Structural Geology
Professor Santanu Misra
Department of Earth Sciences
Indian Institute of Technology, Kanpur
Lecture 32
Ductile Shear Zones 2

Hello everyone, welcome back again to this online Structural Geology NPTEL course. You are in lecture number 32 and week 11. In this week we are learning Ductile Shear Zones. In the previous lecture we learned the different aspects of ductile shear zones and this lecture will particularly focus on the kinematic indicators of ductile shear zones.

In the previous lecture we mostly dealt with the mechanics, how do the shear zones forms, their different characteristics and so on and concluded the lecture with the fact that the shear zones do produce significant foliations and lineation and at the same time because it is a mono-clinic symmetry that means it has a rotational feature within it, the strain is rotational strain. this is why it is a shear strain. And therefore, objects within the shear zones they have some special characteristics, they have some special features that they produce during shearing and when you see them frozen in the rock within mylonite, we see some characteristic features of these objects and by which we can identify the sense or direction of shears.

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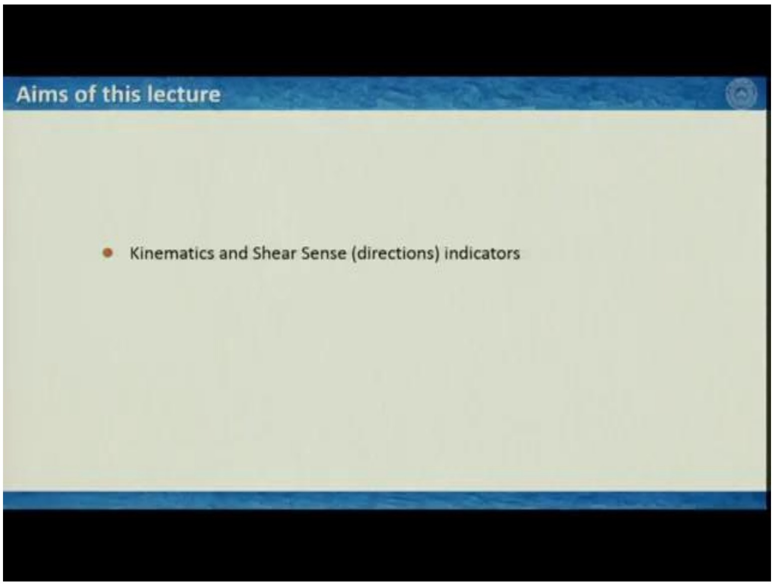

And these are known as kinematic or shear sense indicators or shear direction indicators. And this is the topic of this lecture. To review the fact that where to look at I would like to highlight the fact again that we have to look at the XZ section of the strain ellipsoid. And if you cannot figure out what is X, what is Y, what is Z of the strain ellipsoid of the shear zone that you are particularly looking at, then it is much easier you figure out what is the foliation plane and where is the lineation directed.

Now once you figure out orientation of the foliation plane and the lineation then you have to look at approximately along a plane where it is perpendicular to the foliation plane and parallel to the lineation.

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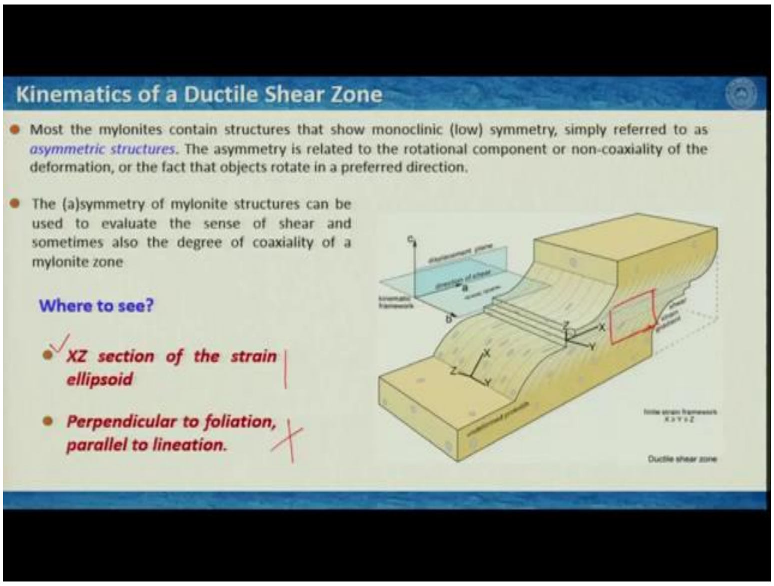

So either way they are very same and unless you look for shear sense indicators along this plane, XZ section or a plane which is a particular to the foliation and parallel to the lineation which is in this case, this plane in particular. Then your interpretation of shear sense would be essentially wrong. So make sure first that you are looking at on XZ plane or a plane which is perpendicular to the foliation and parallel to the lineation.

Once you ensure that then there are series of kinematic indicators within ductile shear zone which could help you to understand what is the direction of shear? And knowing direction of shear is very-very important in the sense that this gives you the essential kinematic features of that particular shear zone and at the same time local and regional deformation and tectonics in general.

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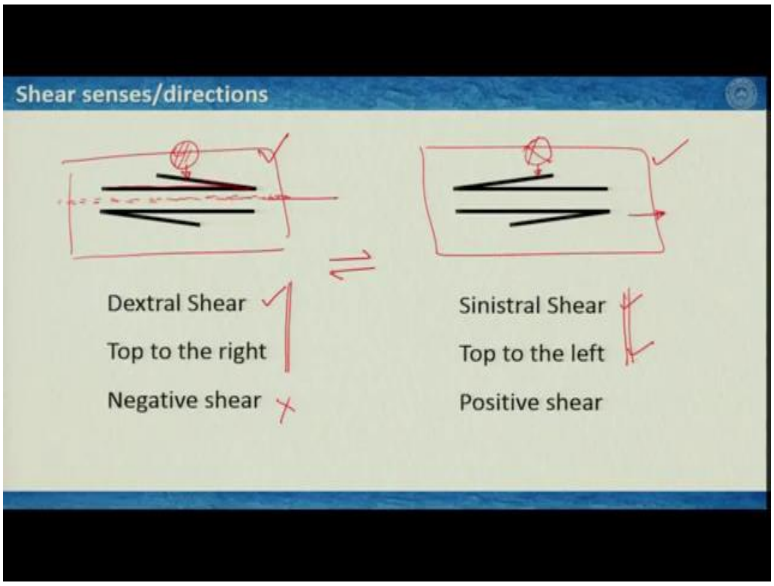

Let us start the first one that what is shear sense indicators? In literature we generally refer the shear senses either by arrows like this or by arrows like this, these are half arrows. And they indicate that this is the shear plane or trace of the plane which is perpendicular to the foliation and parallel to the lineation, so lineation is in this direction.

Now this means this arrow which is heading in this direction means if you stand in this side here then materials are moving towards the right side of you. Similarly, if you stand here it means that materials are moving towards the left side from you and vice versa, if you stand then you would again see facing this shear zone you will see that materials are moving towards your right because this would be right if you stand here facing this.

And very similarly if you stand here and facing this shear zone then you would see material is moving towards your left. The first case this one has several names, sometimes we refer it as dextral shear, if I draw like this and ask you what is the sense of shear? Then you can say this is the dextral sense of shear. Sometimes we call it top to the right the way I explained because the material is flowing towards the right side or moving towards the right side from the observer.

And we also learned that this is known as negative shear but we hardly use this, mostly dextral shear and top to the right, these two terminologies are assigned for this kind of kinematic. On the other hand, if it is this way as it is depicted here it could be sinistral shear, so it is opposite to dextral and also we referred it as top to the left that defines or this phrase actually defines the kinematics in better way.

If you do not understand what is sinistral and what is dextral. Now most of the shear zones they are either dextral or sinistral but there are few zones that may be initially started with dextral sense of movement and then switched with later tectonics or later structural events with a sinistral shear. These things are little complex and that requires a special skill, we will not go into that part at least in this lecture series.

But the sense of shear identification in the field and representing them in doing subsequent analysis is very-very important as I was talking about. And you have to be extremely careful just looking at one particular signature or one particular shear sense indicator unless it is very much convincing, it is better to look for some other evidences to conclude your observation that yes this is dextral, yes this is sinistral.

So in this lecture what I have decided that I will switch from dextral to sinistral, I will switch the scales, we will see some photographs which were taken under optical microscopes, sometimes with scanning electron microscopes, we will have some field photographs and so on and they not necessarily do represent a single sense of shear, so we have a bunch of dextral shear examples and we have examples from sinistral shear as well.

I have given a few images for your brainstorming so you can look at these images and think that or and try to analyse that what could be the sense of shear of this particular image which were deformed at a particular direction.

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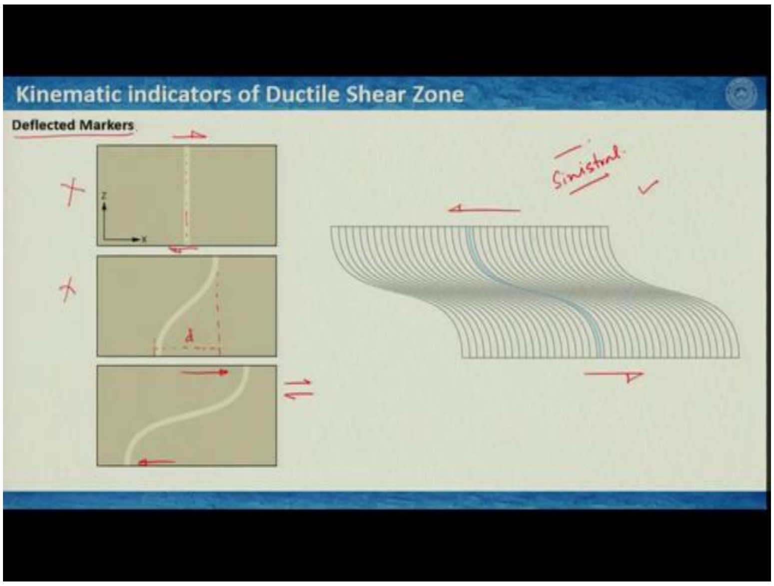

So the first and foremost important shear sense indicator is deflected markers. You have a straight line which is this one this marker and if I deform it in the dextral manner, I had to do it because this is how it is done in this illustration then it would deflect and we know that this distance we know how to measure it, this is d.

So this clearly tells you if you do not have this sequence, if you do not have this image or do not have this image just you look at it you can clearly figure out that this is moving in this direction, this is moving in this direction, is not it? And therefore, we can clearly say that sense of shear in this system is dextral. If you look at this other image here, this marker got deflected towards this side and this one to this side, so in this case this is sinistral.

Now this appears in a very simpler way, but there are several examples and I particularly see that students do a series of mistakes in concluding the shear sense particularly from looking at images or objects. So once we identify this but there is one particular trick that I will also let you know that how does it work. So this is in a very simple way you can identify but let us try to look at some complex situations.

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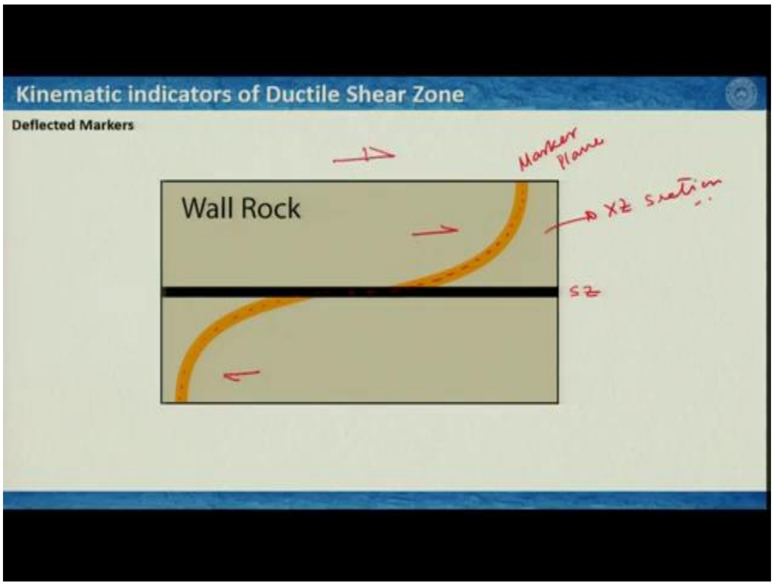

For example, this one where we can see that this is the shear zone and this is the wall rock, but this is the trace of the marker plane on the section, and this is your XZ section. Okay, this is the plane XZ section. Now again it appears little bit easier for you that you can figure out that this is something like that and it is going within the shear zone, got extreme ductile deformation, did not lose the continuity anyway and then it is here in this side.

So you can say that okay this is moving this side, this is moving this side from our previous example and then sense of shear here is dextral no problem.

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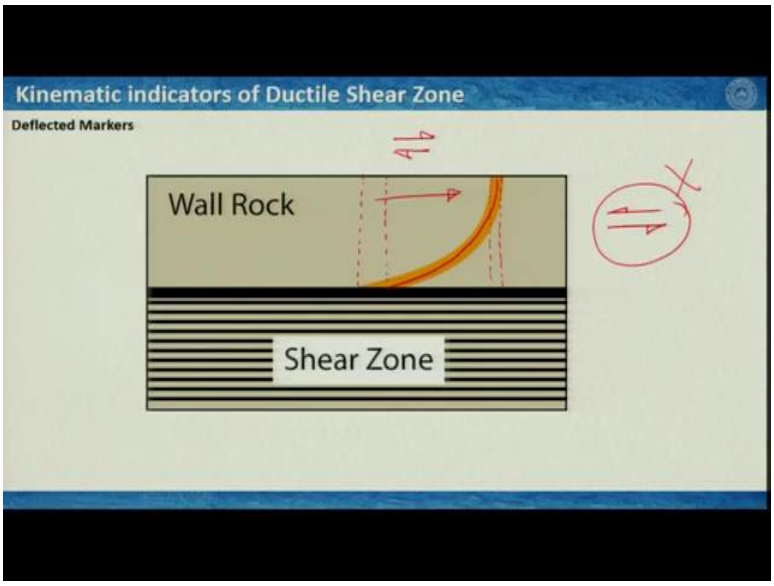

But if we see this image, if you forget about the older images that you do not see the other counterparts of this marker line then the common mistake that we generally do here, what we try to figure out that okay so this is like this, so it must be initially like that and now this part is getting dragged in this side. So therefore, we have a shape like this now, so the shear sense is this way, and you conclude that here the shear sense is sinistral.

And when I check exam papers, I figure out that students generally reply it this way or in some conferences and other places, but this is wrong, why? Because when we talk about shear sense or shear direction, we generally talk about the movement of the wall rocks, not the movement within the shear zones. So in that sense we can clearly understand that it was not like this, but it was like this.

The marker line was initially here, and it got deflected to this side because of the movement within the shear zone which is happening in this way. So the wall rock is moving this way and therefore this marker which has undergone in the shear zone, we certainly can figure out that here if I draw like this or conclude like this, this is wrong, this is actually a dextral sense of shear.

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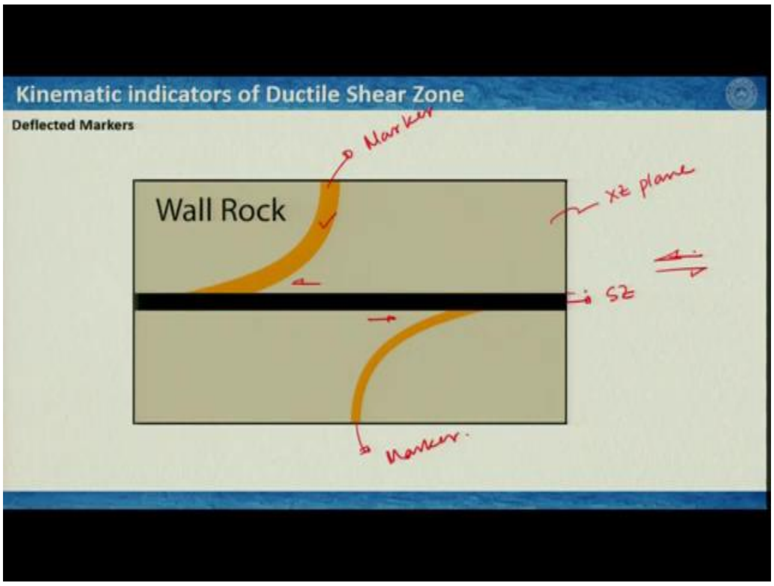

Finally, I have another example where I figure out that people do confuse if I have a situation like this, that we have two marker lines, this is again your XZ plane, this is the shear zone and these two are your markers within the shear zone. Now again looking at it one can immediately conclude oh so this one is going this side, this one is going to this side, fantastic this is sinistral.

But again your interpretation is wrong, the first thing to look at when you see the marker lines from one wall rock to another wall rock, make sure that you are looking at the same marker line. What I mean by that, this marker line has to be the same of this marker line. Not to confuse with this, I made it little thicker and little thinner. So that clearly tells you that this marker line is not the same marker line here so this is a different marker line.

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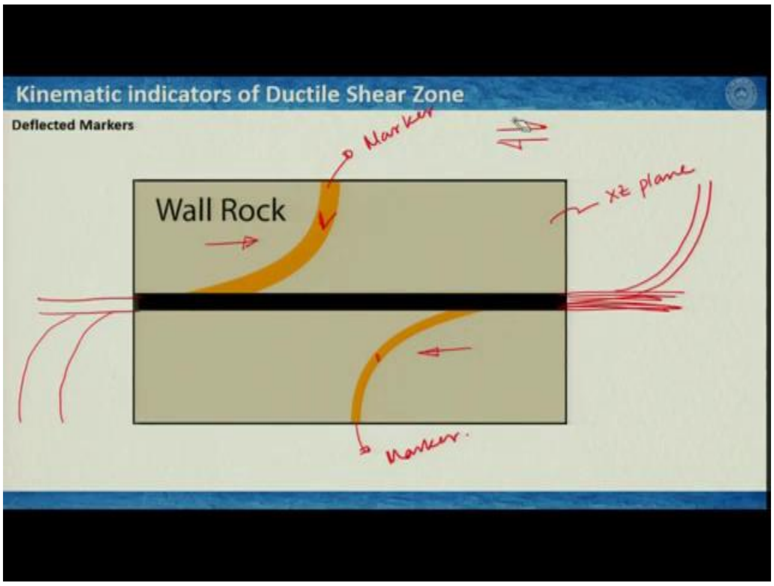

And maybe if I extend it, if I extend the shear zone somewhere here, then maybe it is appearing somewhere like this which is not in my frame. And this one if I extend it here maybe it was somewhere like this again is not in my frame. But what I see within the frame, it is important to first figure out that what I see here and what I see here, they are same or not.

Whether they were once upon a time continuous or not, in this case they are not. So if they are not then this interpretation is essentially wrong. So we have to think in a different way. And again, if this is not like this and then what we have learned in the previous slide so essentially this is moving in this side and this is moving in this side so therefore, the sense of shear here is again dextral. Now I said that there is a little trick that you can use to identify the sense of shear when you have deflected marker.

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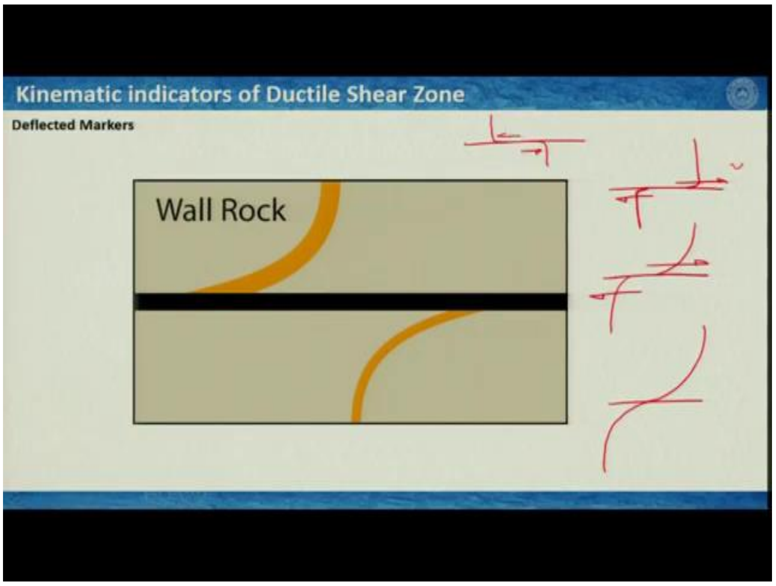

And the trick is you identify the curvature, it does not matter what is the sense of shear the deflected marker has to produce a kind of curvature when it is entering towards the shear zone, this curvature could be sharp, could be very gentle and something like that. So if you have a shear zone like this and you can have a curvature like this, you can have a curvature like this or you can have a curvature even gentler like this.

Whatever be the case, you look for the closing of the curvature that which direction the curvature is closing, and the direction is closing, your sense of shear is towards that side. So in each case this is dextral, if it is sinistral for example if I take this one, this example in sinistral form it has to be like this.

So this is where it is closing so it is this side, it is in this side and this is how you finally conclude it but do not do it mechanically, you understand the mechanics, you understand the kinematics and out of that you conclude it. But if you really do not have any clue then this is something that you can use for your shear sense indicators from deflected markers.

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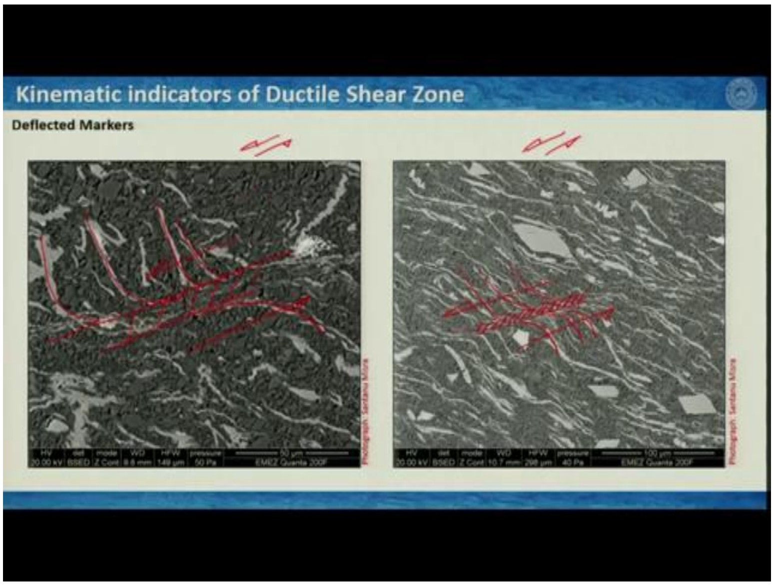

Let us have a look at some examples, these are optical micro photographs that you can see that how does it work, so these are deformed samples and these are experimental deformed samples. So you can clearly see that these black things are quartz grains and these white flakes that you see are biotite flakes. And you see that this biotite flake is deflecting this way, maybe this is not the same biotite flake, but it is deflecting this way, this one is this way, this one is this way and so on.

And this is essentially the shear zone. So at least in this frame we can figure out the sense of shear is this way, so this is sinistral sense of shear. In a similar way you can look at here as well, you see that this is your you can now your eyes must be set to figure out what is shear zone, how do they look like and then again you can say that these markers are going like that, here it is like this.

So they are coming out this way, this is entering slowly here, this was entering slowly within the shear zone and so on. So again, this is similar experiment or same experiment I do not remember exactly but the sense of shear in both cases is sinistral, right so this is how you work. Now in this example we have the marker lines on both sides of the shear zone, but we may not have this case always.

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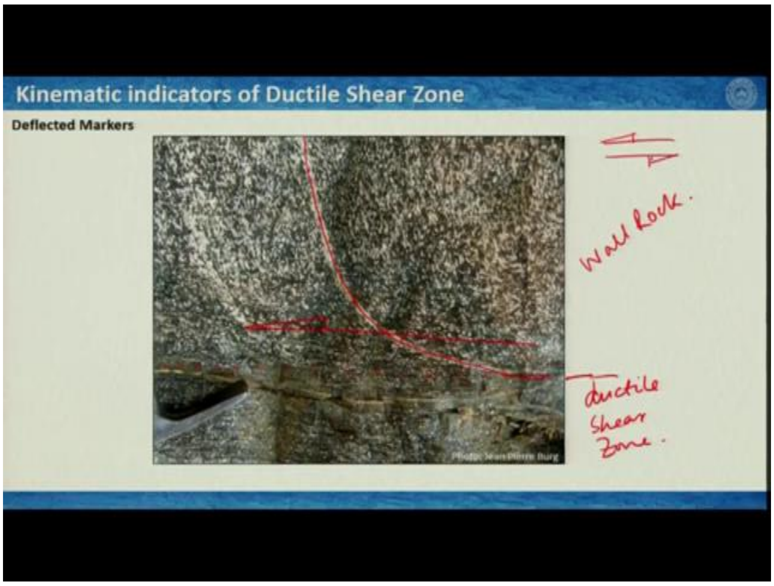

We have seen this photograph in the last lecture, so again this is the ductile shear zone and this part is the wall rock, here we have a marker, maybe a little grain here which is getting deflected towards the shear zone this way and the sense of shear in this wall is like this, so this is again a sinistral sense of displacement from this marker zone.

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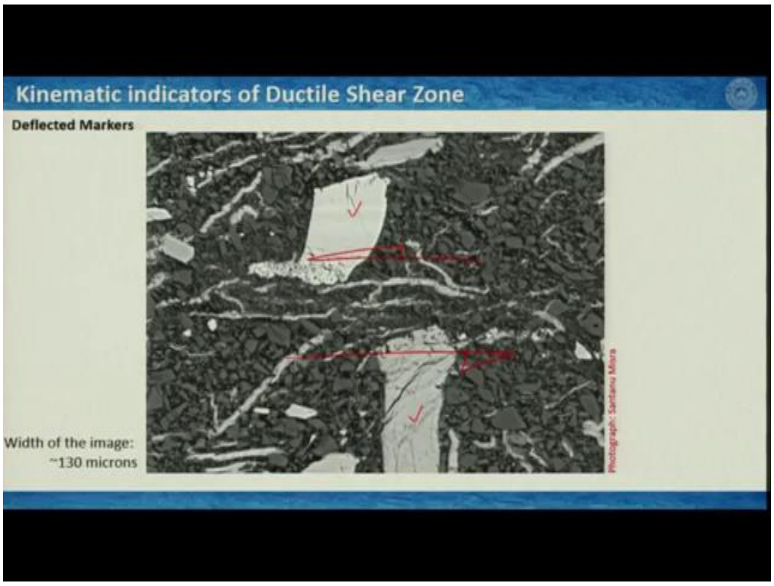

We will go to another image; we have seen the schematic illustration of such kind of features. Now again, I have a large mica biotite grain here, it might be an optical illusion, but you may figure out that this grain and this grain these 2 are together once upon a time such they got shifted this way, so the sense of shear is this way right and you conclude that this is sinistral but it is not.

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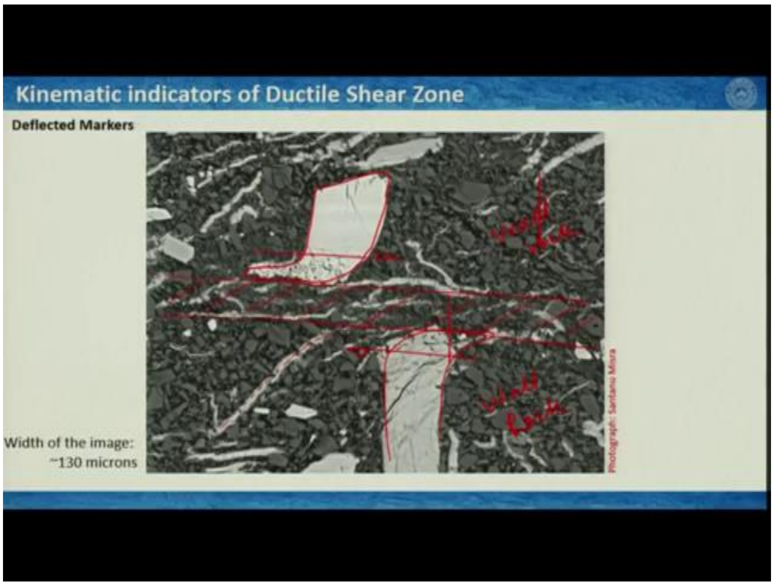

First of all there is no evidence that these 2 grains were once upon a time together, these 2 grains were actually 2 separate grains, I did not see it but you can figure it out from other evidences. What do we see here? This is the shear zone of course as you can figure out and these are the wall rock. This particular grain here if you consider this as a marker, it is deflecting this way and you can see very nicely how this grain is breaking here while it is undergoing the shear, and very similarly you can figure out that this grain is also deflecting this way.

And what we have learned from our trick that the direction it closes curvature it has to be this way, so it is actually suggesting me dextral. Do I have other evidence? Yes, so this one is entering in this way here. So these are a few interesting things that you can use to summarize that what is the sense of shear in ductile shear zone using deflected markers. It may appear very easy, and it may appear as confusing as this image, so be very careful, you look for some other evidences and see what is the actual sense of shear, not necessarily you have to conclude from this particular image.

You have enough exposure you have enough rocks, so if you can figure out in a particular area if you are observing a thin section that what is the sense of shear you do not have to, no one forced you. You go to the other places of thin section and try to figure out, if there is a shear it is not that there is only one evidence or only one object to give you the sense of shear, there could be many other possibilities, so look for them, search for them, not necessarily you have to conclude from only one feature.

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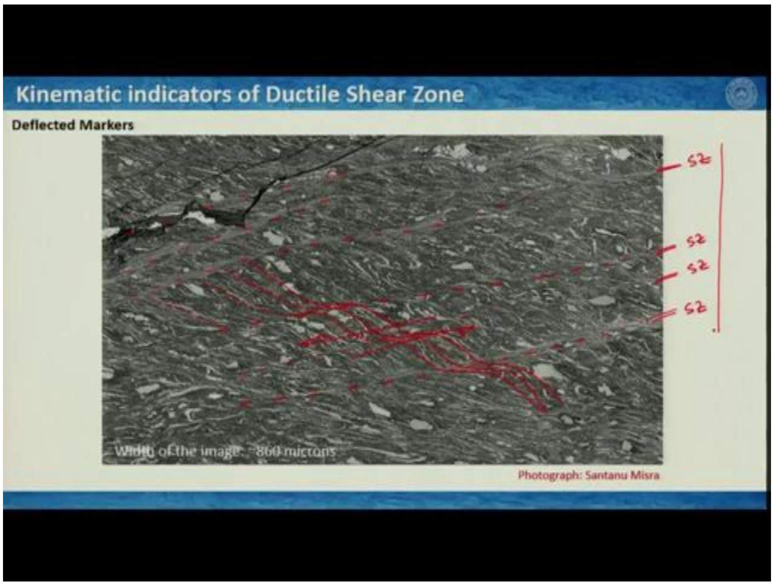

To speak about the feature let us say this image, so this is a large-scale image of what we are looking at of the similar experiments quartz biotite aggregate. What do we see here is a series of shear zones, 1, 2, 3, 4 someone did not match here did not come out here but these are essentially the ductile shear zones and they are oriented at least in this image, here is one weak like this, like this and so on.

We will also see some fractures here we will talk about this later, so you can see that this series of shear zones here, they are producing a new foliation, they are producing a new fabric system. You also see that we have another fabric which is going like this which is your primary fabric, they are getting deflected this way, they are undergoing shear right, so the shear is like this here.

Now this is not an individual shear zone and to think of these consequences as we talked about in one of our previous lectures that shear zones are not only characterized by a single set of foliation. During deformation it produces at least 3 sets of foliations, their disposition that means their orientation and their angular relationship with the other foliation are fantastic kinematic indicators. So in the following slide we are going to learn that and you may come back to this slide again and see what is happening here.

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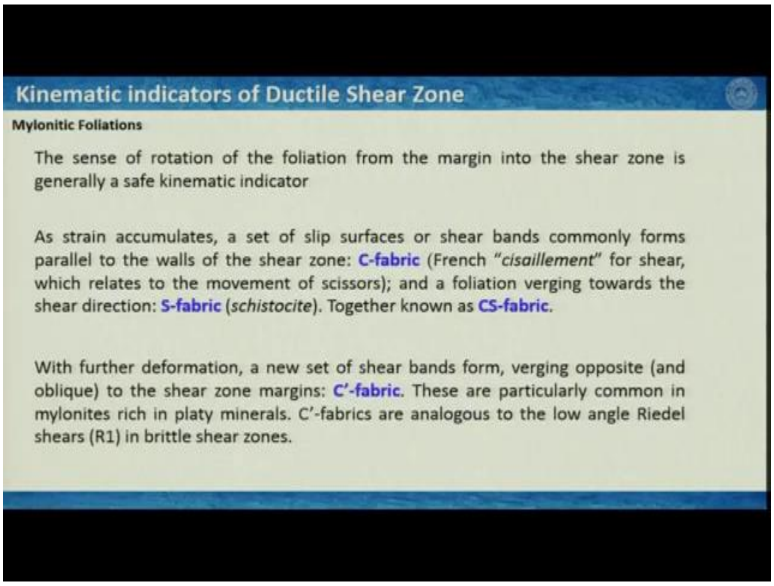

So the sense of rotation of the foliation from the margin into the shear zone is generally a very safe kinematic indicator. When the strain increases, this text I took from the book of (())(23:58) it is very nicely explained. A set of slip surfaces of shear bands commonly forms parallel to the walls of the shear zones and known as c-fabric or Cisaillement in french.

And this word cisaillement means that if you are cutting the movement of scissor, so when you cut it like this that is the movement and this is known as C-fabric, we will see a lot of images on this. And the foliation verging towards the shear direction is known as S-fabric or schistocite or schistocity as we talked about. With further deformation, sometimes this c and s they become almost parallel to each other, even in that case we call it CS fabric or SC fabric or even they are at an angle we also call them SC fabric.

This SC fabric essentially will produce a structure which looks very similar to the crenulation cleavage and we call it sometimes asymmetric crenulation cleavage, we will see this later. Now if the deformation continues then a new set of shear bands or shear localizations do appear within the shear zone involving the previously formed either C fabric or S fabric or both CS fabric. These newly formed shear bands diverge opposite and oblige to the shear zone margins and these are known as C prime or C dash fabric.

And these are particularly common in mylonite rich in platy minerals. So if you have too much mica or so on, then this kind of C prime fabric is very common to observe, C fabrics are analogous we have learned in our fractures class that R1 low angle Riedel shears fractures so in ductile domain this R1 is replaced by C prime fabric, R1 is a fracture and C prime is a tiny incipient shear band produces in series and these are very analogous to the R1 shear fracture.

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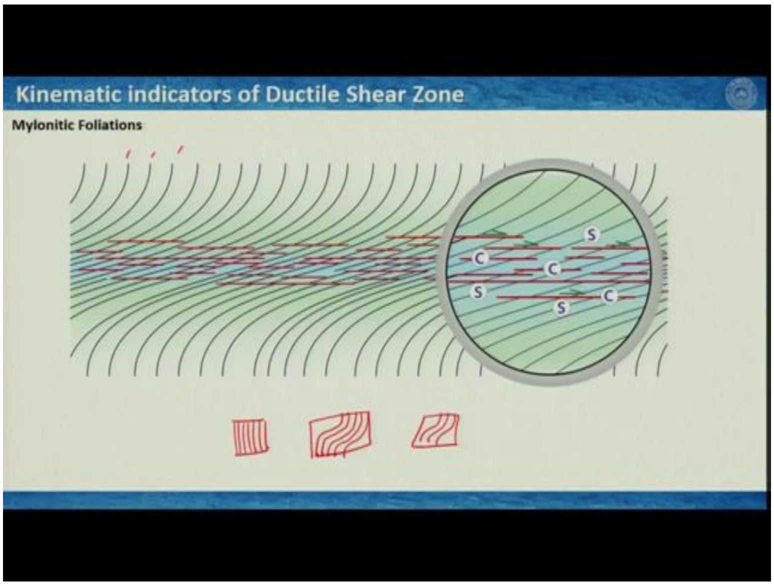

So let us have a look how does it form, we have seen these black lines before right. So you have series of thin and then you can deflect it this way looking at a shear zone or you have anisotropic rock and you are forming new foliation there. So these black lines here could be either initial set or foliations that developed during the shear movement, but in this case we will consider that these are foliations that develop during the shear movement.

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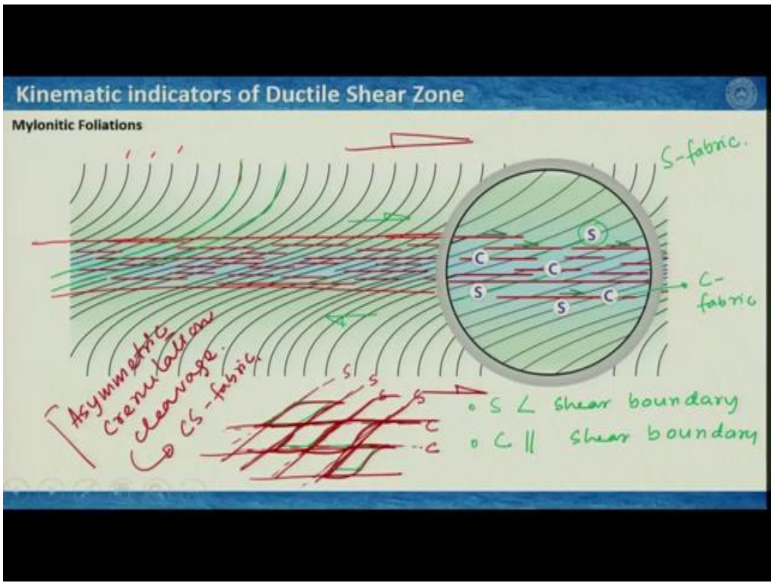

If this is the shear zone boundary then we know that these newly developed foliations I need to change the colour I think that is better for you, they make an angle with the shear zone boundary and they remain at an angle to this boundary. However, you have a displacement in this case yes from the marker deflection you can figure out that this is dextral sense of shear and what do we see here within the shear zone because there is a movement sometimes instead of further rotating the foliations shear zone foliations, the shear zones do develop some tiny shear fractures.

So if I zoom here, you see inside this circle these red lines here are some tiny shear fractures along which these initially developed fabrics are getting deflected. So it enters here and then it isemerging here, it enters here it is going here, it enters here and it is coming out here. So these initial fabrics which are at an angle with respect to the shear zone boundary, these are known as S-fabric as you can see here. And this little slip that you see within the shear zones these are C-fabric and together the fabric is known as SC fabric.

Now, two very important things, S-fabric is a foliation and C-fabric is tiny slip plane, so do not confuse, C is not a typical foliation plane, C is tiny slip planes which are aligned parallel to the bulk shear direction. So S fabric is at an angle with respect to the shear zone boundary such and C is parallel to the shear boundary. Now we can clearly figure out that is the second point I would like to highlight that how do we understand then what is the sense of shear.

Now if you see here that this interaction between c and s would essentially produce a rhombic shape like this, as you can see here okay. Or in other words with mature deformation if you do not follow the geometry very honestly, they produce something like this, where this orientation is the orientation of S fabric and this orientation is the orientation of C fabric.

So S is at an angle with shear zone boundary and C is parallel to the shear zone boundary. Now once we form this kind of sigmoidal shape essentially, so you see that S is somehow deflected and going like that and this deflection is happening by little shear along the c plane. And S always verges towards the shear direction. So once we see this kind of features, this within the shear zone fabric we will see few of them soon.

Then the verging of S fabric defines the sense of shear. So in this case it is verging in this side so the shear sense is essentially dextral. With further shearing this C and S fabrics within the shear zone particularly at the core of the shear zone when you tend to form almost ultra mylonite, it is not possible to distinguish them separately.

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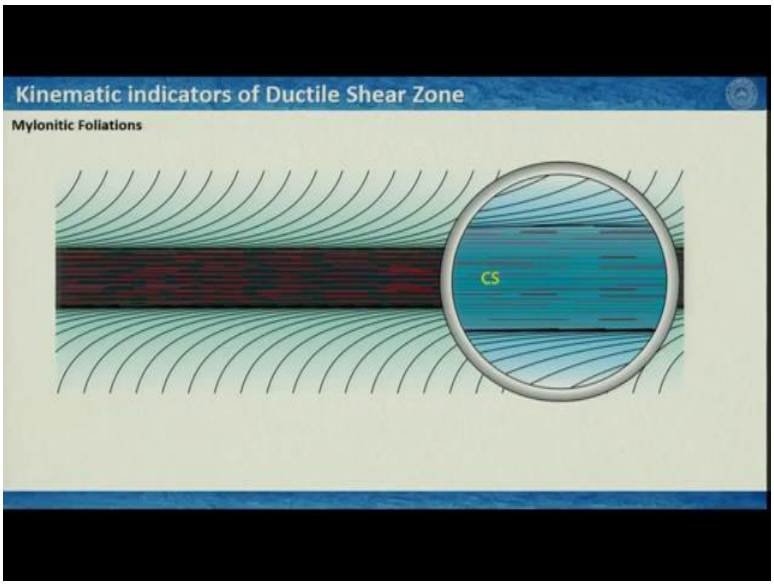

In that case, this C and S they are essentially parallel to each other, so as you can see here in this area or the zoom part here, this CS fabric they are very much parallel to each other and you cannot figure out which one is C and which one is S. However, maybe you can check this scanning electron microscope then maybe you can say something but in general you do not see it, this is ultra mylonitized so this is known as CS fabric also when they are parallel to each other and this is known as CS fabric and sometimes these are known as asymmetric crenulation cleavage, this is analogous to CS fabric. But here we do not see that at least in the scale we are observing here.

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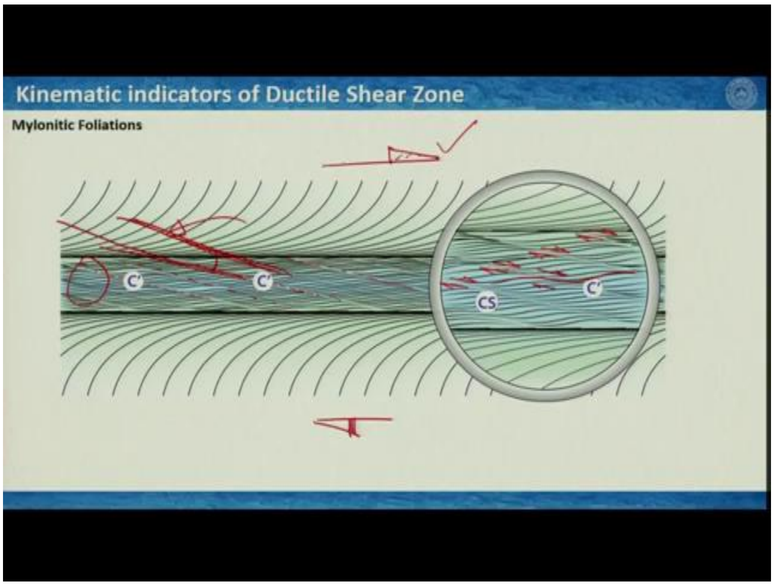

If the deformation continues further then they form a new fabric as we learned from the text this C prime fabric. So here from this marker deflection we clearly figure out that this is dextral sense of shear but if we do not know this, if we just observing somewhere here then how do we know that this is dextral or sinistral, their c prime fabrics are going to help you.

So C prime fabric these are sheared planes, they do develop at an angle and with verging opposite to the sense of shear. As we can see here that the fabric is developing here like this and this is opposite to the verging of these lines or this fabric is opposite to the sense of shear. And if you zoom it then you will see that this fabric initial CS fabric or C fabric or S fabric which was sub-parallel or parallel to the shear zones, shear zone boundaries or bulk sense of shear then these things got also deflected like this.

So the sense of shear is very similar as we have figured it out, so these are the sense of shear within the shear zone. So within the shear zone these micro-shear zones which are producing C prime fabrics, these are at an angle with the master shear displacement which is this one. And if you remember in fracture lectures, we also understood that at low angles you form Riedel shear fractures, a low angle Riedel shear fractures with the synthetic sense or same sense of shear movement with the bulk shear direction.

So this is why this is analogous to this, so if you see that this kind of displacements so which is at an angle to the bulk foliation and you also figure out that where it is verging and once you identify these two then the sense of shear, the bulk sense of shear should be opposite direction. So it is verging this way, so bulk sense direction should be in this direction.

Sometimes in the field if you do not identify all these things in separately then again I repeat you do not have to conclude from looking at C, C prime or CS fabric if you are not convinced that yes this is C prime, this is not S fabric. So therefore, you look for other features because we have plenty of things, we just learned only two, we have learned deflected markers and mylonitic foliations but there are many others that you can use. We have now some examples of mylonitic foliations we will see one after another.

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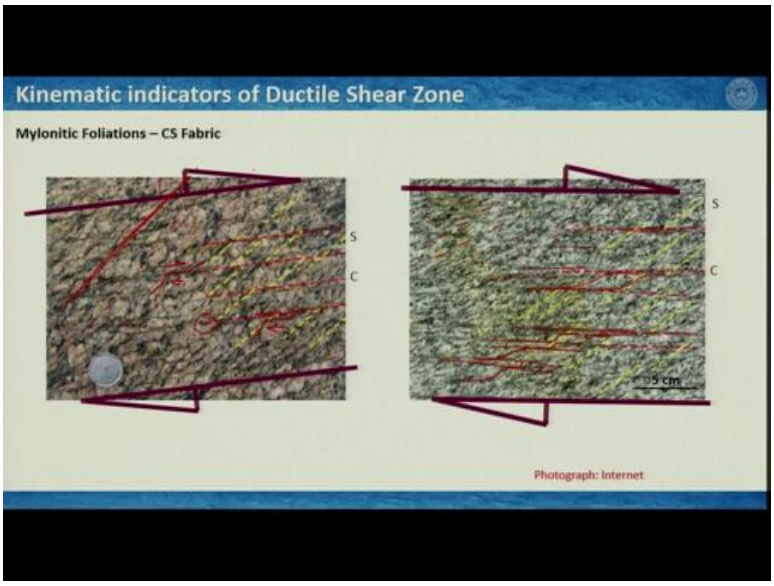

So what we see in these 2 interesting photographs that this is almost a proto-mylonite and we can clearly see that there is a fabric going like this, the fabric is very weak but it is there and we also have another fabric here which is characteristically different from this one. Now, if I consider that this is the fabrics, the initial fabric or somehow the fabric which is developing during shearing then I can clearly figure out that this is verging towards the sense of shear and along this plane or along this fabric there is no shear displacement or something like that, this is just secondary foliation fabric.

But if I try to see here this horizontal fabric here, I can figure out that there is a faint sense of displacement. So it is moving in this way. If I look at here, I can see a faint sense of displacement here such. If that happens then I actually can conclude that this might be the CS fabric. Let us look at the second image as well, the foliation here is more prominent though this is again proto-mylonite, it did not become the ultra-mylonite and then we have another set of fabric like this.

And again you can figure out that there is a sense of movement along this, so these are your micro-shear planes. So this also appearing to be the CS fabric, so if we try to conclude it so it appear like this that this yellow lines in this both images these are the S fabric and the red lines in both images these are the CS fabric.

And if that happens from the study we have just finished with the illustration, the sense of shear must be something like that where the shear plane should be or the bulk shear direction should be parallel to the C fabric that is why I have aligned it slightly not to the frame of this image. So if you can identify clearly that this is your C fabric, the shear direction should be parallel to the C fabric.

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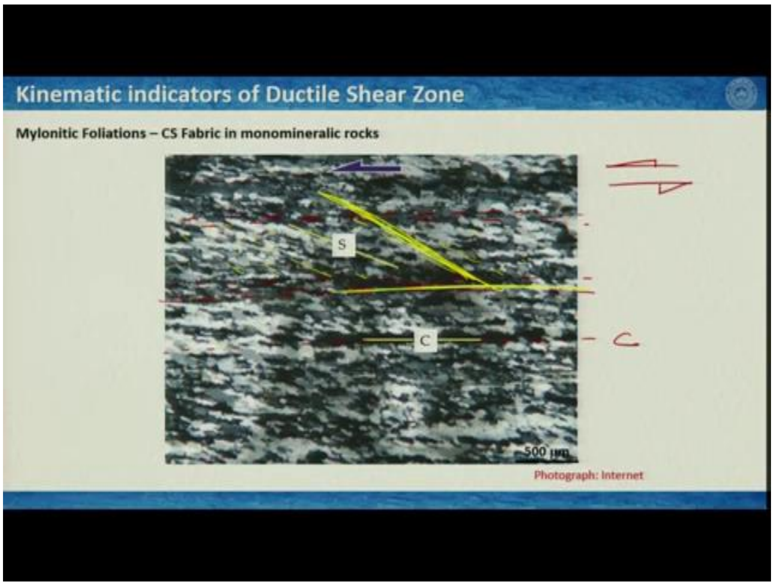

Now you see this also in micro-scale, so this is a quartz mylonite and you can clearly see that we have one fabric which is C and then we have another fabric which is confined between two sets of C fabrics. So this is C fabric and then you have S fabric which is at an angle developing like this right, so in this case S is verging towards like this and C is like this, so sense of shear in this case must be sinistral.

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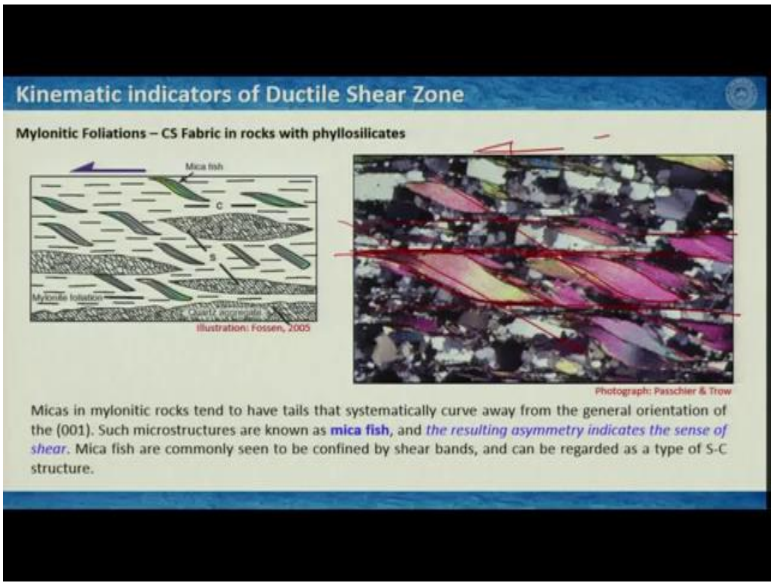

Now in the development of CS fabric we also produce because CS fabrics also do involve lots of phyllosilicates, mica and so on and an interesting structure is being produced which is known as mica fish, and these are your mica fish, let us have a look at this excellent image from (())(40:34). So you can clearly see that these mica grains they are defining this S fabric and these are C fabric okay.

So the sense of shear in this case is also sinistral, it should be parallel something like that. So micas in mylonitic rocks tends to have tails that systematically curve away from the general orientation of the 001 plane of the, this is the crystallographic plane of mica, such microstructures are known as mica fish and the resulting asymmetry indicates the sense of shear. Mica fish are commonly seem to be confined by the shear bands or in other ways c shear bands and can be regarded as the type of SC structure, so this is S and this is C and therefore the sense of displacement at least in this image is sinistral.

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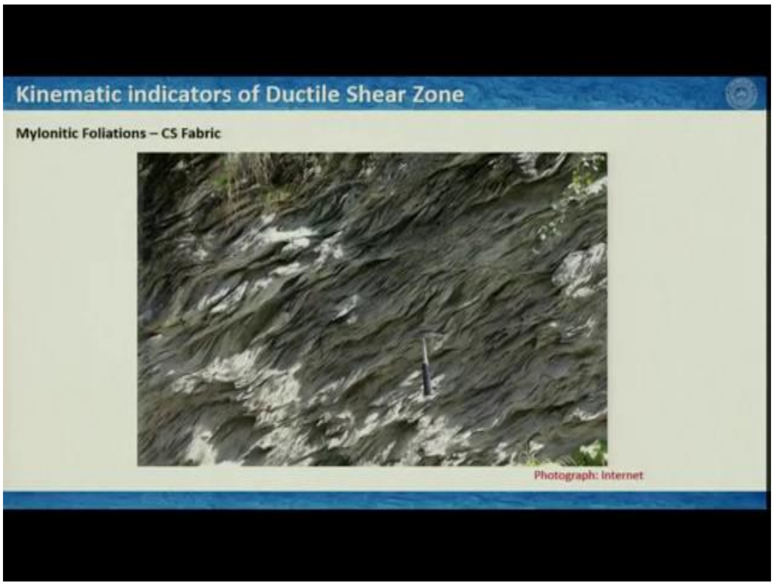

Now here I give you one photograph which are not going to demonstrate what it is, you can identify the foliation and whether this is C or S, which one is C, which one is S and you try to figure out that what is this or this is at all something from which we can conclude this is CS fabric or not.

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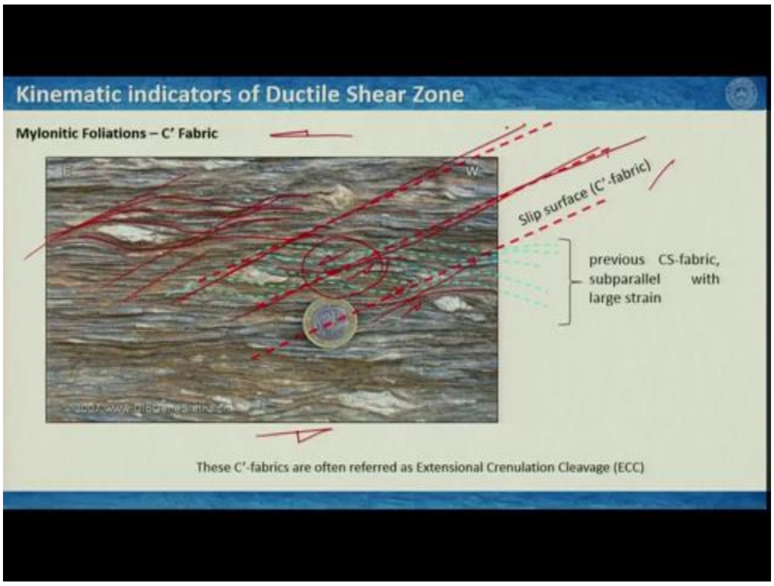

So C prime fabric we see here excellently, here the characters are little bit different so this horizontal fabric that you see with the general horizontal strain this could be either C or S or CS fabric together, but we clearly see that if I try to connect that these are not straight but these are little bit wavy, ofcourse we have something here but we look about it later.

So we have a sense of displacement along this line, so we have a different fabric. And again if we think of our marker deflection for example, if I try to focus it here, the curvature is going like that and it is coming out somewhere like this, so the sense of shear within this displacement is like this and this is consistent everywhere, wherever you look.

If you look at here, you will also see that this is going like this and if you clear here this is going like this, so the sense of shear is at least on these bands are sinistral. So we can figure out that these things are previous CS fabrics which was sub-parallel with the large strain, but with continuous deformation they got sheared again successively stepwise to produce a series of slip surfaces which are the C-prime fabric and altogether they are developing C, C prime or CS, C prime or SC prime fabric.

And in this case because these are verging towards this side they are like this and we also identified the sense of shear within this, a sense with the shear of the C prime fabric is sinistral so bulk shear is also sinistral. You see that these are looking like a crenulation cleavage, so you have this cleavage domain which is c prime, let me clean this.

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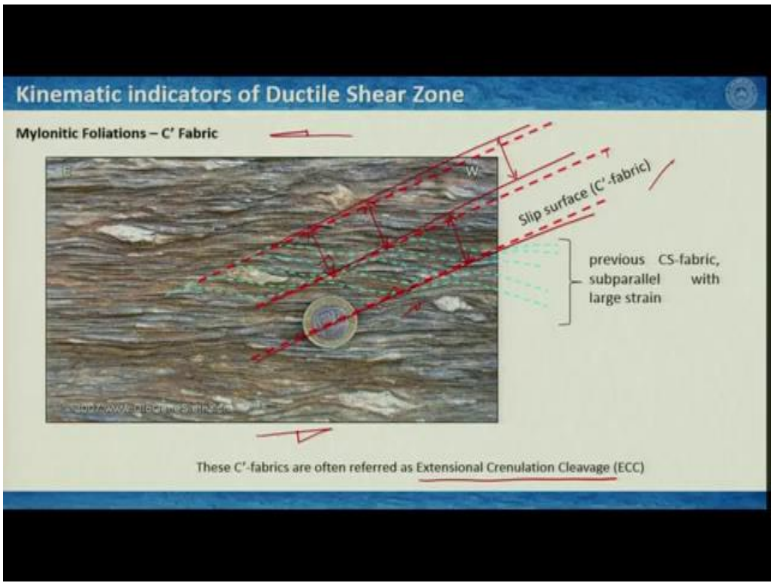

So you have your crenulation domain which is c prime and then you have in between this microlithons which have fabrics, so these are therefore known as also a special type of crenulation cleavage and this is known as extensional crenulation cleavage or ECC, there are few structural geologist or even few texts you can figure out it is like this.

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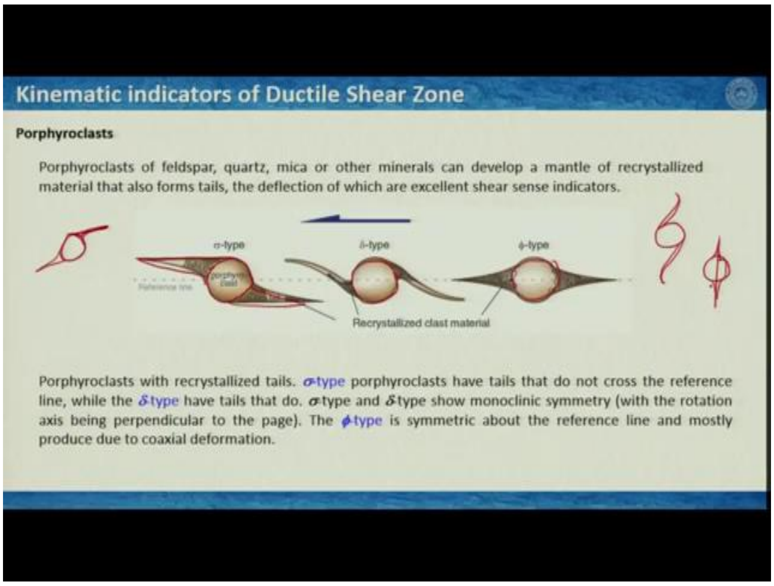

Now we switch to the next type of kinematic indicators in the ductile shear zone and these are porphyroclasts or sometimes you can use porphyroblasts as well but we will restrict to the porphyroclasts terminology but it can include porphyroblasts as well as I talked about. So porphyroclasts of fieldspar, quartz, mica or other minerals can develop a mantle or recrystallized material that also forms tails and the deflection of the tails which are excellent shear sense indicators and are excellent for figuring out what is the sense of shear.

And there are 3 types of porphyroclasts in the sense of identifying the shear direction. One is sigma type, one is delta type and another is phi type. What we see here, we will see in this detail in the illustration for individual, so this is the initial porphyroclasts which may be in a circular pattern or spherical pattern in 3 dimension and then they form tails in different ways.

So here it is like this and if you rotate it, it actually looks like the Greek letter sigma, half sigma okay or if you add it here then it forms something very similar to this. This is known as delta because Greek letter delta looks like this and this simply you can add another wing and it forms like this and this is phi because the Greek letter phi is something like that, so you can draw it like this and then it becomes phi structure. So this is the names, so this is the way these are named from the Greek letters.

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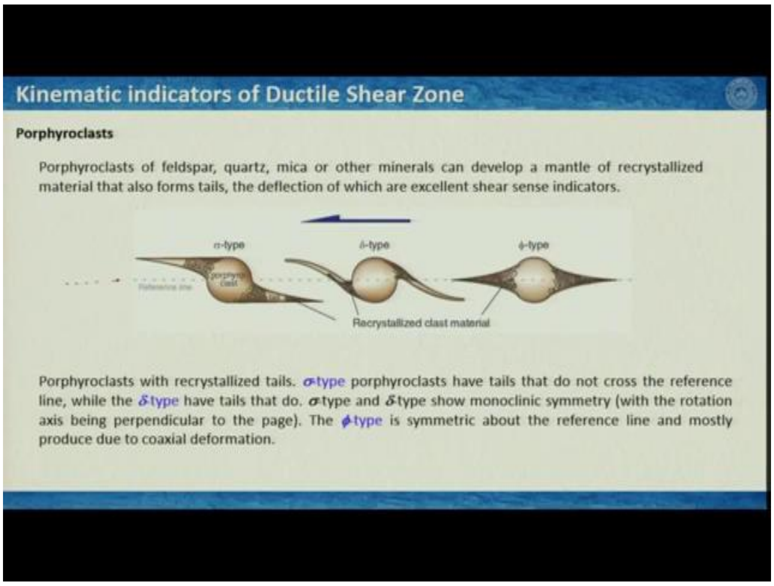

So sigma type porphyroclasts have tails that do not cross the reference line. What do we see here is this one is the reference line so some sort of median line that you can draw from the middle of the clast. So this is the reference line and if the tails do not cross the reference lines, so here it is like this, it did not comeback like this right. So if that happens then these are known as sigma type clasts, the built type clasts they are characterised with the fact that they cross the reference line, phi type clasts are symmetric about the reference line and these are mostly produced in coaxial deformation.

We are not going to look at it at least in this class because these are not good shear strain indicators, only sigma and delta type clasts. So from this we will take now the sigma type and delta type of structures and how they are useful in figuring out kinematic sense of the shear zones we will see one after another.

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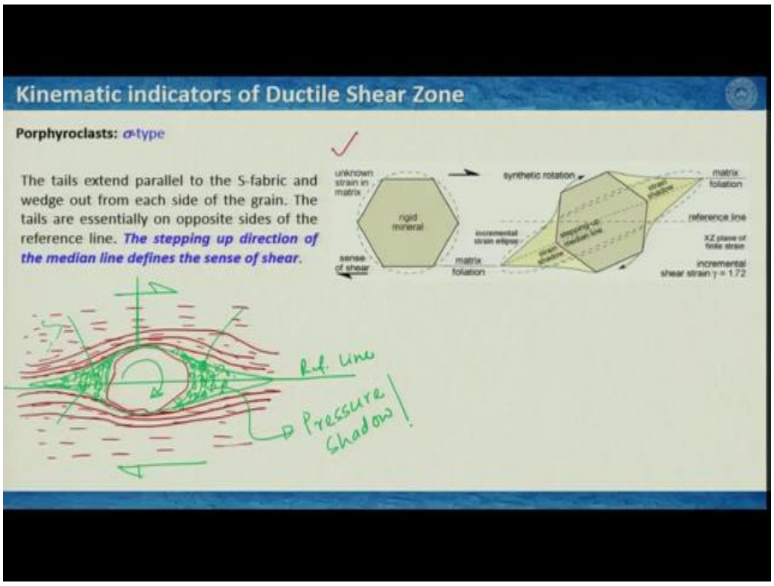

First the sigma type structure, so the tails of the sigma clasts they do extend parallel to the S fabric and wage out from each side of the grain. The tails are essentially on opposite sides of the reference line and the stepping up direction of the median line defines the sense of the shear.

Now before we take look at this illustration, let us first have a very brief understanding what is tail or what is a mantle structure that we talked about in the previous slide. So if you have a large mineral clast something like that which is a porphyroclast or porphyroblast and you can deform it by for example simple shear then the foliations would develop like this perpendicular to the principle axis of stress and around this the foliations would wrap right, we have seen this kind of illustration before.

So if I try to figure this one out, you particularly have seen this in the lineation lecture and this place is known as the zone of pressure shadow. Now this pressure shadow zone is a low-pressure zone so the fluids from this area they migrate here and they rest reside here and they also contain a lots of minerals dissolved within these fluids and they slowly start depositing around this place.

Now this is fantastic when it happens in the static condition, so these are known as mantle structures and these are the tails that is forming this way. Now imagine, if we change the mode of displacement or kinematics of this place, if we apply a shear here then this grain would tend to rotate and while it is rotating it would also drag this tail or mantle structure. and when this is happening, then this eventually would form some very interesting structures and that may not remain symmetric with respect to the reference line.

And if it is not symmetric then we can have two possibilities, one is sigma type which we are learning in this slide, and after a few slides we will learn another type of asymmetric tail structure which is delta, so this is how it happens. Now coming back to this sigma structure, we figured out that sigma structures are asymmetric structures and the tails generally do orient themselves along the S fabric.

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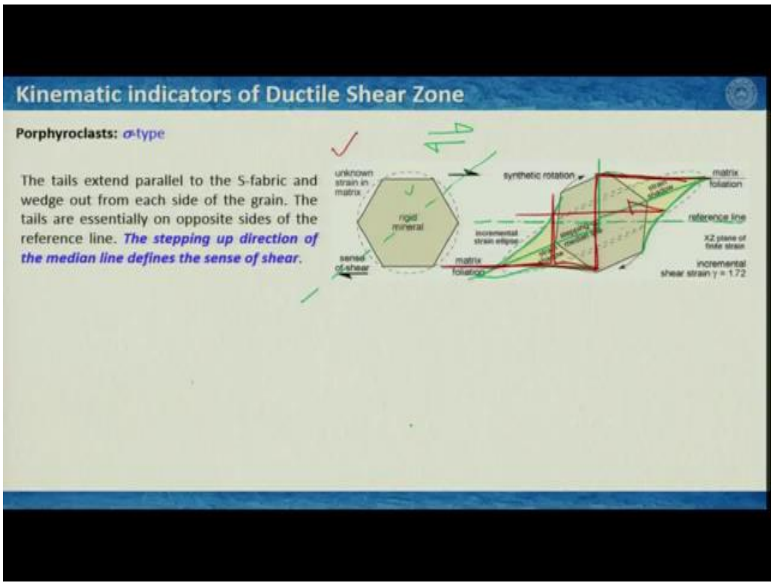

So what do we see here if this hexagon that is drawn here these illustrations are from lecture (())(52:19). So then you have the hexagon here which is the minerals grain and then the tail structure would form if the shear sense is dextral as it is given here with the black arrowheads, so the S fabric would form in this manner and therefore the tail structure would develop something like that and these are the strain shadow or pressure shadow zones.

And if we look at in that case, this is the reference line. So if we follow this it goes like this and then it makes a step and works this way so we can figure things this way to figure out what is the step or you can also think of this way that you can take the tip and then follow the reference line, parallel to the reference line you also take a tip and follow the reference line parallel to the reference line and then you connect these two and you see the step is something like that.

And that tells you the sense of shear towards this side and in this case this is dextral sense of shear at least form this illustration.

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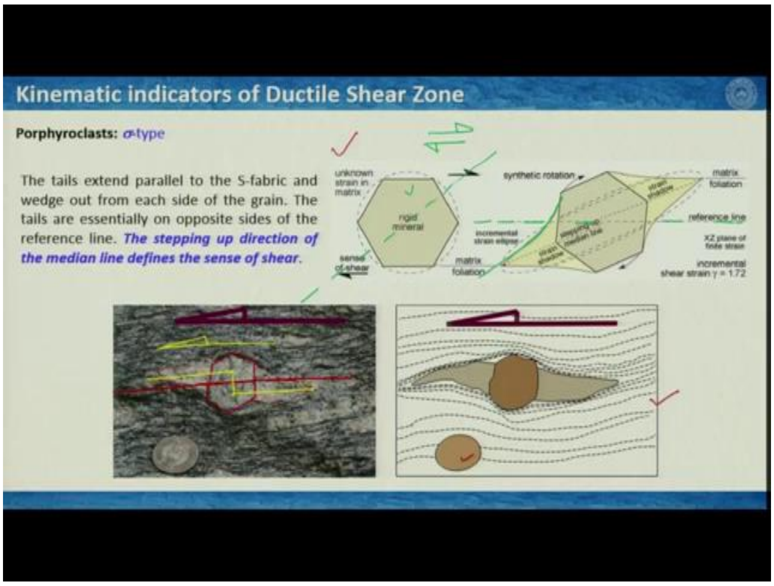

Now let us have some examples, so what do we see in this image illustration that this one is the mineral grain, the rigid minerals grain and this is the strange shadow that we are looking at, the sketch is given here on the other side this one and this is the scale. Now what do we see here that this must be the reference line of this and if we try to figure out the step then I find the tip and then I draw a parallel line with respect to the reference line.

Here is the tip, I again draw a parallel line with respect to the reference line, I connect these two and therefore once I do that, step is moving upwards towards the left so the sense of shear is sinistral in this case. Now these are the things that you should practice initially when you see these kinds of structures but slowly your eyes will be trained and you will see you do not have to do this, you will automatically figure out what is the sense of movement or sense of displacement shear displacement when you see a sigma type clast.

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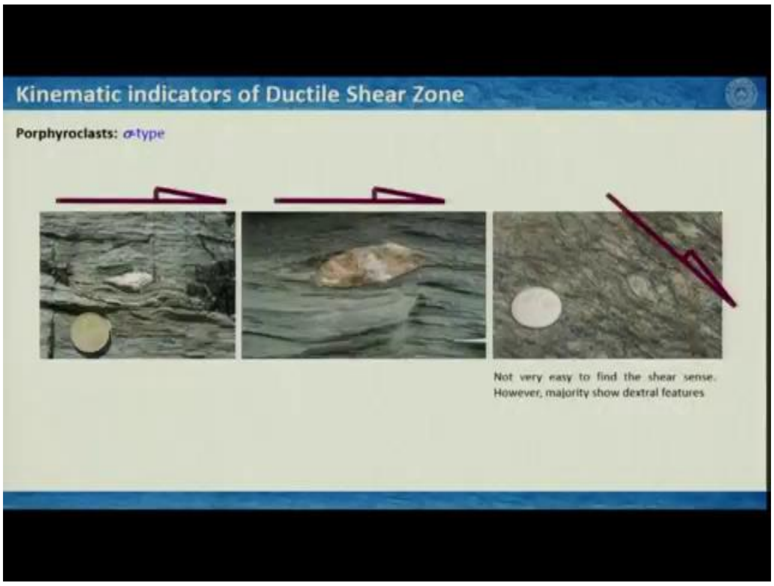

Now here a series of examples that I have provided to you, so I am doing just here so you see this is a clast here again and that line parallel to this and then you see that it is moving up so the sense of shear is this way. This is another brilliant one, so the tail is something like this here and tail is here and the reference line would be in this case something like that and again you can draw a line parallel to the reference line such, you can draw a line parallel to the reference line from the tip you come at the middle, you see the step is happening in this direction, so this is a sense of shear, in this case it is also dextral.

Now this is little bit complex the third image, if I see for example there are many clasts, so if I see this one here, it is referring to this side but if I see this one here this typical clast that I am seeing here then it is suggesting this side. So when this happens it is little confusing so you can take as many as you want, so you see different things and then statistically you say okay the maximum clasts are showing say C displacement in this manner.

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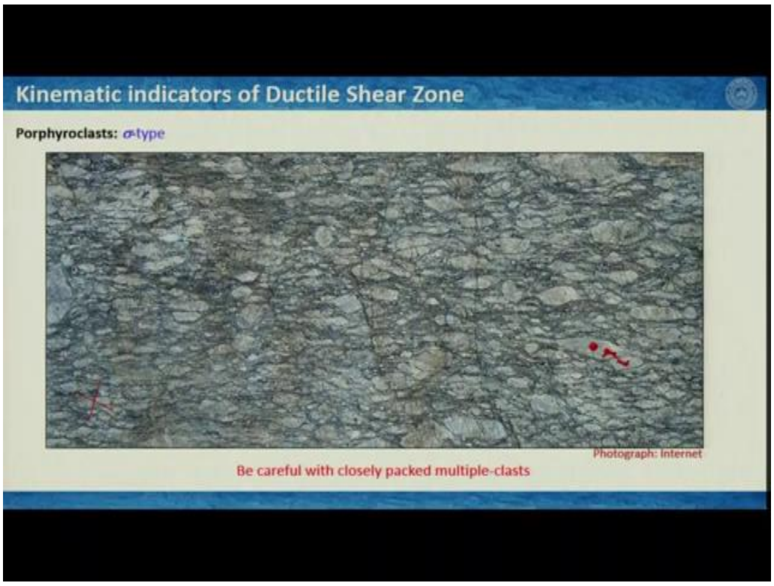

So this is the sense of shear, but that may not be always the true idea of doing it particularly when you see something like this in your field. And you see there are many clasts and they are producing alternate sense of shear in many-many cases. For example, if you look at this you have phi structures, you have also sigma structures and so on all together. When you have lots of clasts and they are highly concentrated, it is advised that you do not interpret the shear sense from this kind of exposures.

The reason is, in this case this clasts are not independent, so the tail and the rotation of the clasts itself is not governed essentially or exclusively by the sense of shear. Sometimes the clast for example, if I consider this one this clast and this clast, the rotation of this clast or the tail structure of this clast would be highly damaged or altered by rotation of this clast so because they are interacting each other.

And this is a subject of study in structure geology, subject of research that when you have multiple clast how do they interact and sometimes the clasts are also deformable, so all these to take into account, it is advisable at the very beginning stage that you do not interpret shear sense for this kind of exposures unless you are convinced from some other places. The bottom line of this slide is that try to see an independent isolated clast which did not get any interference from the other clast the deformation of which is solely or exclusively by the bulk shear direction.

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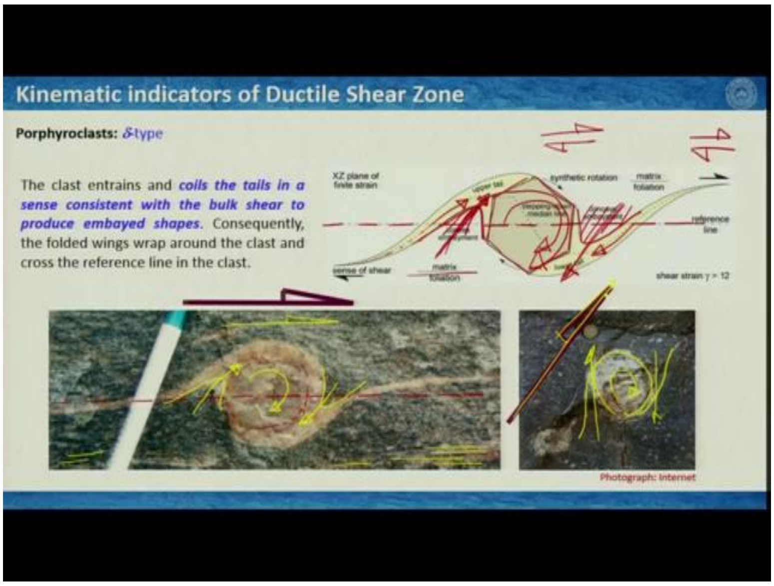

Delta structure is also very interesting, so the clast entrains and coils the tails in a sense consistent with the bulk shear to produce an embed shape. And consequently the folded wings wrap around the clast and cross the reference line in the clast. So in this case what happens, you see this is again the minerals grain that we are talking about, the rigid mineral grain. And because this grain is rotating significantly, so the tail it also gets dragged in this way when the bulk sense of shear is in this case dextral.

And then you see in this side you develop a concave embayment which is this one, and in this side you develop a convex embayment. This is the reference line again and the tails essentially cross the reference line due to the rotation of the grain and at the same time dragging of the tail of the upper tail and the lower tail.

In this case, you can figure out what is the sense of rotation and once you figure out what is the sense of rotation then you also see the embayment, so the direction of embayment actually also suggests the sense of shear. So if I have the direction of embayment convex embayment here and the concave embayment here then the rotation is happening in this way and that clearly tells you with respect to the matrix foliation the sense of shear in this case is dextral.

We have seen this first image before and you can clearly say it is very similar that this is the clast and approximately this is the reference line. You have the embayment here, the convex embayment and the concave embayment, so if you draw arrows this way this gives you the sense of rotation first, and second thing also tells you with respect to the foliation outside which is not disturbed by the rotation of this, the sense of shear in this case is dextral. Not necessarily you will see fantastic images like this, for example here this is the clast again the second one, here it is going like this and here it is going like this.

So it is moving in this way, it is moving in this way, this is the sense of rotation and sense of shear therefore would be something like that.

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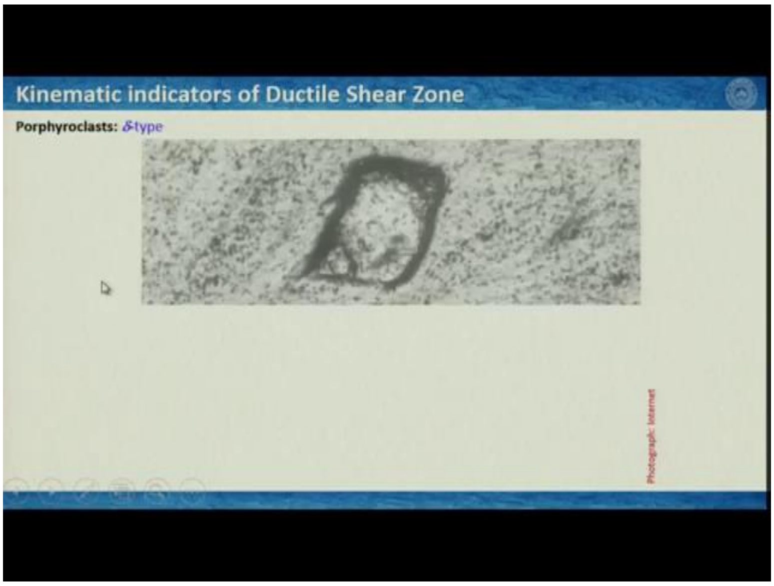

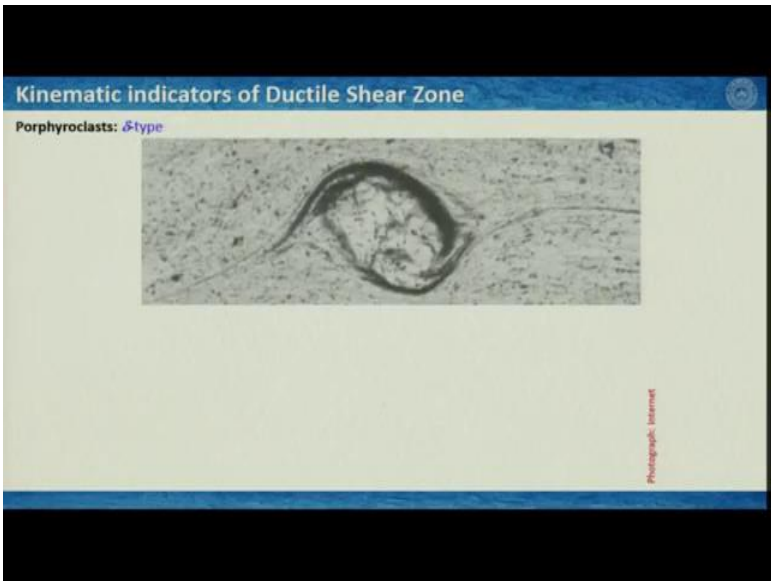

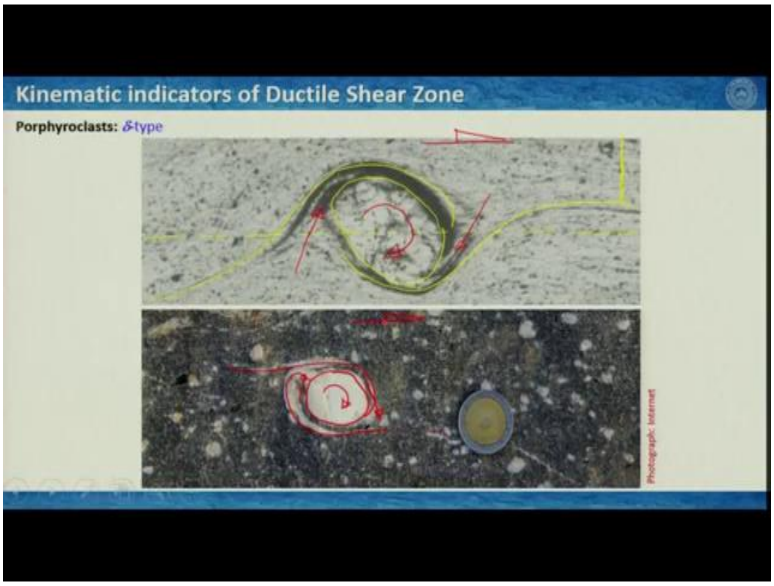

People have done lots of work in understanding this delta structure and here I would like to show you analog experiment and see how it happens. So what do we see here? This is the clast thing and this black thing is a mantle or the fluid that would be dragged so you see here. So you see it is rotating rotating and then you eventually form a structure like this where this was your clast.

This is the tail structure that we see it here, this is the reference line, this is embayment, this is another embayment and we know, we have seen that it was rotating in this manner so the sense of shear here is something like that. And in the field you see in a very similar way the structures like this and this is little complex but it is producing something as we see here, so this was a clast, the tail one is like this and another tail is going like that, so again this is the direction, this is the direction, it was rotating like this, sense of shear is again dextral.

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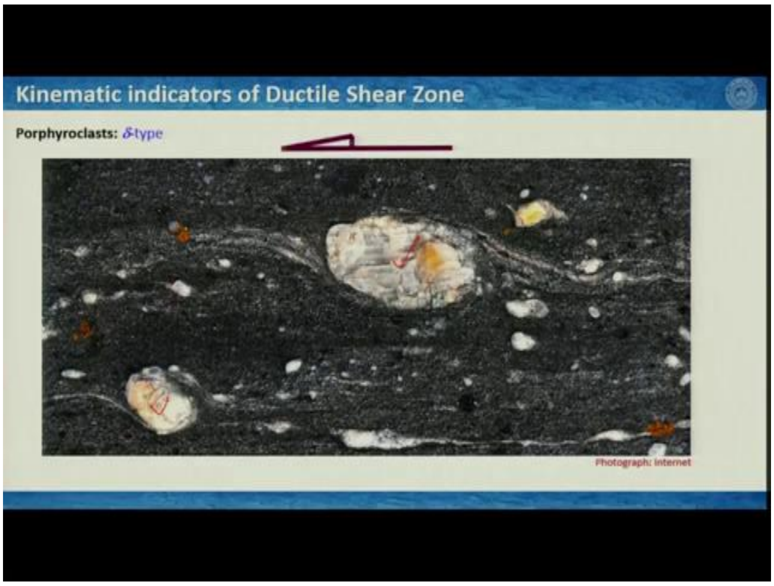

You can also see some very nice images, this one we also have seen and I let you decide that what is the sense of shear. First you figure out the clast then tail structure, you figure out the embayment and then you see the sense of rotation and after that you can also see the step over with respect to the reference line and then you figure out what is the sense of shear. You have two examples here, one is this one and another is this one.

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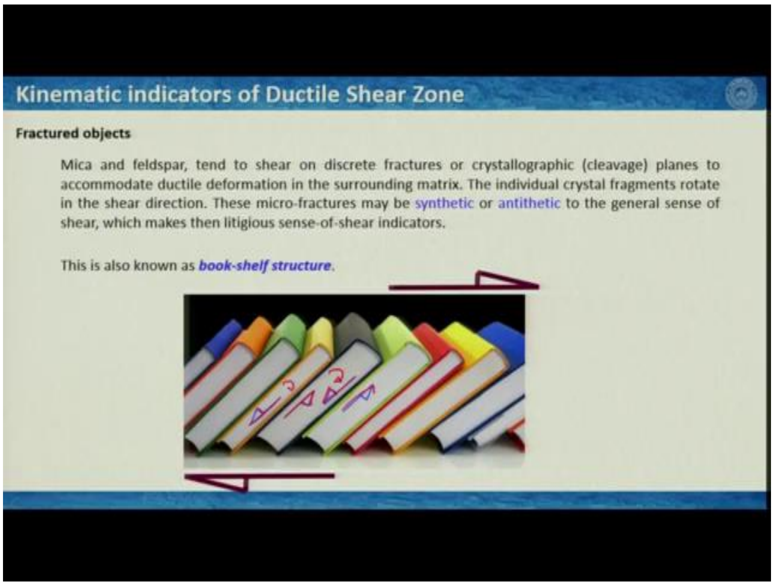

Let us talk about another kind of kinematic indicators and these are known as bookshelf structures or fractured objects. Now sometimes in a ductile shear zone you have clasts which are highly cleaved or the minerals itself are characterised by their own cleavage for example, mica and feldspar. And while the shearing is happening these grains may not undergo ductile deformation but they prefer to sleep along their cleavage planes or crystallographic planes.

And therefore, in the sense of shear or with respect to the sense of shear these cleavage planes act as some minor slip planes and they produce some typical structures, we have learned about it in detail in our boudinage lecture.

So what is written here, mica and feldspar, they tend to shear on discrete fractures or crystallographic planes to accommodate ductile deformation in the surrounding matrix. The individual crystal fragments rotate in the sense of the shear direction and these micro fractures is could be either synthetic or antithetic to the general sense of shear which makes them litigious sense of shear indicators and these are known as also bookshelf structure as I told you.

So if a series of books kept on the bookshelf and if you just tilt them or shear them they would slip on each other for example, here this book is slipping in this way, book is moving in this way, this way and this way and therefore each book is rotating in this manner. Now we will see this in the field as well or in the thin section particularly in ductile shear zone rich with feldspar and mica.

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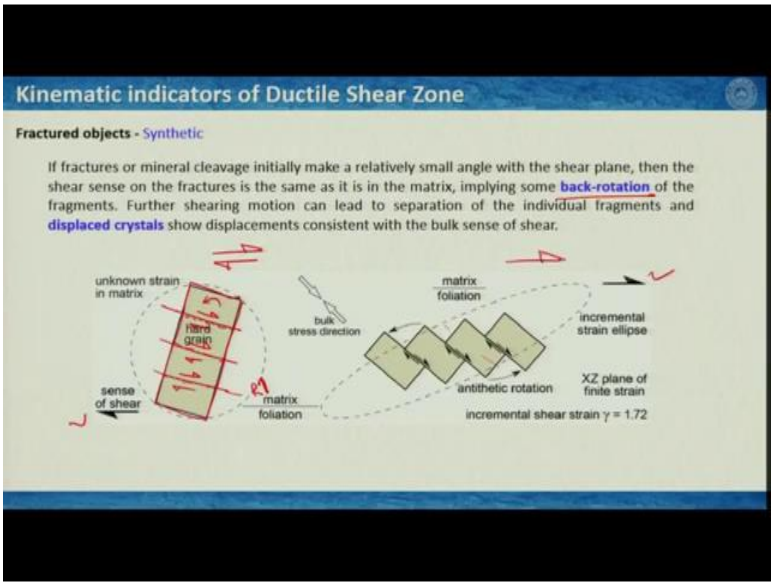

So first we take over the synthetic fracture objects, if the fractures or minerals cleavage initially make a relatively low angle with a sense of shear or with respect to the shear plane then the shear sense on these fractures is the same as it is on the matrix, implying some back rotation of the fragment. Further shearing motion can lead to the separation of this individual fragment and displaced crystal show displacement consistent with the bulk sense of the shear.

So again you can imagine this is a mineral grain this one which is harder and these are the crystallographic planes or some fracture planes, you can imagine this is a feldspar and then the bulk shear in this case again dextral as it is given by these arrows, so what happens the crystals then tend to sleep in the similar sense of shear displacement because low angle and you can figure out these are actually defining the R1 shear fractures.

So with continued deformation these grains actually would try to rotate backwards therefore this back rotation is important and then you develop a step like features and you generate an antithetic rotation of this grain, but the sense of displacement is very much synthetic. If you see this then the sense of shear is essentially dextral, let us see some images.

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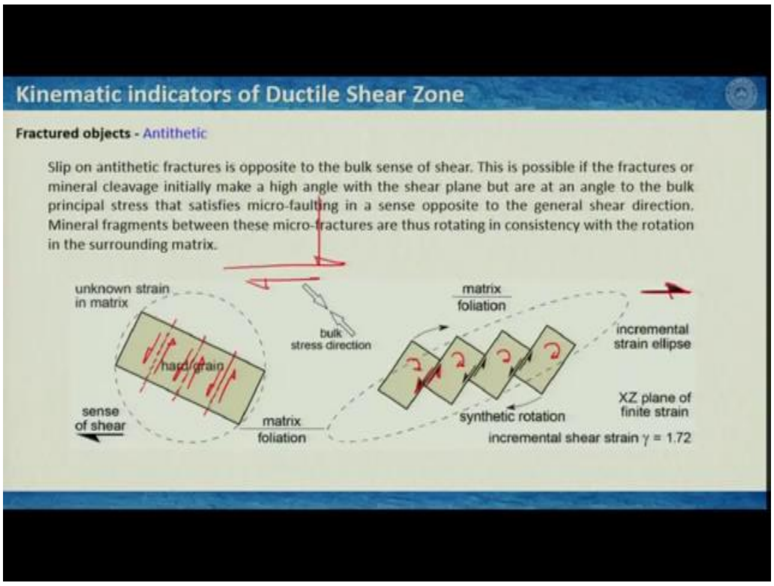

And for the antithetic displacement there, the initial slip on the antithetic fractures is opposite to the bulk sense of shear and that is why we have the antithetic term. This is possible if the fracture or mineral cleavage initially make a high angle with the shear plane, as we see here so this is again the shear direction say for example, here we have given it as dextral and this initial fracture planes or cleavage planes are oriented with respect to the shear plane at an high angle.

If that happens then the sense of shear changes along this fracture planes, they rotate or they slip this way. And what do we see here? So the mineral fragments between these micro fractures are thus rotating consistently with the rotation of the surrounding matrix. So the rotation of these minerals say they rotate this way, so the rotation is synthetic with respect to the bulk shear direction but the sense of shear is antithetic and these are known as antithetic shear fractures and with this it is possible for us to touch identify the sense of shear.

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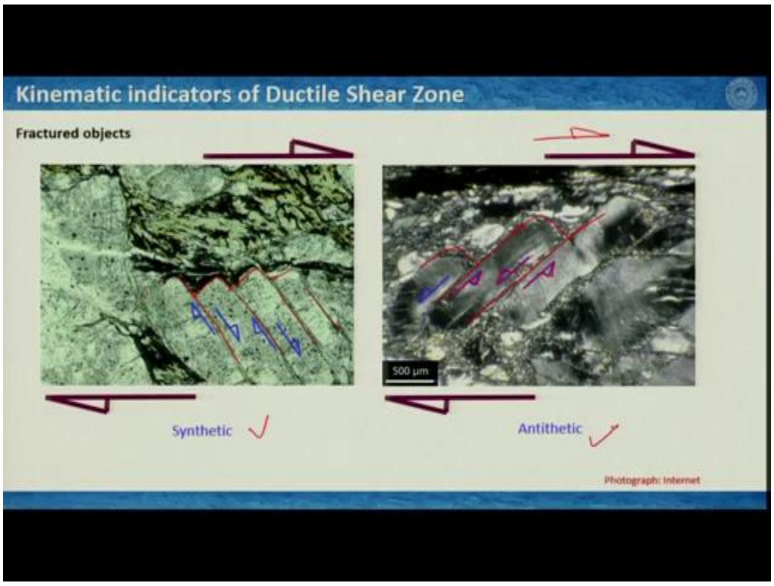

So here are two examples as we see here, so this is the fractured object this one you see these are the fracture planes and they slipped in this manner we can figure out from the steps and the sense of shear is in this case dextral and here as well you see that they rotated in this manner, these are the fractures, we have seen this image before, these are the fracture planes and they are rotating the slipping in this manner which is opposite to the sense of shear and the bulk sense of shear is again in this case dextral, so this is synthetic and this is antithetic.

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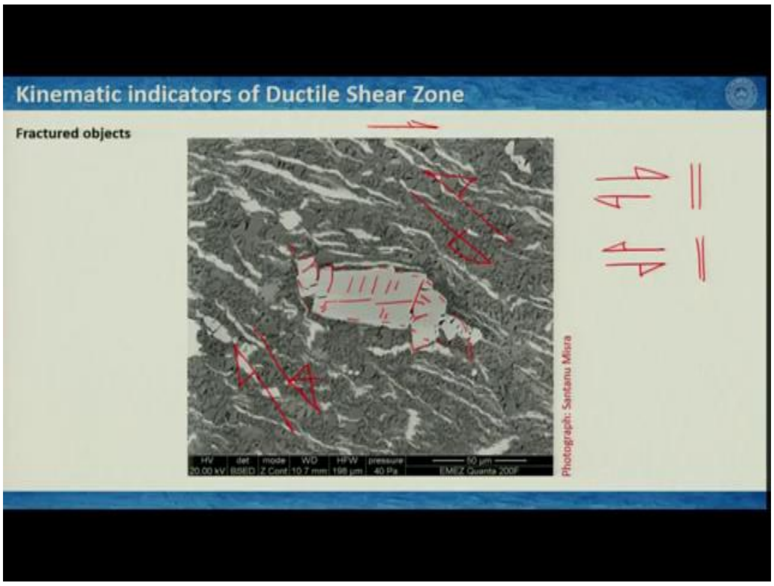

Now I have an excellent image for you to do some brainstorming, again it is from the same experiment and what we see here in this image, scanning electronic microscopy image that this grain overall apparently showing sigma clast when we look at this way, but they are producing lots of fracture, So we can do a kinematic analysis and figure out just looking at it what is the sense of shear. You see I just give you clue that you see two fractures going like this and some incipient fractures are producing here in this case like this, you have some fractures here and here.

First you do a geometric model that means you first try to identify what are the fractures and so on then try to figure out what is the sense of displacement along these individual tiny fractures and finally figure out what would be your bulk sense of shear, it is dextral or it is sinistral, or it is at an angle to this or it is not at an angle to the reference frame or maybe something like that or something like this or it is something like this or something like that.

So this is how you can figure it out, so this is a problem for you to think, you first deal your geometric model then you try to build the kinematic model and figure out what is the sense of shear in this illustration.

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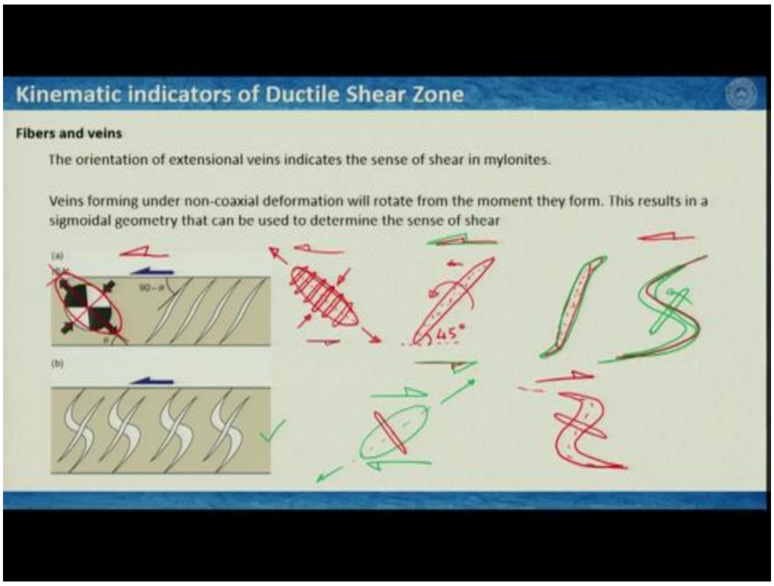

Now we will go to another kind of kinematic indicators which are fibrous and veins. The orientation of extensional veins indicate the sense of shear in mylonites. Now veins forming under non-coaxial deformation will rotate from the moment they initially generate and this results in a sigmoidal geometry that can be used to determine the sense of shear. So here are two illustrations, what we see here that once I have initiated the shear in the sinistral manner as we see here, then the bulk strain ellipsoid could be like this instantaneously ISA, I am just exaggerating it from the original one.

So once I have an ellipse like that in response to the sense of sinistral shear then clearly this is the long axis and this is the short axis. In other ways we can figure out that this is the compression direction and this is the extension direction, if that happens then it is obvious that fractures would produce like this. So they would have this orientation, again we have learned this in our fracture lecture okay.

So we can produce a series of fractures, let us take one of them as an example like this, so this is the fracture which generally tend to form at an angle of 45 degrees with respect to the long axis of the instantaneous strain ellipse. Now the shear continues and this initial fracture which got generated would rotate back this way, is not it? So it would tend to rotate like this.

So if that happens then it would take a shape like this but the second instantaneous strain ellipse which is coming in the next stage with the progressive deformation would still form fractures at 45 degrees because this is the orientation of the instantaneous strain ellipse. So the new fractures or the growth would happen along this direction, so essentially you will produce shape which is sigmoidal like this and this can continue-continue-continue and then you eventually can have a shape like this where (my god) where this is the latest orientation which is about 45 degrees and this was once upon a time 45 degrees but now it got rotated significantly.

But at the same time you see that once this got significant rotation then instead of continuing from its steep it may produce new fracture along this way and then it again continues rotation in a very similar way and so on which is illustrated here. Now if that happens then you see that once the sense of shear is sinistral then you form sigmoidal shape which is like English letter S.

And if this happens in dextral manner then the strain ellipse, instantaneous strain ellipse would be like this, this is the long axis so this is the stretching direction, the fractures would tend to form like this and then it would rotate and eventually would form something like this which is like English letter Z and that may have another fracture like this.

So if you see fibres or veins or extensional shear fractures within the shear zone with a shape of S then this must be sinistral. And if you see in a similar way the shape of Z then this must be dextral, but these are instantaneous references, it is important that while concluding that whether it is S or Z and then you conclude whether this is sinistral or dextral, it is important that you make some sketches, you understand the processes and then go further with your conclusion.

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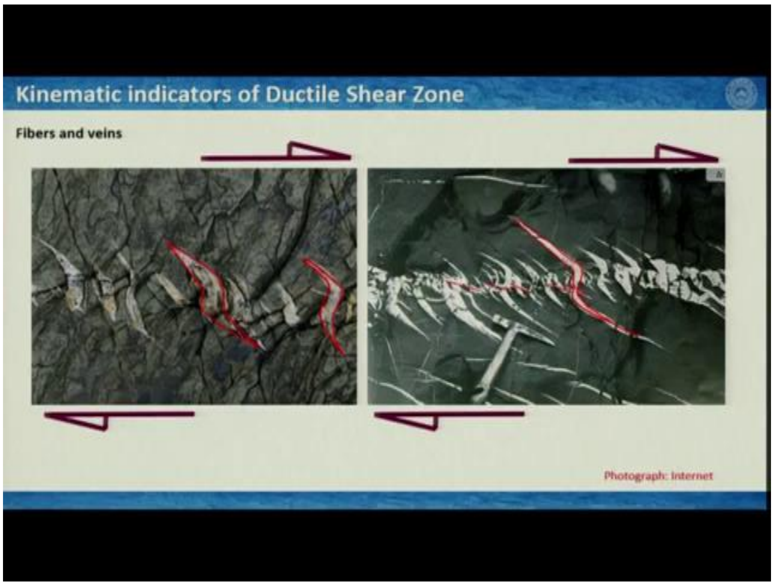

So here are some examples as you can see here, these are excellent tensile fractures, it has a shape of sigmoidal, the shape here and here as well, and you can figure out that what is the sense of shear from the slide we just learned.

And here you see that we have one set of initial thing which is sigmoidal and then you see a series of other fracture planes are coming out this way, these are secondary or latter fractures of later stage, and this is how these fibres and veins, the tensile fibres and veins in particular they help you to figure out what is the sense of shear and in both cases at least in this example we see these are in the Z form, so the shear sense is dextral.

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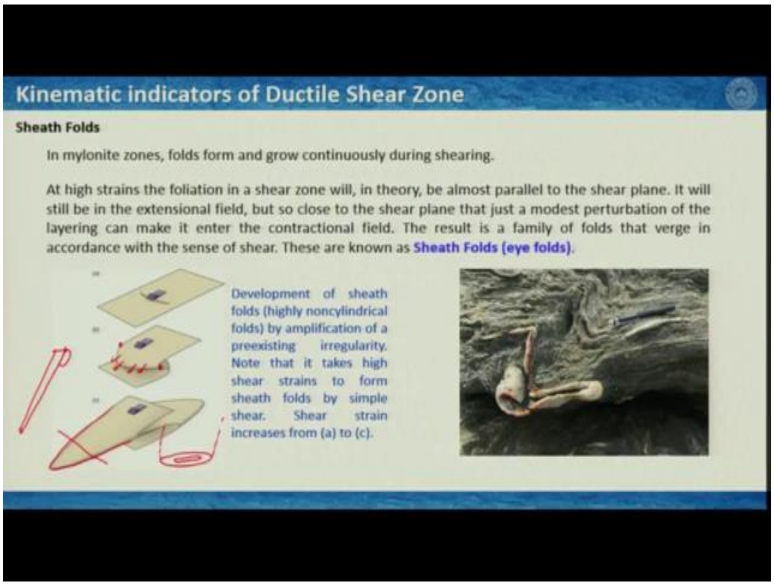

Now finally we will see the folds in the shear zone when we are speaking about or talking about the characteristics of shear zone we said or we spell it out that shear zones are characterised by a symmetric folds and sheath fold and reclined folds. Now sheath fold is one of the very interesting folds which once upon a time was termed as I fold and sometimes people used to confuse it with the dome and basin structures, but later researchers figured out that mechanism of formation of this kind of folds because it was only restricted in the shear zones.

So people researched on it, they performed some analog experiments and they figured out it is essentially a product of shear zone and we see this only within the shear zone and these are known as sheath folds. So in mylonite zones, folds form and grow continuously during shearing. At high strains, the foliation in a shear zone will in theory be almost parallel to the shear plane as we have learned.

It will still be in the extensional field but so closed to the shear plane that just a modest perturbation of the layering can make it enter in the contractional field, layer parallel compression to make the fold. And what is this modest little perturbation or how folds do form in the shear zone is something a topic of research. So the result is a family of folds that verge in accordance with respect to the shear.

So what we see in this illustration that this is the foliation shear is going on which is given in this purple arrow head, so little small perturbation would produce a tiny undulation here that you see here with this little shade. And if things continue then these tiny undulations would accentuate to produce something like that, any further actuates these 2 sides are pinned and this would continue to propagate.

So eventually forms something which is like a flat cone right and this you see in this image excellent field photograph here and these are known as sheath folds. And you know what is sheath? Sheath is a container where warriors used to rest their swords or the shape is like this as you can see here. So sheath is something like that, so where warriors they used to keep their swords in their thing and the sword is inside this, so this is known as sheath and the fold is very much similar to this kind of sheath and therefore this is known as sheath fold. A cross section of this if I make a cross-section then it will look like this as you see here.

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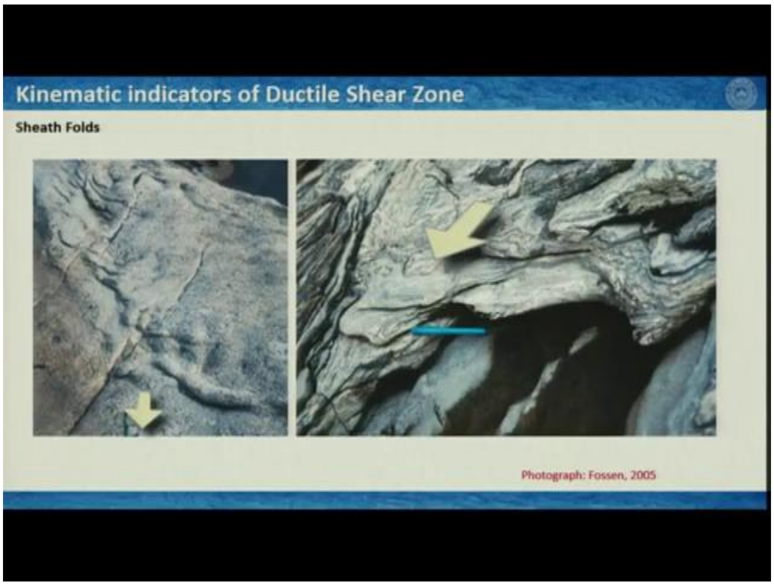

Now people have seen them in the field so this is the initiation of the sheath fold as you can see here, they move like wave and with further deformation you can generate sheath folds like this. So if you go to mylonitic zone and keep your eyes open, you know the theory what is sheath fold, you know how does it look like, it is essential or it is obvious that you must find a sheath fold in the shear zone.

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And here are some excellent examples, I took it from Yun's paper and Yun alsop and then you see that these are extreme beautiful examples of sheath folds. You can also if you are interested, you can go and read this excellent paper in 2007 published in journal of structural geology.

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And finally the asymmetric folds, so the sense of the versions of this foliation plane of the fold, they generally define the shear sense. So for example you see here, this is the general shear zone foliation going like that but few foliations would tend to develop some kind of folds as we can see such here, as we can see such here and in many other places, this also rotated this way and so on.

So if that happens then the versions of the axial plane of this asymmetric folds would give you the sense of shear which is in this case dextral. You can see also you here there are many minor folds and then a large fold and so on, so this is essentially an asymmetric fold the way we learnt in our fold lecture, we see also one here and it is verging in this side so therefore again sense of shear here is like this.

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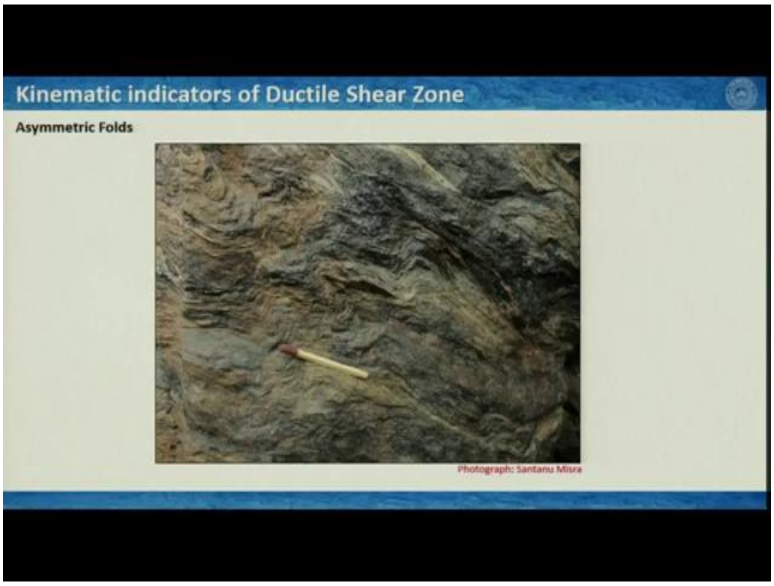

And I have the final picture here what we see here, this is how the mylonite look like extremely foliated rock as we can see here and you see some folds going like this. And the versions is like this, so in this case the sense of shear is sinistral so in this lecture we have learned a number of kinematic indicators of ductile shear zones that can help you to identify the sense of shear.

I said during the lecture but I would like to repeat it again, do not conclude just observing only one feature on the sense of shear, you look for some other evidences, at least collect good number of evidences, you be convinced by yourself and then you conclude that yes this is the sense of shear. So I conclude this lecture and with this I we all finish the basic understandings of the structural geology. We covered all topics which are relevant for structural geology but we learned them only on the slides or with some field photograph.

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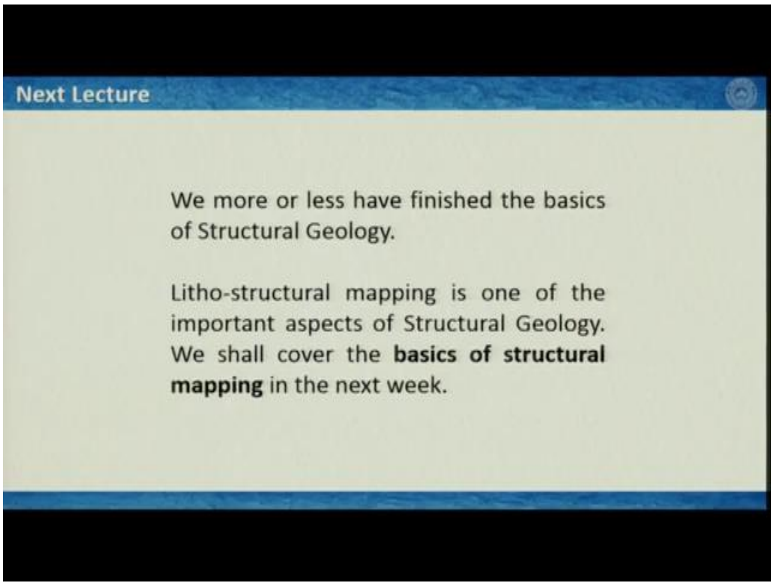

The primary job or what is expected from structural geologist is that he or she should be an expert of reading and performing Litho-structural mapping and this is one of the most important aspects of structural geology, and this is what we are going to learn in the next lecture or the last week which is the basics of structural mapping is the topic of the next week. Thank you very much, have a nice time, I will see you in the next week.