The Evolution of the Earth and Life
Dr. Devapriya Chattopadhyay
Department of Earth and Climate Science
Indian Institutes of Science Education and Research, Pune
Igneous Activity and Plate Tectonics

Welcome to the course, evolution of the earth and life. Today, we are going to talk about specific spots of the Earth, where the rocks melt and we will also try to understand how each of these areas contribute to the melting of the rock.

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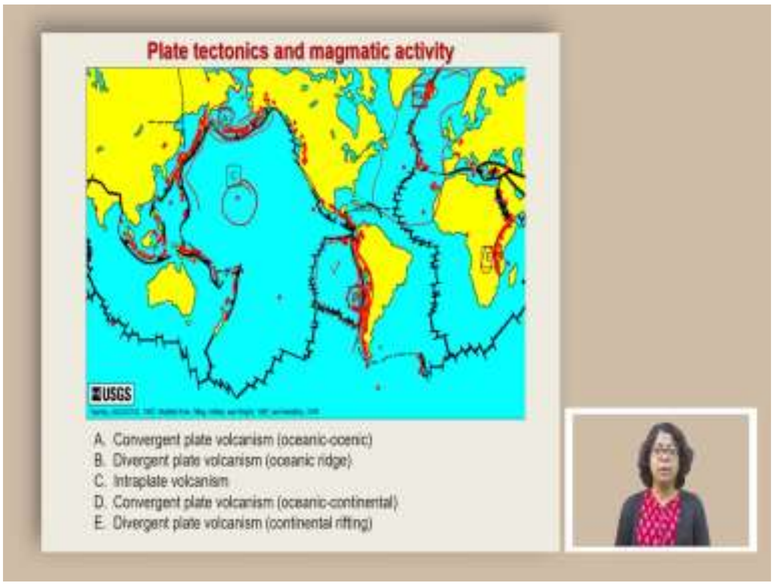

This is a map which shows the plate tectonic margin and magmatic activities. So, there are different lines, the black line shows the plate boundaries and the red dots show volcanic activities or magmatic activities. Now, there are a few symbols and few letters and these letters tell you about what kind of plate boundary are we looking at. So, as we know that there are three main types of plate boundaries, the one which is a convergent boundary is a plate boundary where two plates come close to each other, the second one is a divergent boundary, where two plates are moving away from each other.

And the third one is a transform boundary where two plates are moving past each other. For today's discussion, we are going to primarily focus on convergent and divergent boundary. But even among convergent and divergent boundaries, we can have multiple combinations depending on which kind of plates are involved. So, we know that there can be oceanic plates and there can be continental plates. And depending on whether we are looking at both oceanic plates involved in a particular boundary, we can have different reactions.

So the first one which is marked by A, is a convergent plate boundary, where two oceanic plates are coming closer to each other. So if you look at this particular plate, this is the Pacific Plate and it is meeting another oceanic plate. And therefore we are calling it convergent plate boundary and we are also going to see that there is a major volcanism that is happening all around it. It is also called the Pacific Ring of Fire, because there is a continuous ring along which we have massive volcanism.

So this entire boundary where two oceanic plates are coming closer to each other actually subducting one underneath is going to give rise to this convergent plate volcanism. Another type of magmatic activity associated with the plate boundary is called a divergent plate volcanism and we find it somewhere here. This is an example of mid-Atlantic ridge. So these are oceanic, mid oceanic ridges, along which new oceanic plates are being created. And here, what we see is a formation of new oceanic plates and pragmatic activity associated with it. So these are called divergent plate volcanism.

We can also find examples of D somewhere around here, where it is oceanic continental plates meeting each other. So we find this part as an oceanic plates and this part as a continental plate and the oceanic plate is going underneath the continental plate. And this gives rise to volcanism all along the coast of South America. The other type of divergent plate volcanism can be found in continental rifting. So the example that we talked about in mid-Atlantic ridges, it was happening within oceanic plate, but this one, which is symbolized by E, this is happening within a continental plate, it is the African plate.

And if you look at the eastern part of Africa, you will find that there are a lot of volcanism that are happening right around the eastern part of Africa. So this is a part where continental plates are going away from each other, creating a rift valley and along this rift valley, we also do see effect of volcanism. The one that I escaped is the C, it is interesting because it is literally in the middle of a plate and unlike B, where we do series a few red dots, so that means there are series of volcanism along that divergent boundary within the ocean; here, these are quite separate points, we do not really see a series of things at least in this scale, and these are called intraplate volcanism and we will try to study each of these types and we will like to understand how each of these types differ from each other, and what are the factors that contribute to the melting and volcanism.

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So, first one that we are going to talk about would be a divergent plate volcanism. Again, quick summary that we are talking about a situation where two plates are moving away from each other. Often, when a single plate actually rifts apart, and makes way to development of a new plate or new floor, that is characteristic of divergent plate boundaries. So ocean ridges are a very clear example as I said that B is an example.

So when these continental lithosphere, it can be continental lithosphere, it can be an oceanic lithosphere. But these lithospheres when they are split apart, and they are moving away from each other, they create these kind of rift valleys, and also associated with volcanism. So when we look at them, in terms of the oceanic areas, they lead to something like Mid Atlantic ridge, and they also can create oceanic islands, volcanic islands such as Iceland. There can be a continental counterpart and one great example of it is Mount Kilimanjaro in Africa, where continental plate is drifting and therefore, releasing a lot of magma and therefore, creating these volcanoes.

Now, the question is what is the responsible mechanism? As we recall, that a rock can melt by the contribution or by the influence of temperature, pressure and fluid. So, we are going to see what kind of influence is there and what kind of rocks are being formed here.

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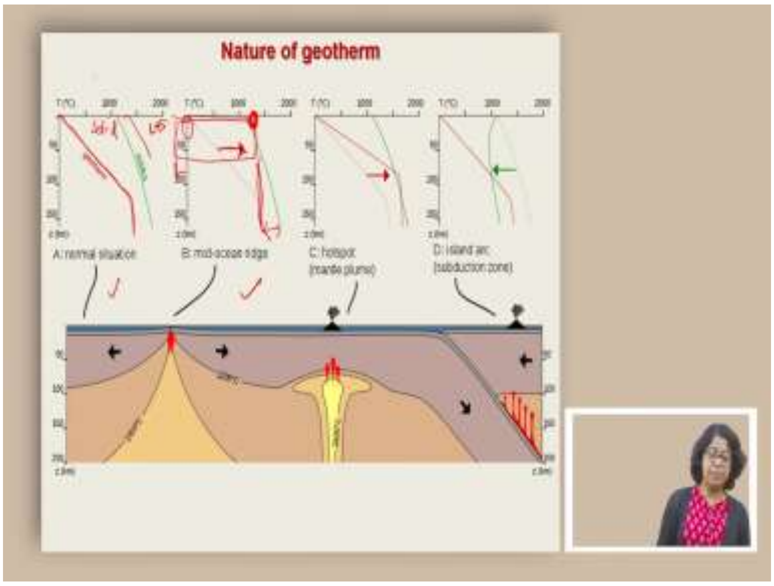

So, this is the nature of geotherm and because we are talking about mid oceanic ridge or divergent boundary, we are going to focus on these two situation - one is the normal situation where it is within plates and there is no tectonic boundary, there is no plate boundary. In that situation, we do find a geotherm, which looks something like this. And then there is a solidus line, which means everything in this side is solid and everything around here is liquid, I mean liquid plus some amount of solid, so it is a partial melting starts right around here.

So now, if we compare it with the mid oceanic ridge, immediately it becomes clear that the geotherm shifts, the geotherm actually shifts around here and it actually shifts somewhere which is very close to the surface, because the pressure if you look at the depth, the depth is not much; we are still talking about something like within 50 kilometers. And the major melting is actually happening right around here which is very, very close to the surface in terms of the depth and the temperatures are somewhere around 1000 degrees Celsius.

Now what is happening? So, quite clearly, the role is somewhat of a pressure because as we are going down, the pressure is increasing and we are not really seeing some melting because the geothermal gradient, this line is actually moving away from this solidus line. So, therefore, it has to be a contribution of decompression melting.

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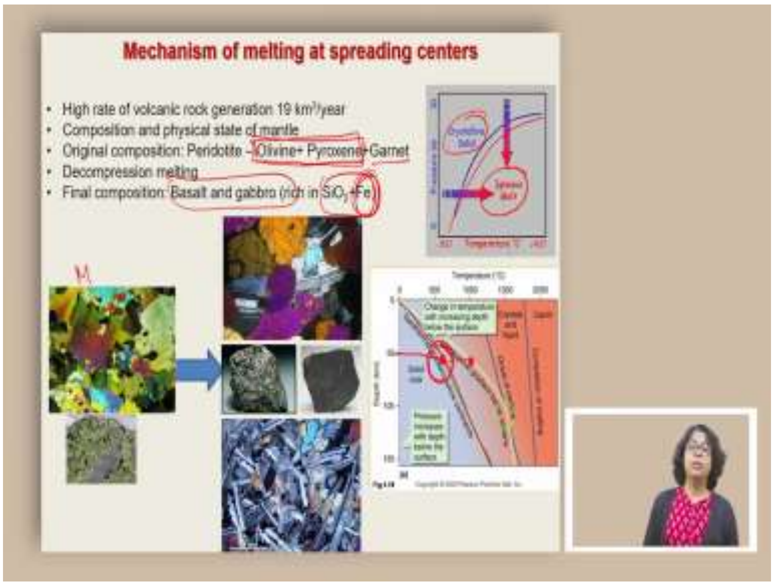

So, again to recapitulate, this is our temperature, this is the pressure and this is the line beyond which this is actually separating line between crystalline solid and igneous melt. And what we see in the areas of geothermal gradient below continents, they look something like this. So, that basically means, at the same depth, the areas below continent are going to be not so hot. But if you go to the same depth and encounter the oceanic geothermal gradient, it is going to be much hotter.

And when these divergent boundaries are encountered, this is a place where because of this rifting, the ambient pressure, overlying pressure on the rocks underneath is fairly low, it reduces and because of the drop in pressure, they tend to melt more easily. And this is a place where the rate of volcanic rock generation is extremely high; we are talking about 19 Kilometer cube per year. And these are the major production factories of volcanic rocks. All around the oceanic lithosphere wherever there is a mid oceanic ridge, we can expect this high production of volcanic rocks.

In comparison, if we look at the continental lithosphere even if there is rifting, we are going to expect a relatively lesser amount, lesser volume of volcanic rock generation because one part of it also lies with the fact that for continental lithosphere, even if it is rifting, the temperature requirement would be slightly higher, we are talking about relatively thicker areas and what kind of rocks would they form?

So, when we are talking about volcanic rocks, we know some of the important points such as that they are cooling down at the surface and therefore they are going to cool very fast. And therefore we are going to expect relatively small crystals, probably there will be parts where there will not be any crystals formation and it will be completely volcanic glass. But that does not tell us anything about the composition. So to know the composition, we have to understand what is the original composition.

And the original composition, because it is coming from the mantle like any other magma, the original composition is peridotite, which basically means it will have this mineral olivine and pyroxene and a bit of Garnet. We primarily talked about olivine and pyroxene and we are going to focus on that. So these are minerals, which are sitting at the very top part of the silica tetrahedra. It is primarily made up of a single silica tetrahedra, which we call independent structure. And for pyroxene it is a chain structure.

Now from there, it starts to have a melting which is called a decompression melting because you are reducing the pressure. But the final composition of this, do no longer remain this olivine pyroxene combination producing peridotite along with a few garnets. It is actually going to make something called basalt and gabbro. So, again, please recall how things are melting. When they are melting, the things that will melt first are going to be the silica rich phase and therefore they are going to be rich, the melt phase are going to be rich in silica and iron, a bit of iron and once they solidify, they are also going to reflect that.

But it is important to remember that when things start to melt in the magma, they are going to be primarily rich in silica, the lower part of Bowen’s reaction series or the lower part of the silica tetrahedral structure, the three dimensional network structure. So those are going to melt first, and they are going to contribute relatively heavily in these kinds of rocks. Yes, it is true that it will also have some iron component and producing basalt and gabbro.

So if we look at the rocks, how do they look like? Mantle peridotite will look something like this, because of the olivine, they look greenish. Also, because they also have pyroxene. But then the rocks that are forming in the divergent boundaries in the mid oceanic ridges will vary anywhere between gabbro and basalt and you see the change in the crystal size depending on how fast or how slowly they are cooling. These pictures are microscopic pictures.

So if we cut that rock and look at it under microscope with crossed polars, so in polarized light, we are going to see these minerals, and these minerals are basically showing how these rocks have formed and these, the identification of minerals are much more accurate when we are looking at their optical properties under the microscope. So looking at these microscopic features of minerals, it is quite clear that although it started from the peridotite, it eventually produces basalt and gabbro in the areas of divergent boundaries under the ocean. So, we will eventually find a lot of production of basalt and gabbros.

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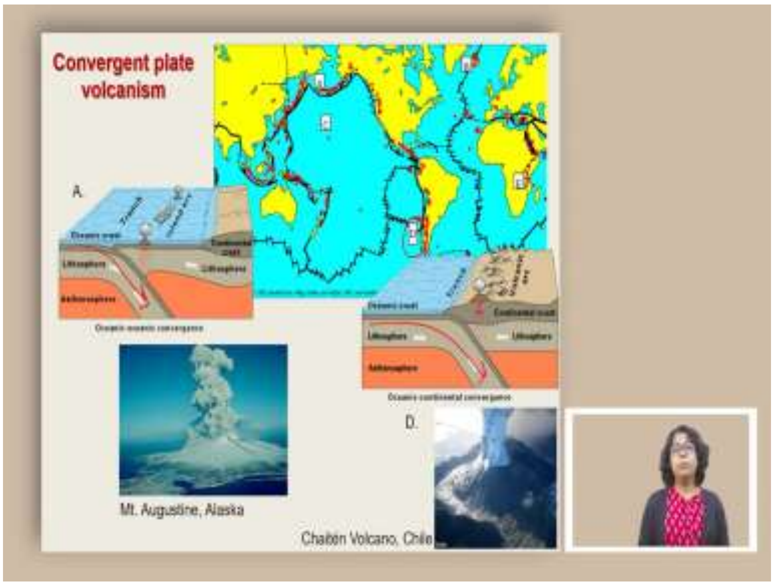

The conversion plate volcanism actually works in a slightly different way. So, again, we are talking about where the lithosphere is going under another crust, and it can be a continent-continent collision, it can be an island-island convergence, it also can be a continent-ocean convergence. When we talk about the continent-ocean convergence, because oceanic crusts are denser, they will have the tendency of going down underneath the continental crust.

If it is a continent-continent convergence, often because both of the plates are relatively light, they will have lack of any subduction. They often collide and make long mountain chains such as Himalayas and melting is relatively limited. So therefore, we are going to skip it at this point, we are also going to focus on oceanic-oceanic convergence. In oceanic convergence, which plate is going to go down is going to be dependent on the density. And the density of two oceanic plates depend on how far ago they were formed.

Because as they cooled down, as they get old, as they cool down, they get even denser. And because of that; old, cold, dense oceanic crust will actually subduct underneath relatively newer, more hotter and slightly less denser oceanic crust. And examples of such convergence is found in Alaska, where we do find quite a bit of magmatism. It can also be found from areas like here, where in Chile, we do find magmatism. What is the primary mechanism of such volcanisms of rock melting in convergent boundaries?

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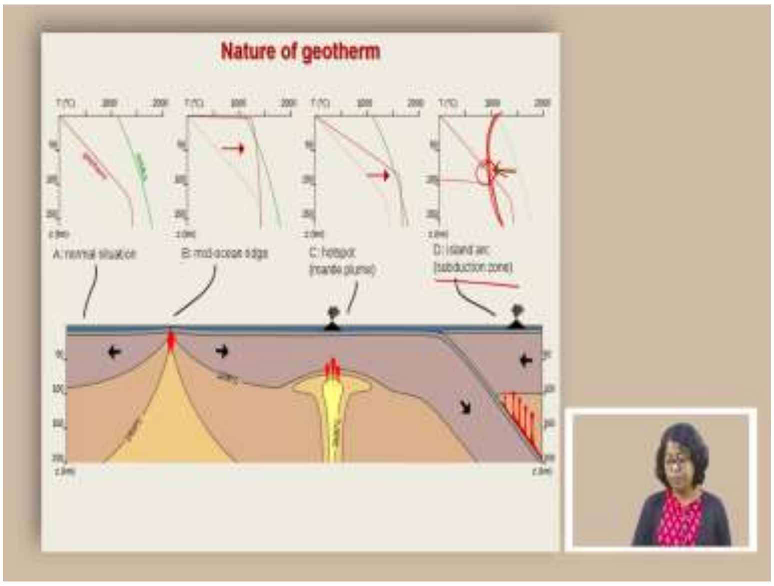

So again, a quick look at the nature of geotherms. We are talking about these subduction zones. If it is an oceanic-oceanic convergence, often it develops an volcanic island and a chain of volcanic islands and they are also called island arcs. So the geotherm stays the same, but then the solidus actually shifts. So unlike this one, the geotherm does not really shift, the geotherm stays the same, but suddenly we find that the solidus is actually moving towards a low temperature phase.

So in other words, something is happening around that place, which makes the rock melt at a lower temperature than what was originally required. And because it is happening right around here, because if we look at how it progresses, it used to be like this and now it progresses here, that basically means that it is changing much more at a deeper part. So, we have to observe how the solidus line, why the solidus line is changing at a deeper part and why does it require lesser temperature for melting.

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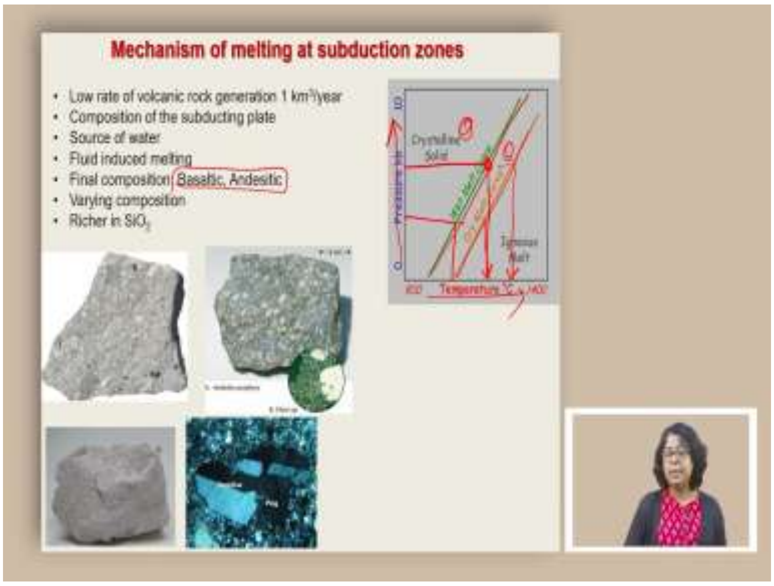

And what we find is, this is the region where the fluid induced melting actually helps a lot. Because this is the part where the plates are going down. As they go down, they initially have an increase in temperature and also a bit of pressure, these are the situations where the volatile will be released, the hydrous minerals will lose the trapped h2o inside and all of these are going to contribute to the area surrounding it and making them melt. It also depends on the composition of the subducting plate, because if the subducting plate has a lot of sediments, and those sentiments have pore fluids, they also additionally contribute, making them melt even faster.

And the final composition of it is going to be basaltic and andesitic. So, if you recall these are, basalt, we all have already seen, but andesites are things which are of intermediate composition. So they are not completely felsic, they are not mafic, they are actually of intermediate composition. And we do find quite a bit of andesitic volcanism associated with subduction zones. So, when we look at the pressure, where pressure is increasing, and temperature is increasing, we do find that this is the wet melt curve, that means the wet melts faster than the dry melt and it kind of goes to the melt phase at any point of pressure at a lower temperature than the same pressure at higher temperature which is required for the dry melt.

So, given a specific pressure point, at any point of time, you can predict that if the rock has hydrous mineral or you are adding water, because of the pore fluids, it will go from crystalline solid to a melt phase at much lower temperature than if you had to do it for a completely dry rock which will require a much higher temperature. And because of this, subduction zones will see the fluid induced melting. The production of volcanic rocks in these places are much less compared to the divergent boundaries in the oceanic plates that we have seen before.

Here the amount of rock generation, volcanic rock generation is only 1 kilometer cube per year and the overall composition will have a tendency of rich enrichment of SiO2, but variants in what kind of composition you are going to see associated with subduction zone is going to vary a lot simply because the composition of the subducting plate, the amount of water there is in the subducting plate will contribute a lot in determining what would be the final composition.

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The last one that we are going to talk about would be the intraplate volcanism. So here also, we are going to talk about this examples where it is within a plate and it is relatively short area where we are finding these volcanisms. Now the primary responsible mechanisms are decompression melting and the way it happens is also related to how the magma is rising.

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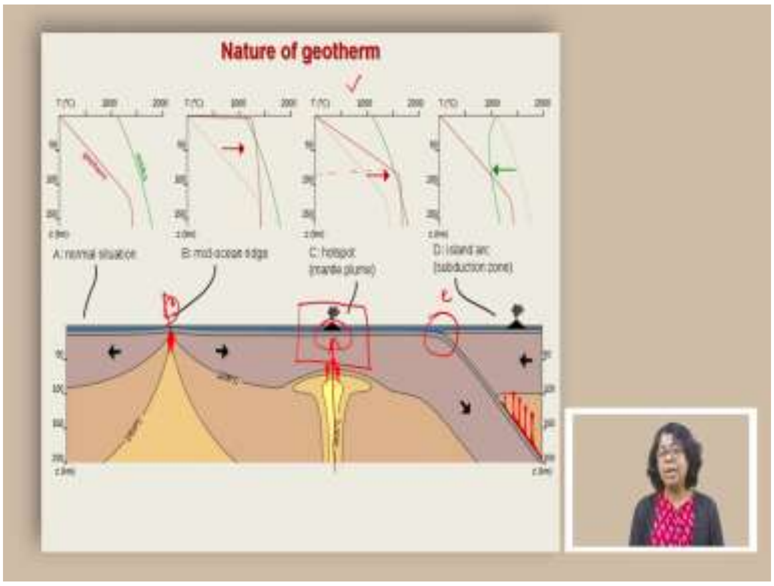

So again, let us concentrate on this one. So now we are looking at a geotherm movement. So the geotherm actually moves closer to the solidus line at a particular depth, and therefore it starts to melt. So, these hotspot or mantle plume activities start with a relatively deeper part of the mantle where magma which is very hot, it starts to rise because of increased buoyancy. And when it rises, it also forces the surrounding rocks to melt because it is also heating up the surrounding rocks.

Part of it, when it starts to solidify, it also releases more heat to the surrounding rock, again, melting them farther. And because it is a relatively narrow zone along which it is moving up, and starts to melt, things like here, it is not going to give you a extended area of volcanic activity along a plate boundary. So this is happening far away from any plate boundary. So in this cartoon, you can see this is the subduction zone which is a convergent plate boundary; this is a mid oceanic ridge, which is a divergent plate boundary. And then this hotspot activity is creating a volcanism which is far away from any of these boundaries, it is happening within the plate.

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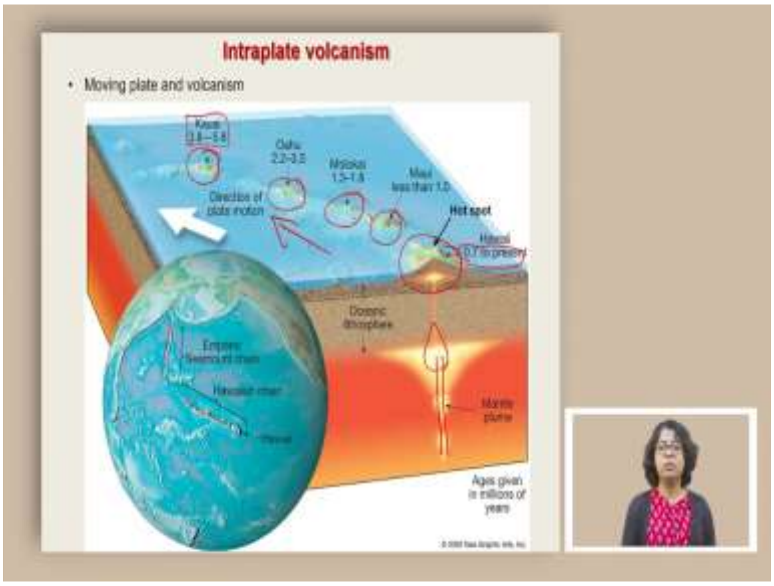

Now when I said that it is going to create volcanism, not a lot of volcanism, I was actually talking about within a small scale. Now, if you recall, that Pacific Ring of Fire where we have along the plate boundaries, a lot of volcanisms; in the intraplate volcanism it is primarily concentrated in a smaller zone. However, there can be series of volcanoes and a series of volcanoes that we have, it has nothing to do with continuous volcanism happening at the same point of time, creating these volcanoes simultaneously, which is the case of these convergent boundary volcanisms.

In convergent boundary volcanism, the entire plate boundary sort of gets involved in the volcanic activity, and therefore, the volcanoes that arise out of this will have the same time along which they are erupting or they are forming. But if you look at these intraplate volcanism. they are corresponding to a single source of magma generation and because of the plate movement, the plate slides on top of the single mantle source, so you can kind of imagine that this being a candle, and on top of this candle, if you keep on moving a paper, you are going to see burn marks on a chain like fashion. And this is exactly what is happening in the intraplate volcanism as a correspondence to a mantle plume.

So if we look at the classic example of Hawaiian volcanoes, what we will find that there are actually a few, a chain like volcanic series in that area. However, when we date them, when we recognize their ages, we realize that the one which is still active is the youngest and the one, which is farthest away, is also the oldest, because when this point was active, the plate was actually right on top of this mantle plume, and then as the plate moved in this direction, it progressively made this volcano followed by this volcano, followed by this volcano, and eventually now it is situated here.

So, once you have the ability of dating it, it is also possible for these scenarios to calculate how fast or how slow the plate is moving on top of this fixed point of mantle plume. The reunion hotspot close to Indian Plate is also an example of such an activity. Now, let us summarize what did we learn today. So we talked about different plate boundaries and what is the relationship of such plate boundaries with volcanic activity and magmatic activity. We also learned in each of these plate boundaries, what are the responsible mechanisms of rock melting.

Finally, we also tried to understand the difference in the production of rock and composition of rock in each of these boundaries. If we remember all of these things, it is possible to recognize a particular plate tectonic boundary in the old record, just by recognizing all these factors of rock composition, their crystal structure, their texture, and connecting it to the present day plate tectonic activity. There are some resource materials that I have shared, as well as some questions for you to think about. Thank you.

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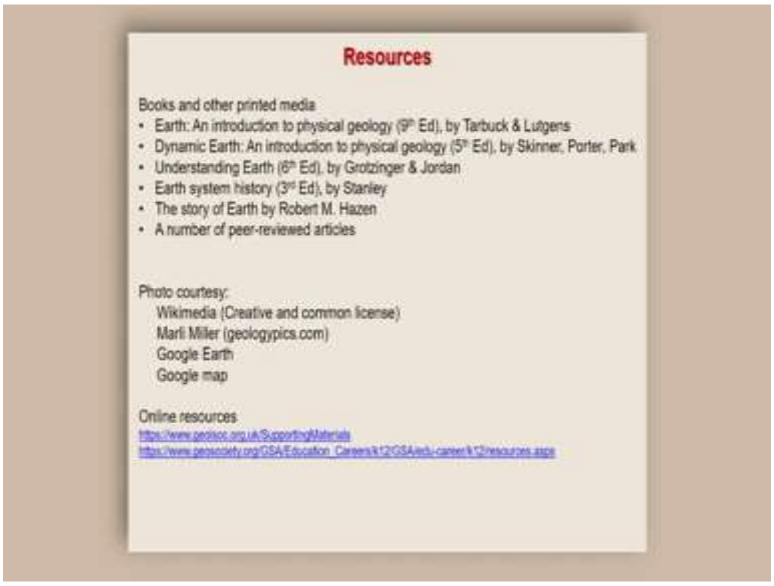

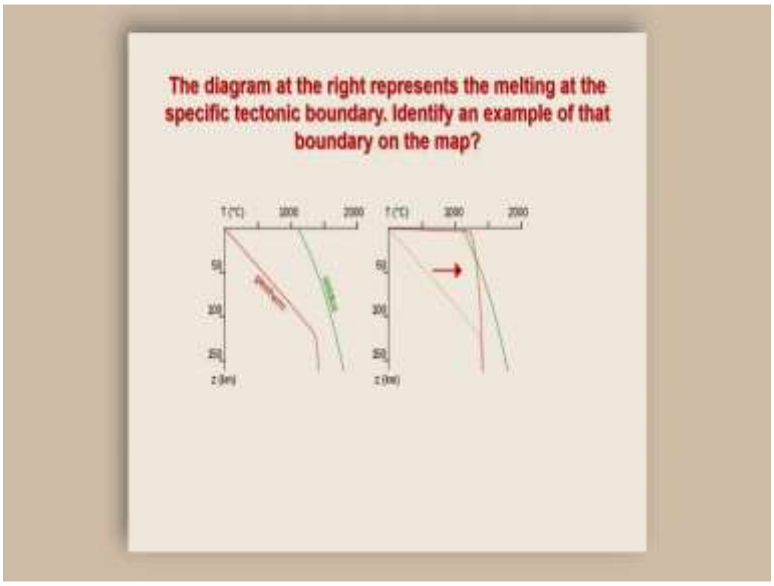

Here are some resources that I used for making the lecture. And here is a question for you to think about. Thank you.