The Evolution of the Earth and Life
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Igneous Structures

Welcome to the course, evolution of the earth and life. Today we are going to talk about the journey of magma from the deep earth to the surface.

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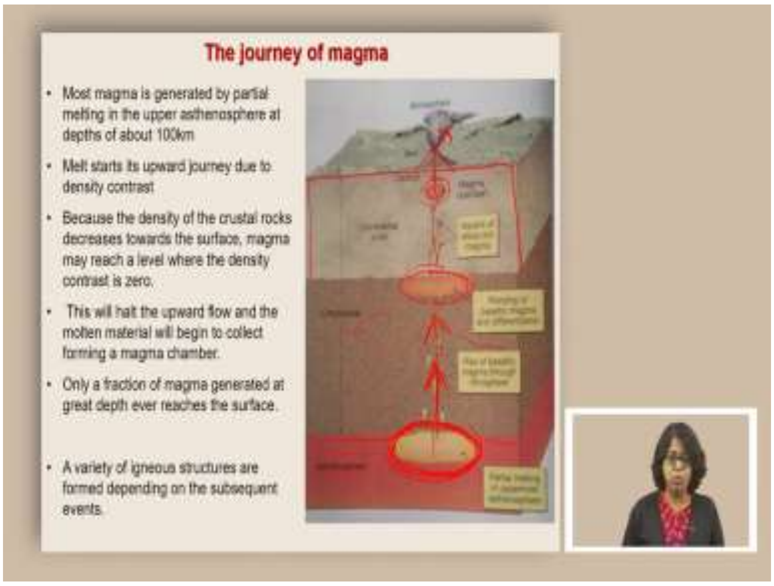

Most of the magma is generated by partial melting in the upper most asthenosphere, at depths of about 100 kilometers. Asthenosphere is part of the mantle, and the reason the magma starts to rise up, is because of the density difference. So the rocks in the asthenosphere are quite dense and once, because these magma are partially molten, they become relatively less dense, and hence they gain buoyancy, they start to rise up.

But the situation does not stay constant as they go up because the density of the rocks that we encounter in asthenosphere versus in lithosphere, or in the crust is different. So the crustal rocks are generally less dense. Whereas the rocks in the mantle in the asthenosphere, they are quite dense. So there would be a point in the magma’s journey, upward journey, where they are going to eventually encounter a situation where their density is pretty similar to the density of the surrounding rock.

In that situation, they are going to stop, they are not going to move upward. And that is what we mean by a density contrast of zero. It can also happen that it can still rise a little bit and encounter rock which is relatively lighter than its composition, and hence, stop. But in general, wherever it is going to encounter materials, which are not denser than their own composition, they tend to lose their buoyant force, and therefore they will not rise upward anymore.

What that means is they are going to stay in a place and accumulate more and more magma because these magma, this part of the journey still continues. And this is the place which is generally called either around here or somewhere here, it is called a magma chamber. Now, it can so happen that this magma chamber can freeze and eventually give rise to rocks underneath the surface. It could also happen that part of this magma chamber for certain reasons can come to the surface, and eventually we can see formation of igneous rocks because of these magma chamber activity on the surface.

What will happen whether the rocks are going to form inside this underneath the surface or above the surface depends on how the magma chamber is behaving? What is the composition of the magma? What is the temperature profile like of where the magma chamber is forming? And also what is the amount of volatiles involved in it. So a variety of igneous structures can form depending on the subsequent evolution of this magma chamber.

And in today's class, we are going to discuss some of these commonly found structures. Unlike our common understanding of when we hear the word igneous rock or magma, we immediately think of our triangular shaped volcano and magma emanating from that, it is not always true. In fact, only a small fraction of magma that is generated at great depth ever reach the surface. Many of these magma which actually start from the asthenosphere never reach the surface, it actually forms various kinds of igneous structures inside the Earth.

In fact, it never comes to the surface. And those kinds of structures are called plutonic structures. So we are going to see some of these examples.

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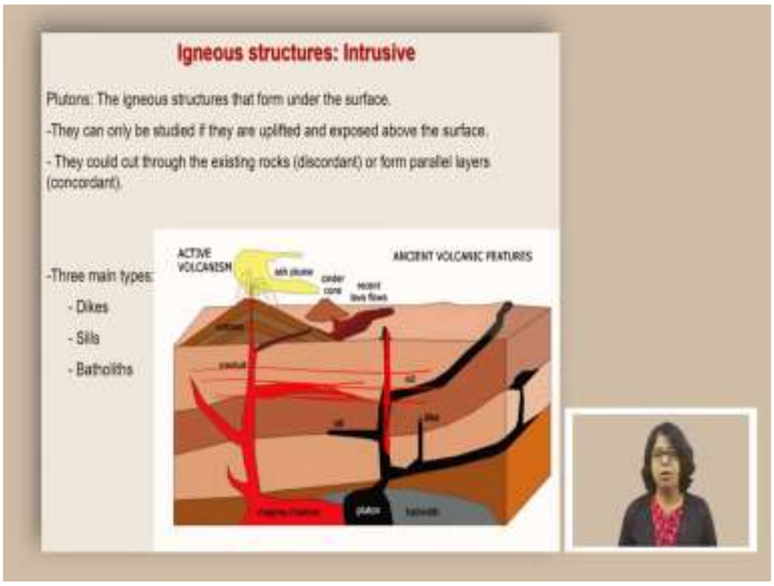

So plutons, the definition of plutons are the igneous structures that form under the surface, it never comes on the surface when they are forming. It is possible that once they form underneath the surface, subsequent geologic processes such as uplift may bring them to the surface. As a result, we do see a number of plutonic structures on the surface, but by definition, they must be forming underneath the surface.

And the only way they can be studied in detail is if they can somehow be brought on the top of the surface and therefore, we can study them in detail, we can sample them, we can look at their structures, we can look at the rock composition either by looking at the hand specimens or by making thin sections and looking at the detailed composition as well as texture of those igneous rocks. But, they could also do other kinds of things such as they can cut through pre-existing rocks and these kinds of relationships also tell us something about the relative age of such an event, such a plutonic event in comparison to the pre-existing rocks.

And we are going to talk about it in great depth when we discuss the concept of relative time, relative geologic time. Today, we are going to focus more on how these structures form and what do they look like and what are the different types. So, as long as these plutonic structures are cutting pre-existing rocks, then they are called discordant structures. So, one example would be if the pre-existing structures have a pattern like this, and if there are structures, igneous structures which are crosscutting this pre-existing rocks, then these will be called a discordant structure, but they can also form parallelly to these structures.

In those cases, they are going to be called concordant structures and we can see one example right around here. This red layer is a concordant structure. So, there are three major types of such igneous structures and these are called dikes, sills and batholiths. There are plenty more structures that we can find, but I am going to restrict today's discussion on primarily these major structures, and they are all called intrusive igneous structures.

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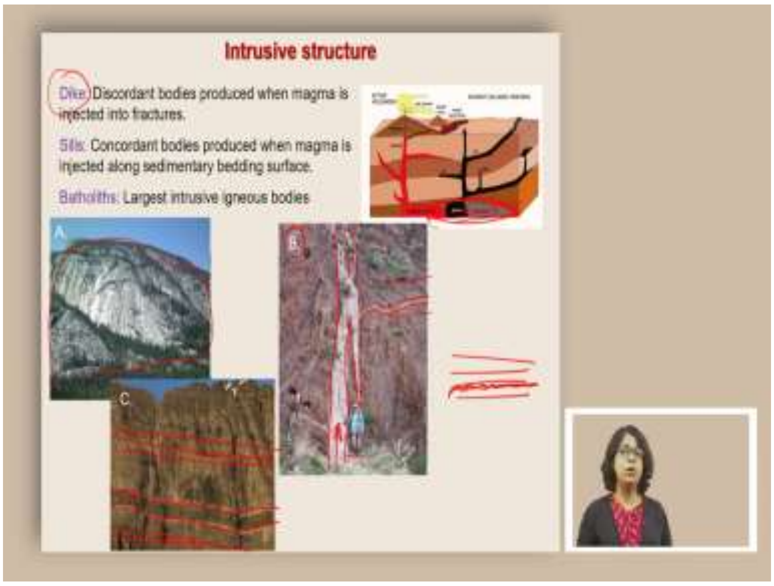

So, let us look at these three different structures and how do they look like. Once they are uplifted, brought on the surface and we can see them in the field in the exposure. So, the first one is called a dike, it is a discordant structure. So, by that we mean that it crosscuts pre-existing rocks and it is generally a narrow structure where the magma has been injected through fractures, and these fractures have to be perpendicular to the or roughly perpendicular to the pre-existing rock strata.

So, here I have put these pictures not in a regular fashion, it is just to adjust your eyes to which kind of structure would be connected to which definition. So, if you look at this structure, structure B, we see that the general rock orientation is somewhat here. But then we find this particular rock which is cross cutting all these rock strata and therefore, this would be an example of a discordant structure. It is quite a big structure because, you can see a scale of around six feet and there is not just this one structure. In fact, in this figure also there are other structures too.

For example, there is a structure are right around here, which is not cutting across, it is actually parallel. So, the one which is cutting across, it is a narrow structure, it generally forms when the magma is protruding through these fractures along the rocks. These are the kinds of structure what we call a dike.

There can be parallel structure also and those are the structures which are called sills where the magma injected along the sedimentary bedding surface. What that means is if you think that the existing rock is a sedimentary rock, sedimentary rocks have this tendency of forming layers and if those layers are showing parallel relationship with an igneous body, then that igneous body is going to be called a sill. So, an example is here. So, if you look at this particular igneous body, this igneous body is parallel to the structure of the pre-existing sedimentary rock.

And this one is going to be called a sill. In contrast to these dikes and sills which are relatively narrow structure, and they often show a pattern where they are moving along the fractures either parallel to the bedding plane or perpendicular to it, batholiths are large bodies. So, this is an example of a batholiths. The entire structure is a batholith, it is a large intrusive igneous body.

So you can imagine, if the a large portion of this magma chamber moves through the pre-existing rock, it is going to create a sort of structure less unit, which is going to be parallel as well as perpendicular to the pre-existing rock simply because it is really large, these are going to be called a batholith. So one example of batholith in the cartoon diagram will look something like this. So it has a direction in the parallel sense of the strata but it also cross cuts some of the pre-existing rocks around here. So it is a massive body.

And these are very, very common intrusive structures that we can find. And it also tells you that because they originally formed inside the surface, their texture is going to be very characteristic, you are going to encounter relatively larger crystals, because they have cooled down very, very slowly.

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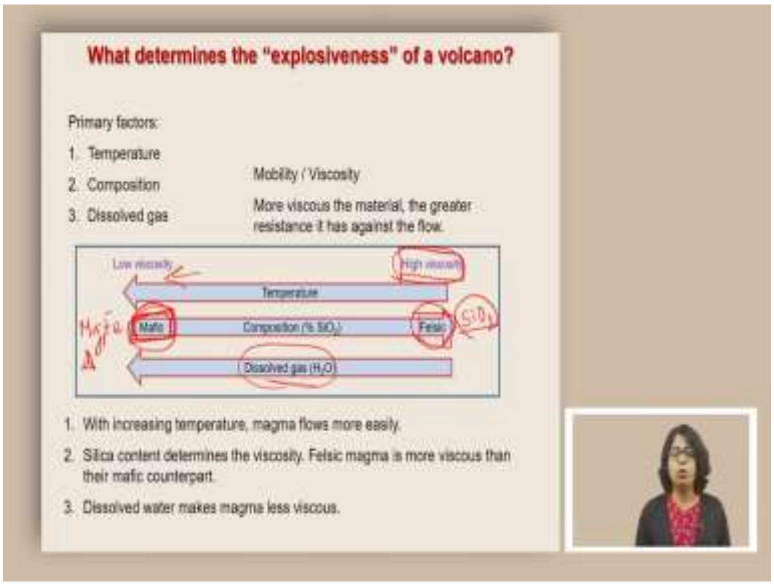

Now we are going to focus on more about volcanoes, which are examples of rocks that form outside the surface or they are extrusive in nature. So again, let us try to understand that we talked about intrusive rocks, which form underneath the surface. Now we are moving on to a situation where the magma actually reaches the surface and creates some structures, igneous structures, and we call them volcanoes.

Now the question is, we already talked about this that once the magma reaches a certain position, where the surrounding rock density is similar to the magma density, and then therefore it stabilizes there, it does not rise up and it stays in this magma chamber. But then there are situations where it actually moves up from this magma chamber and reaches the surface. So it is important to understand what triggers this upward movement from the magma chamber.

And the three major contribution of this change comes from temperature, second is composition and third is dissolved gas. And when we are talking about movement from the magma chamber, it is worth mentioning a specific parameter which is called viscosity. So viscosity, roughly you can think about how sticky a material is. So, the stickier the material is, the high viscosity it has. So if something is very sticky, and it puts a resistance to movement, then it is called a viscous material.

A material which has low viscosity will have higher mobility. So, if we take a very common example between water and honey, both of them are liquid, but if we let them flow, we will see that water moves faster and it moves very smoothly. And that means water has low viscosity, whereas honey, which puts a lot of resistance to flow, they will be more viscous. And how does these factors such as temperature, composition, dissolved gas plays a role?

Well, with increase in temperature, the mobility increases. In fact, if you make the fluid warm, generally they tend to have more mobility. As a result, they can flow they do not put in so much resistance that they used to do at a lower temperature. So, they basically lose their viscosity. So, a thumb rule is, if you are increasing the temperature, they will have a lower viscosity and hence, they will move faster. But if you drop the temperature, they tend to behave in a more viscous way and they will have very high resistance to movement and that works for the magma.

The second important thing is the composition. The viscosity is dependent on the composition of the magma. So, if we look at the silica composition, we can recall that there are two major types of igneous rocks and one is mafic, the other one is felsic. In the mafic, we have talked about it that we find Mg and Fe, and that is where we get the name mafic. Whereas, in felsic, it is primarily feldspar and quartz, and therefore, it is very rich in SiO_2.

Now, the silica, if you recall the structure of the quartz itself, it is a three dimensional structure and it basically puts a resistance to mobility. Whereas, the ones which are in the mafic, and they are independent, silica tetrahedra, and they have relatively low viscosity. So, when it comes to mobility of the magma, if you are talking about mafic rocks or mafic magma, they tend to flow relatively easily, whereas, we are talking about felsic rocks, they will put a lot of resistance to movement.

And therefore, the more silica rich magma becomes, it will have high viscosity, it will not like to move. The third one is the dissolved gas. Now, the reason behind the dissolved gas and primarily water vapor, and its contribution to viscosity is a bit more complex and therefore, we will not go into the detail, but roughly what it does, it basically stops the long chain formation of the silica tetrahedra.

So, the more water you put in, it will tend to behave more of like independent silica tetrahedra and therefore, it will have low viscosity. But if you do not have enough water, then it will tend to have very low silica tetrahedral structures, more connected silica tetrahedral structure, as a result, it will have a very high viscosity. So these are the three major factors that finally control how a magma is going to behave once you change the temperature, composition and dissolved gas.

Now, let us start to imagine from the magma chamber. So, in the magma chamber, we have these magma residing. Do we have reason to believe that these things are going to change? Well, there can be. One very common way of changing things, changing the stability, the influx of new magma, the moment influx of new magma comes to this magma chamber, often they are much hotter.

So that means in the entire magma chamber, which cooled down considerably over time, and therefore gained a relatively high viscosity, you are suddenly injecting newer magma which is hotter, and therefore, it is increasing the temperature of the overall magma chamber, making it low viscosity material overall, because the temperature is increasing. The moment it becomes relatively low viscous, it will have a tendency of movement. The second thing that happens is, again in the magma chamber itself, some of the materials are settling down following the Bowen's reaction series.

And the things that are going to settle down first would be the mafic material and if the mafic material is selectively settling out of the magma, then it will be rich in felsic material, making the SiO_2 high in the magma, making it highly viscous material. The other thing that can happen is because the magma chamber is also often connected to the surface, this reduces the pressure in which the magma is residing and as the pressure reduces, the dissolved material is going to behave in a different way.

And the other reason is, once the mafic portion precipitates or crystallizes out of magma, the relative proportion of the dissolved gas and H_2O actually increases and that makes it more viscous. So you have factors which can contribute either to low viscosity or to high viscosity. But it all depends on the combination of things that are working on the magma chamber.

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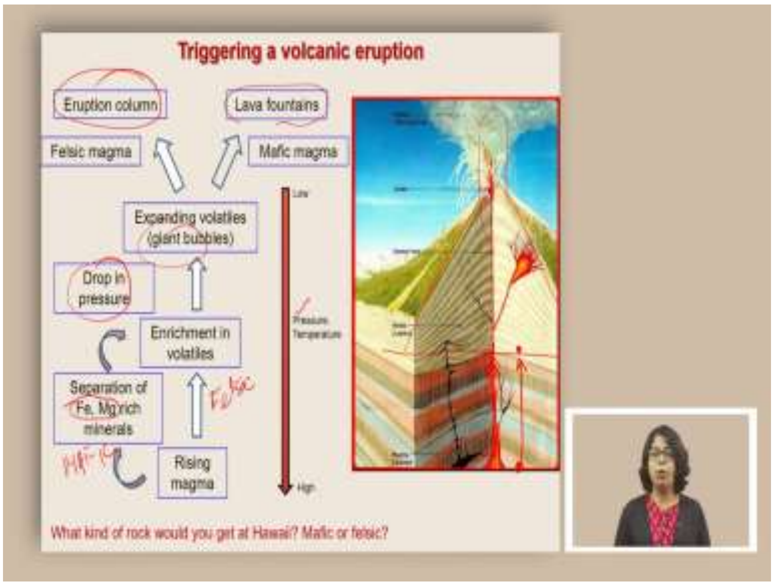

So let us go through the steps once we start with the rising magma. So when we think about a general structure of magma coming out to the surface, we generally imagine a structure like this, which looks conical, and magma comes out from the surface. But at the start, it does not have to be a conical surface, it can be a flat surface through which the magma is coming out. Now, when we come from the deeper part to the shallower part, the changes in physical parameters would have these components.

One is the pressure. So as we are going from this point to this point, the pressure is actually dropping. The second one is the temperature. The temperature is also dropping as we are moving up. So what is going to happen is as the magma is coming up, it is experiencing lower temperature and lower pressure. Now lower pressure can increase the volatile volume, and we will come to that in a minute. But first, because things are rising up, and also because things are losing the heat, we are going to see first settlement of certain minerals, and those minerals are going to be rich in iron, and magnesium.

So we are going to see the separation of mafic minerals. So what that means is the remaining magma is going to have an enrichment of felsic mineral and it is also going to have an enrichment in volatiles. So we are not adding extra water or any other volatiles. It is simply because you are trying to conserve the proportion. Once a certain material is removed the relative proportion of the volatile increases. And this relative proportion of increment of the volatile further helps the magma to become less viscous so it can move.

Further, there is a drop in pressure again, because it is sort of rising up. Once the drop in pressure happens, this volatiles start to make large bubbles, we can kind of imagine this situation where we see a very warm coke bottle and we will see there would be the moment you open the cap, you are reducing the pressure and you will see that the coke bottle actually fizzes out and it is creating a large bubbles.

So similarly here, the moment you are removing pressure as it is going up and encountering lesser and lesser pressure, it is going to create larger and larger bubbles, often they are called giant bubbles. Now, if we are talking about primarily felsic magma, where the silica proportion is somewhere around 70 percent to 80 percent then they are still quite sticky, because as we said that silica actually makes them highly viscous. So they cannot really flow, but they have enough or lack of pressure or loss of pressure. which basically pushes them to go up and they also have giant gas bubbles.

So both of these things in combination is going to make a column, which is consisted of all kinds of magma and it erupts, and then it falls down and these are called eruption columns, which are typical of these felsic magma. On the other hand, there can be mafic magma, and mafic magma does not mean that it does not have any silica. It simply that in contrast to felsic magma, the mafic magma has a relatively lower proportion of silica, probably we are talking about something around 50 percent to 60 percent of silica.

And in that case, it is going to have a higher mobility. So therefore, it is going to move in a much smoother manner, and it is going to create a lava fountain. So it is hot lava coming up to the surface, creating a smooth, not very explosive, or eruptive nature, but it is a relatively smooth flow, which can go up and these are called lava fountains. Now, what kind of material comes out when we are talking about the final eruption, finally, when the magma reaches the surface?

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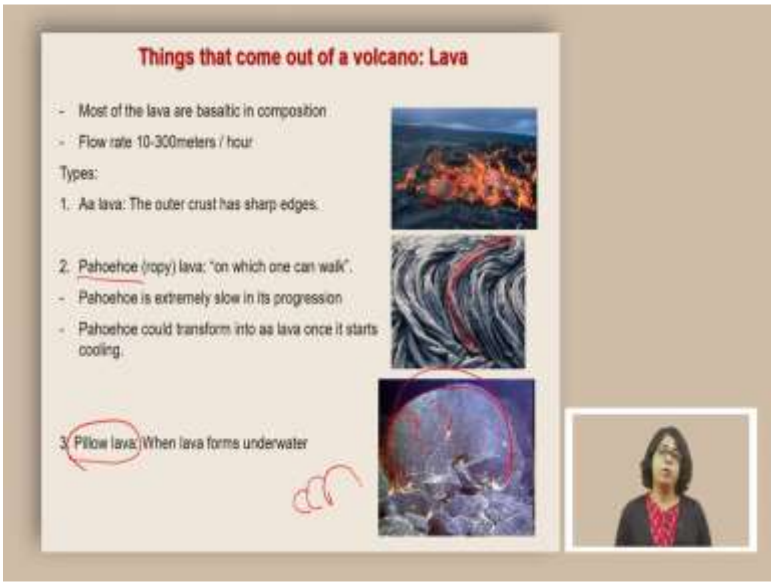

So there are again different kinds of components, there is a solid component, there is a liquid component, and then there is a gaseous component and each of these components are extremely important, because they have relationship on the overall structure of the earth, including the other spheres, such as atmosphere, biosphere, and hydrosphere. So the liquid phase that comes out is primarily the lava. So once magma reaches the surface, it is called lava.

And most of the lava are basaltic in composition. And the flow rate of those lava could be anywhere between 10 meters to 300 meters per hour. So here, just to give examples, I have used three specific types of, two specific types of lava at the beginning. One is called Aa lava. These are lava, which has very crusty edge, sharp edges. So this would be one example. And most of these examples come from the Hawaii, where you can still see the flow of lava today on the surface, and therefore, these names are from the Hawaiian words describing them.

So Aa lava is quite, it has these sharp edges, what it says is basically, it is moving where part of it is also solidified, but because it is moving relatively faster, therefore, it is not getting the entire surface covered by solid rock pieces and therefore you have these sharp edges forming and getting pushed by the liquid part of it. Pahoehoe lava is quite slow in its progression, because it already lost most of the push for the movement forward and you can see that there are no sharp edges, it actually creates a rope like appearance, where the entire surface is covered by these crust formation or the formation of the solid rocks.

And Pahoehoe literally means something on which one can walk indicating the fact that it is very very slow. So one can actually escape the lava flow. And these kind of lava flows can go back and forth depending on how much temperature a lava flow is encountering. So increasing temperature can change one lava flow to the other. A very distinct type of lava flow is called a pillow lava when the lava forms underwater, and this is the point where you should try to recall that where commonly we can find pillow lava, because those are underwater magmatic activity.

So the one that comes to our mind is the one which is forming near the mid oceanic ridges, where always it is the formation of magma coming in contact with the water. So when it happens, it forms a bubble shaped form where part of it will be cracked through which the liquid material will bruise up and form another blob. But it is generally spherical in nature, because the moment it comes into contact of the water, it immediately solidifies and that forms that initial crust.

Generally, the formation of these pillow lava creates multiple blobs. And often these are very characteristic feature, when you see them in ancient rock record to identify that they are product of underwater volcanism, underwater lava activity.

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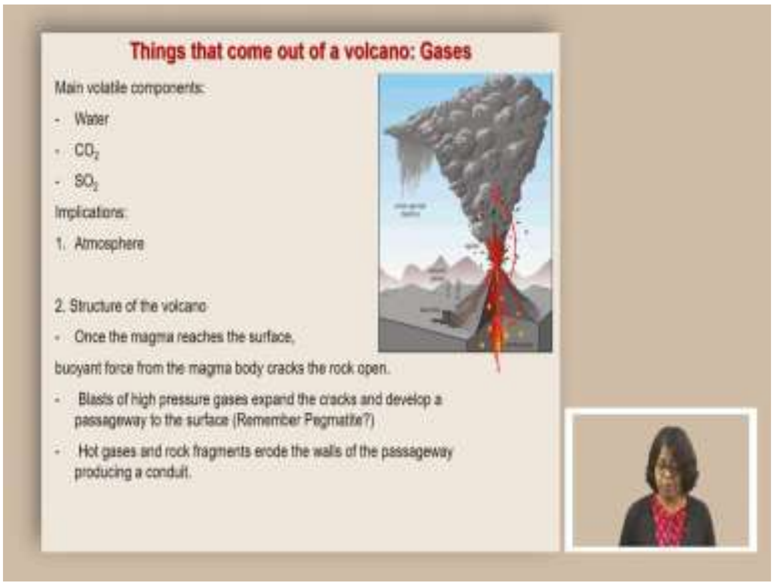

Now, let us take a look at the gases that comes out of a volcano. So the major component of the volatile material includes water vapor, carbon dioxide, and sulfur dioxide. And it has important implication in terms of relative proportion of each of these materials. Because the carbon dioxide is a greenhouse gas, and if a lot of carbon dioxide is released through the volcanism in the atmosphere, then it can eventually lead to change in the atmospheric temperature, it can lead to the heating up of the entire atmosphere, finally, leading to a greenhouse world.

On the other hand, there can be structure, which basically create a lot of dust, a lot of volcanic ash and these kinds of ashes cover the entire atmosphere, and they block the sunlight for at least some time, leading to a drop in the temperature in the atmosphere leading to a more of an ice out, say thing. So depending on which kind of volcano we are looking at, and what are the volatiles that are coming out of that volcano, can have a very important effect of on the atmosphere, and the overall temperature profile of the earth.

Now, the structure of the volcano is primarily controlled by, once the magma reaches the surface, what kinds of things are coming out, as I mentioned before? So the buoyant force of the magma body cracks the rock open, and once the rock gets blasted, the high pressure gases expand the cracks even more and it basically develops a passageway to the surface. And this is the time when we can find a magma with lots of high volatile content and lots of gaps, lots of kind of narrow holes.

And these are characteristic feature that these are the places where lots of volatile have escaped. So you can form things like pegmatite, where these are large gas escape structure, which is later filled up by other crystals. It also contributes to some of the solid fragments that we recover from these kinds of activities. So hot gases and rock fragments erode the wall of the passage of the conduit. So this is the part through which the magma is moving. And once it expands, it is going to break part of it, and they are also going to contribute to what comes out.

So it is not only what is coming from deep inside, which is the lava? Which is the liquid phase? It is not only what how the volatiles are expanding as they are subjecting to lower pressure, it is also what is surrounding because they are also going to be broken off because of this high pressure movement.

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And that contributes to the solid component. And those solid components are called the pyro clastic material. So Pyro means fire and clast means fragments. So fire fragments recovered from these igneous activities are called pyroclastic material. So these are things which are ejected from the volcano and it can vary in size, there can be powder like things, which are generally called the ash to really big chunks which are called blocks. And depending on the size of the particle which it can be called, one is ash and the others are lapilli, cinders, bombs and blocks. These are increasing in their size.

Now depending on the texture and composition, these kinds of pyroclastic material can be brought together and can form rocks, which can differ in their composition. And depending on whether it is a mafic type, it can be called a scoria versus a pumice. And these pumice are extremely light material, they are made up of pretty much volcanic ash. And they are so light because of the holes inside, that they can float in water. So literally, this is one rock which can float in water.

And we are talking about a light felsic composition that also adds to this. A mafic version of it is called scoria, where you will also see these volatile escape structures, but it is not going to be as light as pumice. So, with all these things, let us try to summarize what we learned today. We talked about the different kinds of things that come out of volcanic activity, the materials that come out of it, including the liquid, the gas and the solid particle; we also learned the mechanism, how the magma can actually reach the surface and produce rocks such as the volcanic or extrusive rocks.

We also learned that many of the magma which starts from the upper mantle actually never reach the surface, yet create all kinds of igneous rocks as intrusive structures. These intrusive structures can be brought by later geologic activity to the surface and we can observe them.

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Here are some of the resource materials that are used for this lecture. This is a question for you to think about. Thank you.