Lecture 7: Marine Sediments – 1

Today, we will focus on what marine sediments are, how they are formed, and what secrets they hold. You might be thinking 'how interesting can the mud at the bottom of the ocean be?'. The truth is, it can be very very interesting. In fact, the sediments on the sea floor are the key to unlocking the secrets of the history of the Earth. Ocean sediments are full of microscopic fossils that can tell us about the biological history of the ocean, the way that ocean currents have changed over geological time, how the sea floor has moved. Ocean sediments can tell us about historical climates on Earth – details that are critical to how we understand today's changing climate. Ocean sediments are in essence the Earth's memory!

Let's start with what ocean sediments are. Ocean sediments are organic or inorganic particles that accumulate loosely (or unconsolidated to use a fancy term) on the sea floor. These particles come from weathering and erosion of rocks, biological activity of living organisms, volcanic ash, minerals that form in water (known as hydrogenous minerals), the atmosphere or outer space (known as aeolian particles), or they can be man-made. They can accumulate on the bottom of the ocean relatively quickly (>cm per year), or very very slowly (<1cm in 1000 years). They can be things like smooth sediments in which you might see tracks from animals that crawl across the sea floor, or rippled bottom sediments that reflect the wave action above. They can be muddy sediments in the intertidal zone that you may have walked on over the summer break, or sediments that have been transformed into sedimentary rocks (called lithified sediments).

Marine sediments are typically classified by their origin. They can be derived from rocks on land, which are called *terrigenous (or lithogenous)*. They can come from organisms, or be biologically derived, which are called *biogenous*. Terrigenous and biogenous sediments are the most common (see chart below). Sediments can also come from water, called *hydrogenous,* or from space, called *cosmogenous.* Hydrogenous and cosmogenous sediments are very rare.

*Terrigenous Sediments:* Sediments that come from rocks on land are created by weathering of rocks on land which breaks down the rocks into smaller and smaller pieces.

Weathering of rocks happen when they are exposed to water, extreme temperatures, chemicals, of biological processes such as plant roots. Once the rocks have been broken down into smaller pieces, they become easier to transport via erosion. This eroded terrigenous material is carried by streams, wind, glaciers, and gravity into the ocean where they become marine sediments.

Each year, streams carry approximately 20 billion metric tons of terrigenous sediment into the continental margins. If you think about how erosion carries terrigenous sediments to the ocean, it isn't surprising that most of it in the ocean is found along the margins of the continents. Even still, microscopic sediment particles (dust or volcanic particles) blown by the wind can be carried way out into the open ocean. How else would terrigenous particles reach the deep ocean? Recall the turbidity currents from a previous lecture – that's how!

Since terrigenous sediments are broken down pieces of rocks, the composition of terrigenous sediments will have the same composition and characters as the rocks they came from. Rocks are made of particles that are actually crystals that are made from minerals. One of the most common minerals in the Earth's crust is quartz (chemical name $SiO_2$ because the crystal is made from silicon and oxygen). Quartz is also really stable and super durable (it is actually made of the same base elements, silicon and oxygen, as glass). Because it is so stable and durable, it can be transported great distances. If you take a very close look at the sand stuck between your toes at the beach, you will see that it looks like teeny tiny rocks, and now that you know about quartz, you will see that much of it is tiny bits of quartz.

Terrigenous sediments can vary in size, and the size of the particle is related to how far it gets transported. Coarser sediments, composed of larger particles, tend to get transported shorter distances and end up closer to the shore; whereas fine sediment composed of smaller particles are transported further and tend to be found further from shore. Some of the smallest particles can be transported vast distances by wind. There are terrigenous quartz dust particle deposits in the deep ocean that are transported there by strong prevailing winds from the deserts of Africa, Asia and Australia where there is little rainfall and vegetation is minimal. The map below shows the locations of some of these deep ocean quartz sediments along with the winds that blow them there. These wind-driven sources of quartz dust in the deep ocean is an important mechanism that delivers trace elements to the ocean that are important natural 'fertilizers', such as iron (chemical name Fe).

Glaciers are especially good at eroding rock as they advance and retreat. The bottom of the ice in a glacier can pick up rocks (sometimes very big ones) and can carry those rocks along with them. As they do, those rocks grind over the rocks beneath and break them up (think sand paper!). Glaciers can also melt, and that flowing meltwater can weather and erode rocks, or water that gets into cracks in underlying rock can break the rocks if the water in the crack freezes (we will learn about how in an upcoming lecture). Ultimately, those glacially derived terrigenous sediments will flow through rivers or meltwater and make their way to the ocean. Here is a cool picture of a black sandy beach that is made of terrigenous sand that came from basalt, or ancient volcanic magma chambers that have been exposed to weathering and erosion.

One of the underlying trends with where we find terrigenous sediments in the ocean is related to the size of the sediment particles. Bigger particles are heavy and do not move very far, so they tend to be found closer to the shore in shallow areas. Smaller particles that are light can be carried much further and tend to be the primary sediments found in the deep ocean basins. The table below illustrates this concept. The particle size in the second column shows how big a particle is (big particles like boulders at the top), and the third column shows the velocity that size particle will fall through the water at. The dashes for the bigger particles means that they drop almost instantly, whereas the clays at the bottom drop (or settle out) very slowly. The column to the far right shows the amount of time it takes a given particle size to drop or settle the distance of the average ocean depth (4km). Those bigger particles take almost no time to drop to the bottom, while the clays will take around half a century to drop the distance of the average ocean depth giving them plenty of time to be transported by ocean currents to the deepest parts of the ocean.

Particle sizes, the way they are eroded, and how they are transported determines where the marine sediments will end up in the ocean. Terrigenous sediments that are eroded from land and carried to the ocean by run-off tend to be heavier, and get transported shorter distances, often ending up in river deltas near shore. On the other hand, lighter particles like dust and volcanic ash that are transported in the atmosphere by winds, tend to have low sedimentation rates and are transported long distances often into the deeper ocean basins farther from land.

*Biogenous Sediments:* These are sediments that come from the hard parts of living organisms that range from microscopic algae and protozoans to fish and whales. When the organisms that build these hard parts – shells, bones, teeth – die, their remains drop to the ocean floor and the soft parts go away, but the hard parts remain and become sediment. The bigger things like bones and teeth are macroscopic (meaning we can see it with the naked eye), but the majority of what makes up the biogenous sediments come from smaller organisms and are microscopic in size. These are the tiny shells (also called exoskeletons) of microscopic organisms (algae and protozoans) that, although small in size, are produced in huge numbers and continually fall through the water to the bottom of the ocean as these organisms die. The sediment layer in the deep ocean that is made up of the shells of these organisms is called ooze. Ooze is defined as sediments that are composed of at least 30% biogenous material (shells of plankton) by weight.

The two most common components of these biogenous hard parts are calcium carbonate ($CaCO_3$) and silica ($SiO_2$). Some examples of organisms that create calcium carbonate exoskeletons are foraminifera (these are actually tiny animals) or coccolithophorids (these are actually tiny plants). Both armor themselves with carbonate shells. Blooms of coccolithophores can be so vast and abundant that they can be seen from space! You might have even seen a bloom yourself when the ocean off the Jersey shore turns a Caribbean blue – the blue color is light reflecting off the calcium carbonate shells of the algae. The sediments that accumulate on the ocean floor from these coccolithophore blooms can be so massive that they create geological features like the white cliffs of Dover. Some examples of organisms that make silica shells are radiolarians (these are tiny protozoan animals) or diatoms (these are tiny and beautiful plants). Silica is basically glass, so these tiny creatures shield themselves in tiny glass houses – how amazing is that!? The silica sediments that are created when these radiolarians or diatoms die and sink to the bottom of the ocean are actually quite useful (they are tiny bits of ornately shaped glass after all) and are called diatomite and are used in products like diatomaceous earth. Diatomaceous earth is used in all sorts of products like filters, abrasives (facial scrubs, toothpaste, etc.), absorbents, chemical carriers, and even the tiles on the space shuttle.

Where in the ocean do you find biogenous sediments? The factors controlling where biogenous sediments end up are *productivity, destruction* and *dilution*. Productivity is how much and how fast algae and phytoplankton grow. Basically, the likelihood of generation of biogenous sediments starts with how much material is being generated to start with. These marine plants need sunlight, carbon dioxide and nutrients to grow. Just like land plants, they photosynthesize, which means they use sunlight turn carbon dioxide into organic carbon and oxygen. High productivity surface waters in the ocean have lots of algae that are reproducing quickly. These high productivity areas are locations where biogenic sediments can accumulate.

Destruction is the dissolution or respiration of the hard parts of these microscopic organisms before they reach the ocean bottom, or after they reach the bottom. Destruction is largely driven by microbial respiration. Respiration is basically the opposite of the photosynthetic process and involves taking the organic carbon and oxygen, and converting it back to carbon dioxide and water. In the ocean, the fate of the phytoplankton and the biogenic materials (calcium carbonate or silica) that they produce is determined by microbial activities. There are certain processes in the ocean that can help accelerate their trip to the ocean floor after they die. These are grazing by other planktonic animals, which then package up the waste into fecal pellets that sink relatively quickly. There are also bacterial processes that create clumps of algae which help them to sink faster – these clumps are called marine snow. Both of these processes that help to accelerate the sinking of biogenic material to the bottom increases their contribution to the sediments. If they do not fall quickly to the bottom, the will be more likely to be decomposed by microbes in the water column, which then recycles the biogenic materials back into the water column where they can be used again by other organisms. This is called the 'microbial loop'. The likelihood of biogenic material accumulating on the bottom once it is created then depends on how likely it is to end up in some sort of clump that sinks quickly (fecal pellets or marine snow), or whether it ends up in the microbial loop and gets recycled. Locations where 'destruction' is high are areas where biogenic sediments are unlikely to accumulate.

Dilution occurs when other sediments accumulate and dilute the amount of biogenic material on the bottom. Recall that biogenic sediments are those that have at least 30% biogenic material, so if other sediments are being mixed in at a high enough rate to keep the biogenic component below 30%, you will not get biogenic sediments at that location.

Consider where that might happen – maybe in locations that have high terrigenous sediment accumulation like river deltas or continental margins?

Both silica and calcium carbonate will dissolve in seawater when it is low in those solutes. Almost all of the ocean is low in silica, so that will always tend to dissolve at all depths. The only way to accumulate silica ooze is to produce lots and lots of it and overwhelm the dissolving process. You can think of that as trying to get sugar to layer the bottom of a cup of coffee. If you put just a little sugar in the cup, it will dissolve. Put a whole lot of sugar in and some of it will layer the bottom of the cup. Calcium carbonate is a bit different. It will tend to dissolve in the deeper parts of the ocean, but not in the shallower parts. This happens because calcium carbonate tends to dissolve more in colder, higher pressure low pH water, that contains more carbon dioxide, which is found in the deep ocean. The depth at which the water temperature is cool enough, and the pressure and carbon dioxide concentration high enough is called the *lysocline*. Below the lysocline, calcium carbonate will dissolve and this happens faster as you go deeper until the *carbonate compensation depth (CCD)* is reached. Below the CCD, sediments tend to not have calcium carbonate because it dissolves away. On average, the CCD is 4500 m deep, but varies in depth throughout the ocean because of differences in local ocean chemistry (which alters the carbon dioxide and pH).

Calcareous ooze will accumulate on the top of the mid-ocean ridge because it is high enough to be above the CCD. As the sea floor spreads, those calcareous sediments are moved away from the ridge into deeper parts of the ocean. If the calcareous sediments are not covered by a protective layer of some other sediment when it spreads below the CCD, it will dissolve away. If it is protected, it will remain below that protective layer of either abyssal clay or silicate ooze even though it ends up below the CCD. Abyssal clays are the sediments that remain after the carbonate has dissolved away below the CCD therefore they are found in only the deepest parts of the ocean, and these clays accumulate on the bottom very slowly. Check out the figure below to see how this all works, then look at the map below that and think about the locations of calcareous ooze relative to the plate boundaries, and how those work together to determine where we find calcium carbonate sediments in the ocean.

*Hydrogenous Sediments:* These sediments are made from minerals that precipitate (crystalize) directly from material dissolved in seawater. Recall above that hydrogenous sediments make up only a small amount of all marine sediments, and in our previous lecture we discussed how hydrothermal vents create conditions that allow water to take up dissolved minerals and then create conditions for them to precipitate out of solution. Even though they are rare, they are a very important ocean sediment and are critical to paleoceanography (that is the field of science that studies the ancient oceans). There are many different kinds of hydrogenous sediments, and many different environments that make them.

Metal sulphides are a kind of hydrogenous sediment that is associated with hydrothermal vents and black smokers along the mid-ocean ridge. They contain iron, nickel, copper, zinc, silver and other metals. As the plates along the mid-ocean ridge spread, the metal sulphide deposits are transported away from the mid-ocean ridge.

Manganese nodules are another kind of hydrogenous sediment. These deposits are characteristically round lumps of manganese, iron and other metals. They form very slowly, accumulating only 5 mm per million years, and range in size from 5 to 20 cm in diameter. When cut in half, you can see that they are formed in layers around some central object, kind of like a jaw breaker candy. Because they form so slowly, they are only found in locations of the ocean where other sediment accumulation is very low, otherwise they would quickly become buried in sediment.

Also known as 'fool's gold', pyrite is another hydrogenous sediment formed in the ocean. It is shiny (that's why it is called fool's gold) and contains iron and sulfur. This particular deposit forms only where the ocean is anoxic, which means that the conditions there are depleted of oxygen. Because pyrite only forms under anoxic conditions, the locations of these sediments then tells us about the ancient conditions of the ocean at that location.

Evaporites are hydrogenous sediments formed in locations with high evaporation rates and where open ocean circulation is limited. The floor of the Mediterranean Sea has thick evaporite deposits which tells us that at some time in the geological history of that place, the ocean dried up completely allowing these evaporite materials to form. These evaporite minerals include halite (this is common table salt) and gypsum.

We have now learned about a number of types of marine sediments, their origins, and how they are distributed. We can think of sediments as having two provinces or types based on their destination (where they end up in the ocean). One type is neritic sediments. These tend to stay close to land because they settle out relatively quickly, and are mostly coarse, lithogenic sediments. Another are pelagic sediments. These are deposited relatively slowly, so they are found in the deep ocean, and are mostly biogenic in nature or are very fine grained. Neritic sediments cover about 25% of the ocean floor, and pelagic sediments cover about 75%.

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