**Evolution of the Earth and Life**
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**Metamorphism and plate tectonics**

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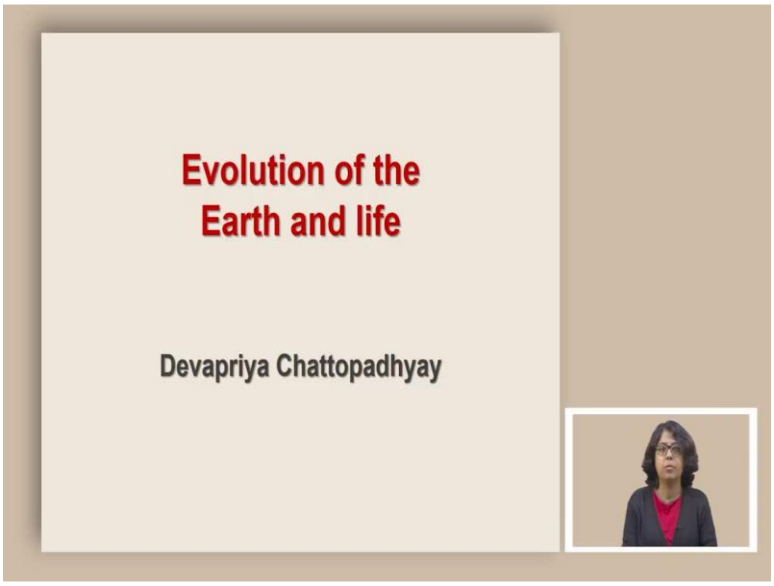


Welcome to the course, evolution of the earth and life. Today we are going to talk about different kinds of metamorphic rocks and their relationship to play tectonic boundaries.

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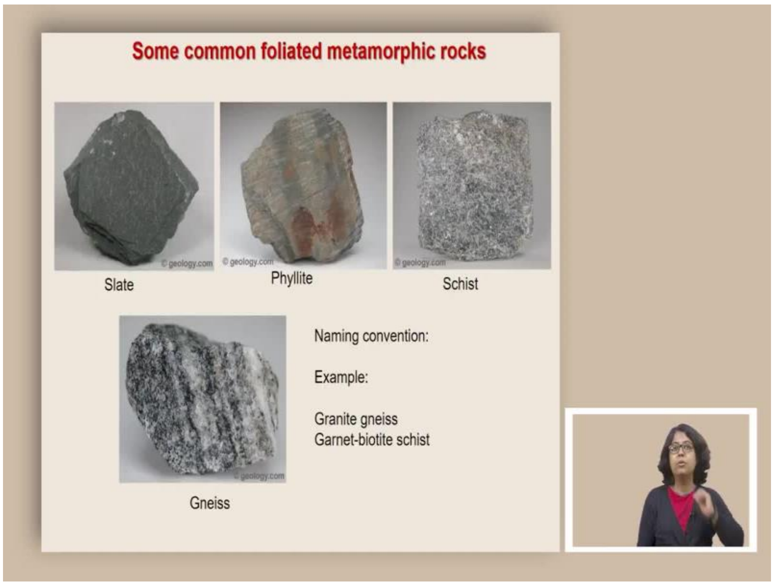


So some of the common foliated metamorphic rocks that we can find in nature are Slate, Phyllite, Schist and Gneiss. If we look closely, they differ in terms of their grades of foliation. In slate, we find something, which is called a rock cleavage. So if we try to break the slate, it is going to rip apart along a certain plane. In Phyllite its pattern which is more stronger than Slate, but it does not really cleave apart as easily as Slate.

When we look at Schist, we actually see some separation of dark and light colored minerals but it has a sparkly appearance. And when we come to Gneiss, we actually see complete separated bending of light and dark colored minerals and this is a typical pattern of Gneiss texture. So now when we try to name them we understand that all of them are foliated rocks, and they actually show preferred mineral orientation because of which these foliations are being created. When we try to give a name to them, we have to keep track of these foliations or the textures, and also from which parent rock they started from.

So for example, it can be something called granite Gneiss, which basically indicates that the parent rock was a granite, and now it is showing a Gneiss texture. It can also be something called Garnet-biotite schist, which basically says that it is a metamorphic rock which shows historicity, it also contains Garnet and biotite. So there are different ways of naming of metamorphic rock, which all should indicate some amount of textural information and also what was the composition of the rock or what was the parent composition of the rock.

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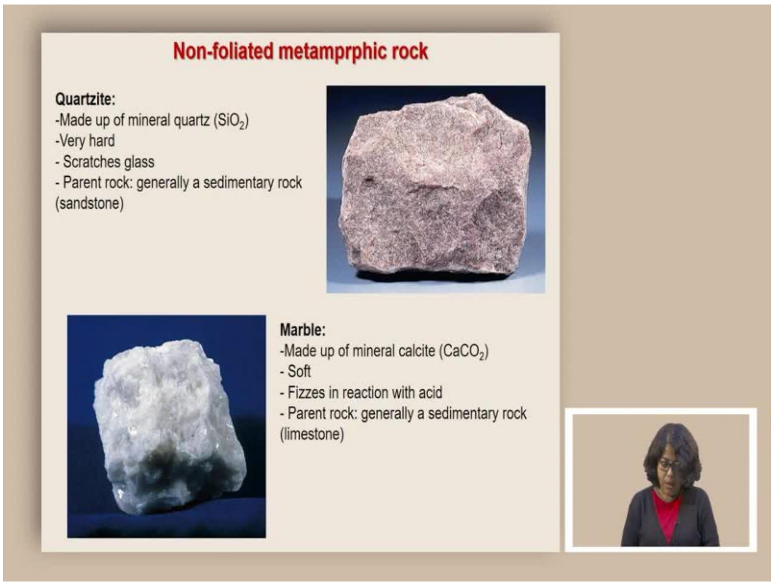


There are other types of metamorphic rocks which are not foliated and among those non foliated metamorphic rocks, the most common ones are quartzite and marble. So quartzite is made up of mineral quartz SiO 2. And because the mineral quartz has a very-very high big stability field where it is stable under very high and low pressure temperature condition, we actually find these kinds of minerals everywhere. And quartzite are the rocks which are primarily composed of quartz, it is very hard, it even scratches glass, showing that it has a very hard composition. The parent rock could be generally a sedimentary rock, it could be a sandstone.

Now, looking at this one, it is quite clear that there is no preferred orientation plane and that is why we are calling it a non-foliated metamorphic rock. The other example a common example of a non-foliated metamorphic rock is marble. It is made up of the mineral calcite, which is CaCO 2. It is relatively soft, and generally the parent rock is the sedimentary rock limestone. And if you pour a drop of acid on it, because it is composed of calcium carbonate, it is going to fizz out and it is going to release carbon dioxide. So these are some of the common ways of knowing what kind of rock it is.

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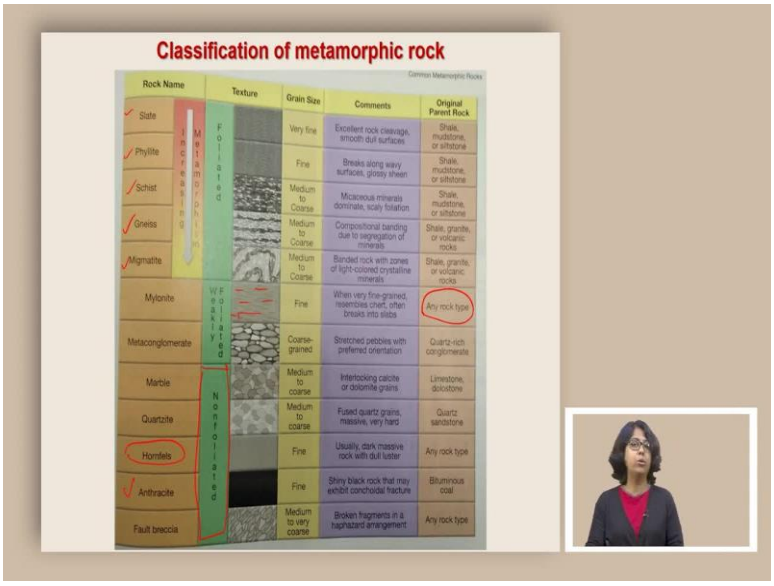


| Rock Name | Texture | Grain Size | Comments | Original Parent Rock |
|---|---|---|---|---|
| Slate | Foliated | Very fine | Excellent rock cleavage, smooth dull surfaces | Shale, mudstone, or siltstone |
| Phyllite | Foliated | Fine | Breaks along wavy surfaces, glossy sheen | Shale, mudstone, or siltstone |
| Schist | Foliated | Medium to Coarse | Micaceous minerals dominate, scaly foliation | Shale, mudstone, or siltstone |
| Gneiss | Foliated | Medium to Coarse | Compositional banding due to segregation of minerals | Shale, granite, or volcanic rocks |
| Migmatite | Foliated | Medium to Coarse | Banded rock with zones of light-colored crystalline minerals | Shale, granite, or volcanic rocks |
| Mylonite | Weakly Foliated | Fine | When very fine-grained, resembles chert, often breaks into slabs | Any rock type |
| Metaconglomerate | Weakly Foliated | Coarse-grained | Stretched pebbles with preferred orientation | Quartz-rich conglomerate |
| Marble | Nonfoliated | Medium to coarse | Interlocking calcite or dolomite grains | Limestone, dolostone |
| Quartzite | Nonfoliated | Medium to coarse | Fused quartz grains, massive, very hard | Quartz sandstone |
| Hornfels | Nonfoliated | Fine | Usually, dark massive rock with dull luster | Any rock type |
| Anthracite | Nonfoliated | Fine | Shiny black rock that may exhibit conchoidal fracture | Bituminous coal |
| Fault breccia | Nonfoliated | Medium to very coarse | Broken fragments in a haphazard arrangement | Any rock type |

Here we are going to present an overall classification scheme of metamorphic rocks, which comprises different kinds of metamorphic rocks and their parent material. So one of the most common parent material are the shales and mudstones and silt stone these are all sedimentary rocks, they can be very fine grain, they can be coarse grain. And depending on what kind of metamorphism, it is going through, it can basically create all types of rocks, which includes slate, phyllite, schist, gneiss and migmatite.

And if we look closely, we are basically talking about an increasing degree of metamorphism. And because of the increasing degree of metamorphism they are also going to show you an increase in the grain size, sometimes an increase in the degree of foliation.

So for example, in slate you are going to find the rock cleavage, but then when you come to migmatite, it can be completely separated foliated and may show you bending. The things which are relatively difficult to relate to their parent rock are the things like mylonite. So we talked about mylonite when we talked about a particular metamorphic environment such as fault zone, when the rocks can be completely crushed and create different rock type, different kinds of metamorphic rock which is mylonite.

In these cases, it is quite difficult to pinpoint the parent rock because it can actually originate from any type of rock and eventually convert to mylonite. These are the types of rocks where we do not really find well-formed foliation there might be some foliation but it is not going to be as well partitioned foliation like slate, phyllite, gneiss and migmatite.

There can be other things such as mega conglomerate, again from sedimentary conglomerate, it can be metamorphosed and form mega conglomerate. And the foliation or is not always well observed it also depends on what kind of grain size, the original conglomerate was made up of.

The ones which are completely non-foliated where we cannot expect to find any preferred orientation of the mineral grains would be these ones which are categorized under non foliated rocks and they include marble, quartzite, which we already talked about. Some more rocks, which are also found in certain metamorphic environment, which includes Hornfels, anthracite, fault breccia and so on.

If you think about it, that these anthracite is very interesting rock because it is coal. So if you think about coal, there are different types of coal, in terms of the stage of maturation, and the finest and the well matured coal is anthracite, which actually goes through the process of metamorphism and therefore, it is a metamorphic rock.

In these kinds of rocks, we do not really find any kind of foliation. And for many of these rock types, such as hornfels, for example, it is hard to pinpoint the parent rock. So now we are in a situation that we have a general understanding of what kind of metamorphic rocks are available in nature. But we also understood that it is not always easy or possible to relate it to the parent rock.

Then what are the importance of metamorphic rocks when we are trying to reconstruct the environment? Clearly, it cannot be used always to identify from which rock it has converted.

Then what other information can we deduce by looking at a metamorphic rock? So that is the discussion that we are going to start from now.

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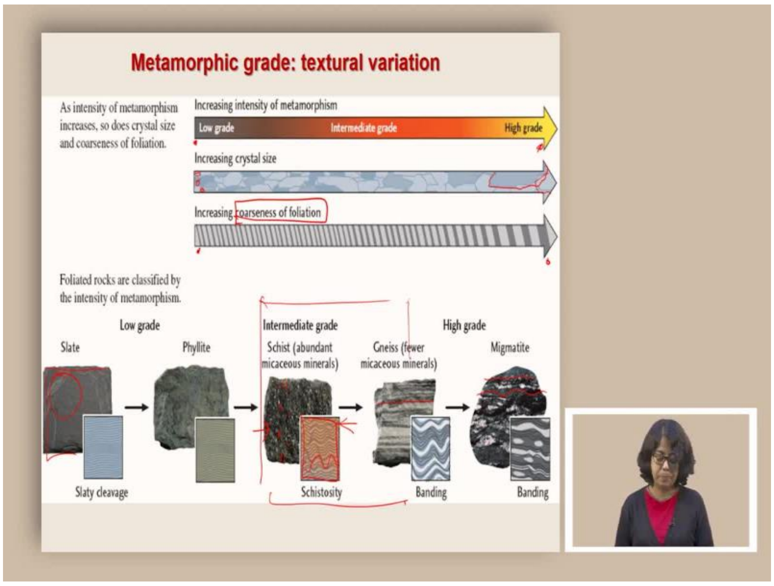


And the most important idea that we should focus on is the metamorphic grade. So to a very simple explanation metamorphic grade is basically an increasing intensity of metamorphism that we want to track. And often, a combination of mineral composition and the texture actually gives us very important information about the increasing degree of metamorphism, what we call a metamorphic grade. And as the intensity of the metamorphism increases there are some predictable changes in textural variation, one of them is that the crystal size increases and the coarseness of the foliation also increases.

So what do I mean by that? Let us take a look at this particular diagram. So this particular diagram goes from low grade to high grade of metamorphism. When we look at the Crystal size it basically starts from smaller crystal size, and then when we go to this part, we actually start seeing a fairly large size of crystals. And this can happen by two processes, one is the formation of newer crystals, which are larger.

The second one is related to gluing off existing crystals and making the size larger and larger. And one of the reasons for seeing so is there is a relationship with temperature with higher temperature it is expected to find larger crystals, because temperature actually favors increase in volume and hence, we can expect to see larger crystals. The second one is temperature also aids for the joining of surrounding crystals, hence formation of larger crystals. The relationship with pressure is not so simple and we are going to revisit this issue when we in a few slides.

Increasing coarseness of foliation is also a very typical association that we find with increasing metamorphic grade. So when we think about a low grade metamorphism, we are going to see a relatively fine foliation where we are going towards the extreme end of high grade metamorphism we are going to see that things are partitioning at a much coarser resolution. So let us take a look at the examples of these. When we think about slate, which is an example of a very low grade metamorphism that means we are encountering an metamorphic environment, which has low temperature and low pressure condition.

We see first of all fine grained crystals and also we see our fine foliation. So it is not very clear if you just look at the slate in macro-scale, but if you actually take a section or cross section of this slate look at it under microscope, what you are going to see is this pattern, which is called a slaty cleavage. And these slaty cleavage, they are extremely fine in terms of its resolution that are very fine regions also you are going to see these foliation arrangements. Phyllite is another example of a low grade metamorphic product, where also you are going to see similar pattern.

Then we come to intermediate grade and in this intermediate grade, we are going to encounter these kinds of rocks which are which has schistosity and at sometimes bending. So when we talk about schistosity, it requires abundance of micaceous mineral so there has to be different types of mica and these mica are those minerals, which are very good in organizing itself along the preferred direction, they are platy in nature, they have a silicate tetrahedral structure, which forms thin plates and these thin plates or the platy arrangements are joined together by weak bond. And that is why if you are given a piece of mica, you can actually peel off one layer from the other.

Now during metamorphism, these mica minerals, they basically orient themselves all along the preferred direction, depending on the stress direction. So it is always going to be if we are talking about compressional force, we are going to see that it is basically orienting itself perpendicular to the force of compression and we see the patterns which are lining up like this. Now, in this we can also find some of the bending. So in this particular plot we see first of all orientation of the mica grains, but then also because of the compression, we see some sort of a bending pattern which is like this.

Now, in gneiss we do not really find a lot of mica, but what is very important that we find clear variation at a much larger scale in terms of separation of dark minerals versus light minerals. What is important to notice here is in slate, in order to observe the foliation we have to look at the microscopic structure and when we come to gneiss it is visible even without a microscopic structure and that is what we meant by increasing coarseness of the foliation. The coarser it gets the easier it is to see them without any microscope. And that is what we find in as we progress with the metamorphic grade.

Now, the final grade are very high grade, in fact part of the gneiss can also be part of the high grade metamorphism, but a clear example is migmatite. In migmatite, you actually see these flow structures, even without microscope. So it is not just separation of dark and light minerals, we already discussed about it that it is a partial melting that we start seeing in migmatite, where the dark ones tend to be there and the light ones tend to flow, you basically see also a bending.

So increase in the coarseness of the foliation and increase in the size of the crystals are all indicative of increasing metamorphic grade. Or in other words, it means that we can be confident about that the intensity of the metamorphism is increasing.

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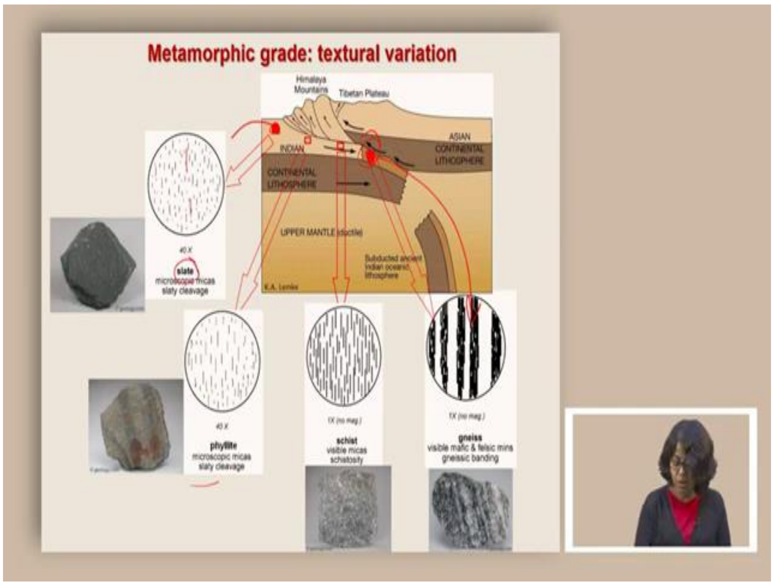

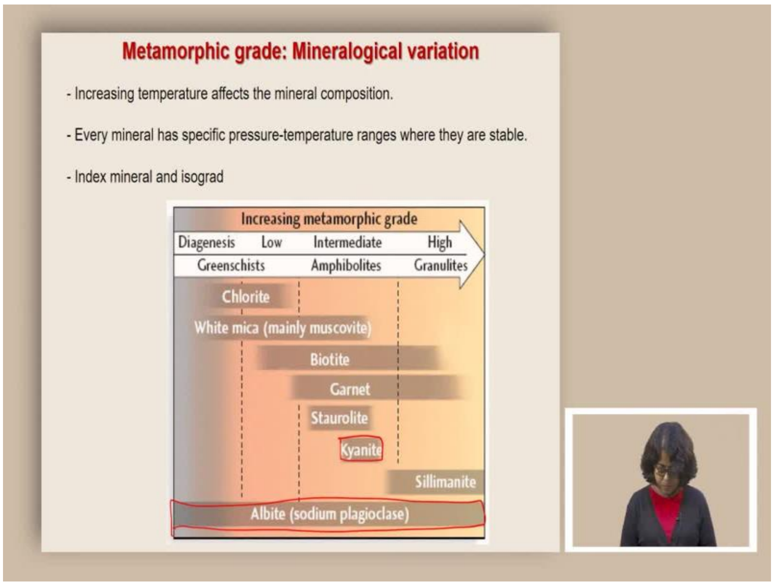


Apart from textual variation. So here is another example of textual variation in the context of plate tectonics. So if we look at Himalayan Mountains, and if we tend to look at the rocks, which are situated here, versus deeper part of the convergent boundary, we are going to clearly see a variation in their texture.

So again, the rocks which are collected from here are only experiencing some change in pressure and temperature, but not so much. In contrast, the rocks which are sitting right here are the rocks, which are experiencing much higher temperature because it is basically going down but more than the temperature it is also facing enormous amount of pressure. As a result, we are going to see a textural variation, if we are going to look at rocks collected from here versus rocks collected from here.

So what we see is the rocks that are collected from this shallower region, probably we are going to encounter slates. Increasing metamorphic grade will produce phyllite then schist and eventually somewhere here probably we are going to encounter gneiss and if you take a look at the microscopic structure, the coarseness of the foliation actually increases from slate to gneiss, which becomes more clear, so each band becomes tickled and well separated.

Moving on to a slightly different aspect of variation is the mineralogical variation. So far we have been talking about the textural variation, but it can also be the composition of the minerals that we are looking at. Increasing temperature affect mineral composition. In fact, pressure also plays a role in terms of mineral composition, but in a slightly different way. So every mineral has a specific pressure temperature range when they are stable and therefore we can actually use those minerals to talk about the potential temperature and pressure conditions under which they formed.

Now, there are some minerals which are stable in very-very large range of temperature and pressure. For example quartz is actually stable on a very-very large degree of temperature and pressure variation. On the other hand there are minerals like kyanite, which are stable only in relatively narrow range of temperature and pressure conditions. So if I compare, for example kyanite with, let us say albite, I am going to see that the albite actually is found in all types of metamorphic grades starting from low to high.

On the other hand, if I look at kyanite, it is only stable in a certain type of metamorphic grade. Therefore, in certain ways, in order to reconstruct the temperature and pressure, the minerals which have relatively lower stability field would be very useful and those are often called index minerals. Index minerals are those which give us very specific understanding of temperature and pressure are stable under a relatively narrow zone and can be easily identifiable. And therefore, if you are finding those minerals in the field, as part of certain rocks, it actually conveys something very specific about their pressure and temperature condition.

And if you can connect all the rocks spatially, that have the same composition of minerals, they can fall into a line which is called an isograd. Now, let us take a look at a bit more detail in terms of how this pressure temperature stability works for certain minerals and what do we mean by mineralogical variation? Do we mean that their chemical composition is going to be similar or different or is it something else?

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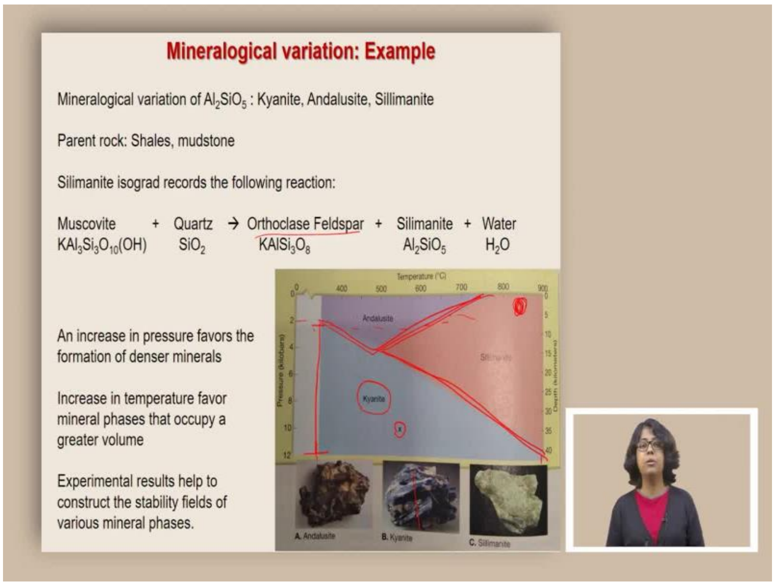


So we are going to look at an example of three minerals, kyanite, andalusite, and sillimanite. All of these have the same chemical composition, Al 2 Si O 5, it is one of the most common aluminosilicates that we find. And therefore, the parent rock can be shales, mudstones, these are sedimentary rocks, once they get converted to metamorphic rocks, they form slates, phyllite. And among these slates, phyllite, you can actually find these minerals kyanite, andalusite, sillimanite. And they are composition is pretty much the same.

Now how are they vary? Well they vary in terms of their texture, in their crystal arrangement, as a result, they are basically polymorph. So they have the same composition, but they look different. So if we look at these three minerals andalusite versus kyanite versus sillimanite, they look quite different even without microscope. If you are looking at them under microscope, there you will find a very distinct crystal structure of kyanite versus andalusite versus sillimanite. So they are easy to identify in a rock.

Now, in terms of the mineral in terms of the chemical reaction, you can clearly see that it can be produced with the involvement of Muscovite and quartz with a rearrangement, which produces a different types of feldspar, sillimanite and water and the same thing can happen for other minerals such as kyanite and andalusite. Now the interesting pattern is that they are not really stable in all kinds of pressure temperature condition. Each of these polymorph is stable into a relatively narrow zone of temperature and pressure and that is one of the most interesting part of this mineralogical variation.

Why does it happen? Well, an increase in pressure favors the formation of denser minerals, the minerals which are more compact. So an increase in pressure favors those. On the other hand an increase in temperature favors those mineral phases that occupy a greater volume. So if you are talking about the same mineral that means it has to be less dense, if it has to accommodate increasing pressure, increasing temperature.

Now, these are somewhat contradictory points, because as we are thinking about increasing depth, both temperature and pressure increases. So a priory it is not possible to predict how mineral is going to stabilize with increasing pressure and temperature. Because by theory we can predict pressure will increasing pressure will favor those minerals, which are denser, but at the same time increasing temperature will favor those minerals which have greater volume and hence less dense. So how do we figure out which are the minerals that are going to be stable at a certain depth? For that researchers carry out experiments.

In controlled setup to increase the temperature and pressure of certain minerals, and then look at when they are going to change and that is how they define the stability field in terms of pressure and temperature. And this is an example of a stability field diagram of this aluminosilicate. And what you can find is there are three zones partitioned by the color and they are showing the stability field of Al 2 Si O 5, depending on which mineral they are being represented by. So andalusite has this purple stability field, kyanite has this blue stability field, whereas sillimanite has this reddish stability field.

What does it tell us? It tells us that, if I am going to encounter a rock, which got metamorphosed at, let us say very high pressure and temperature, the chances are high that I am going to encounter kyanite. In other words, if I actually find kyanite in a rock that immediately tells me that they must have formed in this range of pressure, and this range of temperature. And by combination of other minerals, you can probably narrow down this temperature and pressure range even more.

Let us take a look at some of the types of metamorphism that we already know, let us say contact metamorphism. So for contact metamorphism, we know that it encounters relatively low pressure, but high temperature in those cases, we will expect formation of andalusite, because andalusite in general has a low pressure range, but a high temperature range. Well there can be possibilities of finding sillimanite also if that rock is forming somewhere here. But sillimanite, just by finding sillimanite it actually tells you that probably it formed at a very high temperature and it can be a high pressure zone too.

So this also tells us that just by finding one mineral is good indication of certain temperature pressure zone, but if we want to narrow down it even further, it is better to have multiple such minerals associations so that we can be more precise about the temperature pressure condition.

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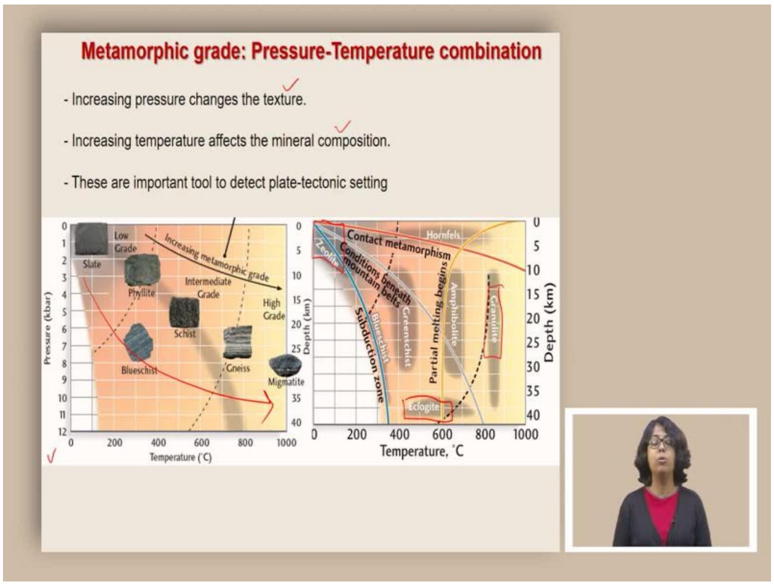


And that is one of the ideas of reconstructing past pressure temperature combination using a variety of texture and mineral composition. So this particular plot shows the variation of metamorphic texture varying with increasing metamorphic grade. So as we just discussed that the coarseness of the texture will increase as we go with increasing metamorphic grade as well as the crystal size. And then when we are talking about mineral composition, the mineral composition also changes as we are increasing the metamorphic grade.

Now, we also understood just by identifying one mineral is not always the best approach because they can have a relatively large field of stability. But if you can find multiple such minerals with intersecting pressure temperature ranges, then it can help you to narrow down the pressure temperature range of the rocks that are forming out of it. And that has been one of the approaches to identify that what kind of temperature pressure is responsible for developing a certain type of metamorphic rock and these are often called the facies and these are some of the examples of facies.

For example, if you look at the low temperature pressure condition, we are going to expect metamorphic facies, which is similar to zeolite means the index mineral is zeolite that is the mineral you are also going to encounter along with certain other mineral association.

And when we go to very high temperature, we are going to find something called a granulite. If you are going to go to very deep places with high pressure, we are going to encounter metamorphic rocks such as eclogites. So these are all different combinations of rocks, which has certain types of texture as well as mineral association, and giving you very nice information about the temperature pressure condition.

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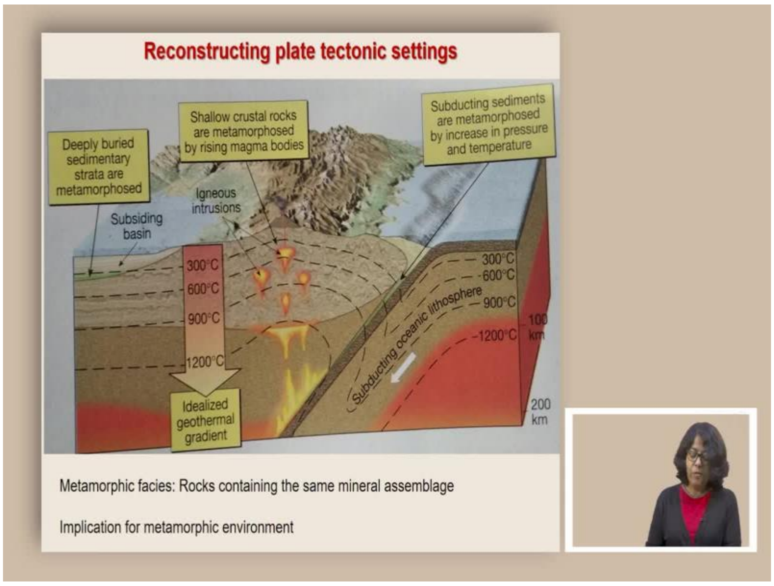


So metamorphic facies is the rocks that contain same mineral assemblage, and hence tell us somewhat of exact information of where they formed. And therefore it is possible to reconstruct the metamorphic environment using those metamorphic facies, as well as textual information. So if we look at the plate tectonic boundaries, we know how the temperature changes and we also have a good understanding of how pressure changes with depth. So once we know the stability field of these mineral associations, it is possible to actually put together a composite picture of where we were going to expect what kind of rock.

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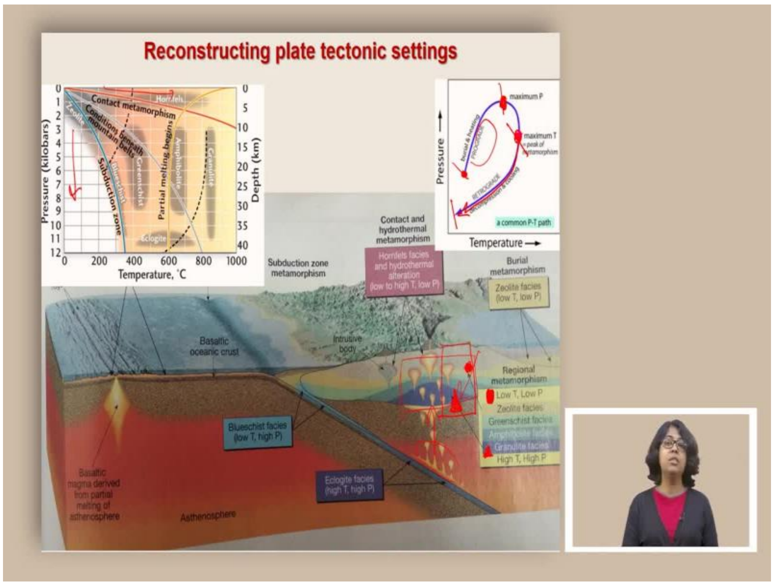


And this is what the picture represents. So for example, if we look at this zone, where things are basically right around subduction zone, and things are melting and as they are going up, they are also affecting the areas which are right above and the rocks which are right around here. And these are the rocks which are getting affected, but at a different degree.

So there would be things which are right around here, which are experiencing relatively low temperature and low pressure, but the rocks which are right around here are the rocks, which are experiencing high pressure because of the depth and high temperature because of their because of the geothermal gradient, as well as these increasing magma volume.

So as a result, in these cases, we are going to expect metamorphic facies, which is granulite, which corresponds to high temperature and pressure. And in these cases, we are going to expect a low metamorphic low grade metamorphic facies, which is something like zeolite. So we can actually have a variation in metamorphic facies as we are increasing the temperature and pressure.

And that is what is captured in this particular plot, because as you are increasing the pressure and increasing the temperature, you can actually predict what kind of rocks you are going to encounter or what kind of metamorphic facies you are going to encounter as you move along.

And this is really a comprehensive understanding that helps us to reconstruct the old plate tectonics setting. So even today, the rocks that we find in the surface, the metamorphic rocks, we can look at them and we can find out that exactly where it was formed by looking at their mineral assemblages. If you want to dive in deeper, that we want to actually recreate the entire metamorphic history, even that is possible by looking at each individual mineral grain, and to reconstruct that using their compositional variation.

So there are certain types of minerals that form during metamorphism, but they do not stop growing they actually grow over time as the metamorphism progresses. And every time they grow, they record the specific temperature and pressure in terms of their compositional change. As a result, if you track those changes in those mineral greens it is possible to reconstruct the entire metamorphic sequence.

And when you are looking at metamorphic sequence, it basically means you are reconstructing the pressure and temperature path. You can start with a rock which started here and which got buried and then experienced increasing heating. So that means it is basically moving from this point to an increasing pressure temperature path probably it reached somewhere here, which is showing you the maximum pressure and eventually a drop in pressure, but increase in temperature and therefore, it is the maximum temperature. And that can be considered a peak of metamorphism.

But finally, it can be uplifted up back to the surface, and therefore, this can experience a drop in pressure and temperature. This is the phase, which is called a retrograde metamorphism, whereas in the initial part where it is experiencing increasingly high temperature and pressure, they are called prograde metamorphism.

So in summary, you can actually look at a metamorphic rock and reconstruct not only where it formed, but the entire history of how it deformed, how it went through multiple stages of metamorphism. And that is an really good source of information when we are trying to look at the history of the earth and when we are trying to understand what were the events that took place a long time ago. So these rocks are really good record keepers of the history in terms of changes in pressure and temperature.

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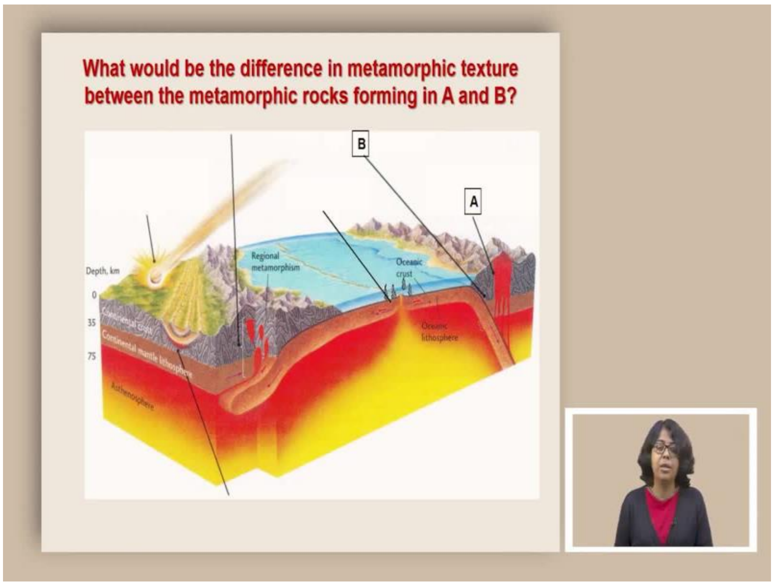


So in summary, today, we learned different types of metamorphic rocks and how we can name them. Or if we look at the names of certain metamorphic rocks, what can we infer just from the names. We also learned how the metamorphic texture and metamorphic mineral composition changes as the grade of metamorphism increases. We learned the facies concept of metamorphism and how it is related to different metamorphic environment.

Finally, we also saw some examples where using the combination of mineral composition, textural variation, it is possible to reconstruct where exactly that metamorphic rock has formed. Here are a few resources that I would encourage you to look at, and also a question that you should spend some time answering. Thank you.