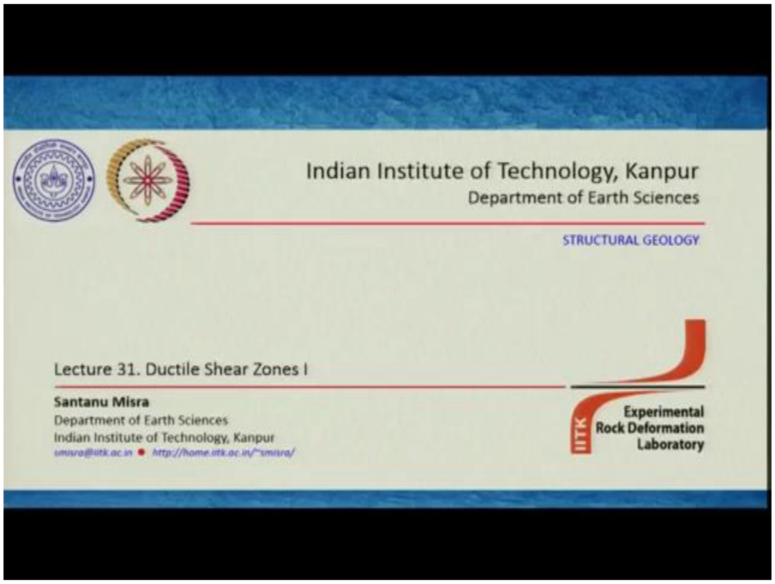
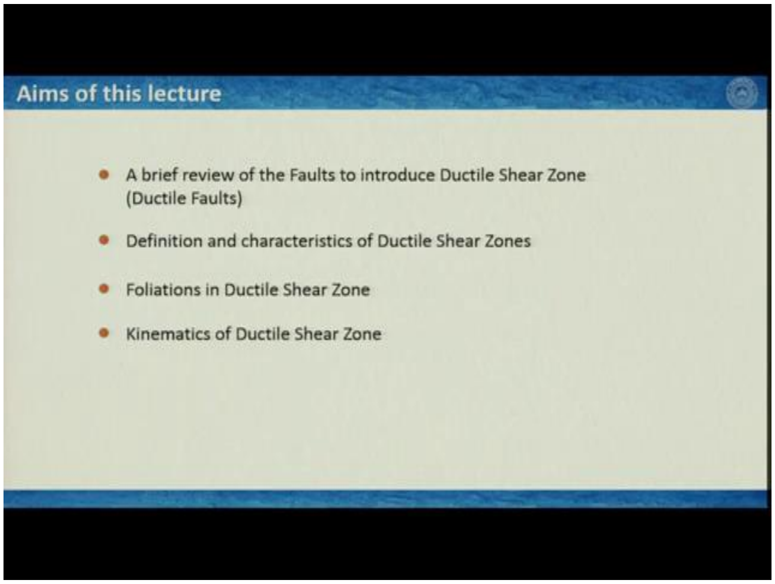
Structural Geology
Professor Santanu Misra
Department of Earth Sciences
Indian Institute of Technology, Kanpur
Lecture – 31
Ductile Shear Zones – I

(Refer Slide Time: 0:28)



Hello everyone, hope you are doing well. Welcome back again to this online structural geology NPTEL course. We are in all week number 11 and we are learning faults, ductile shear zones etc. So today we will start our first lecture on ductile shear zone and this is lecture number 31.

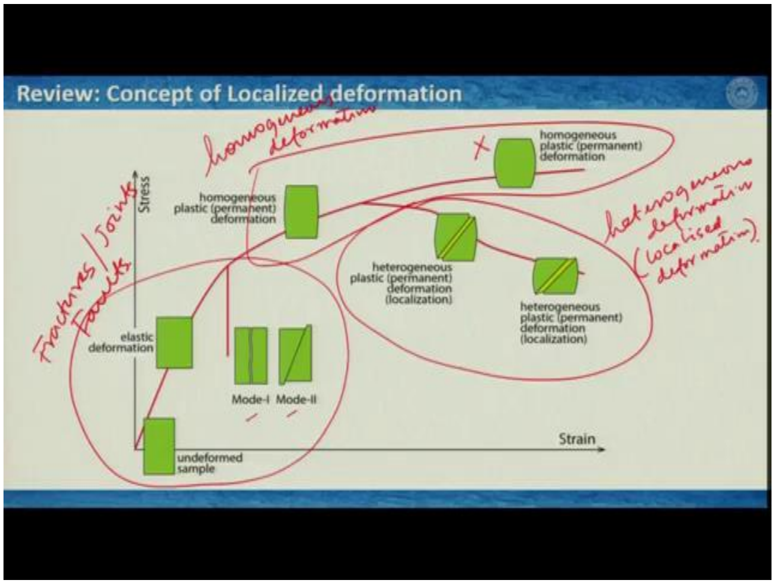
(Refer Slide Time: 0:42)



So, in this course we will initially, very briefly, review what we have learned so far. The faults and from the faults we will slowly switch to a ductile shear zones, so most of the slides or comments that we will hear, these are said before, but I would like to repeat them again for a review. Then, will define a ductile shear zones and look at their different characteristics. After that, we will see two very important features of ductile shear zones. One is foliations and another is kinematics.

And, in the next lecture we will figure out what are the different microstructures and at the same time the kinematic indicators of ductile shear zones. So, what I mean by this that how to know that which way the shear zones moved past one another with respect to the rocks, which are undeformed. But we will learn all these things in this lecture and then in the next lecture we will learn further.

(Refer Slide Time: 1:40)



So, what are you going to do first as I said that we will review, so, these illustrations we have seen before. We know that in the low pressure and temperature we generate a mode 1 or mode 2 fracture so rocks generally do show brittle deformation and these are attributed to fractures, joints, and faults.

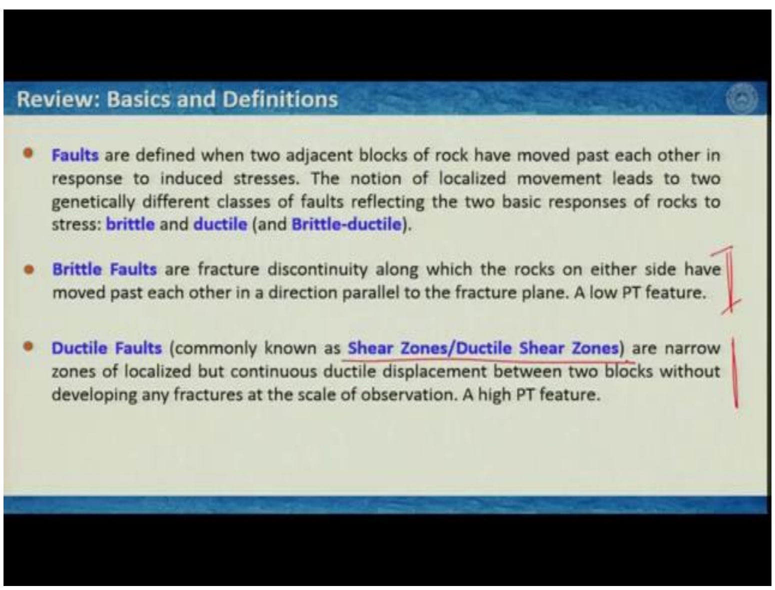
These are essentially the homogeneous deformation at high pressure and temperature and this part which we are going to learn in this lecture and in the next lecture are the heterogeneous deformation or in other ways localized deformation.

So, at high pressure temperature when deformation does not happen this way, that means, deformation is not distributed in the entire rock mass or in this case in the entire sample. But it is restricted allow a narrow zone. Then we have localization of deformation and this is in a way is the concept of ductile shear zone and we will see this soon in theory and also with many of photographs.

(Refer Slide Time: 3:20)

We have also learnt that the brittle domain we have within the fault range and then we have ductile domain where rocks deform in ductile manner and in between we have brittle ductile deformation where rocks do show both brittle and ductile signatures in deforming the rocks.

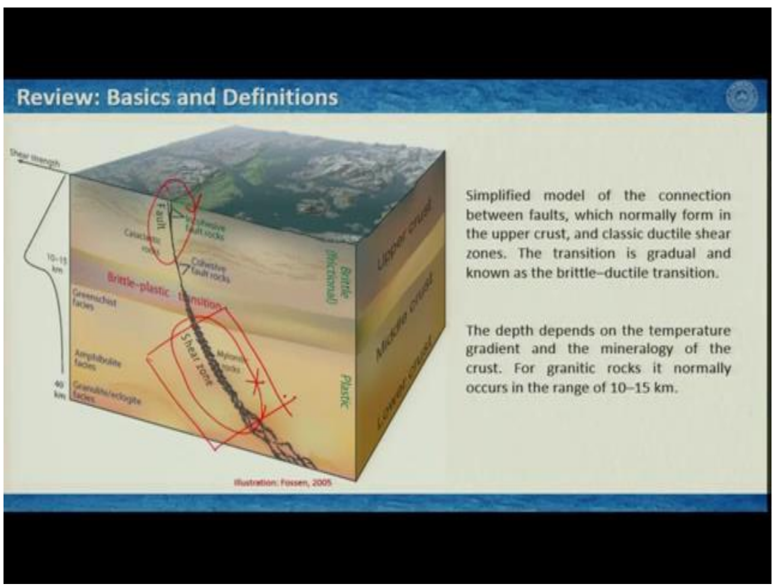
(Refer Slide Time: 3:37)



So we also have learnt it that initially we classify any localized type of deformation in terms of faults and then we call it brittle faults if the cohesion is not maintained, the continuity is not maintained during the deformation and on the other hand we have ductile faults that means where the cohesion is maintained or the continuity is maintained and whatever we have in between is brittle ductile faults. We learnt about brittle faults in the last few lectures and in this lecture we will talk about ductile faults or which are commonly known as shear zones or ductile shear zones.

So initially there are two terms faults and shear zones. You may aware of this fact, so one part is fault which are the faults the way we understand brittle fault where 2 blocks moved past each other producing some fractures in between. Now whatever are not faults, they are categorized as shear zones or something like that. But Ramsey in 1980, he came out with this kind of classifications that everything that we can imagine in terms of localized deformation these are faults and then you have brittle faults, brittle ductile faults and ductile faults.

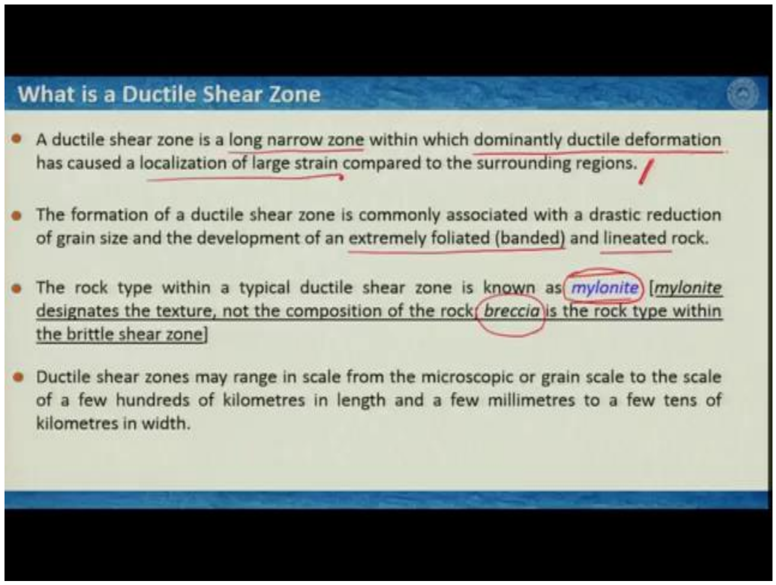
(Refer Slide Time: 5:04)



So the ductile faults are known as also shear zones or ductile shear zones and this is exactly what we are going to learn today. And also in terms of the geological context, so at the surface we generally see faults, the brittle faults in other ways and at depth we see the shear zones and this we have also seen with the first illustration of this lecture. That at high pressure temperature you only can have localization without producing fractures and these are shear zones. So here you have fractures but here you do not have fractures.

The grains do deform in the manner of intra-crystalline plasticity. You have learnt about it in a neology and reformation mechanism lectures. So this is the mechanism by which the grains deform and they are localized the deformation. So we are going to focus on this part in todays lecture.

(Refer Slide Time: 5:56)



Let us define what is a shear zone or what is a ductile shear zone in specifically. A ductile shear zone as it is written here is a long narrow zone within which dominantly ductile deformation has caused a localization of significant magnitude of strain compared to the surrounding regions. There are many important phrases here, which are important in defining the ductile shear zone or important in characterizing ductile shear zones. And the first one is long narrow zone, so that means the zone which ease a ductile shear zone has to be long enough compared to its width. So it is a narrow lenticular zone.

Within this zone you should not have significant fractures or no fractures. The deformation must be dominantly ductile deformation and this ductile deformation has to cause by localization of large strain or ductile deformation has to accommodate the maximum strain of this region and therefore it remains localized deformation compared to the surrounding region.

The formation of a ductile shear zone is commonly associated with drastic reduction of grain size. We will see some slides or photographs later that the grain size in the surrounding regions are much higher compared to your localized domain and this is a mechanism how the grains actually accommodate the deformation and the mechanism we learnt about it is intra-crystalline plasticity.

And while doing this the rock within the ductile shear zone produce extremely fine foliation. So the characteristic of ductile shear zones also include the rock has to be extremely foliated and at the same time lineated. Now one may be absent but the lineation may or may not be present, but foliation is a must in defining a ductile shear zone.

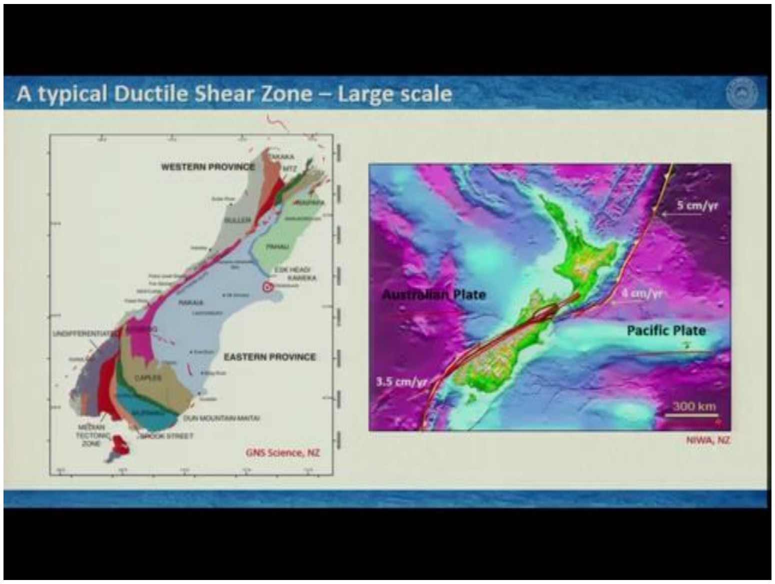
Of course, this is a secondary foliation we are talking about. The rock type that we see in a typical ductile sear zone is known as mylonite. Now mylonite is not a composition of the rocks. So it is not like gabbro or anorthosite or granite and so on. These terms define a typical composition. But mylonite generally defines, or it designates a texture, a character of the rock not the composition of the rock.

A similar type of rock so when we see in brittle shear zones then we call it breccia, so mylonite is the rock that you should find in ductile shear zones and breccia is the type of rock that you should find in brittle shear zones. Mylonite should be characterized by extreme grain size reduction, so the breccias.

But in mylonites the mechanism of grain size reduction is crystal plastic deformation or intra-crystalline plasticity. Whether in breccias it is mostly cataclastic deformation. Mylonites also do possess a lot of fabrics, breccia also does but not as prominent as mylonites do have fabrics within themselves.

Now ductile shear zones as many of the geological structures can range from very very micro scale to mega scale so as it is written here that it ranges in scales from the microscopic or grain scale to the scale of a few hundreds of kilometers in length and a few mille meters to few tens of kilometers in width. We will see some examples in one of the next slides that how big a ductile shear zone could be.

(Refer Slide Time: 10:12)



Now this is exactly what I was talking about. This is an example of ductile shear zones, what we see here this is South Island of New Zealand. The Christ Church is somewhere here and the North Island is somewhere there. Now we know that New Zealand the South southern part of New Zealand is characterized by a fault which is known as alpine fault which is this one.

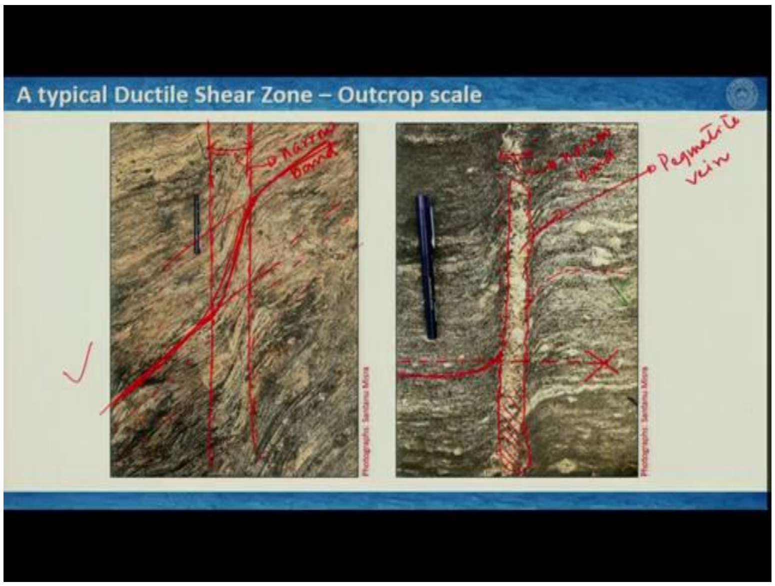
Now we can see the rock types here in this part, the way they occur they tend to occur in a very similar way here. And you may figure out the fact that if I considered this green horizon. So this green horizon probably went like this and then it is again appearing here the same with the red horizon, the pink horizon.

Now of course on the surface it is a fault because it is a low-pressure temperature feature but at depth it is essentially ductile, and this is a very large scale shear zone. Tectonically we can see what is happening here. So, on this side we have Australian plate on the western side of New Zealand and on the eastern side we have Pacific plate.

And this Pacific plate subducts here along the Hikurangi subduction zone, which has a velocity of 4-to-5-centimeter per year and then we have another subduction zone, which is Australian plate is subs duct sub ducting below the southern Island of New Zealand. There we have velocity 3.5-centimeter per year.

So these two subduction zones they actually collide and meet each other and they produce this excellent alpine fault or in a way at depth a ductile shear zone. A lot of structures and other features are there to see and look at, but we are not going into this. But take a message of this slide that I would like to convey that the scale is almost covering an entire country from one end to another end. And you can see the scale this is 300 kilometers.

(Refer Slide Time: 12:18)



Let us look the ductile shear zones in the field scale or out crop scale. Now first of all how to know that these are ductile shear zones, it is very very easy once you know this. So, what we see in this side in in this illustration or in this photograph that this is a granitic rock or granite nise and if I concentrate on this corner this are nisic foliations.

So in normal way the nisic foliations should go like this. But here I find a region where this nisic foliation is deflected. The region is essentially narrow, and the deflection is mostly restricted in this narrow band. So this is the narrow band that we are talking about.

So, if I consider it is going very much well but when it touches the boundary it goes like this and where it comes out from the boundary it follows more or less the same terrain as it has before. So this and this, so these two were probably together and now they got deflected and this deflection has happened due to extreme localization, shear localization along this.

So this we can designate as a ductile shear zone. If you look at in the next image again you can figure out that we have something a very narrow zone and this does not have exactly similar appearance as we see here in the other image. So, this is again your narrow band and what interestingly we see here that it is going like this again these are nisic foliation and we do not see anything here.

The trace of the foliations we do not we do not find it here the way we are finding here. So it is missing and let us assume that it is coming out of here. But essentially the fact we can figure out that it is this this foliation or this layer if I consider is not continuing this way. So this is not exactly what is happening here.

This foliation enters here got dragged and say for example it is coming out from here. So same situation we see here. But here we see some large crystals and we just defined that ductile shear zones must be defined by extreme grained size reduction. And here something very interesting things do happen in the ductile shear zones.

What we see here this is nothing but a pigmatitic vein. And how did it happen? These ductile shear zones are excellent for carrying the fluids because you have extreme grain size reduction in the ductile shear zone. At the same time, it is happening at high pressure temperature. So the few minerals that have water in their structure, they release the water during deformation and at the same time during metamorphism. Now these waters sometimes find the best place to reside ease within the ductile shear zones and it has a significant implication in our life. I will show you later.

So when these fluids they do reside within the ductile shear zones, sometimes they occur as veins and this is one of the examples pegmatite veins. And these ductile shear zones not necessarily always in a simple shear mode it can have a dilatational mode and if that happens then it becomes much easier to fluid to flow to these dilatational zones because this is a low-pressure zones, Fluids generally do flow from high pressure to low pressure. We will see the importance or what is a role of fluid here and so on and why it is important in our life in one of the next slides.

(Refer Slide Time: 17:00)

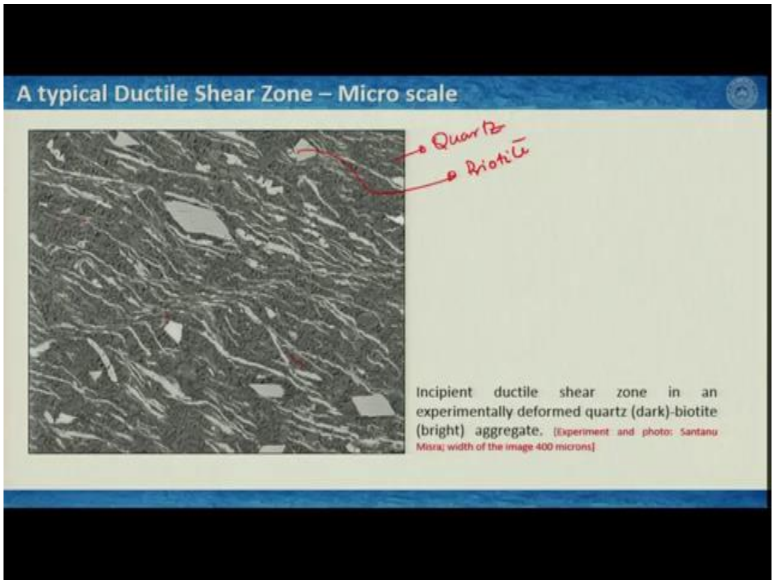
We saw the ductile shear zones in very large scale now we saw it in field scale but let us have a look what happens in micro scale. It is a very similar thing that we are looking at. We see that we have again a narrow zone here, which is essentially different. So this is the same image, this one and this one. So this is plain polarized light and this is cross polarized light.

What we see here that we can identify the grains here individual grains you can figure out but here these are very fine and again it is occurring along a narrow zone. And it is a same composition. So and if we see here as well, the same narrow zone of course at the same piece of slide we see it here.

So here the grain size is drastically reduced compared to the grain size here and this rock piece is a granite. Now what is important to observe here that it actually has a very very sharp boundary from the high grain size to the low grain size. Now this grains that we see here they actually did not undergo any fracturing or so on.

So if we zoom this part which I am not showing you here but we can see that the grains underwent some sort of crystal plastic deformations that we have learnt in the other cases. So the movement of dislocations and so on the reduction of grain size has happened through dynamically crystallization and so on. So these are the mechanisms that only you can see in thin sections.

(Refer Slide Time: 18:39)

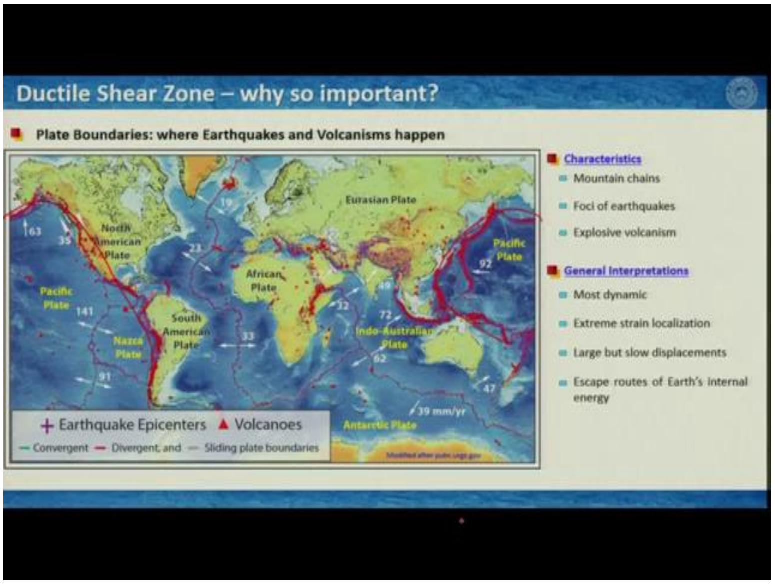


And you can go even farther down to the scale and this is a scanning electron microscope image. This darker thing you see here, these are quartz grains and these white things that you see here these are Biotits grains. I deform them experimentally in the laboratory to see something else but it produces as you can see the initial foliation was straight like this but here it has produced again a long narrow zone something like that.

Where these foliations got deflected, and you can also see if I wipe this one out that within this narrow zone the character of the biotites they are not as white as we see in the outside. They are little diffused fussy and something like that and exactly some reactions are going on.

The biotite started releasing their waters in this condition and they are forfeiture formation is going on and all these processes do happen inside the ductile shear zone. So people still do research on this and they continue working in this direction to understand the localization phenomenon and ductile shear zones and these are very very important.

(Refer Slide Time: 20:02)

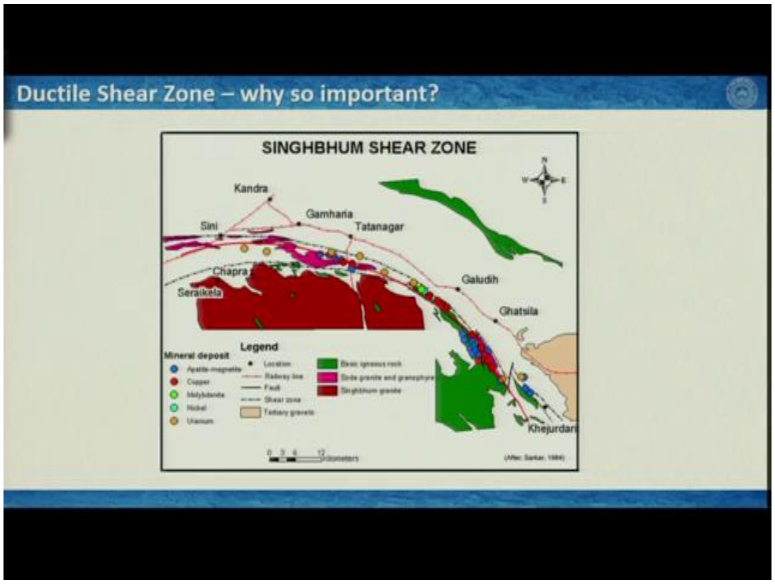


So exactly why studying ductile shear zone is important? Now if you look at the global map and we particularly see that where earthquakes and volcanisms do happen. Interestingly we will see that these essentially coincide with the plate boundaries. So it could be convergent, divergent or sliding plate boundaries but most of the earthquakes and volcanisms do happen along the plate boundaries.

And what happens at the plate boundaries? Plate boundaries are essentially high strain zones because we see large number of mountain chain there, you can think of Himalaya. It is also a fossil of the earthquakes and explosive volcanisms you know the ring of fire here along this pacific, so this one and here this one.

So these are the places which are most dynamic places in the earth and we see extreme stair localization because the plates do collide past each other, they move away from each other, they slide past each other and so on. So these are the places at depth if you follow this you will see extreme localization at very large scale. The displacements here are extremely large but that happens in a very slow way. We know that it happens, and these are also avenues to release the earth interal energy and therefore we have earthquakes and volcanoes and so on along the plate boundaries.

(Refer Slide Time: 21:34)

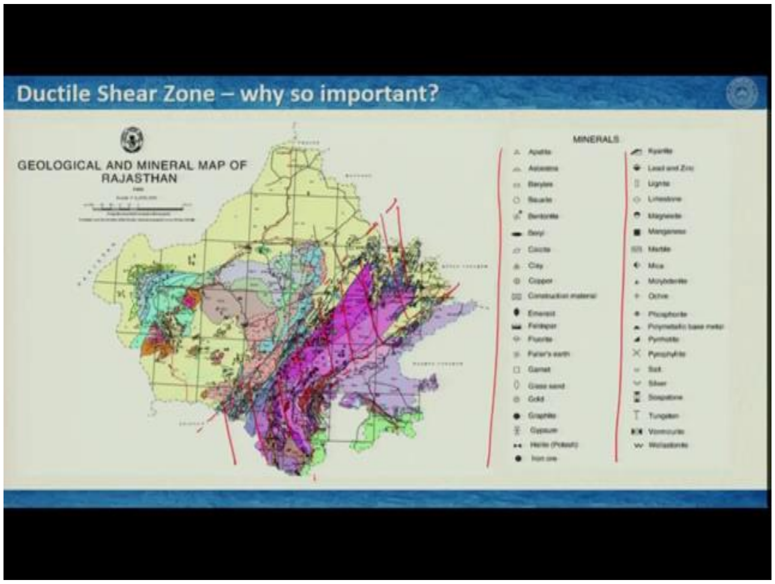


So I will take you to another aspect of ductile shear zones. You must have seen, or you must know the fact that if you go to the eastern part of India and if I ask you the question, of course it is written here that which one is the most rich zone in terms of mineralization. And we all know that this is the copper mines, the iron mines, the uranium mines these are mostly along Shingbhum region along the chota Nagpur nisic complex.

And this Singbhum region is characterized by a shear zones which is known as Shingbhum shear zone. And if you travel from ghat shiela to Tata nagar and so on you will see series of mines of mines where people extract appetite, copper, molybdenite, nickel, uranium and so on.

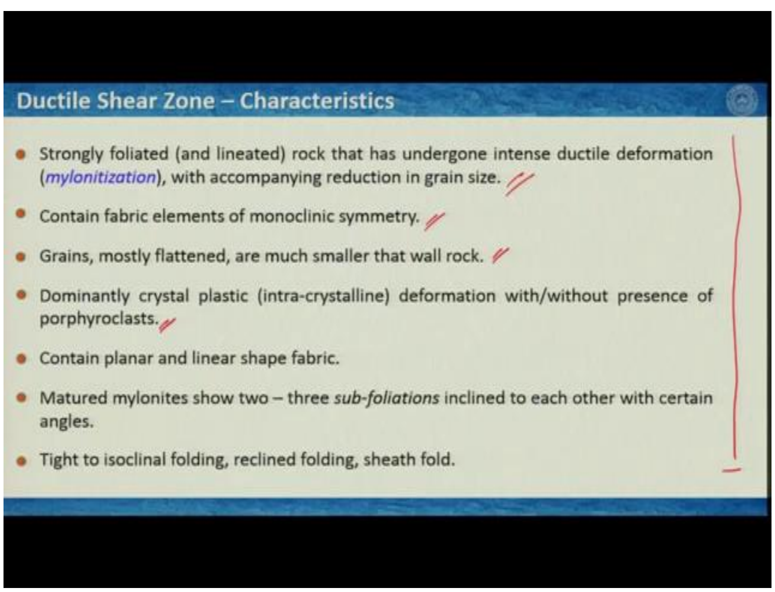
Now all these things why they deposited along the shear zone boundary? Now again I answered this question partly that these things do occur along that shear zones, simply because shear zones have extremely different dynamics compared to where strengths are not localizing. So mineralization is essentially a process which is extremely dependent on the deformation phenomenon. So this is the Shingbhum shear zone and along with you have series of mines which extract important economic deposits.

(Refer Slide Time: 23:17)



If you go to the north western part of India, in Rajasthan this is also a state where we have lot of mineralizations and I tell you this is a map of geological survey of India. And all along this these are the shear zones together with (())(23:33) fold belt and you see these places are the places where you have series of economic mineral deposits you can find. So ductile shear zones not only important to understand the dynamics of the earth but it is also important to understand the mineralization processes and also to mine them and work up on them and explore a further for economic mineral deposits.

(Refer Slide Time: 24:02)



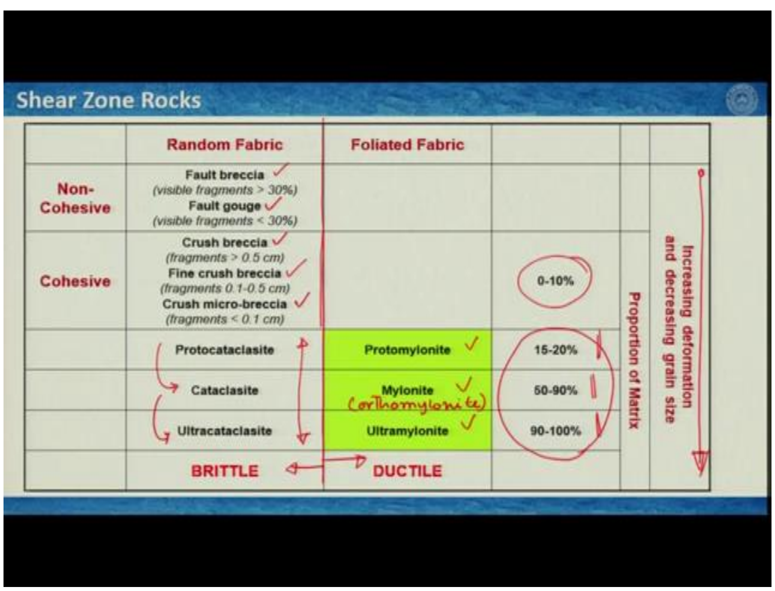
Let us look at what are the characteristics of ductile shear zones. We will learn more but here I have summarized a few points. So ductile shear zones as you have learned that this is strongly foliated and lineated rock that has undergone intense ductile deformation or in other ways, we call it mylonitization or mylonitization with accompanying reduction in grain size.

This we have learnt, it contains fabric elements of monoclinic symmetry. Grains, mostly flattened, are much smaller than the wall rock. This we have also learnt. The deformation is dominantly crystal plastic or intra-crystalline deformation. We learnt the mechanism in the deformation mechanism lectures with or without presence of porphyroclasts.

Now if there are porphyroclasts or porphyroblast, we have some type of classifications. We will learn it soon. It contains planar or linear shape fabric. So it has foliation and lineation. The matured mylonites generally show more than one flanar fabric. So 3 sub foliations mostly inclined to each other with certain angles.

We see them and they are very important kinematic indicators. We will learn about it in the next lecture. At the same time in the ductile shear zones, we see most of the times tight to isoclinals folding, reclined folding and also a very special type of fold we did not learn yet is sheath fold. So these are the characteristics of ductile shear zones or in other ways you can say this is the characteristics of mylonites.

(Refer Slide Time: 25:47)



So this is how we can now classify knowing everything the entire shear zone rocks including faulted rocks. So in this line along this line, everything happen in this side is brittle and what is happening in this side is ductile. In the brittle domain we mostly see random fabric, in the ductile domain we mostly see foliated fabric.

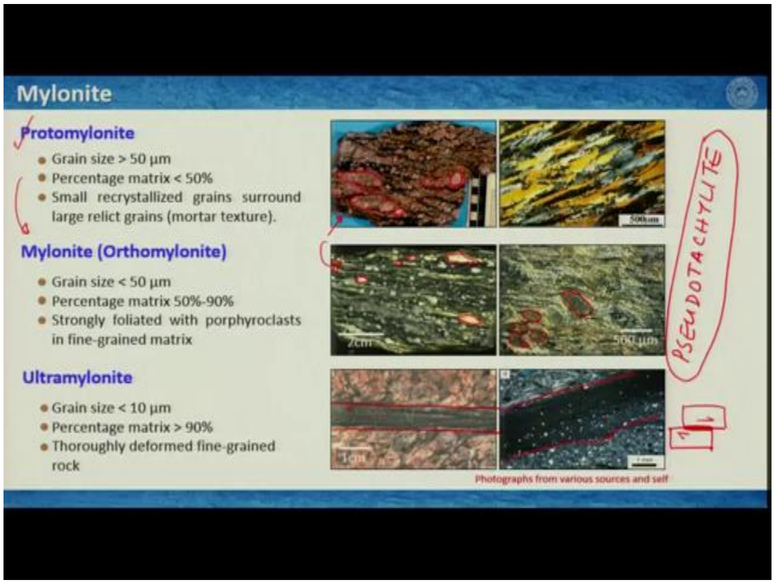
Now within this brittle domain we can classify the rocks as non-cohesive which is mostly at the very very near surface area and cohesive it is near the sub surface area. Now within the non-cohesive domain we can have two types of fabrics or two types of rocks. One is fault breccia where the visible percentage of fragments should be greater than 30 percent. And if it is less than 30 percent then we call it fault gouge.

Within the cohesive domain we have crush breccia where the fragments should be greater than 0.5 centimeter. If we have fragments in between 0.1 to 0.5 centimeter then we call it fine crush breccia and if the fragments are less than 0.1 centimeter then we call it crush micro breccia. And if we have grain size even smaller than 0.1 centimeter then we call it protocataclasite, cataclasite and ultracataclasite. So proto is going to be cataclasite and ultracataclasite is more deformation or more grain size crashing has happened after cataclasite phase. So the stages are something like that.

In the foliated fabric we have protomylonite, mylonite and ultramylonite. We are going to learn it soon. These mylonites are sometimes also call orthomylonite in older literature. And this classification this protoclataclasite, cataclasite or ultracataclasite and at the same time protomylonite, mylonite and ultramylonite is mostly function of the proportion of the matrix that how much bigger brains you have and how much smaller grains you have.

So if we go to the cohesive domain, the matrix should be 0 to 10 percent. So it is mostly large clasts you have. And in the protocataclasite or protomylonite you should have matrix 15 to 20 percent in mylonite 50 to 90 percent and in ultracataclasite or in ultramylonite the matrix should be almost 90 to 100 percent. So the rock is mostly full of matrix, so you do not have any visible grains there. And this is how this entire process can happen if the deformation increases from here to here.

(Refer Slide Time: 29:10)



Let us have a look now, the different characteristics of protomylonite, mylonite and ultramylonite. So the first column of images that we see these are hand specimen scale and the second column this column that we see these are photographs from thin section in cross polarized light.

So protomylonite as we have learnt, the grain size has to be greater than 50 microns. Percentage of matrix less than 50 percent, small, recrystallized grains surrounded by large relict grains or it is known as mortar texture. So you see here the black stuff in this hand specimen are actually your matrix which is very less in terms of the total volume of the rock or total area of the rock that you are seeing in this image. And this brown is things along with these large clasts are your porphiroclasts or some other features.

With further deformation, we arrive to the rock which is known as mylonite or orthomylonite where grain size is less than 50 microns, percentage of matrix is 50 to 90 percent and it is strongly foliated with porphiroblasts in fine-grained matrix. So what we see here you can clearly see that matrix area has significantly increased compared to the, this figure.

So here we have more matrix, but we have few porphiroclasts or blasts floating within the matrix. Also in the thin section we see, these are porphiro well these are experiments I have done it so I know that these are porphiroclasts but outside you have muscovite and these are matrix material.

In ultramylonite the grain size is extremely fine less than 10 microns. You cannot identify them through optical microscope. The percentage of matrix is extremely high greater than 90 percent and thoroughly deformed fine grain rock. What we see here this region in this image, this is our ultramylonite.

You see only a few clasts here but otherwise it is extremely fine grain and even if you see this kind of rocks under thin sections still you do not see any visible rock fragments here or any visible grain size. They are so fine even you cannot look at or even you cannot see them under optical microscope. Maybe you need SCM or some other high resolution photography technique.

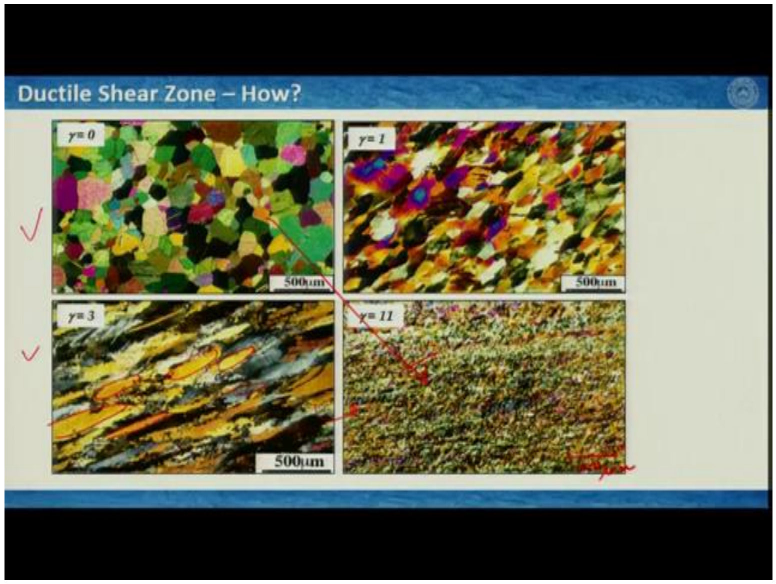
So we have protomylonite, we have mylonite or orthomylonite and we have ultramylonite. We have defined this term. In this context I would like to use another term or introduce another term which is known as, let me write it here, it is pseudotachylite. Now pseudotachylites are something that you generally find in faulted rocks or in ductile shear zones.

Pseudotachylites you can consider them a kind of ultramylonite in a way, but the mechanism of formation of pseudotachylite is little bit different. The deformation has to be extremely fast and when you have extremely fast deformation, because of the frictional movements between the two blocks.

It produces significant amount of heat along the contact zones. And when you have significant amount of heat along a very localized zones, this heat or this high temperature which is produced by this frictional heating it melts the surrounding rocks. And when that happens then it stays as a melt or very fine grain rock along a very narrow zone.

So apparently it appears like ultramylonite, but this is not exactly ultramylonite. But this is the mechanism you form pseudotachylite where you have two blocks moving past each other and because of the slip, very first slip. In this zone enormous amount of temperature generates and here it melts and what stays here is a very very glassy material, dark glassy material and that is known as pseudotachylite.

(Refer Slide Time: 34:10)

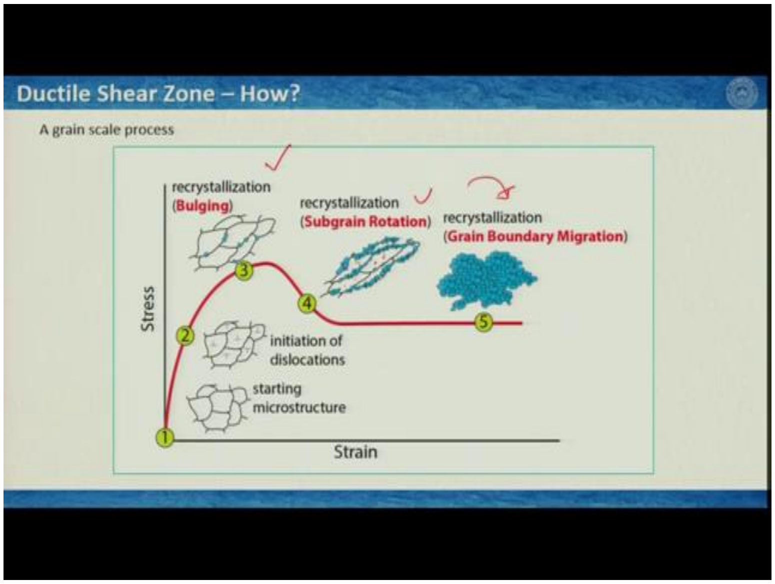


Now how the grain size reductions do happen? We learnt about it but let us let us have a look again. So this is an experiment by and we see here this is initial sample where this is Carrera marble and the crystals we see in this very colorful image these are calcites. Now if you start deforming it shearing it, they initially undergo to produce some kind of fabric here like this.

And later at this stage where (())(34:42) is 3 it is almost kind of protomylonite that we have learnt, that we have large crystals and fine grain matrix but which is less than 50 percent or even less. But when we have a significant amount of deformation, the grain size reduced to very very fine scale. So this is also similar size, similar scale here, same magnification we have taken so this is 500 micron again.

And what you see here the grain size is extremely small compared to this. So just increasing shear strain from 0 to 11 we can see the drastic grain size reduction. And this is the mechanism how the shear zones, ductile shear zones do accommodate the deformation and now you know why it has very very fine grains compared to the surrounding rocks.

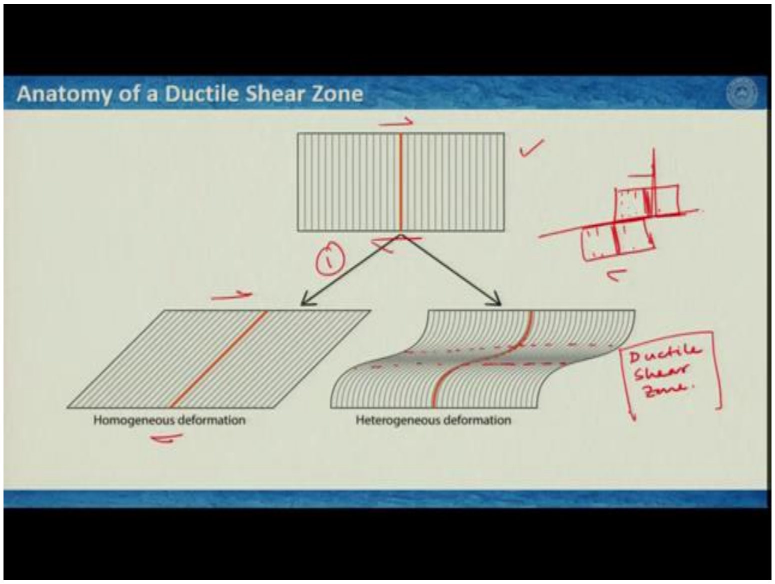
(Refer Slide Time: 35:40)



And we also have seen this, this how the different deformation mechanisms do operate in accommodating the strain, within the ductile shear zones. So you have dynamic recrystallization process. So initially it starts with bulging, the new grains appear at the grain boundary, sub grains and then you have the sub grains they rotate while this parent grains are still here.

But finally, when you have grain boundary migrations at even higher pressure and temperature, the parent grains are completely gone. They produce new smaller grains through the process of dynamic recrystallization. So essentially again as I was talking about in the very beginning of our deformation mechanism lecture that does not matter how big is the structure, it has to initiate from a very very small scale. And this is also true for ductile shear zones.

(Refer Slide Time: 36:36)

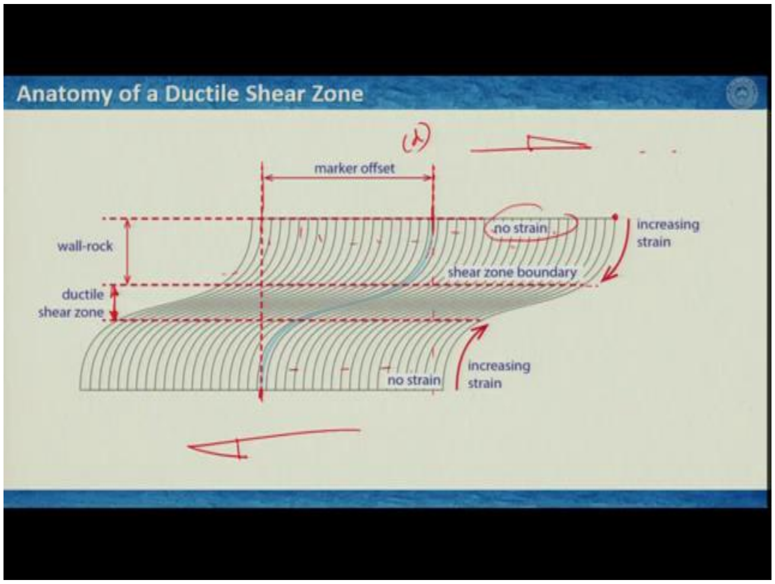


Now let us have look of how do we describe a ductile shear zone or in other way other words the anatomy of a ductile shear zone. So if this is the undeformed rock, whether all these are passive markers as you can see here or active markers, then there are two possibilities. Possibility one is that if I shear it like this then one possibility is that the entire piece of the rock or entire rock mass is deformed homogeneous manner.

So in that case we produce some deformation features like this where the rock accommodated the deformation in homogeneous manner. If that does not happen, if it happens in localized manner then it should take a shape like this where the deformation got localized along this narrow zone. And this is nothing but your ductile shear zone as we are talking about.

Now if it was like this, say this block this block as you are looking at here, this is a red line and this is again a red line that we see here and all this other lines. So it can happen in a very similar way, but this is essentially a brittle shear zone. So there is no breakage of cohesion, there is no discontinuity. So this layer is continuing here without any visible fracture in this scale and therefore we call it ductile shear zone. And this is a localized heterogeneous deformation.

(Refer Slide Time: 38:21)



Now there are some terminologies involved. So clearly we can see that from here which will call actually the wall rock. The strain increases towards the ductile shear zone which we have just defined is this zone. Now you can argue that why I have plotted this line along this way, why I did not put it like this or why I did not put it much closer.

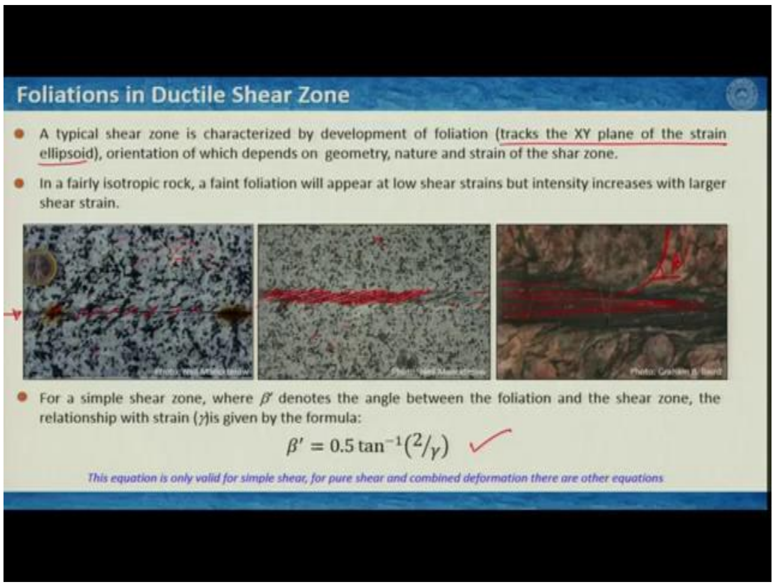
Now yes you have a very valid question. There is not always a very sharp boundary between the ductile shear zone and the wall rock. This boundary most of the time is extremely diffused. However, there are some ductile shear zones where it just goes like this. Where you have very sharp shear zone boundary. But these are functions of the rheology, the viscosity of the rock and so on. We are not going into that part right now.

But for the timing yes I have drawn it arbitrarily but with some logic. And the logic is visually I inspected that this must be the boundary. Now you can plot it a few millimeters up or down but that would not be anything wrong. So clearly this region has 0 strain or very insignificant strain this area.

So entire area they did not suffer any deformation. Now these marks are if I think of, so this marker was initially here along a straight line and because of the shearing, now it got deflected to here. So this is known as marker offset. We will later figure it out as D or displacement, and we see how to calculate that. But these are the basic anatomy of a shear zone.

So you know what is, you define the ductile shear zone, you define the wall rock and therefore you define the high strain zone and no strain zone. And strain generally increases from no strain zone to high strain zone to shear zone. And this increase is mostly nonlinear, we will see that soon. So this is how we generally construct or we generally identify or name the different parts of a ductile shear zone.

(Refer Slide Time: 40:52)



Now as this third part of this lecture we suppose to talk about the foliations in ductile shear zone. So far, we talked about most of the ductile shear zones are characterized by development of foliations and it also is a fantastic kinematic indicator as it is written here, it tracks the XY plane of the strain ellipsoid.

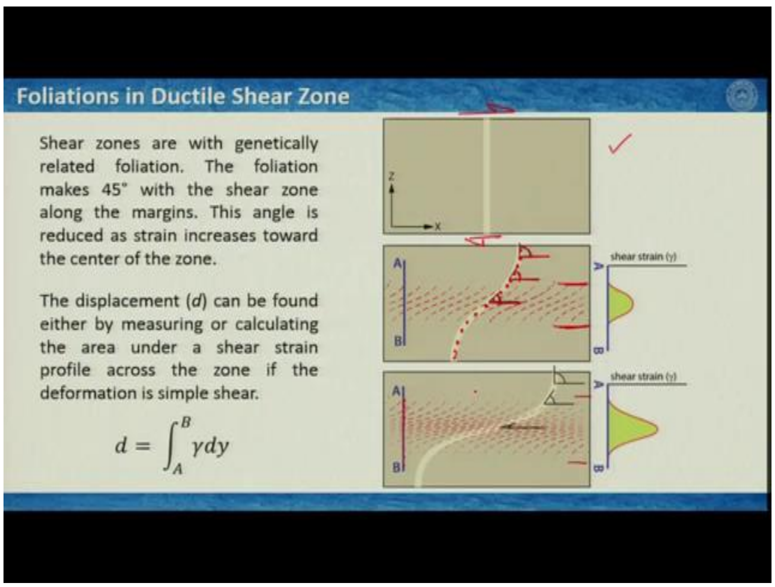
We will learn about it soon, let us not concentrate too much on that. Now orientation of the foliations depends on the geometry nature and strain of the shear zone. Now if you consider a fairly isotropic rock, a faint foliation will appear at low shear strains but with more and more and more ductile shearing, the foliation would be intense and so on.

And this is exactly I collected 3 photographs is showing the similar feature. So what we see here, this is a piece of rock and you see here we have this very narrow thin incipient shear zone. And you see this outside this rock actually it does not have any foliation. But here when you see this, you probably can see a faint fabric is being developed here along this very very incipient magnitude of shear strain.

If the strain increases clearly you see again the outside the rock is very much isotropic. But along this narrow zone which is your ductile shear zone that we have identified, we see that fabric is intense and it is just along a narrow zone. Is not it fascinating? And just to ask how do how does it happen?

And if we continue then we see that this fabric inside this excellent photograph is like this and it is extremely intense. Now for a simple shear zone, you can actually calculate the relationship with the strain and this foliation angle by this formula. Where Beta prime is you can consider as this angle. We will not go into the detail part of this, but this is how people do calculate in the field or also from the experiments the relationship between strain and the foliation orientation.

(Refer Slide Time: 43:27)



Now let us see in a different way with the help of the illustrations that how does it work. So shear zones generally they are related to the foliation as we talked about. The foliation initially makes a 45-degree angle with the shear zone along the margins. And this angle is reduced as a strain increases towards the center of the zone.

So if we assume this block here to be sheared this way, and this little whitish band here is a marker band and then we can the very beginning of the deformation, we can figure out that these are the foliations, this red dotted or dashed lines are appearing here as the fabric of the shear zone. This marker bed got also deflected and the deflection the disposition of this marker bed may or may not coincide with the orientation of the shear zone fabrics which are the red ones here.

So you see the red ones has, red one here in this case it has an orientation like this and this has an orientation like this. So they may or may not coincide like this. Now I can calculate the shear strain by through the deflection of these markers. Or I can also calculate through the orientation of this newly developed fabric with respect to the direction of bulk shear.

Which is in this case this horizontal lines. So if you can continuously measure, you draw tangent and you measure along a profile A to B then you can plot you can calculate it and you can plot it and it clearly shows the profile, strain profile of the shear zone and in this case it is like this.

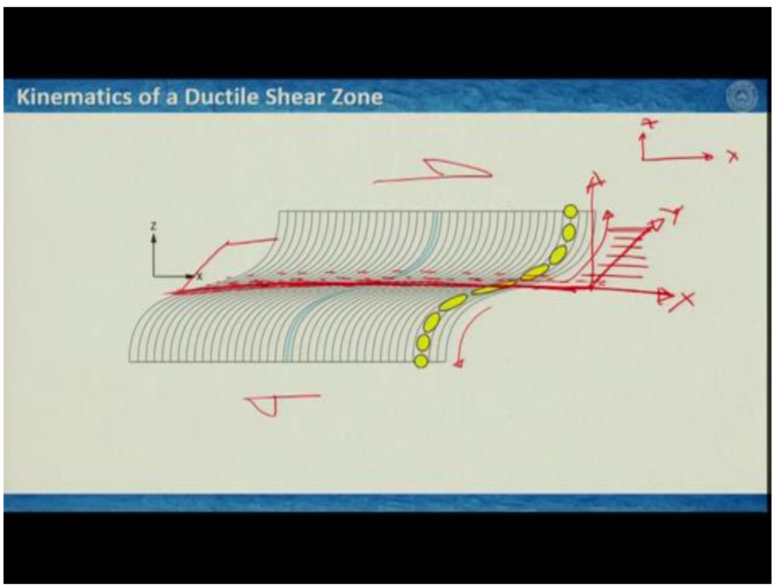
If the strain continues then you see that these foliations was restricted the foliation planes was restricted here and now, they have increased. So the shear is also increasing along their width and if you again do the same practice of profiling the shear strain along the shear zone, so again you do measure shear strain at different points and then you see that strain has increased compared to the previous one.

And this is how in a shear zone you can actually measure the strain profile. You can also if you do not know, if you do not see the deflections of the markers with this you can calculate the deflection of the markers with this equation. So you know from A to B, you can integrate the shear strain with respect to the turn Y direction. So perpendicular direction that you can talk about.

(Refer Slide Time: 46:35)

Now we see this in the field very very commonly. So you see this was a marker probably and this is going into the shear zone. So continuously this angle, so now it is here like this, here it is this. If you come here it is little reduced, if you come here this is further reduced, if you come here this is here. So this is how you enter in the shear zone and this is your ductile shear zone. You can see the similar thing here and you can figure out this strain along this along this and you see it is always getting reduced and finally when you come here, it is almost horizontal.

(Refer Slide Time: 47:27)



Now, the final topic of this lecture the kinematics of a ductile shear zone. So far, we understood the foliation part, how does it develop and so on. And as we talked before that strain in the ductile shear zone is extremely heterogeneous. And this if you have some circles here initially and then the circles would probably deform in this way.

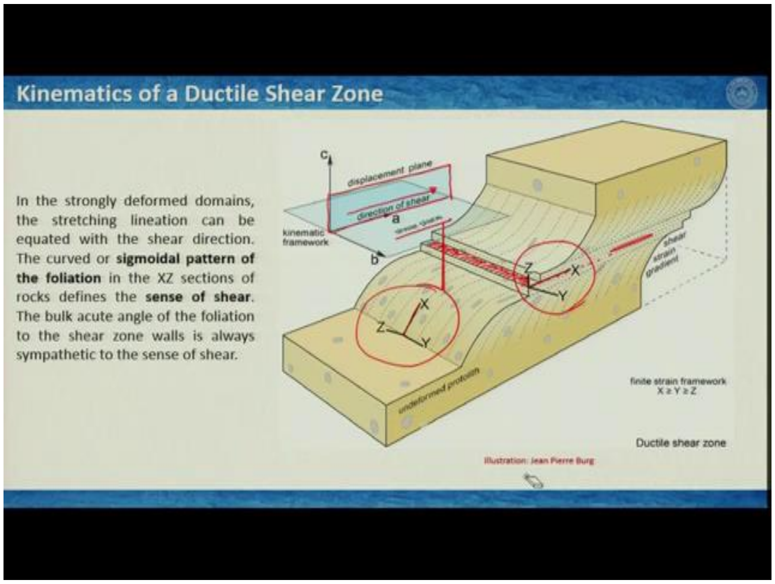
So the middle of the shear zone the circle is you can see it is forming an ellipse which ease suffering the maximum deformation and slowly diffusing away from this part. Now considering this, if I have to fit it atleast in 2 dimensions with respect to the strain ellipsoid, we know we call it X, Y and Z where X is the maximum stretching direction, Z is the minimum and Y is intermediate.

In this case we are not going to consider Y because we are looking at in 2D. So we can clearly figure out if this was the deformation direction or shear direction. The flow direction is approximately like this. So shear zones are mostly parallel to the X direction of the strain ellipsoid and Z is the other direction.

And we have seen that foliations also do form parallel to the shear zone in a mature ductile shear zone. So foliations generally do track the X direction and the other direction if we considered the 3 dimensional then this is the Y direction. So this is X, this is Y and this vertical direction is Z, so foliation has to always form along the XY direction.

And if this is the X direction, so the lineations must follow the X direction because that is a maximum stretching direction. So kinematically the foliations in the shear zone, the new foliations in the shear zone are along the XY plane of the strain ellipsoid. And lineations are along the X direction of the principal axis of strain of the strain ellipsoid.

(Refer Slide Time: 49:51)



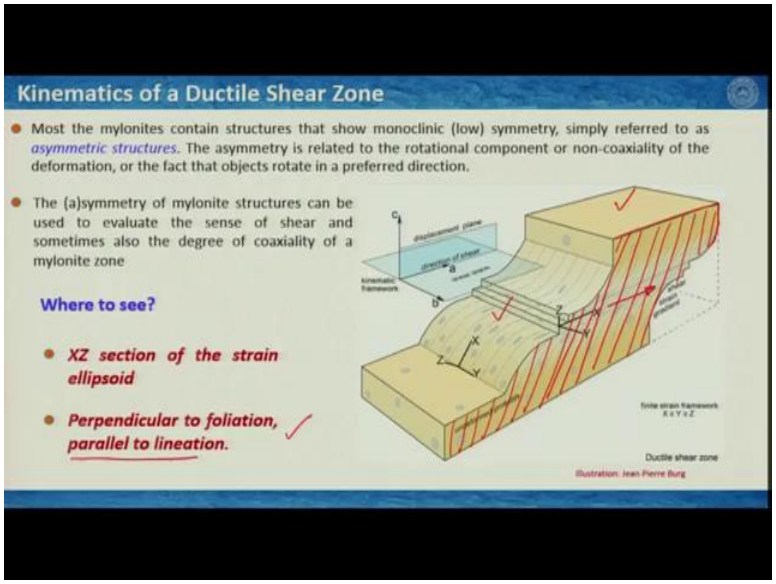
Now we can look at in 3D, so in a strongly deform domain, so we see here that this is undeformed protolite. This is also undeformed protolite and this where you have your maximum shear. So you see the foliations here are like this and this is the XY plane. So foliations or in other ways I can figure out these are your XY plane and these are the foliation plane.

The lineations also do form along the X direction as you can see the stretching is slowly rotating to this side. So XY plane is also the shear plane and X is also direction of the shear. In this case A and this vertical plane is your displacement plane of the shear zone and this is the kinematic framework.

Now this is some kind of monoclinic symmetry. We will we talked about it before but the way it appears this complex 3-dimensional feature, it is important at this time to understand that how we can observe the shear zone or what is the best section to understand the kinematics of the shear zone.

And this is very very important because we see here that here the orientation of the principal axis of strains and here the orientation of principle axis of strain are different, so it is rotating. So it is that is why this is simple shear and simple shear we learnt about it that this is a rotational deformation. So here X is like this and here X almost getting parallel to the direction of the shear. So in this context it is important to understand that what is a best section to look at ductile shear zones.

(Refer Slide Time: 51:57)



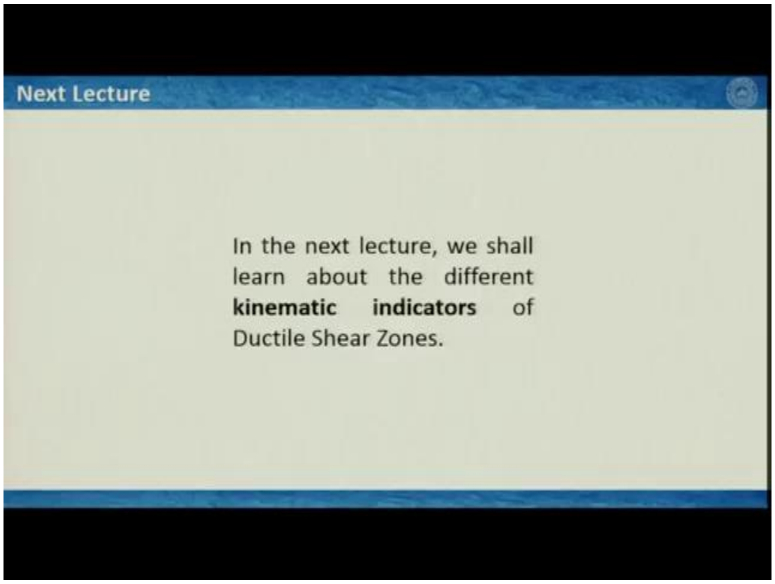
And this next slide summarizes this. Most of the mylonites contain structures that show monoclinic a low symmetry simply referred to as asymmetric structures. So this is essentially asymmetric, this is not symmetric. The asymmetry is related to the rotational component or non-coaxuality of the deformation, or the fact that objects rotate in a preferred direction.

The asymmetry of mylonite structures can be used to evaluate the sense of shear and sometimes also to the degree of coaxiality of a mylonite zone. And to do that the thumb rule is or also this is kinematically very important that we generally see or observe the XZ section of the strain ellipsoid or in other ways this section.

No one is stopping you to see here or see here but this is the best section to figure out the asymmetry of the shear zone. Because the flow is happening in this direction and at the same time this is the perpendicular plane of your symmetry plane which is the foliation XY plane. So we can say that this is XZ section of the strain ellipsoid but not necessarily in the field you always recognize it.

So in other ways we generally say it is perpendicular to the foliation and parallel to the lineation. This one is important because this section is also perpendicular to the foliation. But this section is perpendicular to the lineation and then it is not the section you are looking for. You should look parallel to the flow direction. So it has to be parallel to the lineation. So whenever you prepare a thin section from a sheared rock or you observe a sheared rock make sure that you are looking at the XZ section or a plane which is perpendicular to the foliation and parallel to the lineation of that particular shear zone.

(Refer Slide Time: 54:49)



With this note I finish this lecture; I conclude this lecture. In the next lecture we will actually see, or we will take over from this slide that how to see or how to recognize with different micro structures. How to recognize or understand the direction of shear or in other ways we will see the different kinematic indicator of ductile shear zones. Thank you very much, stay well I will see you in the next lecture.