Evolution of the Earth and Life
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Lecture 9
Compositional Variation of Igneous Rocks

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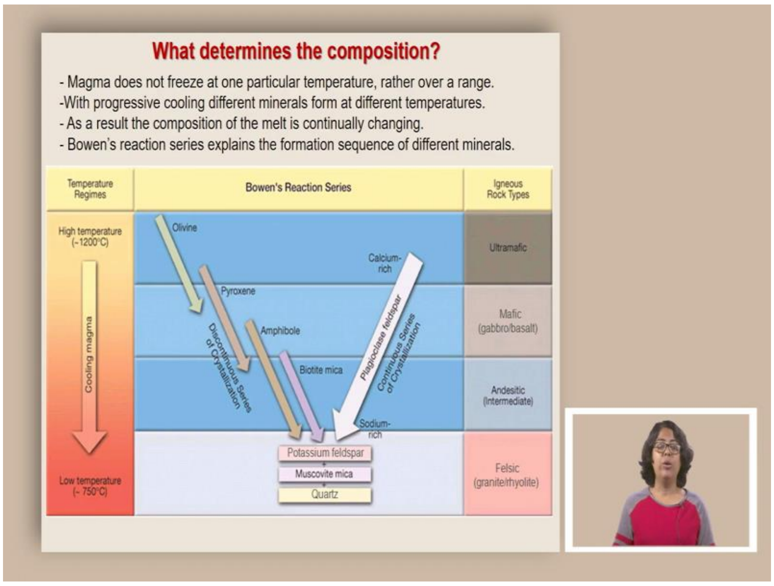

Welcome to the course Evolution of the Earth and Life, today we are going to talk about how igneous rocks can vary in their composition and what are the factors that control the composition of an igneous rock. So igneous rocks are forming from magma and this magma has three components one is volatile, one is melt and one is solid and these melt and solid they have different ratios during the progress of this magma from the deep interior to the surface of the Earth.

Because the solid phase does not crystallize from the magma at one go, it progressively crystallizes and gets settled at the base of the magma chamber as the magma cools and that is very important concept to remember because it controls heavily how the magma can produce different kinds of rocks the same composition of the magma can produce different kinds of rocks simply because the rate of settling and development of the specific crystals are going to be different depending on the temperature profile of the path that the magma is following.

So, one very important contribution to understanding the nature of igneous rocks and compositional variation is Bowen's reaction series, Bowen's reaction series explains the formation sequence of different minerals, so let us try to understand this particular diagram, so in the left hand we have the temperature regimes, these are high temperature at the top and the bottom one is low temperature and then we also have in the right hand panel there are different rock types, ultramafic, mafic, andesitic and felsic so this andesitic is the same as intermediate composition.

What Bowen's reaction series tells us that if things are crystallizing at very very high temperature then it is not going to be any mineral but the minerals such as Olivine, so you can imagine a scenario where the magma started to rise from the deep interior and as it is rising it gets progressively cooler, so the first mineral which will crystallize would be Olivine because the crystallization temperature or the temperature at which it can solidify is very high.

Next it will be pyroxene, next it will be amphibole and next it will be mica, a specific type of mica called the biotite mica then it will be followed by potassium feldspar, muscovite mica and quartz, on the other hand there is another series it is also called a continuous series where the mineral remains the same it is all feldspar which can crystallize at different temperatures but the solid solution that develops the plagioclase feldspar the contribution of the N members of the solid solution is going to be different depending on at which temperature they have crystallized.

So, if they have crystallized at very high temperature they are going to be calcium rich feldspar whereas as you encounter very low temperature it is going to be a sodium rich feldspar, now couple of important points this immediately tells us something about what minerals to expect at which kind of temperature setting.

So, if the magma is cooling down at a very deeper level and it has solidified at that part of the depth, then we are going to find rocks which are predominantly Olivine based and in those cases Olivine is a dark mineral where there is very high amount of Fe and Mg and therefore the corresponding rock is going to be an ultramafic rock, it is also a rock which is completely made up of Olivine it is called a peridotite.

Then as we come to the second phase or a relatively lower temperature we can expect to find pyroxene there can be some contribution of Olivine too and that will basically create rocks which are mafic in nature there can be contribution of both Olivine, pyroxene and amphibole, all of them are still darker minerals and they will contribute to form mafic minerals, it is also important to remember that apart from these Olivine, pyroxene and amphibole you will also expect feldspar the plagioclase feldspar with a specific combination of calcium rich versus sodium rich N member.

Because the proportion of calcium and sodium rich N member depends on the temperature, so that means if you look at a mafic rock depending on the contribution of the N members within plagioclase feldspar you can actually tell something about the temperature at which they settled, the same can be done looking at the relative proportion of Olivine, pyroxene and amphibole so they can be quite good in terms of understanding the temperature profile.

Finally at very relatively low temperature we will encounter a combination of amphibole, biotite mica and plagioclase feldspar primarily dominated by the sodium rich N member, now if you drop the temperature even more then it becomes one of the most stable minerals that will start to crystallize and those would be the potassium feldspar, different kind of mica, it is called a muscovite mica, the biotite mica is dark in colour whereas in muscovite mica is lighter in colour and finally quartz.

So, if you look at a magma and it is rising in from the deep interior and it is reaching towards the surface over time it will keep on crystallizing minerals such as Olivine, pyroxene, amphibole, biotite the potassium feldspar muscovite and eventually quartz in a progressive fashion and if the entire sequence is preserved you will find the Olivine at the base and progressively quartz at the very top.

It also gives us some understanding that because these Olivine and pyroxene these are high temperature minerals they are unlikely to be very stable at surficial condition where the temperature is low and we see an effect of this when we look at the distribution of minerals on the surface, if a rock is exposed at the surface and they have been exposed for very long these high temperature minerals always have this tendency of breaking down and converting to a more stable low temperature phase such as quartz and muscovite mica or something like potassium feldspar so this also gives us some insight in terms of what kind of minerals we can expect on the surface.

But a more complex question is why does it happen like this? Why does it follow this particular arrangement? Well this particular arrangement was first discovered by researchers by Bowen and that is why it is called Bowen's reaction series empirically so looking at the melting of the rock and when does it crystallize he developed this particular thing, but later when people try to understand the mechanism of it they could also find a very similar progression when we look at silica tetrahedra arrangement.

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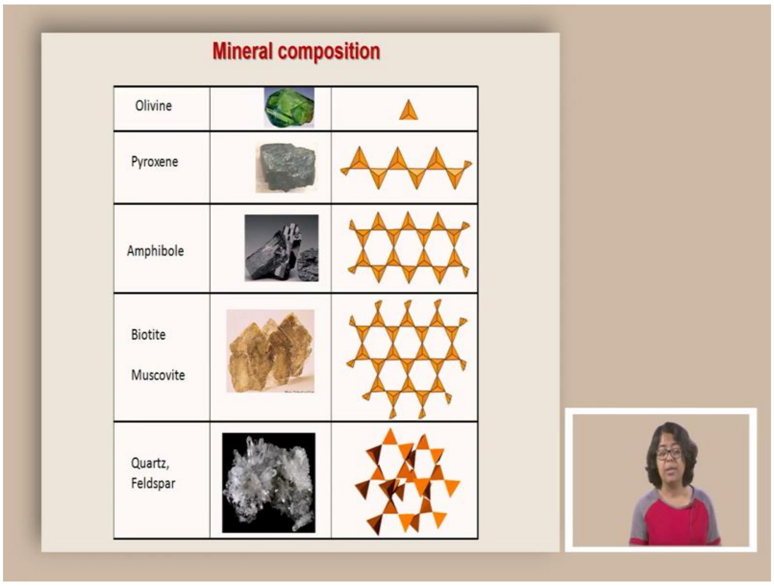

So, if you recall the mineral composition and silica tetrahedra arrangement you will actually see it follows the discontinuous series of Bowen's reaction series where Olivine is at the top followed by pyroxene followed by amphibole, biotite, muscovite and quartz feldspar, so the argument is that to develop independent silica tetrahedra it does not require a high temperature change and therefore it settles, it crystallizes with a very small temperature change and it is stable at only high temperature.

On the other hand, the feldspar and the quartz only at low temperature these kinds of extremely stable structures develop and they do not break so easily when you are trying to start melting it is the complete opposite series that we are going to observe. Finally, if we try to understand that when we look at the surface and we find all kinds of igneous rocks but we also know that these igneous rocks are coming from the deep interior of the earth primarily mantle and these mantle have the same composition.

If you look at the understanding of what is the mantle composition it is pretty homogeneous that means we do not really find a lot of variation in the mantle composition, now the question is if the magma composition of the mantle is the same then how can we produce a variety of igneous rocks on the surface what is causing it?

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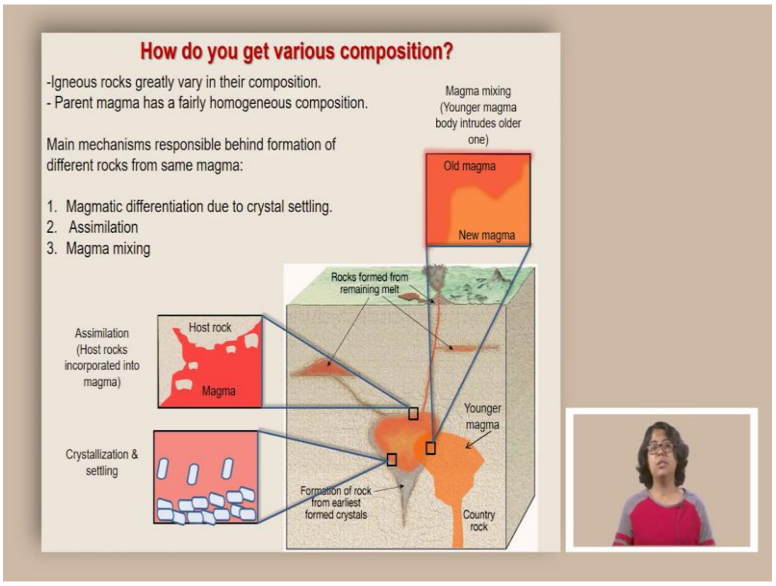

So, now we are going to look at some of the mechanisms to produce this high variety of igneous rocks in terms of its composition on the surface with this fact that the parent magma composition in the mantle is fairly homogeneous, so we are specifically focusing on the compositional aspect and not the textural aspect, so even if you forget about the textural aspect if you simply focus on composition we do find a very high variety of igneous rocks based on composition on the surface of the Earth and there are three major mechanisms that contribute to this.

The first mechanism is the magmatic differentiation due to crystal settling and we talked about it, it is also called fractional crystallization, so as we know that different minerals are settling at different temperatures, different minerals are forming, crystallizing at different temperatures as a result when a hot magma is rising every time it is cooling down it is losing part of its composition because some of the minerals preferentially crystallize and they get removed from the original melt because they are settling the original melt composition does not remain constant and it keeps on changing.

So, again if we think about an original composition of the magma and at the first phase there would be a removal of Olivine so that means it is also taking with it a high proportion of iron and magnesium as a result the remaining melt composition will be slightly more silica heavy so as progressively it goes up it will be more dominated by silica with time that can create a compositional difference of which are the paths which are getting crystallized and eventually gets uplifted to the surface and shows up as an intrusive igneous rock.

Because the path is not the same, the rate at which the magma moves to the surface is not the same we can find quite a bit of variation in the magma in the final igneous rock composition simply because of these fractional crystallization and resulting in magmatic differentiation because the crystals are settling as they are forming.

The second one is called assimilation and these assimilation basically means that when the magma is moving up it is actually passing through especially in the crust through solid rocks and those host rocks are often melt because of the high temperature of the magma and because it melts it also contributes to the magma.

So, the magma composition changes as it goes up not only because of fractional crystallization and crystal settling but it is also incorporating more and more materials of existing rock through which it is moving and that depending on how far it is moving through which kind of rocks it is moving it is basically creating a new composition of the magma as it is assimilating the existing rocks.

The third type which contributes can equally significantly is magma mixing, there can be different types of magma in different parts of their cooling history which can mix and develop a new magma composition so not all the magma start from the same point and have the same velocity of rising up and two magma can mix at some point of time which did not originate at the same time.

As a result, their composition they are individual composition of the remaining melt would be different and when they are mixing they can generate yet another composition and the final result of the rocks made from them is going to be quite different. So, because of these three interlinked mechanisms we do find this high variety of igneous rocks although the original parent magma has a fairly homogeneous composition.

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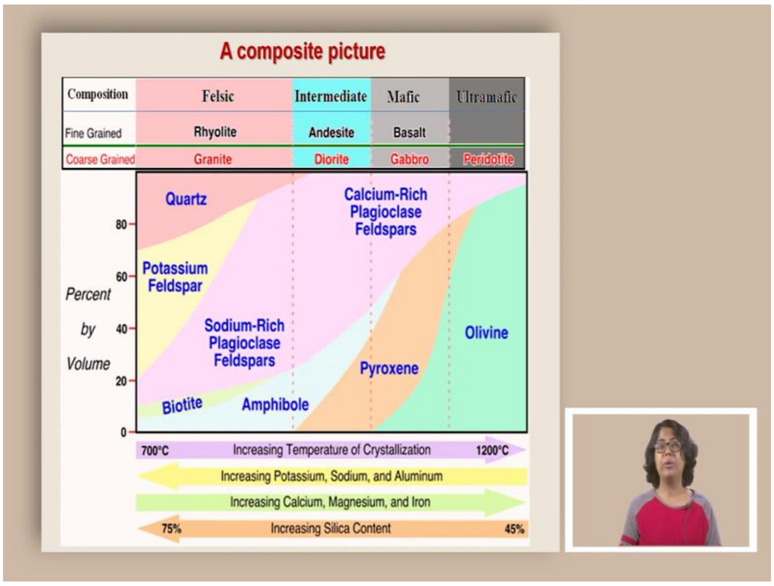

So, to wrap up everything in terms of the composition, the texture and where do we find it this picture gives us a pretty comprehensive pattern of the igneous rocks, so what it shows is that there are variations in terms of texture you can find fine grained and you can find coarse grained materials you can also find quite a bit of variations in terms of composition it can be felsic which is silica heavy and it can also be ultramafic which is very, which has relatively less amount of silica.

But how do they form and when we talk about how do they form we can look at all these parameters which comes with these rocks, so if you look at the first one it is the increasing temperature of crystallization so temperatures can vary between 700 degree centigrade to 1200 degree centigrade and depending on which minerals we are looking at they can either be crystallized or not crystallized.

So, for example Olivine sits somewhere here which basically means that they require very high temperature for their crystallization so if you are looking at the resulting composition they will have a little bit of Olivine, a little bit of pyroxene and calcium-rich feldspar that would be the composition of these ultramafic rocks called peridotite, on the other hand if you look at the felsic rocks, these felsic rocks will have the minerals which form at relatively high relatively low temperature and you will have high proportion of words potassium feldspar, a bit of sodium plagioclase feldspar only a small amount of biotite and amphibole.

An intermediate would be somewhere in between where you do find some of the high temperature minerals and some of the low temperature minerals, these rocks also tell you something about what kind of other ions you can expect, so for example if you are thinking about potassium sodium and aluminium as we are going from ultramafic to felsic it is going to increase and where you are going looking at calcium magnesium and iron they are going to increase as we are going to look at the ultramafic rocks.

And because these metal ions are going to increase such as calcium magnesium and iron as we go towards the peridotite or ultramafic rocks it is basically also reducing the silica content so as we are coming towards the felsic rocks just by the name of it, it indicates that it is going to be very very rich in silica.

And this is one of the simple ways of relating what are the physical factors that are controlling the composition of all kinds of igneous rocks so whenever you pick up one rock which has a colour which is light and maybe a large crystal, it automatically tells you something about constituent minerals, it also tells you a range of temperature at which it may have crystallized, it also tells you something about which kind of metal ions you can expect there at a higher percentage and what would be the silica content. And that is the whole goal of this classification scheme which is process based so that using simple identification you can deduce quite a bit of information from some general principles about their formation.

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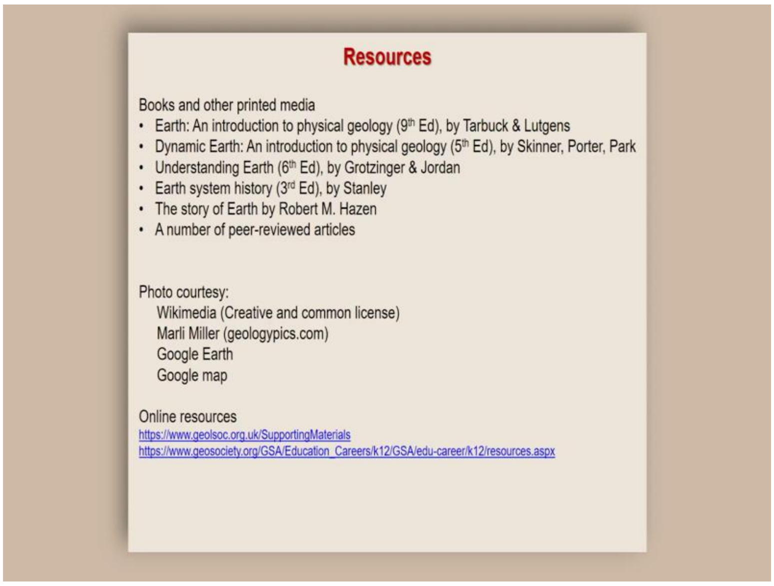

In summary today, we learned how the variation of igneous rocks can be possible, we learned a little bit about Bowen's reaction series, how different minerals crystallize at different temperatures out of the original magma and how it changes the composition of the remaining magma. We also learned the relationship of Bowen's reaction series with the structure of the minerals or silica tetrahedra.

We learned what are the three major mechanisms of creating different composition of magma although the original source of magma from mantle has strikingly homogeneous composition and this explains why we find so many different types of igneous rocks on the surface. Here are some of the resources that are used for this lecture. Here is a question for you to think about. Thank you.