current, broken-up, configuration from Pangaea.

The pattern of tectonic forces causing supercontinents to form, breakup, then form once more is called the Wilson Cycle (named for J. Tuzo Wilson). This cycle has been operating for at least a billion years; before Pangaea, a supercontinent called Rodinia had assembled around 1 billion years ago. Current modeling suggests that the Wilson Cycle will continue well into the future. Hundreds of millions of years in the future – about 250 million to be precise – a new supercontinent will form on Earth. We are currently referring to it as "Pangaea Proxima" or "Pangaea Ultima".

Pangaea Proxima, a supercontinent that will assemble on Earth in about 250 million years.
Figure 2.9.2. A rough approximation of what the world map will look like in 250 million years.
All of this shows that our planet has been undergoing a tremendous cycle that continuously reshapes its surface over billions of years, and we are just beginning to understand this process!

2.10 Attributions and References

Creative Commons Resources for Chapter Text

The following resources have been used for research, starting points, and inspiration for this chapter. Unless otherwise noted in Attributed References or Media Assets, materials have been significantly reworked by this text's authors.

Dastrup, R. Adam. (2020, Jun 1). “3.6 Theory of Plate Tectonics.” Physical Geography and Natural Disasters. https://slcc.pressbooks.pub/physicalgeography/chapter/3-6/ CC BY-NC-SA.

An Introduction to Geology by Chris Johnson, Matthew D. Affolter, Paul Inkenbrandt, Cam Mosher is licensed under CC BY-NC-SA 4.0

Geology by Lumen Learning is licensed under CC BY-NC-SA 4.0

Earth Science by Lumen Learning is licensed under CC BY-NC-SA 4.0

(Natural Disasters and Human Impacts by R. Adam Dastrup, MA, GISP is licensed under CC BY-NC-SA 4.0

(Physical Geology – 2nd Edition by Steven Earle is licensed under CC BY 4.0.

Introduction to Oceanography by Paul Webb is licensed under CC BY 4.0.

United States Geological Survey (USGS) is licensed under Public Domain.

Google Earth is available as Fair Use under Section 107 of the United States Copyright Act.

Chapter Text Attributions

[1] Richardson, Eliza. (2020). Contracting Earth v. Continental Drift v. Plate Tectonics. Earth 250: Plate Tectonics and People. https://www.e-education.psu.edu/earth520/content/l2_p2.html CC BY NC SA.

[2] Dastrup, R. Adam. (2020, Jun 1). “3.Planet Earth” Physical Geography and Natural Disasters. https://slcc.pressbooks.pub/physicalgeography/chapter/3-6/ CC BY-NC-SA.

[3] Earle, Steven. (2019, Sep 23). 10.1 Alfred Wegener: The Father of Plate Tectonics. Physical Geology – 2nd Edition. https://opentextbc.ca/physicalgeology2ed/chapter/10-1-alfred-wegener-the-father-of-plate-tectonics/ CC BY

[4] Wegener, Alfred. The Origin of Continents and Oceans (Fourth and Revised German Ed.). Trans. by John Biram. (1966). Dover Publishers, Inc.: New York, New York.

[5] Conniff, R. (2012, Jun). When Continental Drift Was Considered Pseudoscience. Smithsonian Magazine. https://www.smithsonianmag.com/science-nature/when-continental-drift-was-considered-pseudoscience-90353214/

[6] Bressan, David. (2017, Jan 6). Alfred Wegener's Lost Cause For His Continental Drift Theory." Forbes. https://www.forbes.com/sites/davidbressan/2017/01/06/alfred-wegeners-lost-cause-for-his-continental-drift-theory/?sh=18acad721149

[7] Crust. (2015, May 29). National Geographic. https://www.nationalgeographic.org/encyclopedia/crust/

[8] Mantle. (2015, Aug 11). National Geographic. https://www.nationalgeographic.org/encyclopedia/mantle/?utm_source=BibblioRCM_Row

[9] Grant, Ray. (n.d.). Arizona Rocks 8 Ultramafic rocks, peridotite. Pinal Geology Museum. https://www.pinalgeologymuseum.org/index.php/learn-play/arizona-rocks/232-arizona-rocks-8-ultramafic-rocks-peridotite

[10] Core. (2015, Aug 17). National Geographic. https://www.nationalgeographic.org/encyclopedia/core/

[11] Fecht, S. (2020, Jul 29). 8 Surprising Facts About Marie Tharp, Mapmaker Extraordinaire. New from the Columbia Climate School. https://news.climate.columbia.edu/2020/07/29/surprising-facts-marie-tharp/

[12] Tharp, Marie. (1999, Apr 1). Connect the Dots: Mapping the Seafloor and Discovering the Mid-ocean Ridge. Chapter 2 in Lamont-Doherty Earth Observatory of ColumbiaTwelve Perspectives on the First Fifty Years 1949-1999 , Laurence Lippsett (Ed.). https://www.whoi.edu/news-insights/content/marie-tharp/

[13] Earth Science by Lumen Learning is licensed under CC BY-NC-SA 4.0

[14] An Introduction to Geology by Chris Johnson, Matthew D. Affolter, Paul Inkenbrandt, Cam Mosher is licensed under CC BY-NC-SA 4.0

[15] Blay, Chuck, and Siemers. (2004, Feb 4). Robert. Kauai''s Geologic History: A Simplified Guide, Updated Edition. Self-published updated Edition after TEOK Investigations original edition.

[16] San Francisco volcanic field, Arizona. (2010). Arizona Geological Survey. https://azgs.arizona.edu/photo/san-francisco-volcanic-field-arizona

Media Assets
Fig 2.1 World map illustration from 250 million years ago to present.

USGS. “Fig2-5globes.” [Online Image]. This Dynamic Earth. https://pubs.usgs.gov/gip/dynamic/historical.html (Public Domain)
2.1
Dutton Institute. (Sep 6, 2016) EARTH250 Contracting Earth Hypothesis. [Online Video]. YouTube. https://www.youtube.com/watch?v=8Yn2KvRVr28

GeoHub Liverpool. (May 17, 2019). Plate Tectonics – isostasy. [Online Video]. YouTube. https://www.youtube.com/watch?v=t2CFSuvm1A4

Fig. 2.1.1 A photo of Alfred Wegener

Bildindex der Kunst & Architektur. (1910, Jan 1). “Alfred Wegener, 1910”. [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Continental_drift#/media/File:Alfred_Wegener_1910.jpg Public Domain
Aus EarthEd. (Apr 15 2020). Continental Drift. [Online Video]. YouTube. https://www.youtube.com/watch?v=ttg5fZk3ddE

Fig. 2.1.2. Map of the supercontinent Pangaea with fossil evidence for continental drift across now-separate continents.

Osvaldocangaspadilla. (2010, Aug 27). “Snider-Pellegrini Wegener fossil map.” Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Snider-Pellegrini_Wegener_fossil_map.svg
Fig. 2.1.3. Comparison of layers of stacked books and layers of sedimentary rocks.

Estrada, Charlene. (2021, Mar 25) Books and Rocks. [Online Image]. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Screen-Shot-2021-03-25-at-9.30.35-PM.png (CC BY-SA 4.0)
Fig. 2.1.4. World map showing the extent of the Karoo ice age over Pangaea.

GeoPotinga.(2014, Dec 14). “Karoo_Glaciation”. [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Late_Paleozoic_icehouse#/media/File:Karoo_Glaciation.png (CC BY-SA 4.0)
FuseSchool – Global Education. (Jun 1, 2017). Continental Drift: Wegener’s Theory | Environmental Chemistry | Chemistry | FuseSchool. [Online Video]. YouTube. https://www.youtube.com/watch?v=O5jQLKWvYBA
Fig. 2.1.5. Last known photograph of Alfred Wegener before his death.

Archive of Alfred Wegener Institute. (1930, Nov 2).
“Wegener_Expedition-1930_026_(retuschiert)” Wikimedia Commons.
https://commons.wikimedia.org/wiki/File:Wegener_Expedition-1930_026.jpg (Public Domain)
2.2
Fig 2.2.1. Simplified Periodic Table of Elements.

Double sharp. (2021, Jan 18). “Simple_Periodic_Table_Chart-blocks.” [Online Image]. Wikimedia Commons.
https://en.wikipedia.org/wiki/Periodic_table#/media/File:Simple_Periodic_Table_Chart-blocks.svg (CC BY-SA 4.0).
Fig 2.2.2. The structure of Earth and its interior, drawn to scale.

Kelvinsong. (2013, Jan 18). 1920px-Earth_poster. [Online Image]. Wikimedia Commons.
https://en.wikipedia.org/wiki/Mantle_(geology)#/media/File:Earth_poster.svg)CC BY-SA 3.0).
Khan Academy. (Feb 2, 2011). Structure of the Earth. [Online Video]. YouTube.
https://www.youtube.com/watch?v=4AxZ-6MOznY

Facts Beast. (Feb 17, 2018). How deep is Earths core. [Online Video]. YouTube.
https://www.youtube.com/watch?v=60TSVhYj7Zg

Fig. 2.2.3. Comparison of continental vs. oceanic crust.

USGS. (2019, Oct 28). Continental_and_oceanic_crust. [Online Image]. Wikimedia Commons.
https://en.wikipedia.org/wiki/Continental_crust#/media/File:Continental_and_oceanic_crust.png (CC 0, Public Domain).
Fig. 2.2.4. Earth cut in one half.

Argonne National Laboratory. (2014, Jun 17). Composition of Earth’s mantle revisited thanks to research at Argonne’s Advanced Photon Source. [Online Image]. Flickr.
https://www.flickr.com/photos/35734278@N05/14259873660 (CC BY-SA-NC).
Fig 2.2.5. Pie slice of the Earth’s interior.

Steven Earle. (n.d.). earths-interior-9. [Online Image]. Physical Geology – 2nd Edition.
https://opentextbc.ca/physicalgeology2ed/part/chapter-9-earths-interior/ (CC BY).
Fig 2.2.6. Backyard Geology mantle xenolith.

Petr Hyks. (2017, Aug 28). Upper mantle xenolith (mainly olivine & diopside) in basalt. [Online Image]. Flickr. https://www.flickr.com/photos/130789578@N06/36705417242 (CC BY-NC).
Fig. 2.2.7. Diagram of upper mantle, transition zone, and lower mantle.

Smcminn1234. (2019, Feb 23). Phase_transformations_in_the_transition_zone_2.0. [Online Image]. WIkimedia Commons.
https://en.wikipedia.org/wiki/File:Phase_transformations_in_the_transition_zone_2.0.jpg (CC BY-SA 4.0).

Fig. 2.2.8. Atomic structure of perovskite.

Cadmium. (2006, Apr 10). Perovskite. [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Perovskite_(structure)#/media/File:Perovskite.jpg (Public Domain).
Brian Ongaga. (Feb 20, 2019). The Earth's Magnetic Fields Down To Earth Da Vinci Kids TV YouTube. [Online Video]. YouTube. https://www.youtube.com/watch?v=VFzg9XH0dv8

Fig. 2.2.9. Cross-section of the Earth with surface also showing.

alex grichenko. (n.d.). Planet Earth Center Core. [Online Image]. Public Domain Pictures. https://www.publicdomainpictures.net/en/view-image.php?image=50581&picture=planet-earth-center-core (Public Domain).
2.3
Fig. 2.3.1. Photograph of Marie Tharp.

Library of Congress. (n.d.). "Marie Tharp." [Online Image]. The Huffington Post. https://img.huffingtonpost.com/asset/5bb618d93c000020010d2917.jpeg?ops=scalefit_720_noupscale (Fair Use).
Dinoxorg. (Feb 7, 2013). The First Ocean Floor Maps. [Online Video]. YouTube. https://www.youtube.com/watch?v=62D1NrSqVfI

Fig. 2.3.2. The core of the Earth as a magnet.

TStein. (2008, Jun 21). "Earth's Magnetic Field Confusion." [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Earths_Magnetic_Field_Confusion.svg {CC BY-SA 3.0)
Fig. 2.3.3. Magnetic reversals on the Earth over the past 169 Ma.

Anomie, modified by Charlene Estrada. (2021, Apr 2). "Geomagnetic polarity 0-169 Ma." [Online Image]. Public Domain.
Fig. 2.3.4. Animation of an oceanic spreading center.

USGS. (2011, Feb 19). "Mid-ocean_ridge_topography." [Online Animation]. Wikimedia Commons.
https://en.wikipedia.org/wiki/Mid-ocean_ridge#/media/File:Mid-ocean_ridge_topography.gif (Public Domain).
Fig. 2.3.5. Spreading center at Mid-Ocean Ridge with recorded magnetic reversals.

USGS. (2012, Mar 12). "Oceanic.Stripe.Magnetic.Anomalies.Scheme." [Online Image]. Wikimedia Commons.
https://commons.wikimedia.org/wiki/File:Oceanic.Stripe.Magnetic.Anomalies.Scheme.svg (Public Domain).
Fig. 2.3.6. Image of J. Tuzo Wilson.

Stephen Morris. “John Tuzo Wilson in 1992”. [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:John_Tuzo_Wilson_in_1992.jpg (CC BY-SA 3.0).
Fig. 2.3.7. Our modern world map divided into the major lithospheric plates.

USGS. “Tectonic Plates.” [Online Image]. This Dynamic Earth. https://pubs.usgs.gov/gip/dynamic/slabs.html (Public Domain).
Khan Academy. (Feb 2, 2011). Plate tectonics: Difference between crust and lithosphere | Cosmology & Astronomy | Khan Academy. [Online Video]. YouTube. https://www.youtube.com/watch?v=f2BWsPVN7c4

Fig. 2.3.8. Convection cells within Earth’s mantle.

USGS. “Oceanic spreading.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Oceanic_spreading.png (Public Domain).
Aus EarthEd. (Jun 17, 2020). Convection. [Online Video]. YouTube. https://www.youtube.com/watch?v=YHr7ESa3_VA

2.4
Fig. 2.4.1. Cross-section of lithosphere and asthenosphere showing three main plate boundaries.

USGS. “Main types of plate boundaries.” [Online Image]. This Dynamic Earth. https://pubs.usgs.gov/gip/dynamic/Vigil.html (Public Domain).
Fig. 2.4.2. Buzz Aldrin working on the moon.

Kimika Yang. “Apollo 11: Buzz Aldrin at Work.” [Online Image]. Flickr. https://www.flickr.com/photos/48054321@N05/28411508926 (Public Domain)
Fig. 2.4.3. Block diagram of oceanic-continental convergent boundary.

domdomegg. “Oceanic-Continental Destructive Plate Boundary.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Oceanic-continental_destructive_plate_boundary.svg (CC BY)
EarthScience WesternAustralia. (Jul 27, 2020). Convergence (oceanic and continental crust). [Online Video]. YouTube. https://www.youtube.com/watch?v=F9uGSuyMclc

Fig 2.4.4. Block diagram of oceanic-oceanic convergent boundary.

domdomegg. “Oceanic-oceanic destructive plate boundary.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Oceanic-continental_destructive_plate_boundary.svg#/media/File:Oceanic-oceanic_destructive_plate_boundary.svg (CC BY)
Fig. 2.4.5. Age of oceanic lithosphere.

NOAA. (2009, Jun 8), “Age of Oceanic Lithosphere.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:2008_age_of_oceans_plates.jpg. (Public Domain)
EarthScience WesternAustralia. (Jul 27, 2020). Convergence (oceanic crust). [Online Video]. YouTube. https://www.youtube.com/watch?v=3p1N3JzJzFQ

Fig. 2.4.6. Block diagram of continental-continental convergent boundary.

domdomegg. (2015, Dec 25). “Continental-Continental Destructive.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Continental-continental_conservative_plate_boundary_same_direction.svg#/media/File:Continental-continental_destructive_plate_boundary.svg (CC BY-4.0)
AGU. (Sep 15, 2020). Animation: Continents collide and break apart over time. [Online Video]. YouTube. https://www.youtube.com/watch?v=QhIdiOaFqpE&t=39s

EarthScience WesternAustralia. (Jul 27, 2020). Convergence (continental crust). [Online Video]. YouTube. https://www.youtube.com/watch?v=CdVy6ZQ25WU

2.5
Fig. 2.5.1. Block diagram of divergent boundary on continental crust.

domdomegg. (2016 Aug 19).”Continental-continental constructive plate boundary.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/w/index.php?title=Special:ListFiles&dir=prev&offset=20160127214358%7CSimple_diagram_of_animal_cell_%28numbers%29.svg&user=Domdomegg#/media/File:Continental-continental_constructive_plate_boundary.svg (CC BY 4.0).
Fig. 2.5.2. East African rift valley.

Christoph Hormann. “Albertine Rift East African Rift (artificial rendering).” [Online Image]. View of the Earth. http://earth.imagico.de/view.php?site=rift2a (CC BY-SA 3.0)
EarthScience WesternAustralia. (Jul 27, 2020). Divergence. [Online Video]. YouTube. https://www.youtube.com/watch?v=pf5KPXP4exc

Fig. 2.5.3. Block diagram of divergent boundary on oceanic crust.

domdomegg. (2016, Aug 20). “Oceanic-oceanic_constructive_plate_boundary.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Oceanic-oceanic_constructive_plate_boundary.svg
NOC news. (Jun 20, 2016). Hydrothermal vent fields 1080p. [Online Video]. YouTube. https://www.youtube.com/watch?v=R1koFEKfmLw

2.5.4. Age of oceanic lithosphere.

NOAA. (2009, Jun 8), “Age of Oceanic Lithosphere.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:2008_age_of_oceans_plates.jpg. (Public Domain)
2.6
Fig. 2.6.1. Block diagram of transform boundary.

domdomegg. (2016, Aug 20). “transform.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Oceanic-continental_destructive_plate_boundary.svg#/media/File:Continental-continental_conservative_plate_boundary_opposite_directions.svg (CC BY 4.0).
Fig. 2.6.2. Block diagram of right-lateral fault.

Elizabeth Johnson. (n.d.). “Right Lateral Transform Fault”. [Online Image]. Visible Geology. https://app.visiblegeology.com/model.html#ahFzfnZpc2libGUtZ2VvbG9neXIPCxIFTW9kZWwYqunKmAEM (CC BY-SA).
Fig. 2.6.3. Block diagram of left-lateral fault.

Elizabeth Johnson. (n.d.). “Left Lateral Transform Fault”. [Online Image]. Visible Geology. https://app.visiblegeology.com/model.html#ahFzfnZpc2libGUtZ2VvbG9neXIPCxIFTW9kZWwYubfLmAEM (CC BY-SA).
Fig. 2.6.4. Piqiang fault in China.

Bram-fab. (2013, Jul 30). “Piqiang_Fault,_China_detail.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:Piqiang_Fault,_China_detail.jpg (Public Domain).
Fig. 2.6.5. Piqiang fault with red line.

Charlene Estrada. (2021, Mar 21). “Step 1.” [Online Image]. Original image reference in 2.6.4. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Step1.png (Public Domain).
Fig. 2.6.6. Piqiang fault with red line and blue circle.

Charlene Estrada. (2021, Mar 21). “Step 2.” [Online Image]. Original image reference in 2.6.4. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Step-2.png (Public Domain).
Fig. 2.6.7. Piqiang fault with directional arrows.

Charlene Estrada. (2021, Mar 21). “Step 3.” [Online Image]. Original image reference in 2.6.4. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Step-3.png (Public Domain).
Fig. 2.6.8. Annotated Piqiang fault.

Charlene Estrada. (2021, Mar 21). “Step 4.” [Online Image]. Original image reference in 2.6.4. https://open.maricopa.edu/app/uploads/sites/119/2021/01/Step-4.png (Public Domain).
2.7
2.7.1. Map of Hawaiian-Emperor Seamount chain.

NOAA. “Hawaii_hotspot.” [Online Image, adapted by Charlene Estrada]. Wikimedia Commons. https://en.wikipedia.org/wiki/Hawaiian%E2%80%93Emperor_seamount_chain#/media/File:Hawaii_hotspot.jpg (Public Domain).
Storm. (Nov 5, 2010). Hawaii’s Hotspot. [Online Video]. YouTube. https://www.youtube.com/watch?v=bYv6V5EJAKc&feature=emb_imp_woyt

2.7.2. Map of San Francisco volcanic field of Northern Arizona.

NASA. (n.d.). “SanFranciscoDEM.” [Online Image]. Arizona Geological Society. https://azgs.arizona.edu/photo/san-francisco-volcanic-field-arizona (CC BY)
2.8
Fig. 2.8.1. Map of the Pacific Ring of Fire.

Gringer. (2009, Feb 11). “The Pacific Ring of Fire”. [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Ring_of_Fire#/media/File:Pacific_Ring_of_Fire.svg (Public Domain).
Fig. 2.8.2. Subduction zone at convergent boundary demonstrating hazards.

USGS. (2000, Nov 30). “subduction zone graphic.” [Online Image]. USGS. https://www.usgs.gov/media/images/subduction-zone-graphic (Public Domain).
Fig. 2.8.3. Mount Everest and the Himalayan mountain range.

shrimpo1967 (remix by Papa Lima Whiskey). (2012, Feb 3). “Mount_Everest_as_seen_from_Drukair2_PLW_edit.” [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Mount_Everest#/media/File:Mount_Everest_as_seen_from_Drukair2_PLW_edit.jpg (CC BY-SA).
Fig. 2.8.4. The Mid-Atlantic Ridge between North America, South America, Eurasia, and Africa.

NOAA. (2006, Nov 28). “1024px-Atlantic_bathymetry.” [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Mid-Atlantic_Ridge#/media/File:Atlantic_bathymetry.jpg (Public Domain).
Fig. 2.8.5. Animation of an oceanic spreading center.

USGS. (2011, Feb 19). “Mid-ocean_ridge_topography.” [Online Animation]. Wikimedia Commons. https://en.wikipedia.org/wiki/Mid-ocean_ridge#/media/File:Mid-ocean_ridge_topography.gif (Public Domain).
USGS. (Dec 31, 2014). Elastic Rebound. [Video File]. https://www.usgs.gov/media/videos/elastic-rebound

2.9
Fig. 2.9.1. Supercontinent of Pangaea with modern continental borders.

Fama Clamosa. (2019, Dec 31). “Pangaea_200Ma.” [Online Image]. Wikimedia Commons. https://en.wikipedia.org/wiki/Pangaea#/media/File:Pangaea_200Ma.jpg CC BY-SA 4.0.
Christopher Scotese. (May 31, 2019). Scotese Plate Tectonics Paleogeography & Ice ages. [Online Video]. YouTube.
https://www.youtube.com/watch?v=UevnAq1MTVA&feature=emb_imp_woyt

Fig. 2.9.2. Approximation of world map in 250 million years.

Pokefan95. (2015, Sep 26). “PangeaUltimaRoughEstimation.” [Online Image]. Wikimedia Commons. https://commons.wikimedia.org/wiki/File:PangeaUltimaRoughEstimation.png (CC 0, Public Domain).