Lecture 3: Plate Tectonics and the Ocean Floor

This lecture will focus on a process called plate tectonics and how that process shapes the ocean floor. These processes (we will dive into details soon) are super important to all kinds of things like earthquakes, volcanos, evolution, tsunamis, and how the oceans are formed. As before, we will discuss some of the evidence for all of these links, so first lets talk about how scientists figure this all out.

How do scientists determine ancient time on the Earth? Most rocks (on this planet and in outer space) contain small amounts of radioactive materials. These radioactive materials include elements such as Uranium, Thorium, and Potassium. The radioactive compounds break apart and decay into atoms of other elements. The rate at which these break apart into other elements determines the *half-life* of a radioactive element (the speed at which half of the compound is decayed). Some half-lives are very fast (seconds/minutes) while others can very slow (millions of years). These elements with varying half-lives thus become clocks running at different speeds that can be used to age rocks. Based on this, the older the rock, the more of those radioactive compounds should have already been transformed. Over the last century, scientists have been developing increasingly sophisticated instruments that can measure the amount of radioactive materials present in rocks and what kind they are. By this reasoning, the older the rock, the less radioactive material should be present. The scientist then needs to measure the amount of radioactive material AND the amount of resulting decay product in the rocks. By comparing those two quantities, the age of the rock can be determined. This technique is called *radiometric dating*. You essentially know how fast the radioactive compound decays and then you count the radioactive atoms and the decay products. This approach has been conducted on hundreds of thousands of rock samples to reconstruct the Earth's history.

Concept of Geologic Time. Geologists have created the geologic time scale based on those approaches described above. Initially the divisions through time were based on the extinction of species, but that was expanded when the radioactive dating tools became prevalent. The oldest know rocks on Earth are ~4.2 billion years old. The oldest crystals are dated to be around 4.6 billion years old. That goes all the way back to a molten Earth being smacked around by meteorites.

The largest defined unit of time is the **supereon**, composed of **eons**. Eons are divided into **eras**, which are divided into **periods**, **epochs** and **ages**. Geologists qualify these units as Early, Middle, and Late when referring to time, and Lower, Mid, and Upper when referring to the corresponding rocks. The adjectives are capitalized when the subdivision is formally recognized, and lower case when not; as in "early Miocene" and "Early Jurassic." Geologic units from the same time but different parts of the world often look different and contain different fossils, so the same period was historically given different names in different locales. For example, in North America the Lower Cambrian is called the Waucoban series that is then subdivided into zones based on succession of trilobites. In East Asia and Siberia, the same unit is split into Alexian, Atdabanian and Botomian stages. Obviously, for global questions to be investigated, a standardized naming system had to be developed. A key aspect of the work of the International Commission on Stratigraphy is to reconcile this conflicting terminology and define universal divisions that can be used around the world. This is not a very simple process because, unfortunately, the land moves!!!

Imagine living in an earthquake prone area like the West Coast of North America (some of you may even be from that area). Now imagine being awoke around 5 in the morning with your bed being shaken across the bedroom. You can hear the earth rumble and could feel the ground moving as waves. What it typically only 10 to 20 seconds feels like a lifetime.....

Throughout the world there are several thousand Earthquakes and dozens of volcanic events every day (most are relatively minor). The strength of an earthquake is measured using the Richter Scale, which is an exponential or log scale, meaning that each level is 10x greater than the previous. For example a magnitude 5 earthquake is 10 times more powerful than a magnitude 4, and 100 times more powerful than a magnitude 3. Most of the volcanoes occur under the ocean surface. These events essentially show just how dynamic (moving!) the Earth's crust is. It is capable of movement, which unfortunately for humans can be very destructive. Understanding of these Earth moving phenomena is of obvious importance to human health and safety, but also to our understanding of how the Earth (and oceans) work. The theory, which describes these events is *plate tectonics*. Here is a cool article (pun intended) about a fairly recent discovery that shows that plate tectonics may not just be limited to our very own Earth. Plate tectonics is a very powerful theory because it can explain:

-The world wide locations of volcanoes, faults, earthquakes and mountain formation

-Why mountains on land have not eroded away

-The origin of most land and ocean forms

-How the continents and ocean floor are formed and how they are different

-The ongoing development of the Earth

-The distribution of past and present life on Earth.

Plate (plates of the lithosphere) tectonics (comes from "to build") essentially says that the outermost portion of the Earth is composed of a patchwork of thin rigid plates (we discussed some of this already – look back to remind yourself if you need a reminder). These rigid plates move horizontally relative to each other, floating on the molten layer below the plates. This was built on the idea of continental drift.

Some of the first documented ideas that continents could move was discussed as early 1596 by the Dutch map maker Abraham Ortelius in his grand work *Thesaurus Geographicus*. Ortelius suggested that the Americas were "*torn away from Europe and Africa... by earthquakes and floods*" and went on to say: "*The vestiges of the rupture reveal themselves, if someone brings forward a map of the world and considers carefully the coasts of the three continent*s." Continental drift was later highlighted by the German meteorologist Alfred Wegener, who dubbed the once big super-continent Pangaea. His idea was largely ignored as the Earth scientists at the time thought the Earth's mantle was to strong and large to allow them to float. In 1912 the idea of moving continents and that there had once been a super continent finally gathered steam.

What is the evidence for continental drift?

Evidence 1) The continents of today fit together like a jig saw puzzle. This idea could only grow as humanity was able to develop accurate maps. But even before a full global map was available, some people like Sir Francis Bacon guessed that the continents fit together. Wegener postulated that the continents had collided and formed Pangaea (Pan = all, gaea = Earth). This large mass broke up and the pieces drifted apart to form today's continent configuration. Wegener focused carefully on describing not only the shape of the shoreline, but also the composition of the shoreline, both of which should match up. However, not all the locations matched up, some of which could be explained by material deposited by rivers and eroded by the oceans. The problem was that the edges of continents can change, and the edges today may have been underwater in the past or vice versa. In the 1960's using the super new science machine, the computer, Sir Edward Bullard pieced together the continents, using the edges of the continents at a 2000 m water depth.

Evidence 2) matching the sequences of rocks and mountain chains. If Wegener was right, then there should be evidence in rock sequences in mountains if all the continents fit together. Those mountains should have been once a continuous mountain chain. Just like using the coastline as jigsaw puzzle, they used rock sequences as puzzle pieces that must fit together. This required careful inspections as often the “old” rocks that needed to be lined up, might be buried under lots of young rock. When they did find the right age rock, the geologists found a really good fit between the rock sequences across continents. Wegener was really interested in these good fits found on both sides of the Atlantic (check on the figure below). Another piece of evidence was found in the mountain chain of South America, Antarctica and west Australia.

Evidence 3) Glacial ages and other climate evidence. Wegener noticed that in regions that are now tropical, he found evidence of past ice ages and he suggested that this provided evidence of a drifting continent. Evidence of glaciation is found in India, South America, Africa, and Australia at the same time in the past. There are two possibilities here. 1) maybe there was a global ice age or 2) the continents used to reside closer to the poles. The evidence of a global ice age was not supported by the geological evidence of the time. When there was ice in South America and India, north America and Europe were essentially warm swamps. Another piece of evidence was that animals and plants are distributed across the continents, and these animals require certain environmental conditions. For example, corals generally need seawater at least 18 degrees Celsius. So if we find evidence of corals in cold water, again they were either killed by a global cooling or the piece of land they were associated with was moving. The best explanations for the dislocated organisms were that the continents were moving. A particularly compelling example was the fossil remains of Mesosaurus, a weak swimming aquatic reptile that lived 250 million years ago. It was only found in eastern South America and western Africa, separated today by a large Atlantic ocean. If the lizard was a good swimmer we would expect it to be able to roam throughout the Atlantic, and not be limited to just 2 regions. Wegener hypothesized that when Mesosaurus was around, the continents were close together, so it did not have to be a good swimmer to occupy both areas. When it went extinct, the continents split apart. This later had confused scientists who assumed that the lizard had to be a good swimmer. It did not have to be.

Here is a super cool interactive tool that will let you look at how the earth looked at various times in history. You can even look at where certain dinosaur species were located, or even look up where your house would have been 300 million years ago! Use the top left search bar to locate your city.

So the continents have moved around (and are still moving!), but how? The answer lies in Plate Tectonics (from Latin *tectonicus*), which is the theory that describes the large scale motions of the Earth's lithosphere. The theory was built on the ideas of continental drift and largely became accepted in the late 1950s and early 1960s. The Earth's lithosphere is broken into "tectonic plates", which move around the planet over geologic (recall the eons and epochs from earlier) time scales.

As we discussed above, Wegner had compiled a lot of very convincing evidents to convince the science community of continental drift. Unfortunately, Wegner died during an expedition in Greenland in 1930, and much of the evidence that finally proved his theories would not become available until much later. With his demise, the major force behind developing the theory had ended, and not much progress was not made until mid-1940's. There was a large focus during World War II to map the world in order to achieve a tactical advantage. And so began widespread mapping of the sea floor using sonar.

Sonar (i.e. **SO**und **N**avigation **A**nd **R**anging) is a technique that uses sound propagation (usually underwater) to navigate and to communicate with or detect other vessels. Two types of technology share the name "sonar": *passive* sonar is essentially listening for the sound made by vessels; *active* sonar is emitting pulses of sounds and listening for echoes. Sonar may be used as a means of acoustic location and of measurement of the echo characteristics of "targets" in the water. Although some animals (dolphins and bats are among the most familiar) have used sound for communication and object detection for millions of years, use by humans in the water is initially recorded by Leonardo Da Vinci in 1490: a tube inserted into the water was said to be used to detect vessels by placing an ear to the tube. These sonar maps of the bottom of the ocean began to provide critical evidence of plate tectonics. These maps were combined with another technique that allowed scientists to analyze the way Earth's rocks retained their magnetic signature.

Earth's Magnetic Field & Paleomagnetism

The Earth has a magnetic field. The field is generated by strong electrical currents generated by the dynamo process resulting from the flow of molten iron in the Earth's outer core. It is a very complex process, and even today we don't have a complete mathematical explanation of how it works. The whole thing is so complex that new data is showing surprisingly that the magnetic field is weakening faster than anticipated. Nonetheless, the magnetic fields, radiate from within the Earth and radiate out into space. The opposite ends have different polarities (which for the Earth we call north and south) that cause magnetic objects to align parallel to the magnetic field.

As rocks are formed, they actually record the patterns of the Earth's magnetic field – how incredible is that! Specifically *igneous* (igne = fire, ous = full of) rocks that are formed from molten magma in volcanic eruptions are the recorders. These rocks contain magnetite, which is magnetic. When the lava cools and the rock is being formed, these internal magnetic pieces (the magnetite) are locked into an orientation that aligns with the magnetic field. The position would reflect the magnetic field of the Earth at the time and place the lava cools. They are frozen in that position unless the rock is re-melted. Magnetite is also found in sediments, and can be frozen into position when the sediment is solidified into sedimentary rock. Maps of magnetite orientation allow scientists to reconstruct the magnetic field of ancient Earth. These maps can be used to study changes in the magnetic field and the magnetic inclination (bet you didn't know the magnetic field changes!). The magnetic inclination is related to latitude, as there is no inclination at the Earth's magnetic equator. Magnetic inclination is also retained in the rock signature, it can tell you where the rock was formed. *Careful analysis of the rocks over time show that the continents drifted*.

During this analysis, people began to piece together that the apparent magnetic pole also moved with time – check out the figure below to see how much magnetic North has moved.

Another remarkable finding was that the polarity (the directional orientation of the magnetic field) has also reversed. What people have seen, is that the north-south orientation has switched over time. There have been 170 of these reversals over the past 76 million years (every ~250,000 years). The switch is not instantaneous, it takes hundreds to thousands of years. Currently the Earth's magnetic field is weakening, which some argue that indicates we are in the process of a magnetic reversal. ***Consider this: How might a reversal of the magnetic field impact humans and other organisms on Earth? Can you think of two hypothesized impacts and why?***

The paleomagnetic research was largely conducted on land in the beginning. But in the 1950s academic and government scientists decided to explore the sea floor using an instrument called a magnetometer (measures the Earth's magnetic field), which is towed behind the ship. The scientists studying this did weeks long surveys, and discovered a regular pattern. Their survey saw alternating patterns of north and south bands. The alternating bands were found as layers in the seafloor mountains. This was extremely confusing to the community for a long time.

Harry Hess a geologist and Navy Captain decided to leave his depth recorder on all the time he was sailing. His maps showed that there were large undersea mountains. What was found that there were big mountain ranges in the middle of the oceans. At the edges they found deep ocean trenches. Harry spent much time thinking about his maps and wrote a book *History of Ocean Basins*, in which started the idea of sea floor spreading. Associated with the idea was the idea of mantle convection. He essentially suggested that new ocean crust was created at the ridges & mountains. The new crust was made and then moved away from the ridges. The crust then as it moved away disappeared into the deep ocean trenches. He called it "geo-poetry" because he remembered the strong reactions that Wegner endured. Harry, like Wegner, was initially criticized for his ideas and he turned out to be right!

Let's talk a little bit about the way that convection might support the mountain features beneath the ocean. We have already talked about the lithosphere that sits atop other layers, including the core that is hot – very very hot. That relatively cool lithosphere is forced down into the hot core at places called subduction zones. This creates circular convection currents within the core that then leak through the lithosphere at other locations that then make ridges in the ocean as the hot molten rock seeps up into the cold ocean. See the figure below for a schematic of how this works. You might also have observed this process happening in the wax around the wick of a candle as you study late into the night for exams – if not, check out this video to see convection cells swirling ash in molten candle wax.

The mid-ocean ridge is a continuous underwater mountain range that winds through every ocean basin. The entire ridge was formed by volcanoes and is a dramatic feature. It stands 1.5 miles above the sea floor! The new crust comes out at the top of the ridge, to fill the spilt in the sea floor. A good analogy is to think of the mid-ocean ridge as a zipper that is being pulled apart. As that is happening at the outer edges, lithosphere is being destroyed, as the crust descends into troughs. These troughs are where the largest

Earthquakes occur, and are caused by the plate, which is bent downwards and is slowly subducted into the Earth's interior. This can lead to "slips" or "adjustments" as the plates reorient with each other (which causes the tremors/shakes/motion/destruction). These zones are known as subduction zones.

In 1963, two geologists Frederick Vine and Drummond Mathews (both at Cambridge), tried to explain those alternating patterns seen by the early sea floor mappers who were using the magnetometer (see above). They appreciated that the Earth occasionally has reversals in magnetic polarity (switch between north and south). This combined with the fact that new rocks being formed all the time, covering over older formed rocks, could produce the alternating bands found by those mappers. As rock is pushed away from the spreading centers to the troughs, and they retain the polarity signature of when they are formed, they provide a clear picture of sea floor spreading. This is one of the major pieces of evidence that convinced the community that sea floor spreading ideas of Harry had legs. This concept of the sea floor as a conveyor belt was a little bit in conflict with Wegners idea that land masses were moving around through the ocean floor.

While this evidence was important, more evidence was required to convince everyone. In the late 1960s there was an ambitious effort to test the sea floor spreading idea, by drilling into the crust and use radiometric dating to determine the age of the sea floor. If the sea floor spreading idea is correct, then the age of the rock should vary. It should be youngest at the mid-ocean ridges where the sea floor is formed and it should be oldest at the troughs, before it descends into the Earth's interior. This is particularly clear in the Atlantic ocean. Ok, now remember, we think the Earth is 4 billion years old, but the oldest ocean crust is only ~180 million years old. The reason that there is no older sea floor rock is that the old rock is subducted and re-absorbed into the Earth's interior. At this point you are looking at me and then asking the great question, why then are the continents so much older? Excellent question! Contemporary thinking is that continental rocks have a lower density and thus do not get subducted. They sort of float, like the foam on a latte (did I mention I like lattes?).

How fast is the sea floor moving? Is the sea floor speed constant? You guys rock, those are awesome questions! Currently our best estimates are that the sea floor is moving around 2-12 centimeters per year. There is also evidence that plates were moving faster in the past as determined by the width of the crust. For example, India 50 million years ago moved at 19 centimeters second, but 530 million years ago may have been as fast as 30 centimeters per second. We don't know why.

Another piece of evidence for how the sea floor is moving is seen in the Earth's heat flow. The heat flow is from the Earth's interior to the surface. Heat measurements around the Earth show that the heat at the sea floor is not uniform. For example the heat flow at the mid-ocean ridges are 8x greater than then deep-sea trenches. This observed distribution of heat agrees very nicely with what is predicted by the theory of sea floor spreading.

The final big piece of evidence that the sea floor is moving is the distribution of world-wide Earthquakes. Earthquakes are sudden releases of energy which can be caused either by movement in faults in the lithosphere or by volcanoes. Most of the world's large Earthquakes occur along ocean trenches reflecting the energy released by the subduction. The other major zone of earthquakes is along the mid-ocean ridges where the major zones of magma flow to the ocean.

These major lines of evidence that we highlighted above convinced the science community that the idea of plate tectonics and sea floor spreading was a solid concept. Wegner, Hess, and countless of geologists were rewarded. The tectonic plates are pieces of lithosphere that float on the fluid asthenosphere. The lithosphere is a relatively cool rigid shell that includes the crust and upper mantle of the Earth, and is about 100 km (60 miles) thick. The asthenosphere is relatively hot, and more plastic than rigid, and is capable of flow (this is how the lithospheric plates move over the viscous asthenosphere).

Some reasons why plate tectonics is beautiful!

A great science theory can explain many things. Here is an example of how the theory can explain certain apparently divergent phenomena observed in the world. Many regions of the ocean contain tall volcanic peaks. These large peaks are called seamounts. Most are peaked, but some can have flat tops, which are called guyots. They are named after Arnold Guyot who was Princeton's first geology professor. Plate tectonics can explain how sea mounts and guyots are formed. The origin of the two is related to volcanic activity at the mid-ocean ridge. Because of sea floor spreading, active volcanoes occur at the crest. The seamounts form at the mid ocean ridge. As the sea mounts are pulled away from the ridge over time, the ocean waves flatten out the peaks, transforming them into guyots.

How did the Earth look? How will the Earth in the future?

Piecing together the past: The study of historical changes is called paleogeography. Maps of the changing position of the continents shows that the continents have changed location and orientation over time. For example, North America used to be near the equator and swiveled by 90 degrees. All the continents were at one time unified in a big land mass called Pangea. When you look at today's continents, you can see how they fit together like puzzle pieces. Over the last 180 million years Pangea split apart.

Looking to the future: Using plate tectonics we can predict the future positions of the continents on Earth. Some predictions over the next 50 million years include, the formation of a linear sea forming by the Africa rift valleys. The Red Sea will grow in size. India will continue to slam into Asia which will increase the size and height of the Himalaya mountains. North and South America will continue to move west making the Atlantic ocean bigger, and conversely the Pacific ocean will decrease in size. An opening will form between north and south America.

Key words and Definitions

Pangea = a supercontinent that existed during the late Paleozoic and early Mesozoic eras and included almost all of the landmasses of today into one land mass.

Continental Drift = the gradual movement of the continents over the Earth's surface over geological time

Lithosphere = the relatively thin, cool, and rigid outer layer of plates on the Earth that float on the underlying asthenosphere.

Bathymetry = measurement of the ocean depth