Structural Geology
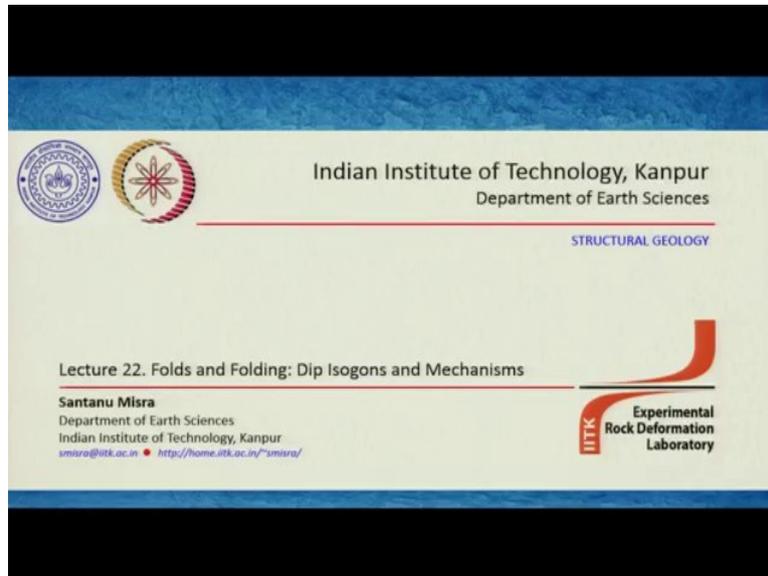**Professor Santanu Misra**
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Lecture 22: Fold and Folding: Dip Isogons and Mechanism

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Hello everyone. Welcome back again to this online structural geology NPTEL course. In this week we are learning folds and folding. We are in the third lecture of this week. It is lecture number 22 and in this lecture we will learn dip isogons and mechanisms. Initially, at the beginning of this week I said that we will cover this entire topic folds and folding in three lectures. However the topic is somehow quite large and I decided to split the last lecture in two halves. So you will have another lecture after this that will deal with mostly the interference folds or superposed deformation.
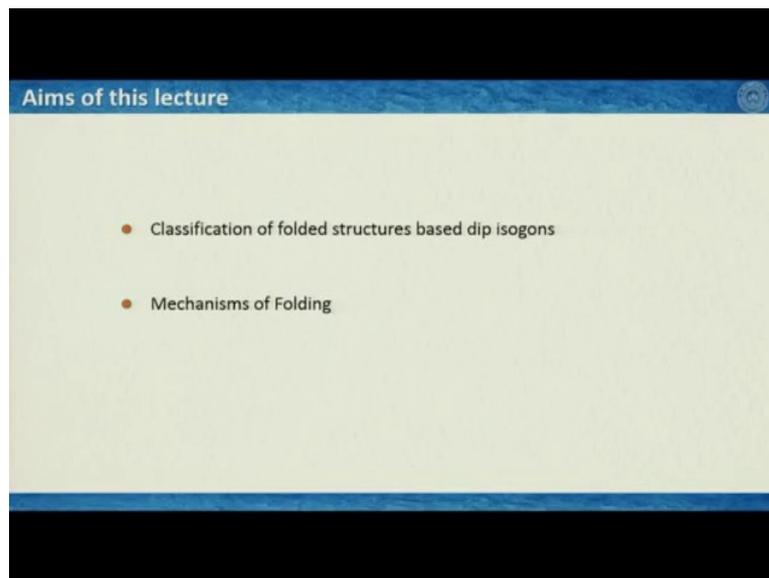
So in this lecture we will classify the folded structure based on dip isogons. And then we will look to the mechanics or mechanism of folding that is how the folds do form in nature. What are the different ways we can form folds in natural deformation.
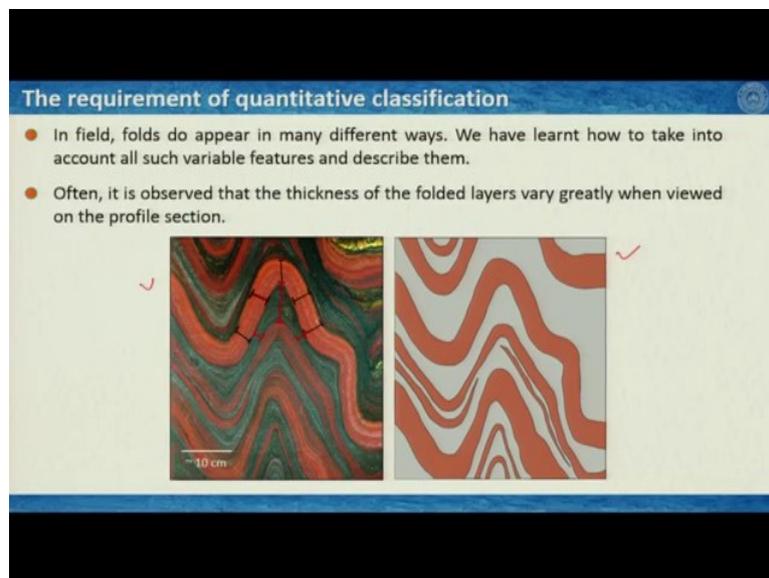
Now we certainly can ask this question that why it is required to classify. Again we have seen a series of classification schemes in the previous lecture. And we now more or less have a very comprehensive idea that how to describe folds, how to term sort off, how to describe the folds and how to present them in different ways, how to popularize them, how to talk about them and so on. But if you remember, I said also at the same time when I was showing the different schemes of the classification all of them were very much qualitative classification.

Some sort of descriptions, their different orientations and so on. None of them have any ideas or any parameters to quantify the folded structure. Be it morphology, be it geometry or be it something else.

So there is only one classification scheme for folds proposed by John Ramsay that actually classifies the folded structure pretty much quantitatively. And this is why it demands a separate attention and I have added it in a different lecture.

So in the field, we have seen from different illustrations and photographs, as you have seen in the field as well and also in the internet that they do appear in many different ways. And in the previous lecture as I said, you have learnt how to take into account all such variable features and describe them.

Now as I said these are all qualitative measurements but at the same time if you look at the folded structures in a different way, then we see that the thickness of the folded layers also do very greatly, when you see them parallel to the profile section or along the profile section or close to the profile section.

So here I have one image. This one and the next one is a sketch of this image or you can say it is a geometric model of this folded structure that we see on the right side. This is a bended iron formation that got folded. I collected this photograph from the internet. And it is spectacular isn't it? It is alternate red and black layers. They got folded. The red layers are chalky layers and the black players are iron rich layers. And what we see in particular, apart from the beauty of this image that this red layers if I try to measure their layer thickness. Say for example, here to here I change the color. It will be easier.

So if I try to measure here to here or here to here and here to here and so on. We see that the thickness is more or less constant along this layer. However if I approach the next layer, which is actually the iron rich layer, what I see here the hinge thickness is much more compared to the thickness we have on the two limbs. Now this is something that we need to consider because if I have to measure the thickness of the layer, then in some layers as it is seen in this image, it is not possible to measure the thickness and the thickness is not constant.

We can see another image in the next slide which is very similar. As we can see here these are alternate layers. These are sandwich layers and the second one is a phyllosilicate rich layer. So this is the sandwiched layer and again, I am sorry. If we try to measure the thickness of this sandwich layer, then it is like this. Here it is like this. Here it is like this. So they are more or less constant. But here in this phyllosilicate rich layer, it greatly varies.

Again, how to take into account all these features, particularly the thickness of the layers? And we also have to justify that, why in alternating, for example here, the thickness the sandwich layer, the thickness is more or less constant. In shell or in phyllosilicate rich layers, the thickness is greatly varying from hinge to the limb. We also can figure out that is it always true that the hinge would be always thicker or the layer thickness would be constant? Is it possible that hinge can be thinner and limbs can be thicker and so on?
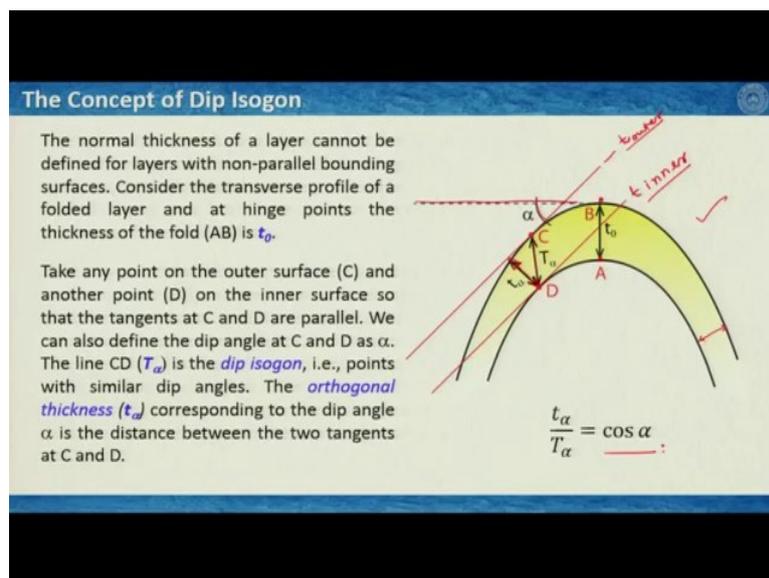
So to take into all these things into a comprehensive picture and ideas, the concept of dip isogon has been proposed by Professor John Ramsay. Now what it says that as I was talking about the normal thickness of a layer cannot be defined for layers with non parallel bounding surface. So what you mean by the bounding surface? That I consider a layer- the top layer and the bottom layer. Or in other ways, the layer that contains extrados and the layer contains intrados. If they are not parallel to each other then there is no meaning of measuring the thickness of that particular layer.

So to avoid that, what Professor John Ramsay proposed that you can consider a transverse profile of a folded layer as it is illustrated here. And then at the very beginning, you figure out what are the hinge points in the outer layer and inner layer. So in the inner layer, the hinge point is here, which is A and in the outer layer the hinge point is here, which is B. Now I can assign this thickness A to B as the hinge thickness or termed it as T0, right. And in that, after that what I can think that as I can see visually that here the T0, if I try to measure here that it is obviously lesser than what we have measured at the hinge.

So what Professor Ramsay proposed that you can take a point any point at the outer surface which is not the hinge point and then draw a tangent, which is the tangent at the outer layer okay. And then you find another point in the inner layer where the tangent of this particular point, which is in this case D, is parallel to the tangent of the T outer. So T inner is parallel to the T outer at point D. Now if I consider the fold is also cylindrical, then you can imagine that the dip of this tangent line, a dip at this point would be alpha. Or we can define it in a

different way that this tangent outer and tangent inner when they are similar, the dip at C and D are equal and in this case there equal to alpha.

Now these lines, this T outer, T inner, these are known as dip isogons. So they always appear in pairs and that means the points with similar dip angles. Now once we figure out the dip isogons, then we can measure the thickness of this layer as the distance from one layer, one T inner to T outer. So this is known as the orthogonal thickness which corresponds to the dip angle alpha. So at particular angle alpha is the distance between the two tangents, in this case C and D.

Now this, if I connect these two points that is C and D where the T outer and T inner are parallel, then the distance I can assign as capital T alpha. Now from geometric relationship you can figure out that small T alpha divided by capital T alpha should be cos alpha. Now these are the concepts of dip isogon or this is how it is constructed. Now it is possible that with the change of alpha, we can actually check the variation of thickness along the layer. And this can be represented by showing, as I said the variation of small T alpha or capital T alpha against alpha.

Now this analysis has also one more advantage that you do not have to have the absolute values. What I mean by that, that in the field you may take a photograph and one of your friends can zoom this photograph and do the analysis of dip isogons. And you print it in a different scale and you do also the analysis, dip isogon analysis. Now of course your friend would measure all the values much higher than what you have measured. But here in this analysis because these are all normalized, so what you are actually measuring is doesn't matter. So absolute values are not important here because all of them will be in the form of ratios.

So therefore, the shapes of the different fold, it is essential to represent the thickness variation by a non dimensional parameter. So therefore, I can define a term T prime alpha, which is the ratio of T alpha by T0 or capital T alpha which is equal to capital T, capital T prime alpha which is equal to capital T alpha divided by capital T0, where T0, the small T0 and capital T0 are the orthogonal and axial planar thickness at the hinge point.

So in this case T0 equals Capital T0. Here T0 would be axial planar thickness, something like that capital T0. We will not consider this for the time being. But the shape of the fold, therefore you can using all these parameters, so either you can use T prime alpha, small T prime alpha or capital T prime alpha. You can use this and you can plot it against alpha and then figure out the different shapes or geometries of the fold, which we are going to see in the next slide.

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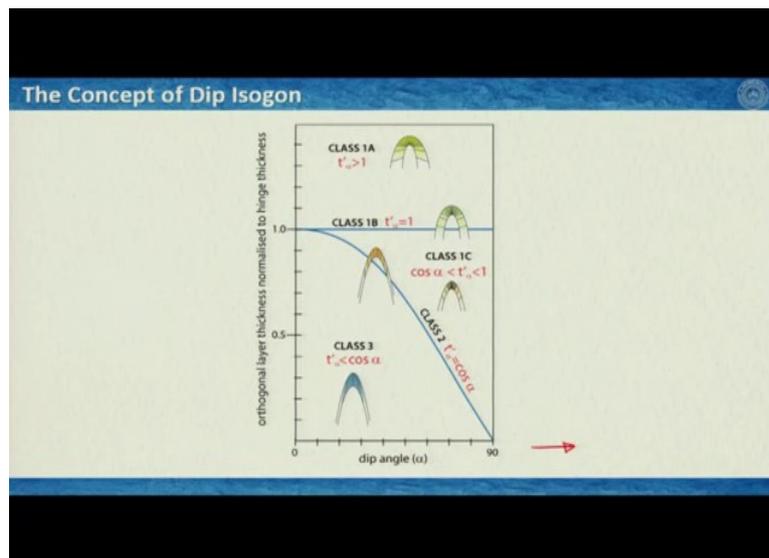
So what we see here that along the X direction we have the dip angle, which can range from 0 to 90 degrees. And along the Y axis, we have orthogonal layer thickness which got normalized to the hinge thickness. And you see that three different possibilities are there, okay. So in one case or you can say that five different possibilities are there. But we will see, we can classify them in three groups.

So the first class which is above the value, normalized value 1, we call it Class 1A, where T prime alpha or small T prime alpha is greater than 1. And the full geometry would look like this. Now along the normalized value 1, we call it Class 1B, where T prime alpha is equal to 1 and the fold would look like this. Now then there is another curve line where T prime alpha is equal to cos alpha, which is this line, which is this line. And the fold would look like something here is drawn.

So between T equal, T prime equal to 1 to T prime alpha equal to cos alpha, we have another class which we call Class 1C, where T prime alpha is greater than cos alpha and less than 1. And then we have another class, which is Class 3 where T prime alpha is less than cos alpha. And therefore, we can actually define three classes. So Class 1, where we have three possibilities – 1A, 1B and 1C. Then we have Class 2 and then we have Class 3. So the field of Class 1 is this. Class 2 is represented by a single curvilinear line. And class 3 is this one, okay.

Now we will see what is the meaning of this Class 1A, 1B, 1C and then Class 2 and Class 3. We will take them over separately and discuss their implications, their geometries and so on.
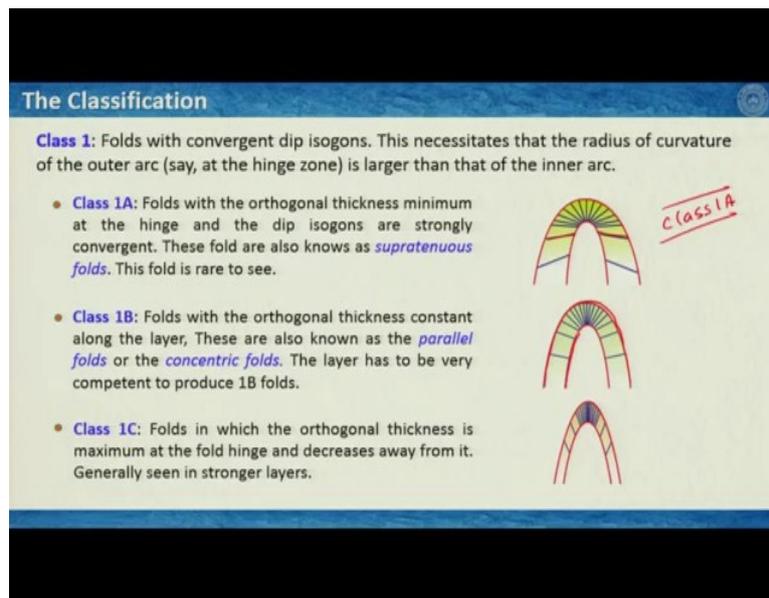
So Class 1 folds are the folds with convergent dip isogons. As you can see here, in this 3 images, we will come here later, that this requires that the radius of curvature of the outer arc or say, at the hinge zone is larger than that of the inner arc. Or in other ways, extrados has higher curvature than the inner arc. So if that happens then all the dip isogons along the hinge and along the hinge zone and limbs would converge towards the fold core.

And here we can have three possibilities one is Class 1A and the folds with orthogonal thickness, minimum at the hinge and then it increases slowly towards the limb side. So as we can see here, in this is your Class 1A fold. And we can clearly see that hinge thickness here is something like that and limb thickness, if we try to measure, it is something like that. Clearly this one is much larger than this one. If this condition happens, we also see that curvature of the outer arc, this one here is more than the curvature here. So in such a condition what we see that dip isogons are converging towards a fold core. The blue lines are the dip isogons.

In class 1B, the folds with the orthogonal thickness are constant along the layer. So here therefore, this layer, the outer layer and the inner layer are arranged such a way that along the hinge and along the limb, anywhere the orthogonal thicknesses are constant. In such a condition as well, you will have your dip isogons converging towards the fold core. And then comes class 1C where folds in which the orthogonal thickness is maximum at the fold hinge and it decreases away from it.

So what do you see here that here the thickness is maximum and the thickness is decreasing away. So what we see here that here the thickness is maximum and the thickness is

decreasing away towards the limb. In this case as well, we can see from this illustration that the dip isogons, the blue lines are converging towards the fold core.

Now the Class 1A folds are also known as supratenuous fold. However these kinds of folds are rare. We hardly see them in nature. Class 1B folds are also known as parallel folds or concentric folds because their curvatures are such a way arranged that these are always parallel to each other. And generally Class 1B folds we figure out, we mostly see in very very competent layers. So if the layer is extremely stronger compared to the surrounding layers then we see Class 1B folds. Now Class 1C folds we generally see in stronger layers, so which is very close to class 1B. But it is different in the fact that the orthogonal thickness slowly reduces towards the limb side.

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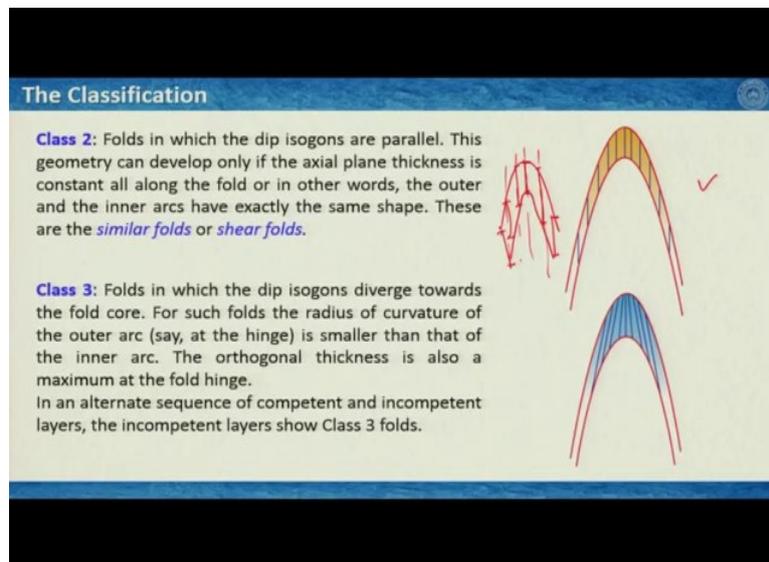
Now Class 2 folds are folds in which the dip isogons are parallel, as we see here. So in this case, the geometry can develop only if the actual planar thickness is constant all along the fold. Or in other words the outer and inner arcs have exactly similar shape. Therefore, it is known as also similar folds or shear folds.

What we see here in this illustration that if I have a fold like this. And then I have a similar curve like that, then this is my actual, the trace of the actual planar cleavages. So if I considered this height, this height, this height and so on. If these lengths are equal then this fold is known as Class 2 fold. And these are also known as similar fold because outer arc and inner arc are geometrically very similar.

Class 3 folds, as it is given here are the folds in which the dip isogons diverge towards; diverge away from the fold core. Or in other ways we can figure out that for such folds the radius of curvature of the outer arc, say at the hinge is smaller than that of the inner arc. So the orthogonal thickness therefore is also maximum at the hinge point. So what we see here? The orthogonal thickness here is maximum and then slowly it is reducing.

Now you can, you may confuse this fold structure or Class 3 folds with class 1C because their hinge thickness was higher. But in this case, the dip isogons are diverging away from the fold core. But in class 1C, the dip isogons diverge towards the fold core. And we will see their implications. The class 1C folds, we generally see in an alternating sequence of competent and incompetent layers. And generally, the incompetent layers show the Class 3 folds.

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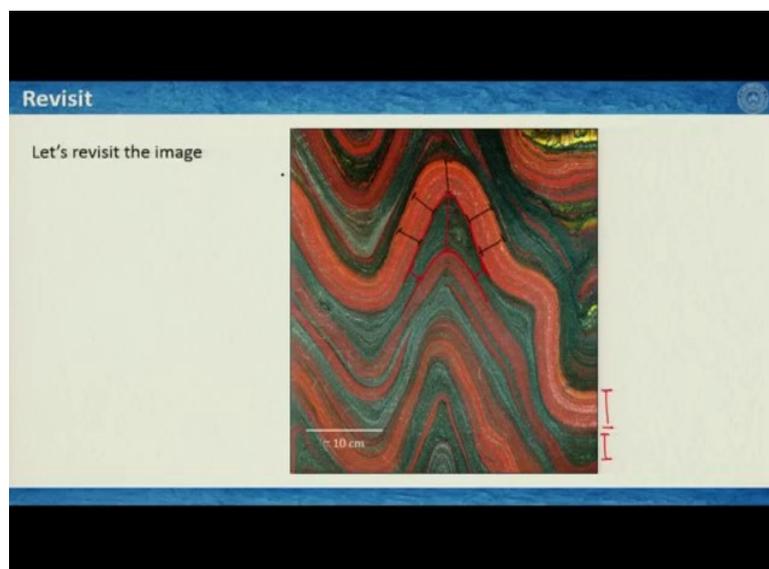
So let us revisit this image, okay. So this red layers, as I have said these are chalky layers and the black layers are iron rich layers. And we clearly see that here the hinge thickness, now you can understand this kind of features much better because we have understood the dip isogons just right now. In other ways, if I look at this red layers, the thickness is more or less constant or slightly variable or so on. So what we can do?

You can download such images, as I have done this one. And then try to draw their outer line as I have done in one of the previous slides. You do a geometric model and then try to figure out or try to draw the dip isogons and then see that which fold is what class. And this is a very important exercise. If you do it by yourself, you will gain more and more experience. And then at one point of time you will be so experienced that you even do not have to

measure. You see a photograph of a folded layer, you see a photo, you see them in the field, you can immediately see them and recognize "Hey this is Class 1A, 1B 1C or Class 2 or Class sorry Class B or Class 2 or Class 3 type of folds."

So we finished the part of this lecture on dip isogons. So I repeat. This is only quantitative scheme of classifications of folded structures, where we can more or less describe the geometry, the shape, the morphology. And at the same time some sort of competent contrast that means their rheology also is taken into account in this classification scheme and this is very very important.

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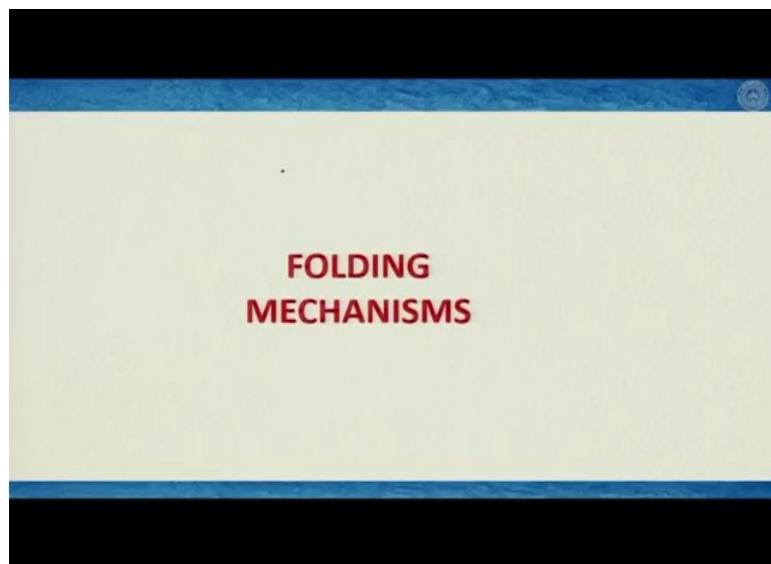
So now we will switch to the next topic which is folding mechanisms. Well the obvious question of to study the fold mechanism is how did the folded structure actually form. That we have learnt all these different terminologies to describe a fold but so far we did not talk or we did not say a single line on the mechanisms of folding or how do they form in nature.
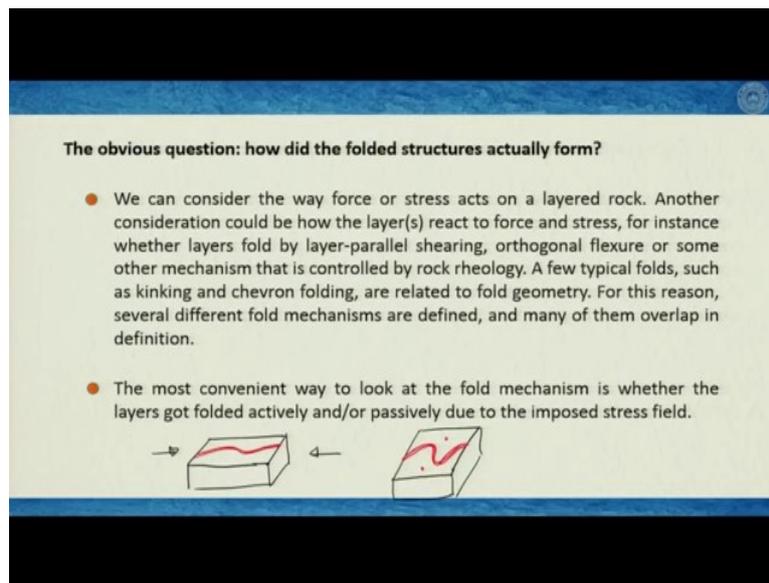
Now there are many ways you can consider. So one way is that you can consider the way force or stress acts on the layered rock. Another consideration could be that how the different layers react to the force and stress, for instance, whether the layers fold by layer-parallel shearing or orthogonal flexure or some other mechanisms which are controlled by rock rheology and so on.

And we have apart from this, a very few typical folds, such as you can consider kinking and chevron folding. They are related mostly to fold geometry. So all these complexities are there and for this reason there are several different fold mechanisms are in the literature and many of them sometimes are overlapping each other. But in this lecture, we will primarily look at some primary mechanisms. And we will try to mostly ask this question or the most convenient way to look at the fold mechanism is whether the layers got folded actively or passively due to some sort of imposed stress field.

Now what I mean by active folding or passive folding? Now you can consider this in a, you can do an experiment by yourself that for example, you take a scale or ruler, a plastic scale or ruler. And then you hold it like this keeping the long axis or the length of the scale in this way. And then you slowly press it. You will see there is a particular point of the loading when the scale will buckle or the scale will bend. And this is active folding. So there is a particular elastic limit when you just start bending the fold or start buckling the fold.

You can now visualize another way that you can take a block of plasticine and so on. And you draw a curved line on this plasticine block. And then you shorten or you compress this

plasticine block almost parallel to the curve line that we have drawn. Or in other ways, what I, better I try to draw here that you may consider a plasticine block like this. And then on the top of this plasticine block you may draw a gentle curved line something like that, okay. Now if you compress this plasticine layer, what you will see?

It would get compressed and then these red things that we have drawn, it may appear something like that. Now you see here, this entire plasticine block is actually getting shortened. And this red line or red curved line that we have drawn is just passively folding or passively showing a curvature with the deformation of this plasticine block. So this is passive or this is something where the layer itself is not folding because you actually do not have any layer. Or even if you have a layer here, the rheology of this plasticine block and this layer, that you have drawn or you can insert something, they do not have any competence contrast. Or there is no viscosity difference, then this we call that this layer got folded passively. So I hope I can communicate you what is active folding and what is passive folding.

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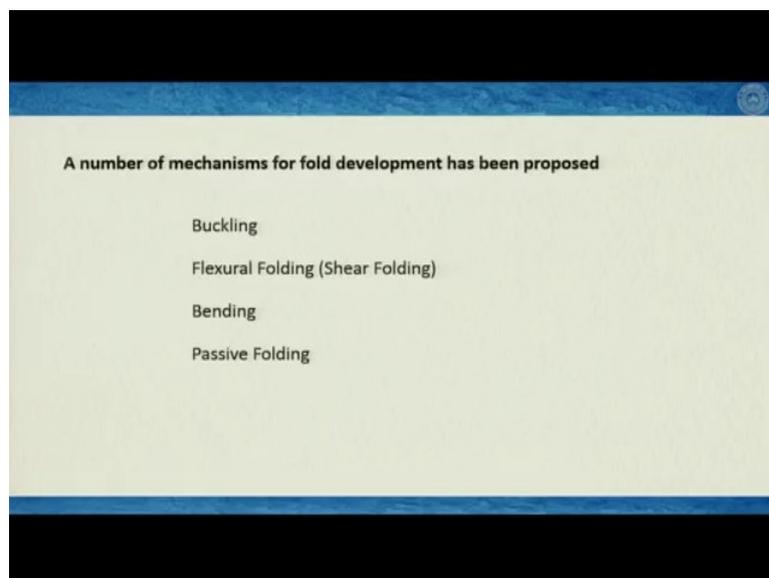
Now based on that, a number of mechanisms have been proposed to take into account the mechanisms of folding. And we will mostly discuss these four mechanisms. One is buckling. Then we will look at flexural folding, which is also known as shear folding. Then we look bending mechanism of folding. And finally, will talk about passive folding.
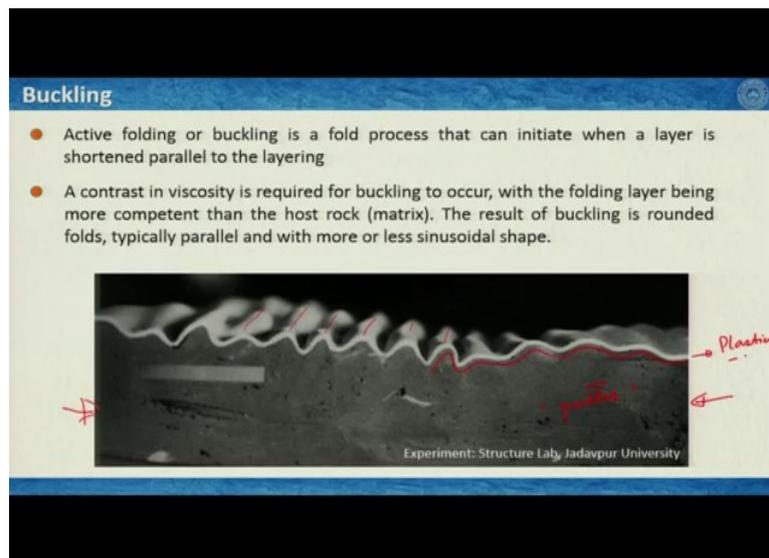
Now first let us take into account the most common mechanism of folding which is buckling. So active folding is kind of buckling. So active folding or buckling is a fold process that can initiate when a layer is shortened parallel to the layering. Now at a constant viscosity, so a constant viscosity is required for buckling to occur, with the folding layer being more competent than the host rock or the matrix. The result of the buckling is rounded folds, typically parallel and with more or less sinusoidal shape.

What do we see here, an excellent experiment most likely perform by Professor Shubhir Ghosh in Jadavpur University or his students. I have this photograph in my collection but I do not know who did this experiment. But you clearly see this; this grayish material here is putty. And this white layer is a plasticine, a thin plasticine layer. Now you see, how nicely when this putty got compressed, then this white plasticine layer made excellent fold. And this is a buckle folding. And you see the fold axis in the third dimension, okay. These are not necessarily cylindrical but the buckling you see here in experiments that have been produced.

So this is a typical buckle folding where you need a layer parallel compression. It happens in few different stages. We will see it soon. But before that let us have a look few of the characteristics of buckle folding.

Now in buckle folding, it is very important that you take into account this ratio of wavelength and thickness. Now for a single layer, this wavelength versus thickness ratio is constant for each folded layer, provided the material is homogenous; the stress you are applying to the system or strain you are applying to the system is very much homogenous. And other physical conditions were kept constant. In buckle folding the folds in the component layers generally are approximated to Class 1B folds or the geometries are very similar to Class 1B folds. That means their orthogonal thicknesses are constant.

The outer part of the competent layer is stretched while the inner part is shortened. And the two parts are typically separated by a neutral surface, where you do not have much strain. Now when you have a fold produced by buckling and then you certainly would form the axial surface. So the axial surface or the axial cleavage, if you have seen in the buckle folded layers, then it indicates the direction of maximum shortening. So if you have buckle folds. And if you generate axial surfaces or axial planar cleavages, then the perpendicular direction to this axial planar cleavage is generally the direction of maximum shortening or Z direction of the strain ellipsoid.

Now you can also quantify in a way, the wavelength versus thickness ratio by an equation and this is the simplest form of this equation, considering the layer is Newtonian viscous and there is no initial layer parallel shortening. Then the relation between wavelength and the layer thickness is given by this equation,

where L is the wavelength, H is the thickness of the layer, μL is the viscosity of the layer, μM is the viscosity of the matrix. We will see this in the next slide.
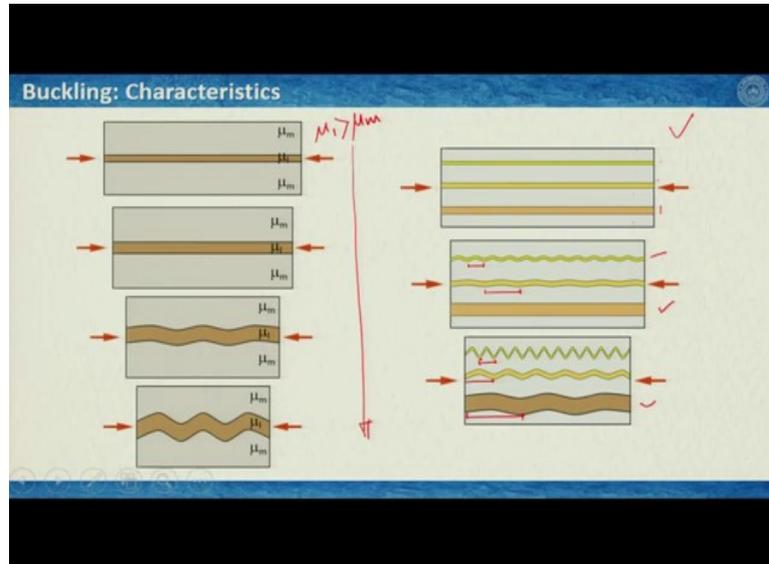
So what do you see here that initially this is a configuration that I have a thin layer with the viscosity μL and which is embedded within a matrix with the viscosity μM. The condition is μL is greater than μM. Now if I try to compress it, at the very beginning I will not see any folding or buckling. The layers would shorten homogeneously the strain is distributed within the layers. And the entire system would shorten along the compression direction.

Now at one point of time, this thin wavelengths or these wavelength would appear and they further titan with continued deformation. If I vary the layer thickness, then the wavelength would vary as well, as it is represented in this illustration. You can see the same matrix with 3 different layers of same viscosity but different thickness. The top layer has the lowest thickness and the bottom layer has the highest thickness. Now when if you start compressing the top layer because it is thinner, it does not take much layer parallel homogenous shortening so it starts folding immediately.

The middle layer also start folding but the bottom layer because it is thicker it is still undergoing homogenous shortening along the compression direction. You also note that this thinner layer has produced shorter wavelengths and the little thicker layer, the medium thicker layer produced higher wavelengths. Here we did not produce any wave yet. With continued deformation, you see here this fold starts tightening. This folds also. But this one,

now we have even much higher wavelength compared to this. So lower the thickness, we can see here from this equation that it is related to the wavelength of this fold.

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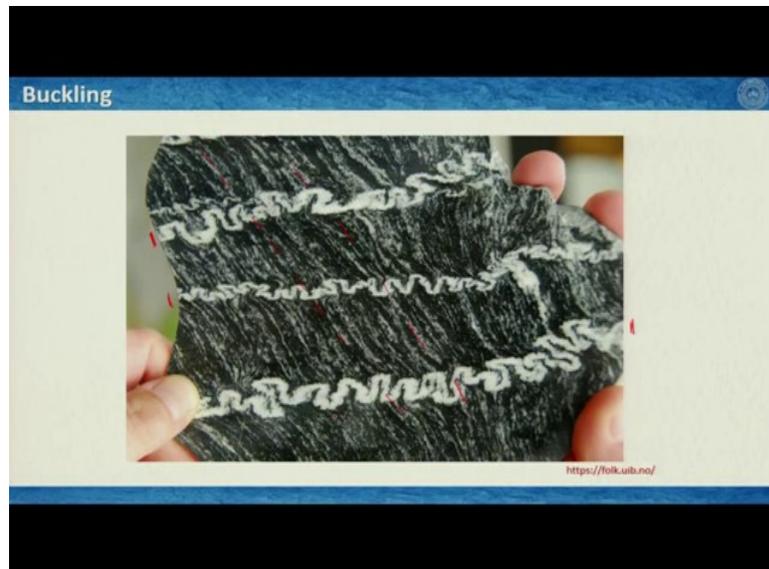
Now this is a fantastic example of buckle folding. As we can see here, this is a little thicker layer compared to this one and this is also a thicker layer of more or less similar thickness initially. These are the axial planar cleavages going on like this and you see the wavelengths here is higher than the wavelengths here. So this is how we understood now that buckle folding is an active folding, where layer parallel compression is required to produce buckle folding.

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Now let us have a look what we understand or what is the physical meaning of flexural folding, which is one of the important mechanisms of folding. Now within the domain of flexural folding, we have two basic mechanisms one is flexural slip and another is flexural shear or flexural flow. Now flexural slip implies a slip along layer interfaces. Or you have very thin layers between the two layers during folding. The fold maintains the bed thickness and thus produces also Class 1B or parallel fold. We will see this in some illustrations soon.

So for flexural slip, it is a prerequisite that the deforming medium is layered and it has a very very strong mechanical anisotropy. And this anisotropy in natural cases could be mica-rich thin layers in a quartzite or mylonite, or very thin shale layers between thicker sandstone or limestone and so on. So you need a plane along which the two adjacent layers can slip past each other. We will see in the next, in the illustrations that maximum slip occurs at the inflection points and it dies out towards the hinge zone, where the slip is zero. And this we will see in one of the slides. But before that let us have a look what is flexural shear.

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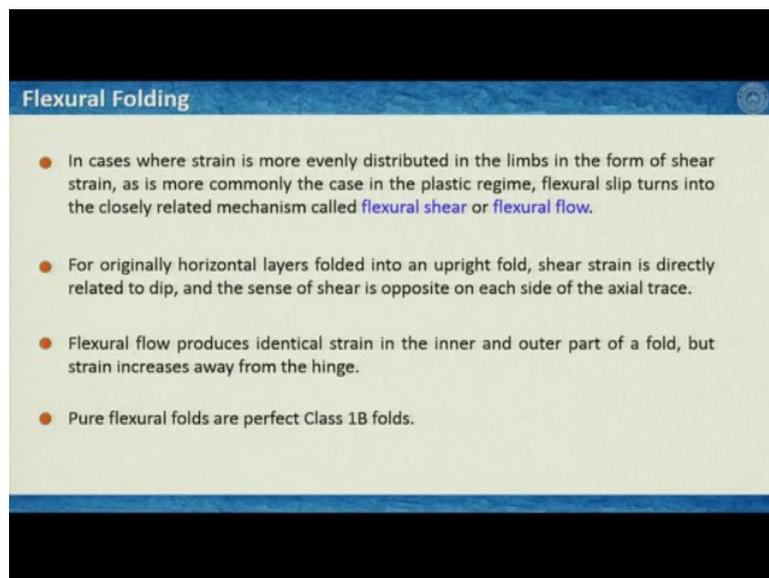
Now flexural shear is something where this individual displacements or individual shears along these layers are sort of homogenized by making the layers very very thin or you can imagine the way, if you have a paperback book and if you try to bend it or if you try to fold it, then the individual slips do happen along the pages of this book. But if you draw a circle or if you do a rectangle and then you deform it, you do not see the individual slips. It may appear a continuous ellipse or a continuous sheared rectangle. So these are known as flexural shear or flexural flow.

So in other ways as it is written here, in case where strain is more evenly distributed in the limbs in the form of shear strength, as it is commonly the case of the plastic regime, flexural slip turns into the closely related mechanism which is known as flexural shear or flexural flow. So individual slips are not visible and it is coming to more or less some sort of shear strain.

Now for original horizontal layers folded into an upright fold, shear strain is directly related to the dip of this limb or folded layers and the sense of shear is opposite on each side of the axial trace. Flexural flow produces identical strain in the inner and outer part of a fold but strain increases away from the hinge and a pure flexural fold generally are also class 1B fold.

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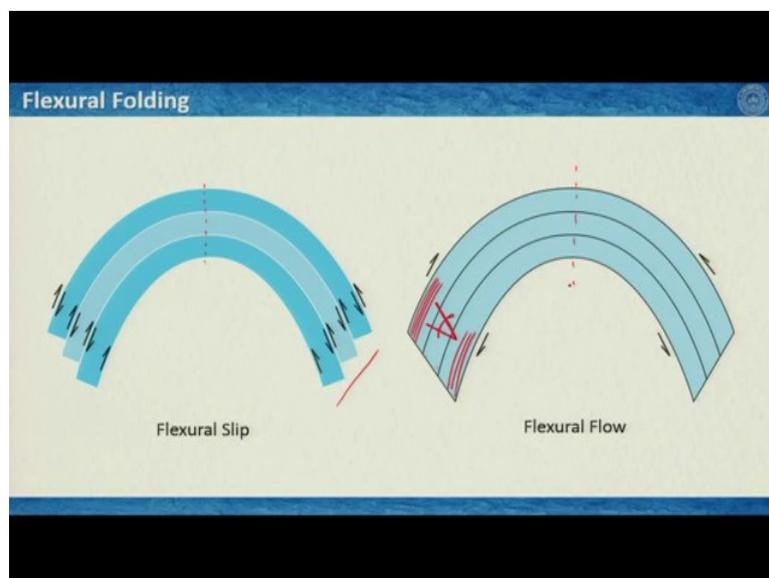
Let us have a look of this two type of folds that we have discussed flexural folding, one is flexural slip and another is flexural flow. What do you see here that the thin white layers in between the blue layers are the slip planes. So when the fold is forming, these individual layers, they slip past each other. So this is the shear direction. So you can see that this layer is shearing. This layer is also shearing and so on. The magnitude of shear is slowly decreasing and at the hinge point the shear is virtually zero.

The similar case happens in the flexural flow that it also gets sheared but not as gross as for flexural slip. So instead I have drawn the three lines here but you can imagine there are number of lines which are involved in flexural slip. So approximately if individual lines like the pages of a book, they start slipping, then you can actually figure out that if you have a straight line this red one, then it rotated due to the deformation, due to shearing of individual

sheets to a certain angle and this angle defines that what is a strain at the limb. So the entire limb is under shear, not the individual layers and so on. But again in this case, at the hinge the shear strain is zero. So now we learnt what is flexural slip and what is flexural flow.

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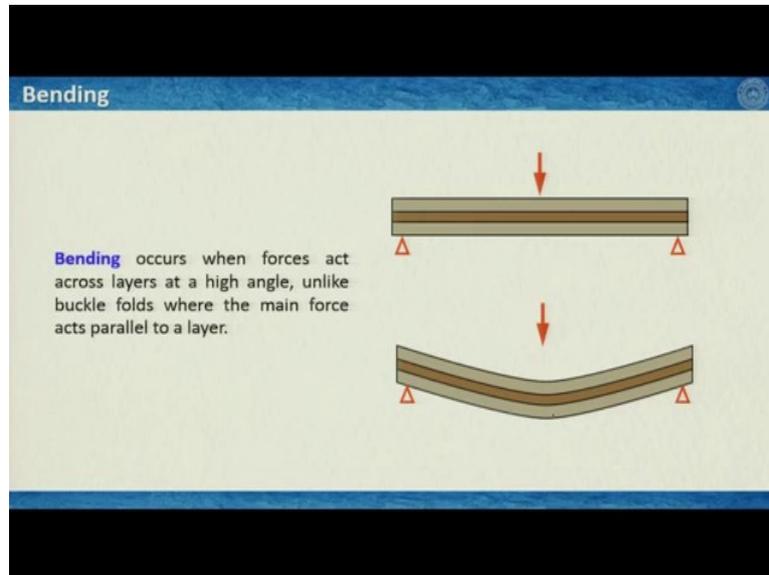
The next one we take over is bending. Now bending occurs when forces act across the layer at high angle, unlike buckle folds where we have seen that you need a layer parallel force. So the configuration mechanically you can figure out like this that these two points are hinged. That means that these two points are fixed, these two little triangles. And if you apply a load, then it would bend like this and this is a fold like structure and if your fold is forming by this mechanism, then we call it bending fold.

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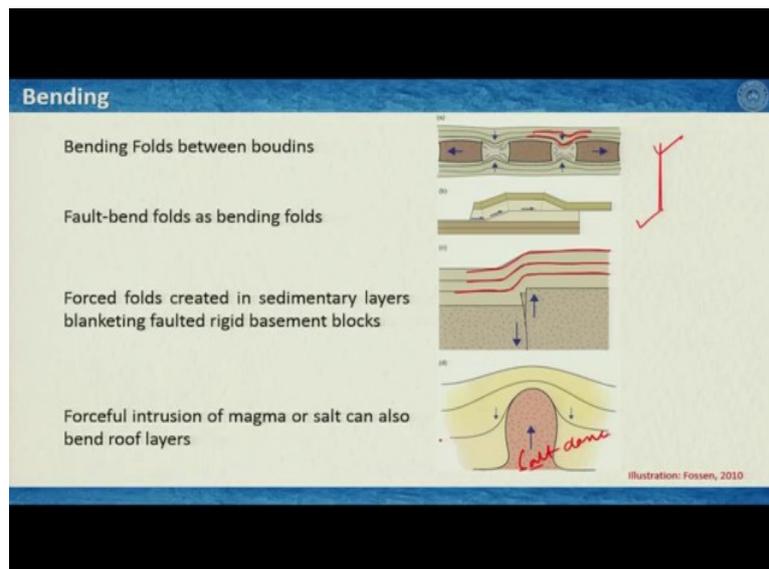
In this slide, we have a series of examples that are very much similar, what we have seen in the previous slide and these are assigned or these are termed as bending folds. For example, here in between the two bodkins, the layers at the top and the layer at the bottom, they try to sync-in in the free space. So they form something like that and this appears to be a folded structure. And these are bending folds. Also we see them in fault bend folds or sometimes we call it forced folds, when you have a fault at the bottom layers which are brittle. And then, if you have some layers that can be adjusted with the fault at the bottom and therefore, you form a structure which is fold like and this are bending fold.

Sometimes in large-scale you also form, bending fold particularly during magma intrusion or in the salt dome comes up to the surface. So these are the examples. You can imagine this is a salt dome, the pink one and the layers surrounding it, it has to intrude and then it forms a folded like feature and this is a bending type of fold.

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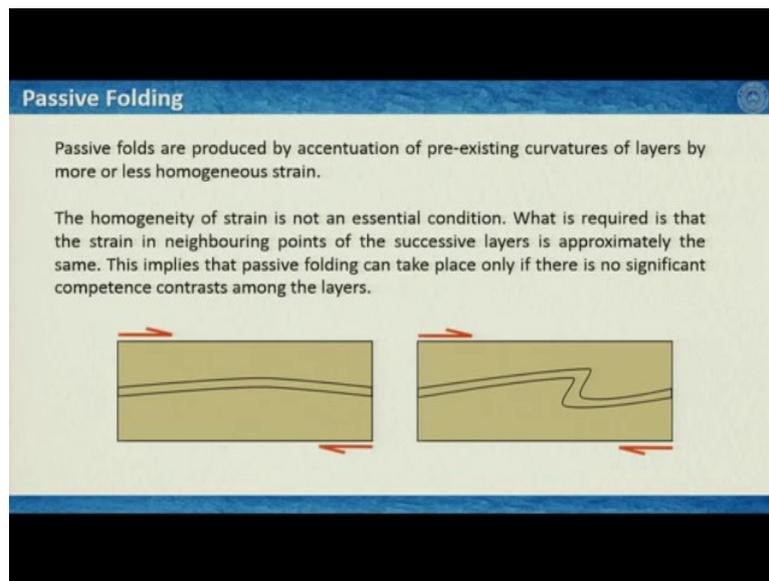
The last one in this classification is passive folding and we have already given an example of the passive folding. So the passive folds are something that is produced by accentuation of pre-existing curvatures. This is very important. If you have a straight line or straight bed, you cannot produce passive fold. You have to have even it on a very micro scale, a little curvature. So when you produce a passive fold, you are actually produced an accentuation of pre-existing curvatures of layers by more or less homogeneous deformation. So deformation all along the layers are more or less similar or all along the body or the rock is more or less similar.

Now the homogeneity of the strain is not an essential condition. However, what is required is that the strain in the neighboring points of the successive layers is approximately the same. This implies that the passive folding can take place, only if there is no significant competence contrast among these layers. So this is an example. We have drawn it before in a different way.

So I have a curved layer here. You see the colors are similar here, here and here. So their viscosity or compositions are very much similar. But they are separated by some sort of layers. And if I apply a shear, then this slightly bended layer may produce a folded like structure, like this. But this is not an active fold. This is passive fold because the strain here, strain here and strain here are very very similar.
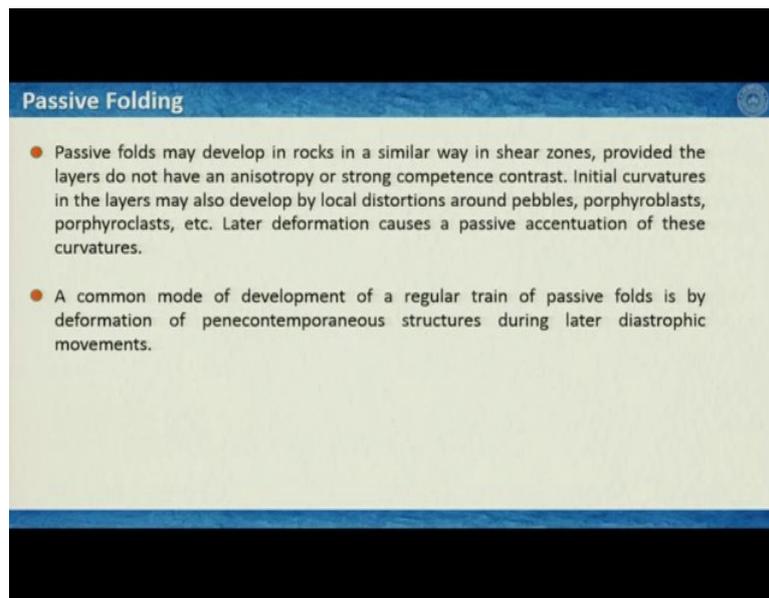
Now passive fold, sometimes they develop in rocks in a similar way in shear zones because in shear zones what you have very very thin foliations and the compositions or viscosity within these foliations of the layers are very much similar. So provided the layers do not have a strong anisotropy or strong competence contrast, in terms of the mechanical properties, then you can form passive fold in the shear zones. The initial curvatures in the shear zones generally developed by local distortions. This could be around pebbles, porphyroblasts, porphyroclasts etc. and later deformation causes also a passive accentuation of this curvatures.

You also see passive falls in penecontemporaneous structures or sort of regular train of passive folds by deformation of sedimentary layers before lithification and this can happen due to some sort of tremors or diastrophic movements.

So with this I end this lecture. So we learnt how to classify folds via dip isogons and then we also learnt four different mechanisms of folding. We learnt buckling, we learnt flexural folding, we learnt bending and at the end we learnt passive folding.

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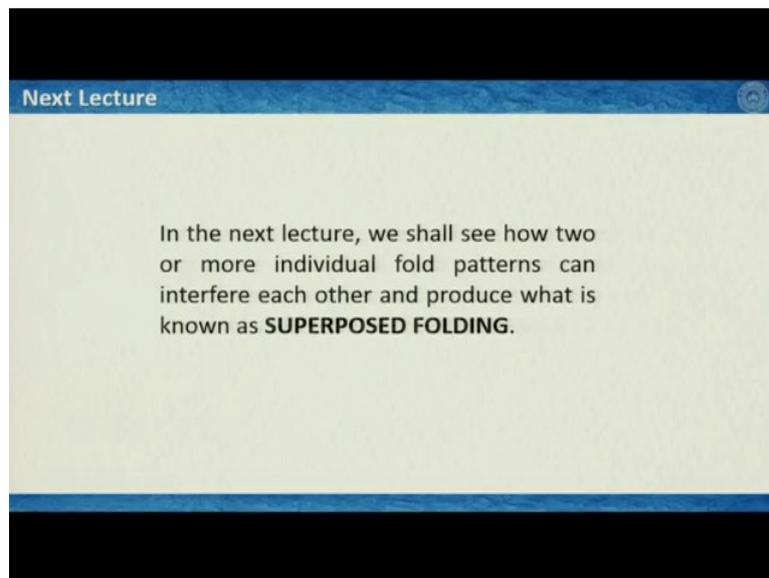
Now based on all these ideas, in the next lecture we will switch to that how two or more individual folds, they may be different, they may be similar; they may be different or they may be similar, they can interfere each other and produce what is called superposed folding. Thank you very much. I will see you in the next lecture.