The Evolution of the Earth and Life
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Why Does the Rock Melt?

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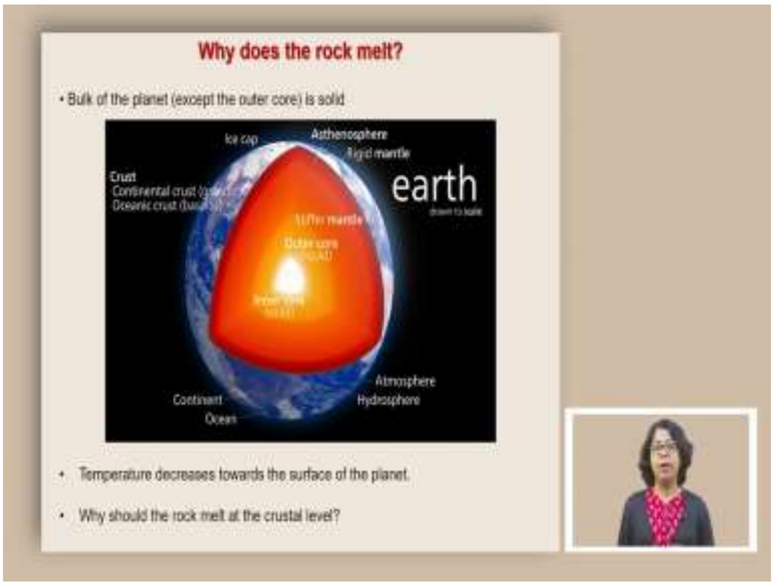

Welcome to the course evolution of the earth and life. Today we are going to learn something about how does the rock melt. If you think about the structure of the earth, it has different layers. At the very top, it has the crust, followed by the mantle and then the core at the very center. The crust is primarily solid; mantle, although it is solid, it can flow. The core has two parts, the outer core is liquid, whereas the inner core is solid. Now, if we look at the structure of the earth, and how thick they are, each of these layers, it becomes very clear that the crust is very thin, and mantle and core primarily contributes most of the thickness of the earth structure.

We can compare it to something like an egg, where the shell is the crust, and the yolk is more like the core and the things in between the white layer once we boil it, that is something like a mantle. That gives you a general idea of how thick the mantle and core is in comparison to the crust. Now, when I talked about the physical states of each of these layers, we already said that the crust is solid, the mantle is also solid, although it has an interesting character that it can flow.

So except for the outer core, everything is solid. Now the question is, if the majority of the earth structure is solid, then how come the rock melt? Because without the rock melting, we cannot really have the development of igneous rocks. It becomes even more confusing with the fact that as we go down from the crust towards the inner part of the Earth, the temperature actually increases. It is quite clear from the experience of the miners. In the old days, when they used to go deeper in the mind, they used to experience higher temperature.

And just to give you a reference, all these mines are not at all deeper in the context of the overall thickness of the earth. It is barely touching the upper part of the crust, even the deeper mines. So the temperature increases with depth and most of the stuff inside the Earth are solid. But we still see that when the rocks are coming up from deeper part of the earth towards the surface, they are in the molten form. So it is important to understand why should the rock melt in the crustal level?

Now when we pose a question, it is also important to understand how do we address it? So researchers started thinking about these questions for a very long time. There were different approaches to address this. The first approach was the observation in nature.

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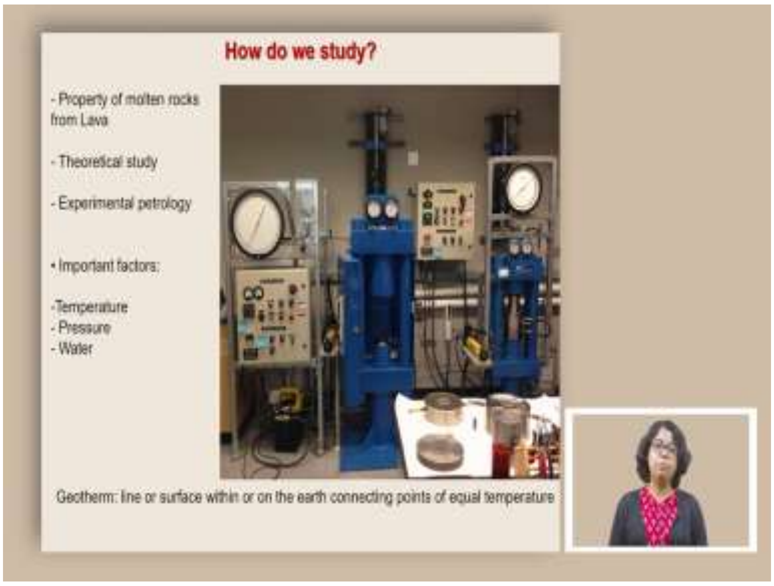

So they looked at the property of molten rocks from lava. So there are places in the earth such as Hawaii, where you do see molten rocks on the surface, and you can study them. That gives you some understanding of how long does it take for that lava to solidify. It also tells you something about, in what conditions does this lava remain liquid for a long time? It also gives us some understanding whether the lava cools down and makes a single rock at the same time or it cools down progressively and parts of the rocks are forming in a progressive manner.

So natural studies are very important and they were the first approach to understand the property of the rocks. The other approach that people took were more theoretical studies. If you know a little bit about the temperature required for the melting of the rock, maybe observing the lava and taking measurements of the temperature, you can also think about how they will behave if you change the temperature from some theoretical point of view about the basic properties of material.

But a more direct and controlled setup is the experimental petrology, where we study the rocks in experimental setup, and we control the temperature and other physical properties to observe the change. It has been believed that the natural observations although they were very, very important to do, it is not always possible to get the correct measurements of all the parameters that are changing and therefore, the experimental setup always gives you a much good understanding, much required understanding of things changing in a very, very controlled setup.

The experimental petrology has not been there for very long, it has a history of maybe 100 and 150 years and the latest advancements, technological advancements also contributed to the setup of experimental petrology. So, there are two major hurdles of experimental petrology, one is how to create temperatures which are so high that they can melt rocks and second is how to create very high pressure at the surficial condition, because all these experimental labs are on the surface of the earth.

And these are solved by making the area of study very small, it is possible to create extremely high temperature at a very, very small spot using lasers and other techniques. And at that pin pointed spot, the temperature can rise up to a level which mimics the deeper part of the earth. The same is true for pressure. It is possible to develop a mechanism where two very hard materials are pressing from different directions and thereby creating a very, very high pressure mimicking the situations of deep earth.

And through these studies of experimental petrology, researchers understood that the major contributing factors in controlling the melting of rock are temperature, pressure and water. Using these factors, one can very reliably predict which rock will melt at what temperature, pressure and volatile or liquid contribution. Now, when we talk about temperature and pressure, we also have to understand that temperature and pressure are not constant when we move from the surface of the Earth towards the deeper parts of the earth.

We already mentioned that temperature increases, but we did not really talk about the pressure, the pressure also increases as we go deeper part of the earth and how the temperature and pressure increase with depth finally tells us a lot about how a rock is going to behave at a deeper part of the earth. So, geotherm is the line or surface within or on the earth connecting the points of equal temperature.

And therefore, if you connect all the points of equal temperature, it also gives you a general understanding of how that line varies with the depth and that is generally, a concept that we will be frequently using, it is called the geothermal gradient. It captures the essence of how temperature and pressure are changing with depth inside the earth.

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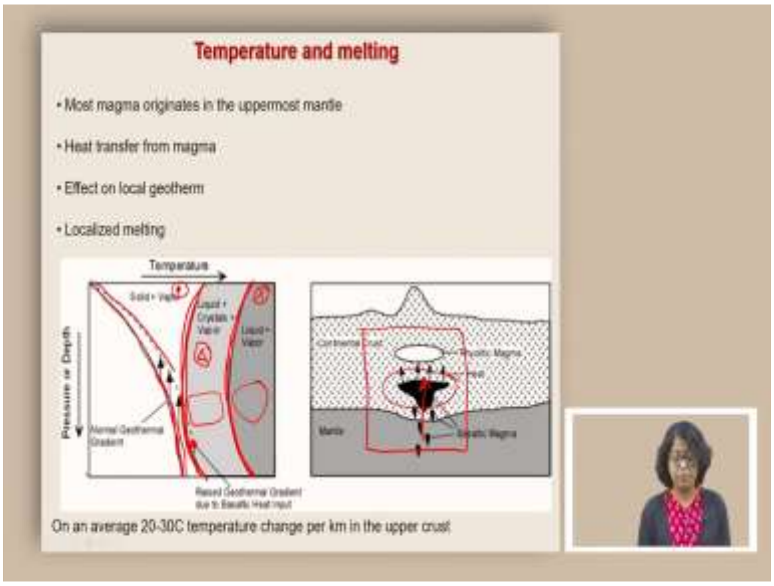

So, as I mentioned that melting is controlled by temperature, pressure and liquid, so we are going to talk about each of these factors sequentially. So, temperature, we know that with increasing temperature, solids have a tendency of melting. And from other observations, it has been reliably established that most of the magma originated in the uppermost mantle. Now, this is interesting, because we already mentioned that the mantle is actually not liquid, it is solid. So, there are certain mechanism by which a mantle or at least part of the mantle can experience relatively high temperature and therefore, part of it can have lower density.

Once it has lower density or it sort of expands because of experiencing the heat, it becomes more buoyant and therefore, it rises. Once it rise, it basically is experiencing lesser pressure, and therefore, it expands more, and there would be a point, because of this pattern of temperature and pressure, it will start to rise up to the level of crust where the pressure is relatively low. And because it is still bringing quite a bit of heat with it, it will start to melt probably not the entire volume, but at least part of it.

Now, once it starts to melt, upon entering the crust, it will also heat up the surrounding rocks. And once it melts, the surrounding rock also starts to melt. Especially important factor is that there are minerals as we said that they have a tendency of crystallizing, when the temperature gets colder, and from this melt, there would be some crystals which will form because those temperatures are not hot enough for them to keep in the melt phase. As a result, they will separate out from these magma.

Once they separate out, this magma will also release a bit of more heat towards the surrounding. And this heats up the surrounding farther. So, a rise of the magma from the mantle to the crust actually ensures that it will initiate more melting in the surrounding rock. And these meltings are not complete melting, neither are they global melting in the sense of the entire crust does not melt. The entire magma also does not contain only the liquid phase. So we are primarily talking about a phase where there is liquid, there is solid as well as a bit of vapor.

And on an average as we go deeper part of the earth within the crust, especially where we encountered these magma on an average, if we go a kilometer, we will experience an increase in temperature by 20 to 30 degrees centigrade only within the upper crust the temperature changes slightly as we move into the lower crust or mantle. And this is what we meant by these geothermal gradient. So, let us try to understand this plot once more.

This part of the plot indicates one line on which all the temperatures are the same, this is the normal geothermal gradient. So, it shows you that as we are going; with depth, the temperature is changing, the temperature is actually increasing. The second important point about these plots are that there is a part right around here, which indicates that if there is a point beyond this, this point has the temperature and pressure combination, which makes it to go into a melt phase and therefore these lines can be called a liquidus.

There is also a line right around here which indicates that if there are points somewhere here, then the temperature and pressure combination is not enough to make it go to any melting and therefore these lines are called a solidus line. So anything that falls on the left hand side in this graph will be solid at this point, and anything which is at the right hand side of this liquidus line would be liquid in this particular graph. What happens if a point falls somewhere here?

In this case, this point is going to be of a composition, which will have some melt, and there would be some part of it, which is solid. And the composition of what is the geothermal line, where is the solidus, where is the liquidus, these control exactly how the rock is going to melt. So, the example that I gave you, in that case, when the magma is rising from the mantle, what we find is this normal geothermal gradient which is supposed to be right here, because of the release of heat from this magma, the overall geothermal gradient in that local area changes.

In this area, the geothermal gradient becomes slightly elevated. What we mean by that, that if we had a rock right over somewhere here, which would not have melted, but now, because these geothermal gradient is changed, the geothermal gradient has made it to an elevated portion, they will start to melt somewhere here, which otherwise would not have been possible. So, wherever this geothermal gradient intersects this solidus line or the liquidus line, we will start at least some level of melting here and probably a significant portion of melting here. So, it depends on the relationship between the geothermal gradient line and the solidus and liquidus line.

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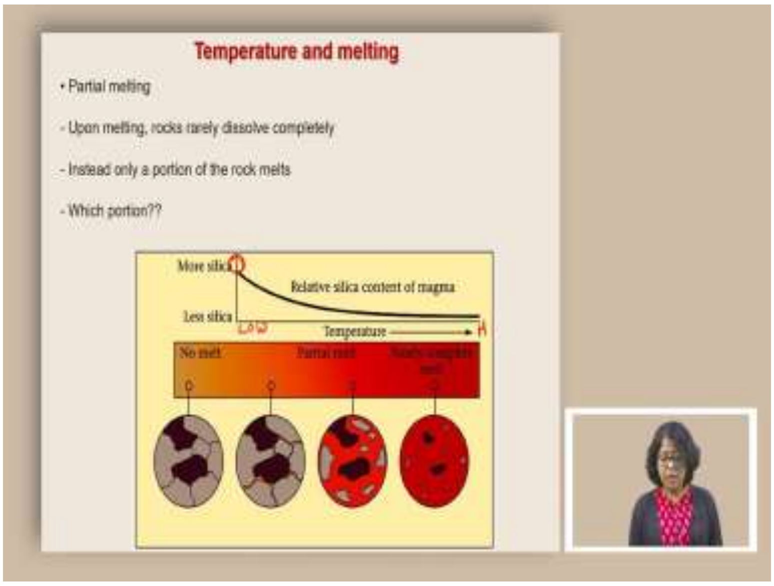

So, let us take a look at it further, where we are going to focus on partial melting. As I mentioned that partial melting is a phenomena, which is sort of opposite of fractional crystallization. So, in partial melting, you do have a melt phase and a solid phase, but it generally is when we do see increase in the temperature. So, with increasing temperature, just like fractional crystallization, the entire volume does not go to the same phase at the same point of time.

What we see, if we start with a solid rock and then increase the temperature, only part of it will start to melt at a single point of time. And eventually, we will see an increase in the melt phase and a decrease in the crystallized phase and eventually with high temperature, the entire rock will start to melt and this is the phenomena of partial melting and it also explains why we do not find a complete melt when the magma is rising from the deeper part of the earth.

Now, the question is which portion of the rock is going to melt first? And this insight also comes from Bowen's reaction series. So, the crystals, the minerals, which crystallize at the very very last phase, which require only a very small temperature or low temperature for crystallization, those would be the minerals and which will go to melting or which will melt first. So now, if we look at this diagram, which is the silica concentration, we see that this is the less silica and the silica increases around here.

So, with increasing temperature, we will find that the high silica actually melts at low temperature. So, this is the low temperature part and this is the high temperature part and what we find is if something has high silica, that actually melts at lower temperature. And if we go towards higher temperature, it can even melt silica which is low. So, it will start to melt, the silica part of it will start to melt first, increasingly going for minerals which crystallize at higher temperature.

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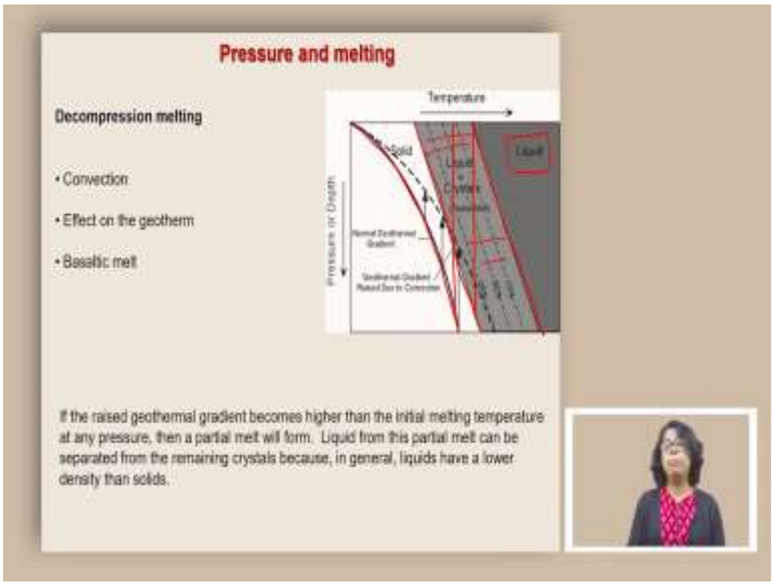

The second important component which contribute to melting is the role of pressure. And the way it controls the melting is something called a decompression melting. So, again, let us look at the normal geothermal gradient, which looks like this. And then we have our liquidus line beyond which everything is liquid. And we have our solidus line before which everything is solid. And this is the portion where we see partial melting.

Now, the geothermal gradient works in such a way that if pressure changes, pressure drops, it has this tendency of getting elevated. So in this place, it is quite obvious that if the pressure if it can be raised, it is going to hit the solidus line, and therefore, it will start to melt at a temperature which is much lower than what was the required temperature. So, if we basically draw a line from here, and draw a line from here, we will see that there are different requirements of temperature depending on whether something is elevated or not.

So for melting on a regular time, it will require a different temperature than if the pressure is playing a role. So when pressure is released, or there is not enough pressure, then what we see is, as I mentioned before, that it basically increases the buoyancy of the magma, and therefore it rises up. As it rises up, it becomes more buoyant, it expands in volume, and that contributes to the melting. It is not very different from how the other materials behave. We know that because of increased pressure, the boiling point actually increases.

And if we reduce the pressure, the boiling point goes down or the boiling point is much lower. So the same principle applies here. If things have very high pressure, then they tend not to melt, it has something to do with the structure. If it is quite compressed, it is hard to melt them. And if it is not so compressed, it can go to the melt phase relatively easily. And therefore, whenever you are decompressing something or if you are reducing the pressure without changing the temperature, it will have the tendency of melting.

And if the raised geothermal gradient becomes higher than the initial melting temperature at any pressure, then partial melt will form and liquid from this partial melt can be separated from the remaining crystal, because in general liquids have a lower density than solids, and thereby the magma will evolve its composition.

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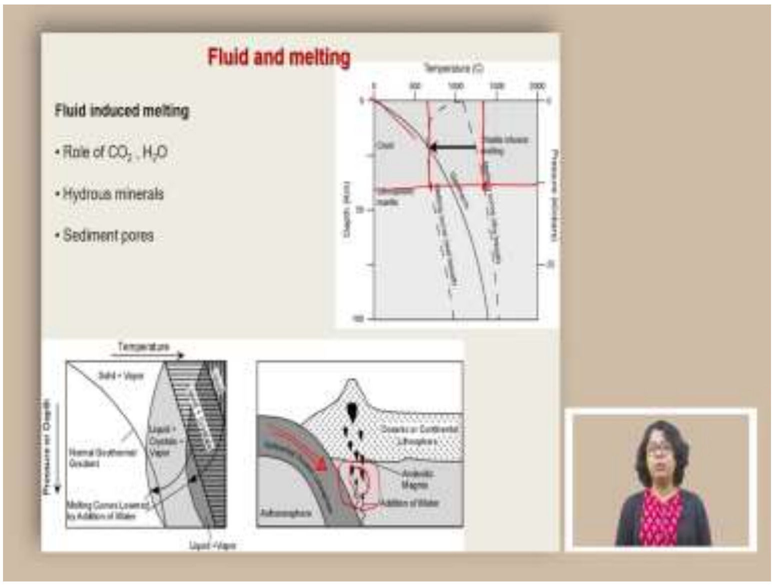

The last point or the last factor that plays a major role in terms of controlling the melting is the fluid. So, fluid induced melting is very important in geologic settings, in certain geologic setting, especially under the ocean. So, we are going to talk about it in detail, where we will see that the rocks when they have water vapor inside, they will behave differently than so called dry rocks. Now, how does it work? So, the water and the fluid inside a rock makes it go to melting more easily than a relatively dry rock. So, what kind of water are we talking about?

So, the way it moves is when the melting starts, the magma expands as I mentioned, and once it expands and because of high temperature and pressure where things are going inside the Earth, even before the formation of magma, because of this increased temperature and pressure, some of the volatiles will be pushed to be released from the rock and they contribute in the surrounding rock making the melt at a relatively low temperature and often at high pressure. It can also make some of the minerals which are called hydrous minerals to go to phases which are no longer hydrous and that contributes additional melting.

And there are other kinds of rocks such as sedimentary rocks, where there are pore spaces. So, we are not talking about water in the part of the minerals, but we are talking about the pore spaces within a rock and those pore spaces are often filled with water. And once you are pressing them and subjecting them to high temperature, they tend to lose that water and that water in turn also contributes to the melting.

So, again, if we look at the geothermal gradient, if this is the geothermal gradient, we see that for a dry basalt at a given point of pressure, the required temperature is somewhere between close to 1500. Whereas something which we are calling wet basalt is quite, require a quite low temperature, something around 600 degrees for melting.

And therefore, the contribution of fluid makes a big difference in terms of where a certain rock is going to melt. So, just a summary of what we covered today is that we tried to understand that in spite of the fact that the earth is mostly solid except for the outer coal, why do we find molten rocks? We also tried to understand that even though the temperature is increasing as we go deeper part of the Earth, how do the rocks melt at the crustal level?

We also understood that what are the roles that temperature, pressure and fluids play in terms of melting a rock, and those help us to understand where we can expect melting of the rocks and which are the factors that are contributing to this melting.

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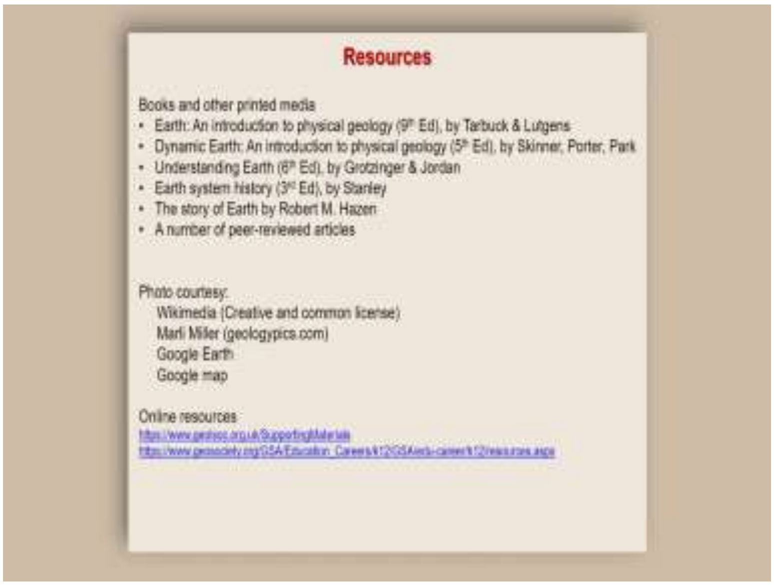

Here are some of the resources that I used for the slides. And here is a question for you to think about. Thank you.