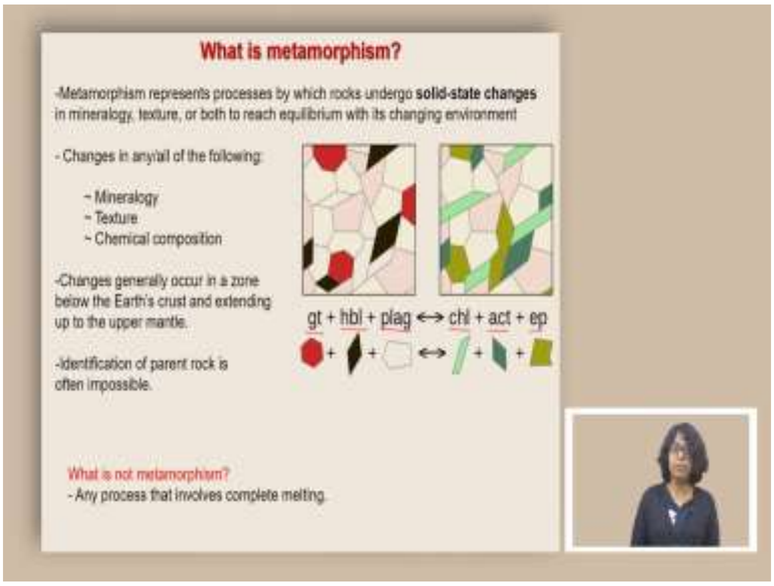
The Evolution of the Earth and life
Dr. Devapriya Chattopadhyay
Department of Earth and Climate Science
Indian Institute of Science Education and Research Pune
What are Metamorphic Rocks

(Refer Slide Time: 0:29)



Welcome to the course, evolution of the earth and life. Today we are going to talk about a different kind of rock. It is called metamorphic rock. Metamorphic rocks are formed through a process, which is called metamorphism. Metamorphism represents processes by which rocks undergo solid state changes in mineralogy, texture, or both to reach the equilibrium in the changing environment. So it is different from igneous rocks, because it never involves complete melting. It is also different from sedimentary rocks, because it undergoes conditions which are high in temperature and pressure. And we do see development of newer crystals, newer minerals, which all reflect the requirement of the changing environment.

So one way to understand metamorphism would be to look at some of the common examples of change when complete melting is not occurring. So if we think about a metaphor, cooking is a good metaphor for metamorphism. In cooking, if we think of ingredients like egg and flour and oil or butter, when we mix them and eventually bake it, we make a cake. And it does not really involve complete melting of any of these ingredients.

Yet, the final product is quite different from the initial product. And when we look at metamorphic rocks, that is something that we should try to keep in mind that the development of it is a result of what was the original material, and what are the conditions through which it has gone through finally dictates what kind of rock it is going to from.

So metamorphism involves changes in all kinds of things that constitute a rock. It includes the change in mineralogy, change in the texture, and change in the chemical composition. And these changes generally occur in a zone below the earth's crust, and extending up to upper mantle. Beyond that, often it starts to have a complete melting. Hence, it will be part of the igneous processes, and not really metamorphic processes. And unlike igneous rocks, where it melts, and hence it does not really retain information of the time or the events that happened before melting.

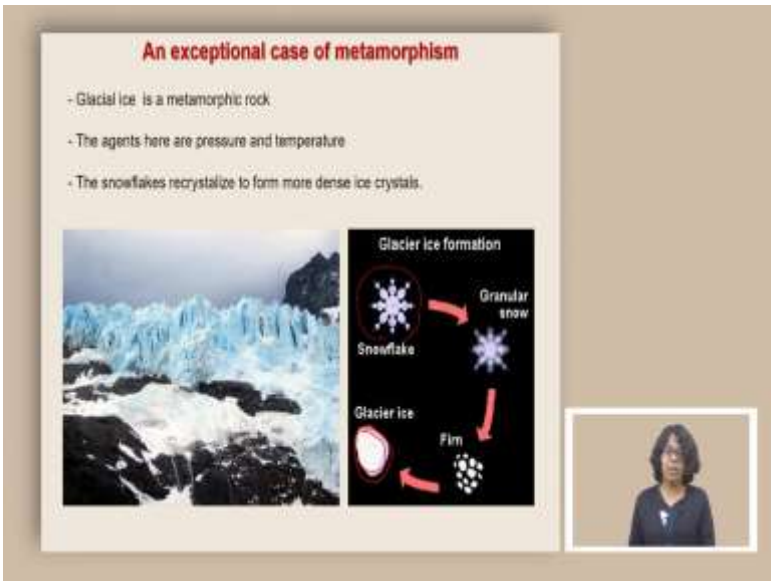
Metamorphic rocks actually preserved many of the instances or events signature of the events that happened in various metamorphic events. As a result, the final product is often a combination of a signature from different events. And therefore, geologists are very interested to study metamorphic rocks to decipher the history of the Earth through time in terms of high-pressure temperature change.

Now, what is not metamorphism as I mentioned, that, if a process involves complete melting of the rock, then we are not going to call it metamorphism. Because metamorphism involves all kinds of changes in mineralogy, texture and chemical composition, it is not always possible to identify the parent rock. However, as I mentioned, that because it involves some signature of different events, it is sometimes possible to identify the parent rock as well as the changes that happened subsequently. So here is an example of our metamorphic reaction.

So the first slide, the first picture shows arrangement of crystals and the composition of it has different minerals such as Garnet, hornblende, and plagioclase and then after metamorphism, it can convert to chloride, actinolite and epidote these are different minerals by sharing some of the chemical composition, sometimes changing the crystal structure, and sometimes by exchange of other minerals which are surrounding. So, it when these changes are happening, it is a solid-state change.

None of these minerals are completely melting and re crystallizing the newer minerals, it is actually forming a different crystal often representing different mineral, simply by changes act that are happening at the solid state. Now we are going to look at some of the exceptional cases.

(Refer Slide Time: 5:45)

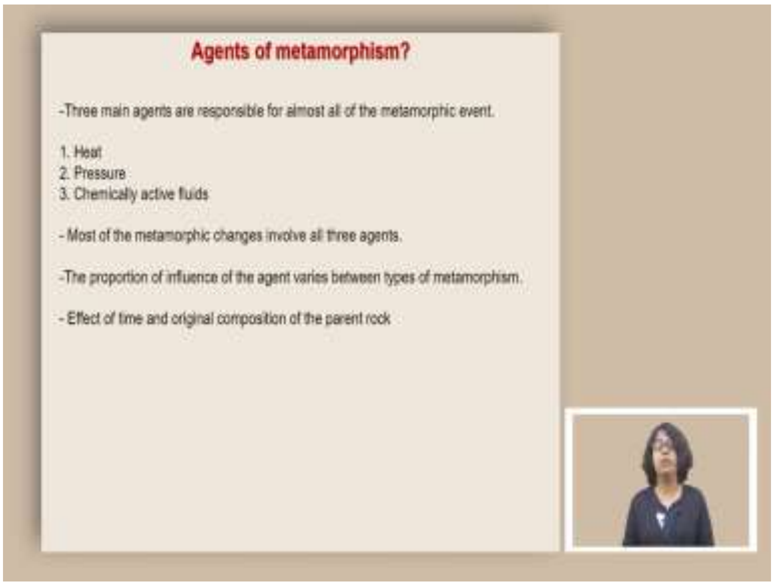


So one of the exceptional case of metamorphism is the glacial ice. So if you think about what it requires, when we call something a metamorphic rock, it means that the original mineral composition, or texture should be changed as a function of the changing environment. And all of these criteria are met in the glacial ice. Because glacial ice start with the snowflake. And if you look at the structure of the snowflake, it looks quite distinct. It has a very nice crystal structure. But then, as it falls down, it kind of forms granular snow. And because of the pressure, overburdening pressure of other snowflakes, it will eventually form something called a firn and then finally, glacial ice.

In this glacial ice, it is quite distinct from the structure where it started from, and this structure is forming because of the overlying pressure, and very low temperature, and this recrystallization of snowflake, are basically tends to give a more dense ice crystal. And because of which we can call this glacier ice a metamorphic rock, you may think, which one is the mineral that is constituting this metamorphic rock, it is actually ice. And if we think about the definition of a mineral ice meet all of the requirements, which is necessary to define something as a mineral, so we have a mineral which is ice, and it is metamorphosing into something, which is quite different from where it started from. And therefore, it would be a good example of metamorphism.

The word metamorphosis or metamorphism involves two parts one is the meta, and the other one is the Morph, meta means change and morph means shape or appearance. So it is a change in the appearance or form, which leads to this definition of metamorphism.

(Refer Slide Time: 8:21)



Now, we are going to look at different agents of metamorphism and how it impacts the overall rock. So the major agents of metamorphism include heat, and when we are saying heat, it basically means it is a change in the temperature, it could also be a loss of heat. The second one is pressure, and pressure again, it can be a combination of things, there are different kinds of pressure that a rock is subjected to and all of them can contribute in terms of change in the solid state. And finally, that chemically active fluid.

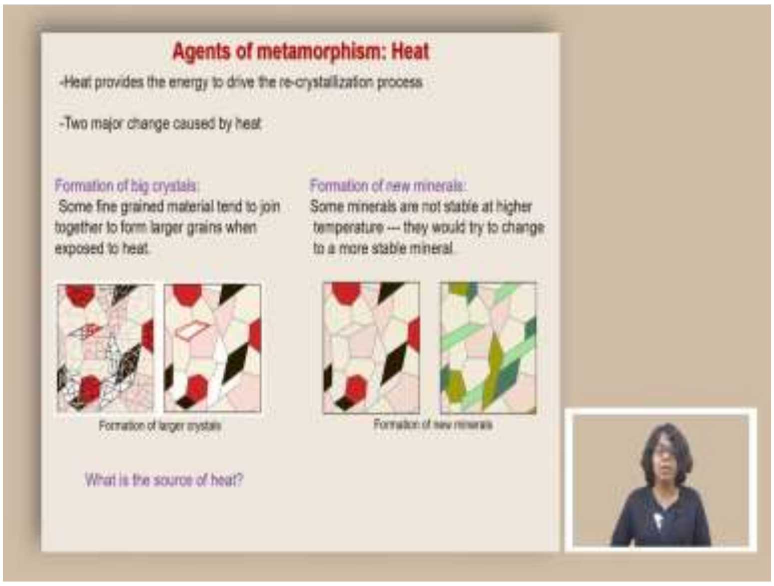
In majority of the cases, metamorphic changes involve all three agents with differential contribution. And sometimes just by looking at the signature of the metamorphic texture, or metamorphic composition, it is possible to identify which agent contributed the most. But one thing to keep in mind that apart from these agents such as heat, pressure and chemically active fluid, to other things play a significant role in shaping the final output of a metamorphic process.

And those two things are the time as well as the original composition of the parent rock. So, if the composition of the parent rock has only silica, then it can change in terms of crystal structure, it can change in terms of the overall shape, texture and things like that, but it is not going to change the overall composition at some point of time are not significantly. So, the original composition of the parent rock contributes significantly in terms of dictating, what is going to be the final product.

The second important thing which is very difficult to understand often and conclude about is the effect of time, many of the processes of heat pressure and chemical reaction do not add up when we increase the time. Sometimes, the changes are non-monotonic in nature, sometimes they change their course, if it happens over a very long time, and therefore, the effect of time is often a complicating factor for metamorphism, because they cannot be scaled down in a small setup. So, when we think about an experimental setup to understand the effect of heat, effect of pressure, effect of certain chemical fluid, we are always doing these experiments in a relatively shorter time, in the time of human timescale.

However, sometimes these processes in nature take more than a million years. And the result of it is quite different from what we observe in an experimental scale, simply because the effect of time is not is not scalable in many of the times. So, that is something that we should keep in mind when we are looking at some of the patterns in the nature.

(Refer Slide Time: 11:52)



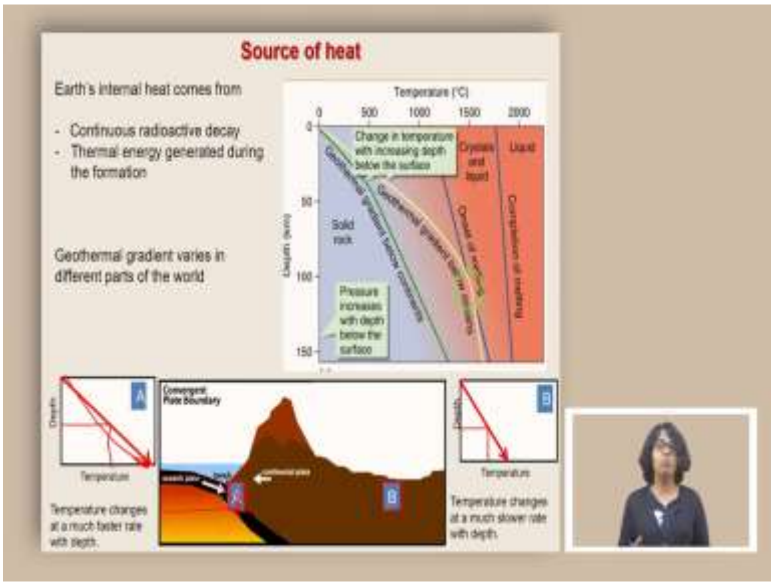
So, the first agent of metamorphism that we are going to talk about is the heat. So, heat provides the energy to drive the recrystallization process. And as a result, we find many of the changes, which does not often involve any change in composition, but simply the arrangement of crystals and therefore, new crystals appear. So, there are two major changes that we see as a result of heat. One is the formation of big crystals. Some of the fine crystals, some of the fine-grained materials tend to join together to form larger grains when they are exposed to heat.

So, if you look at this particular picture, there are really tiny crystals. And if these rocks are subjected to high heat, they tend to glue together to make a larger crystal. And that is often a common reaction to heat in many of the metamorphic rocks. So, as we move in the temperature scale, we tend to get larger and larger crystals, if we keep the other things constant for a metamorphic process.

The second one is the formation of new minerals, some minerals are not stable at higher temperature, and they would try to change to a more stable mineral. And this often is linked to their original crystal structure. If you think about the silica tetrahedra it often includes how silica tetrahedra is arranged in a mineral and in high pressure or high temperature in this case, we are talking about high temperature, whether that configuration is stable enough, if it is not stable, then the mineral will try to attain a crystal structure which is more stable at higher temperature.

And therefore, we either get a gluing of small crystals to make big crystals or we find a conversion from a relatively unstable mineral to a stable mineral at a particular temperature. Now the question is when we are talking about the heat as being one of the major agents of metamorphism. It is important to notice that what is the natural source of heat.

(Refer Slide Time: 14:30)



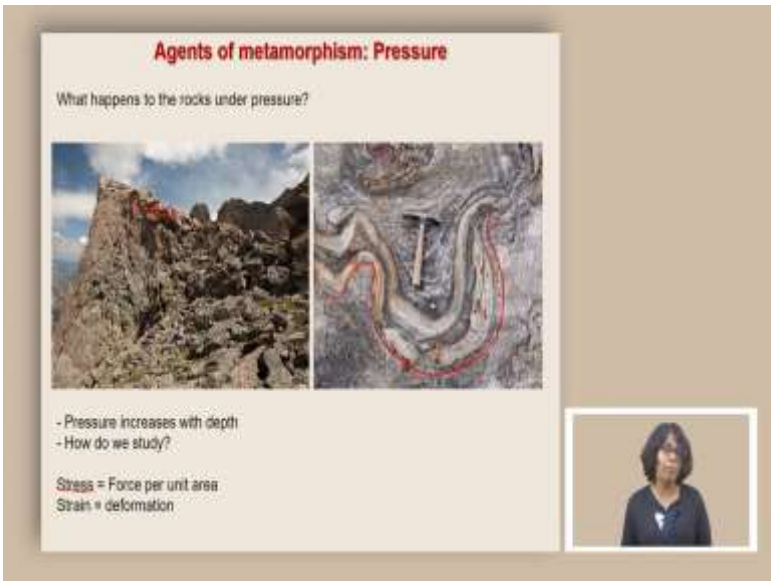
And the natural source of heat in the earth is it comes from the interior of the earth and the interior of the earth gets its heat from the continuous radioactive decay, which are long term radioactive decays, which provides which releases heat as the reaction progresses. The second one is the thermal energy generated during the formation of the earth. So both of these are the major sources of heat of the internal part of the earth. And because the interior of the earth is very hot, it also tries to cooled down and therefore, it tries to dissipate the heat through its body.

As a result, some of the heat also comes to the surface, and when it passes through mantle, because the rocks can flow in the mantle, it basically tries to cool down through convection in the mantle, and some part of the heat is also received at a cluster layer. And these kinds of heat dissipation or that change of temperature as we go down is called a geothermal gradient. And geothermal gradient, whether it is going to be a steep geothermal gradient versus shallow geothermal gradient is going to be determined by which plate tectonics setting we are looking at.

So here are two examples of two places in the normal Earth setting where we are going to look at convergent boundary marked by A. In this convergent boundary, the oceanic plate is going down and as it goes down, if I just look at this particular part and try to understand how the temperature changes, if I am going to look from this point to this point, in terms of the depth, then the plot looks something like this, what it means that at a particular depth change, the temperature change is quite high. On the other hand, if I look at this part of the crust, which is under the continental crust and it is quite thick, we will find that with the same amount of depth change, the temperature changes much smaller.

So depending on the nature of this curve, which is called the geothermal gradient, it will determine whether it is going to be a major temperature change or lesser temperature change. And because of that, the metamorphism can be different. So, as the convective plate is going down, it is experiencing higher temperature relatively higher pressure, and all of them will contribute to metamorphism before it starts to melt. So, there is a considerable time during which the oceanic plate is actually moving from the crust towards the deeper part, but it has not started melting, and that is the place and time and depth where metamorphism will start to occur as a response to heat.

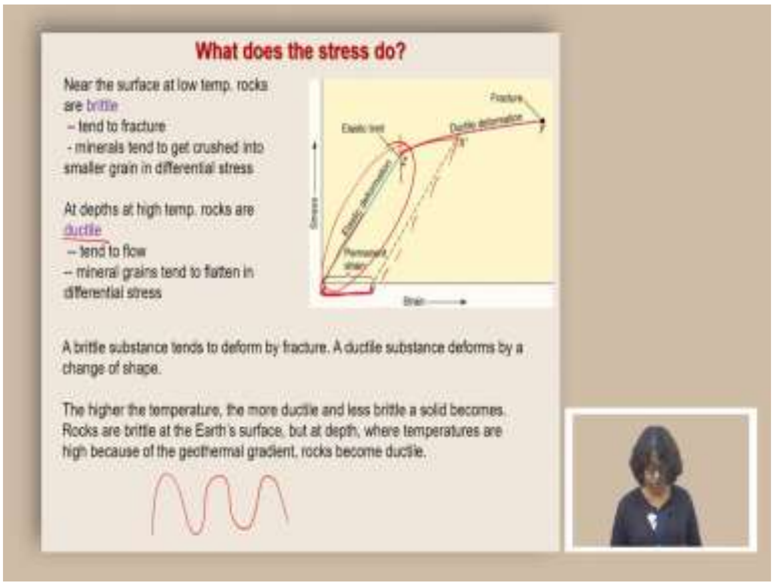
(Refer Slide Time: 17:54)



The second one is the pressure that is the second agent of metamorphism. So what happens to the rocks under pressure. So I have provided 2 pictures, the first picture shows crushed rocks, and you can see blocks of rocks, which are clearly broken into fragments. But the second picture is quite interesting, because it shows folding or buckling of rocks. Now, as we know, that we see when we see the rocks at the surface, they are quite hard. And it is hard to imagine that if we put pressure on it, they will do anything, but to break apart or getting crushed, how can they make structures like this and the clue is how the rocks behave under high pressure.

So, high pressure and temperature makes the rock behave in a certain different way. Then how it will behave if it was at the surface at low temperature and low pressure. And the way to study these things is to do it at an experimental setup and to look at how the rocks behave or even materials behave under high temperature pressure versus low temperature pressure. So, before we do that, let us try to define these two terms that we will be using one is called stress and stress means force per unit area, this is also a measure of pressure and strain is the response of the material property to stress. So in other words, how these materials are changing their shape or deformation. So those are the things which are measured by strain.

(Refer Slide Time: 19:54)



So now if I look at a stress and strain curve for a rock what we will find that at the initial stage, if you increase the stress, the strain is also going to increase, that means that it is going to change in shape. And this is the particular part where we call, it is an elastic deformation. What it means is within this part, if you remove the stress, it basically comes back to the same original shape.

So it does not really change any shape permanently. And this is also the place up to which the rock has the strength to bear the stress. However, when we crossed this threshold, we started finding situation where adding more stress is going to change the shape. And this is the change in shape, where even if you remove the stress, it does not come back to the original position, it actually comes back to a different position, and this is the permanent deformation that we are going to talk about, when we are adding more stress. And this is one factor that we should keep in mind. And this is also a part where we are going to call the rock behaving in a more ductile manner.

So, when we look at the wrong behavior, what we find that near the surface at low temperature, rocks are brittle. So they are more, they are behaving more in this part. And if you put on more stress, often they are going to crack they are going to fracture, but they are not going to change the shape as such. And minerals in those rocks, who are undergoing brittle deformation, they tend to get crushed into smaller grains in differential stress. So if the stress amount is not the same, in all directions, they tend to crush down they tend to get create smaller crystals to accommodate the stress.

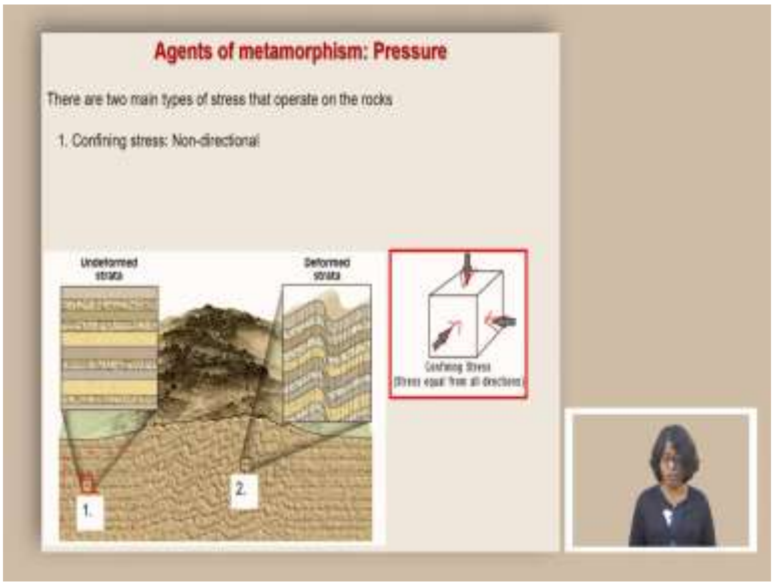
However, if we are making these rocks go down to a deeper depth, where the temperature is high, the rock started to behave in a different way, the rocks started to show permanent deformation, and they tend to flow or they tend to change their shape. And it is hard to see that at the surface. So, therefore, wherever we find a ductile deformation and a telltale signature is we will see the rocks changing the shape and they will give an impression that they almost flowed.

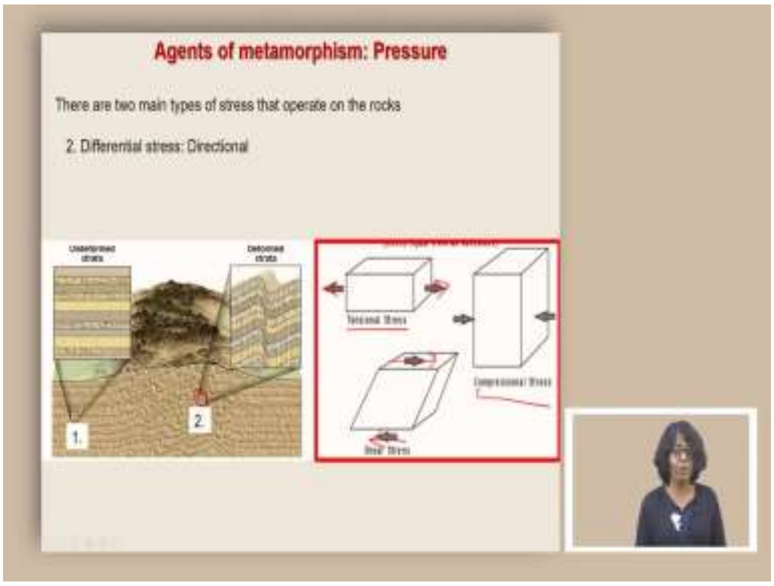
They would be telling you that those deformation took place at a greater depth and at high temperature. In those cases, the mineral grains that make up the rock tend to flatten in differential stresses. So, they accommodate that stress by changing their shape and making it flatter to accommodate that stress.

Now, a brittle substance tends to deform by fracture, as I mentioned before and therefore, you do not really see a change in the shape it simply crashing down into smaller pieces in terms of crystals to adjust to the stress, whereas a ductile substance will show you deformation a change in shape by the change in stress. And to a large approximation, the higher the temperature is, the more ductile and less brittle a solid becomes, and rocks are brittle at the Earth's surface, but at depth, where the temperatures are high, because of geothermal gradient rocks become ductile.

So, all the shapes that you can see which will give you patterns of folding tells you that the rocks are bending, but this bending cannot happen at a surficial condition with very low temperature, it requires the rock to behave in a more ductile manner. And that has to happen at a deeper depth where the temperatures are high. Now, the stress can be of different types.

(Refer Slide Time: 24:43)





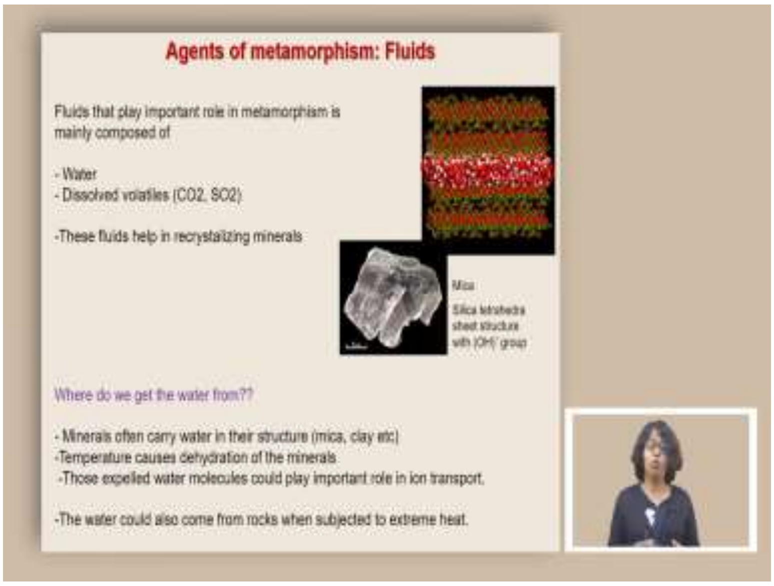
One type of stress is the confining stress or non-directional stress. So if we look at a rock, which is sitting somewhere here, it is actually experiencing quite a bit of stress or pressure because it is surrounded by rocks in all the other direction. And because of this, it is actually experiencing confining pressure, which is to say it is known directional stress, the amount of stress in all the 3 dimensions are equal in its magnitude. And therefore, you are not really seeing any change in shape. It is simply it is experiencing a confining stress. But there can be no directional stress too.

When we are talking about directional stress, it is also differential. So directional stress means that unlike the confining stress, here, the magnitude of the stress in different directions are going to be different from each other. And we can define it in terms of what is going to be the major axis of the stress.

So there can be tensional stress, where the stress axis is basically showing us a pattern of pulling apart, that is the direction where it is maximum in comparison to the stresses on the other direction, there can be compressional stress, again, where it is basically pushing from 2 different directions and that is the maximum magnitude of stress compared to the other stress reduction, it can also be a shear stress, that means the direction of the stress in opposing parts have different directions to each other.

And therefore, it is sliding past each other. And these kinds of differential stresses finally lead to change in shape, if we are talking about rocks, which are already under high pressure and deeper level. So, when we look at rocks, which are underneath and experiencing high temperature and therefore tend to behave in a more ductile manner, they are going to respond to this tensional stress, shear stress, compressional stress with specific textures and specific development of rock types.

(Refer Slide Time: 27:20)

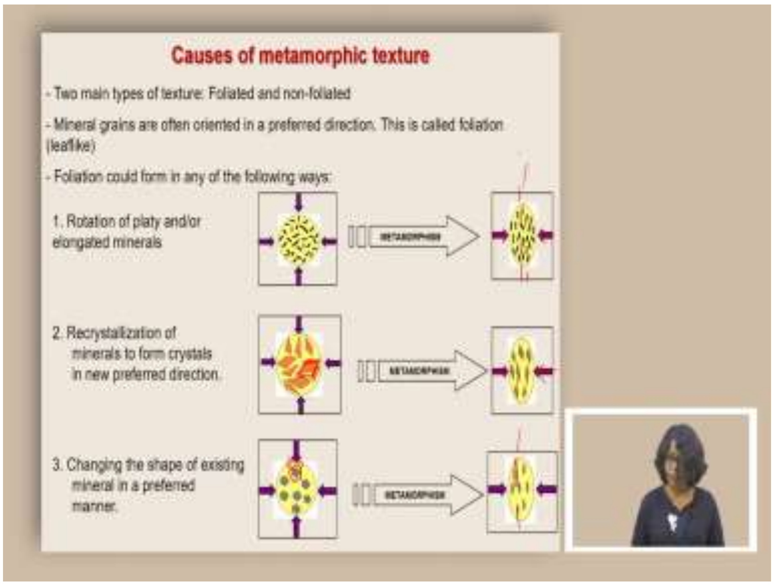


The other important agent of metamorphism is the fluid. Now fluids can play an important role in metamorphism. And those fluids are primarily composed of water, it can be the vapor phase and also the dissolved volatiles like carbon dioxide, sulfur dioxide, and these fluids help in re crystallizing minerals.

So, for example, there are many minerals such as mica, where the structure is that there are silica tetrahedron arrangement, but within that, there are OH groups. And once these rocks are subjected to high temperature and pressure, then these water molecules get released and these water molecules subsequently contribute to what kind of structures are going to be more stable at that high temperature pressure regime. So, fluids actually play quite a bit of important role in metamorphism.

This temperature induced dehydration, changes minerals, and sometimes the expelled water molecules can play an important role in terms of transporting certain things. So the water could also come from the rocks when they are subjected to extreme heat. So it is not it does not always have to be the water molecules which are trapped inside the mineral structure, it can also be some of the water which is between 2 grains and still can be released at extreme heat. And we see the effect of these things when the metamorphism is happening at high temperature on sedimentary rocks, which tend to have quite a bit of water molecules trapped inside the rock structure itself.

(Refer Slide Time: 29:26)

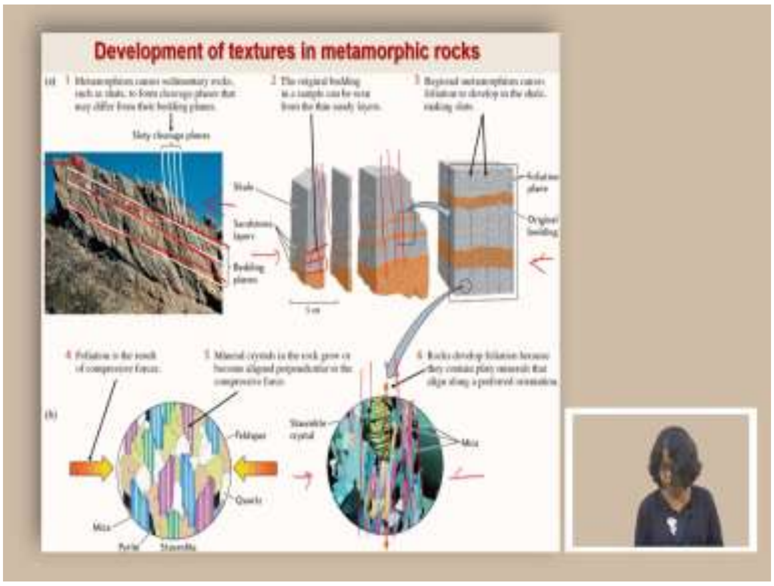


So now, let us put together all of these things and try to understand how all of these agents are going to contribute to form different metamorphic textures. So there are 2 major types of metamorphic textures, one is foliated and the other one is non foliated, foliated textures are those where the mineral gains are often oriented at a preferred direction. And they are actually called a foliation because they are leaf like foliage means leave and if you are stacking up leaves, it sort of gives a preferred orientation and therefore it is called foliation.

Non foliated structure, on the other hand, does not show any such specific direction. And these foliations can be formed in any of these following ways. The first one is, when there is a directional stress, there can be rotation of the platy or elongated minerals, and they are all aligned in a perfect orientation to accommodate the stress. And therefore, we will start to find some foliation along these lines. It can also be a recrystallization of minerals to form crystals in new preferred direction.

So, instead of the original crystal structure, it can have a solid-state transformation to make newer crystal to accommodate the differential stress. The third option is the change of shape of the existing minerals in a preferred manner. And that can also create such foliation where it is not really rotating, it is not re crystallizing, it is simply changing its original structure to a more platy fashion and that leads to such foliation.

(Refer Slide Time: 31:34)

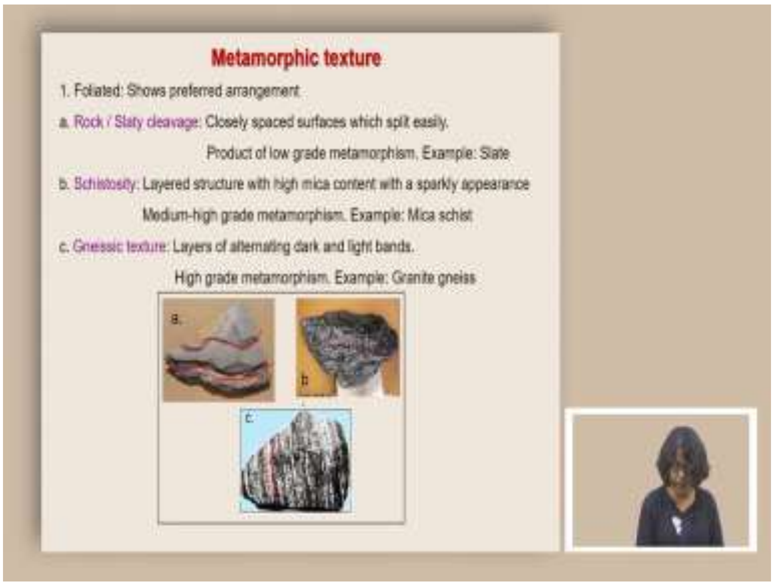


This is one more example of development of textures in minerals of metamorphic rocks. So, if we start with a sedimentary rock, sedimentary rocks have bedding planes, these are planes along which the sediment was deposited, but then because of the stress, it can eventually produce something which are foliation planes and they can be perpendicular to the original bedding plane.

So, if we look at these shales, which are converted or metamorphosed sedimentary rocks, what we are going to find that this was the original bedding plane, which is marked by these sandstone layers, but because of the differential stress primarily of compression, in this direction, we are seeing the arrangement of minerals along these lines and creating a foliation which looks something like this.

So, if we look at it under microscope, what we are going to find that there are minerals such as mica, which are basically orienting themselves in long platy fashion, creating this kind of foliation and other minerals, such as staurolite, they can be slightly rotated and aligned along the orientation of the foliation. And a combination of all of these things is going to give us a preferred orientation along these lines finally defining foliation as a result of compressive stress in this direction.

(Refer Slide Time: 33:20)

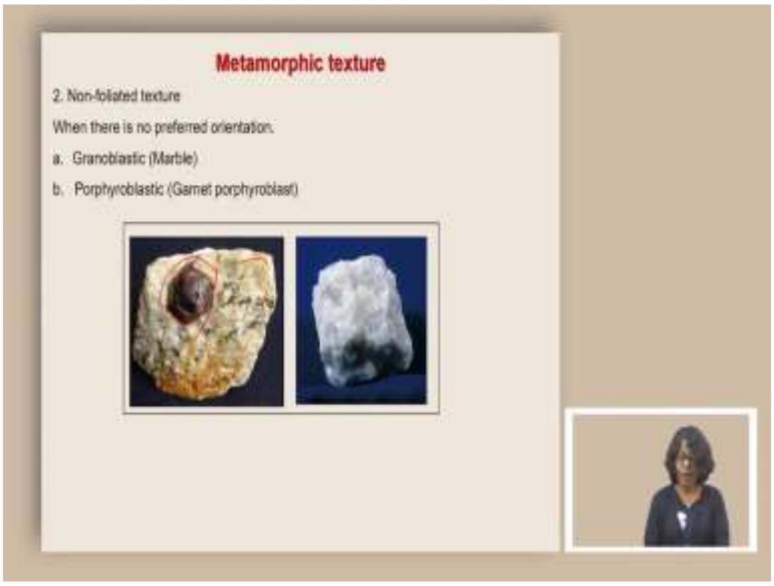


So, we are going to find all kinds of patterns that are inclusive of these foliation planes. And we are going to see that there can be things which are foliated and which has different types. The first one is a rock of slaty cleavage, rock cleavage or slaty cleavage, which are closely spaced surfaces that can be split easily. And it is generally a response to a low-grade metamorphism.

A good example is slate, where if we break it, it tends to break in preferred direction and those are all slaty cleavage. The second one is called schistosity and schistosity is basically layered structure of high mica content and they will have a sparkly appearance. It shows us slightly high-grade metamorphism medium to high grade metamorphism and they are going to give you this appearance of sparkling appearance and these are called Schistosity.

The third one is a gneissic texture. These are layers of alternating dark and light bands. These are generally product of high-grade metamorphism and here is an example where you can see the dark bands alternating with light bands, dark bands again.

(Refer Slide Time: 34:57)



In contrast, there can be non-foliated texture where there is no preferred orientation that you can talk about and it is not easy to figure out what was the direction of the stress and generally, they are developed because of low contribution from the directional stress, rather, it is primarily contributed by the temperature or non-directional stress.

So, there can be one type which is granoblastic, which is marble where you do not really see any change in terms of its texture, but it could also be a porphyroblastic that means, there is a large crystal, which is the porphyroblast in the matrix of things which are very fine crystals. So, these are can be types of metamorphic textures in under the category of non-foliated texture.

(Refer Slide Time: 35:57)

Here are some of the resources and then there are questions for you to think about. Thank you.