Structural Geology
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Lecture 29 – Faults and Faulting - I

Hello everyone! Welcome back again to this online NPTEL Structural Geology course. We are learning fractures, joints, faults and in this lecture we will start faults and faulting. This is part I of this lecture and this is lecture number 29. So in this course we will cover faults.

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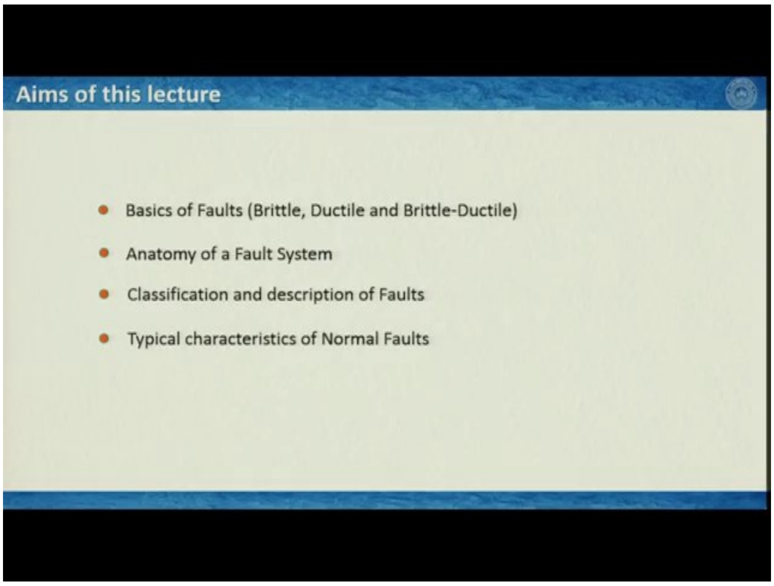

So, we will start at the very beginning that why we have a structure like faults and then we will see the brittle, ductile and brittle-ductile type of faults. Just we will start showing you how these things do occur in nature. Then we will directly jump into the brittle fault, so we will start with the anatomy of the fault systems, What's the different morphologies, geometries and so on. Then we classify the faults and also we will give the description of the faults and their structures and then we will move to the, we will discuss a little bit on the typical characteristics of normal faults.

The thrust faults and strike-slip faults we will discuss in the next lecture. So you have already learnt what is fault; I have shown many illustrations, many diagrams and also from other lectures you may have a little bit of familiarity, what is fault. Now, one part you must have noticed when you were taught or when you learnt about fault that the deformation in faults, it localizes along a very narrow zone. When we will define, we will see this but it is always a question and still we do not know the answer that why deformation localizes along a narrow zone. There are some observations and the best observation comes from the experiment.

So what I will first do, I will try to show you schematically some of the experimental results and then we will figure it out that's why and which domain it is possible to see the faults and under what conditions what type of faults we can expect. So, let us start with the diagram.

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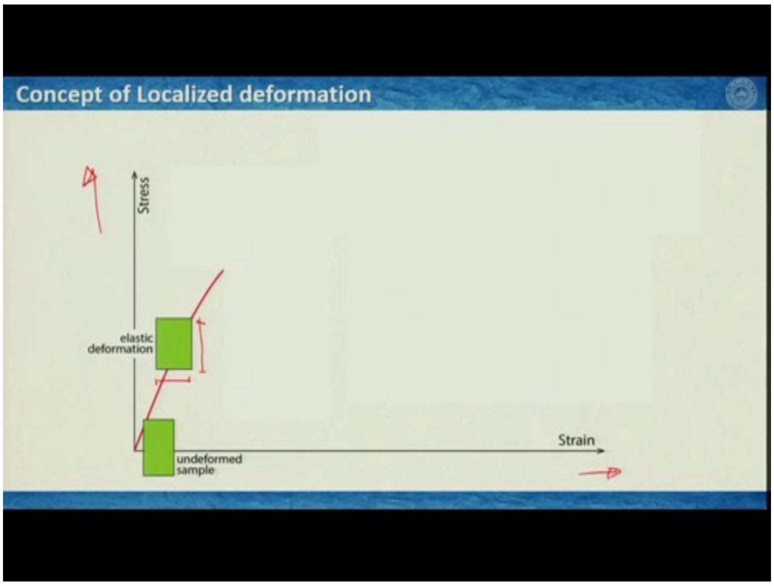

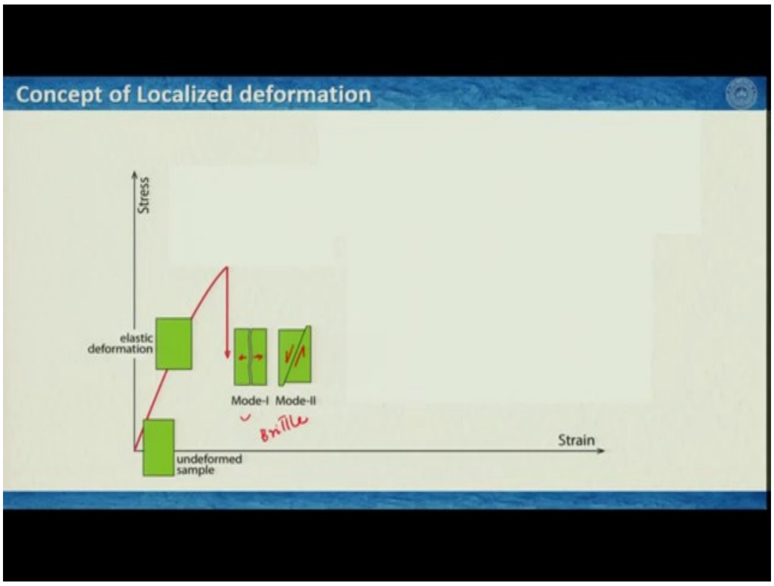

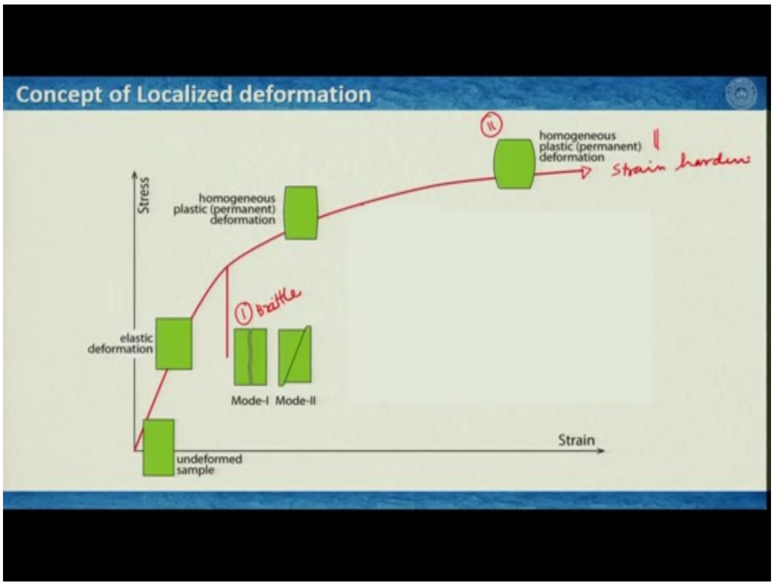

So, on the vertical side we have stress. This is a simple stress-strain plot and horizontal side we have strain. At the very beginning we have an undeformed sample and we know that initially when you load a sample it undergoes an elastic deformation. So the elastic deformation goes on, it shortens a little bit. So the rock would shorten in this direction and also extend in this direction just because of the elasticity and then it continues deforming following this red curve which is the elastic curve. Now after this part there are many possibilities, I show you the one possibility first. That is that the rock is deforming in brittle manner. We saw it in the previous lecture. So it can either fail in mode 1, that means producing tensile fracture or it can produce mode 2 fractures or shear fractures. So here if the curve is something like that, that it reaches the yield stress and immediately after it produces a failure type of curve.

And therefore we interpret that in this domain we expect a brittle type of deformation and the expression of this brittle deformation is either mode 1 or tensile mode or shear mode. Now, we will see soon that this shear mode actually is very similar to what we call fault in large scales. Now if the deformation continues, for example if I have enough pressure and also a little bit of temperature then we know that it would show a little bit of hardening.

That means to deform the rock, we need more stress and the rock deforms in homogeneous manner. And the deformation after this yield stress is permanent deformation. So it shows some sort of barreling, that is the characteristics of the experiments. If the strain further continues and the rock does not produce any fracture then the homogenous plastic and permanent deformation continues and it goes this way with more and more stress requirement.

So we have seen two possibilities. One that the rock may fail in brittle manner or it may continue showing homogeneous deformation without producing any fracture. And this is the second type of deformation. Now a third possibility is there. We have learnt in our deformation mechanism class that it can show strain softening. So here this is strain hardening.

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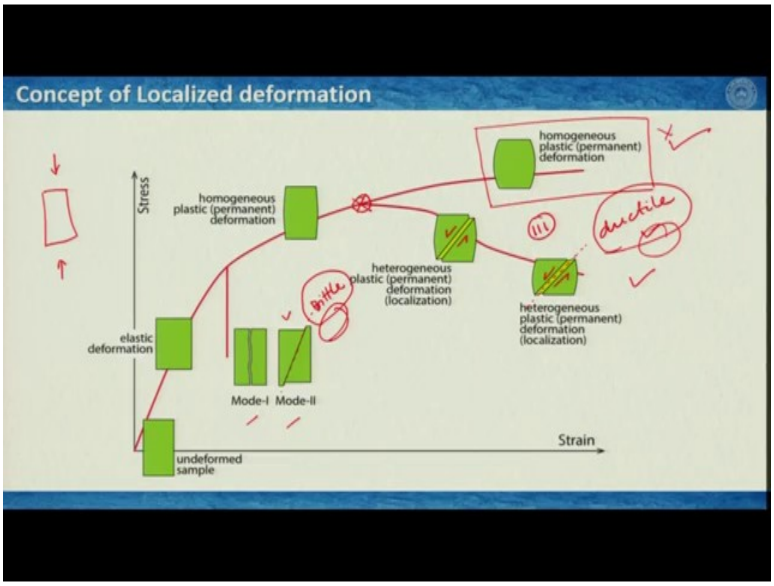

And there is another possibility that we can have strain softening and if that happens then we see a localization here in the sample. And this localization or this shear surface here that we see here, this is characteristically different that what we have seen here in the brittle domain. So this is ductile because the rock is accommodating deformation without producing any fracture and this is brittle. So we see three possibilities here.

Now what happens here at this stage of the deformation? The sample is a little confused. So it tries to understand that whether I should distribute the deformation I am receiving entirely on the sample or I find a zone, a narrow zone where I can channelize all the deformation. And the rest of the body of the rock sample can remain virtually undeformed or less deformed. Now the same thing happens here. But here it happens in brittle manner and here it happens in ductile manner.

So you see that when the deformation is actually under compression, we can have possibilities of brittle deformation in mode 1 or mode 2 manner. We can have possibilities of homogeneous deformation and we can have possibilities of ductile shear localization or heterogeneous plastic deformation which is also permanent deformation. So clearly if we continue with this kind of deformation then we do not see any localization or faulting like features.

So we are restricted ourselves now in brittle and ductile domain, that where localization is happening either in brittle manner or in ductile manner. Now when you have localization of deformation along a narrow zone inside the rock sample we call it shearing stability or localization and so on.

This is still a problem, people do not know how and why we have localization in the deformation and how it extends the way it is on the earth surfaces or even in a tiny micro-scale grains. But we will not go to that part right now, we will avoid this homogeneous deformation part for the time being. We mostly look at this brittle part and ductile part in the context of this lecture of faults and faulting.

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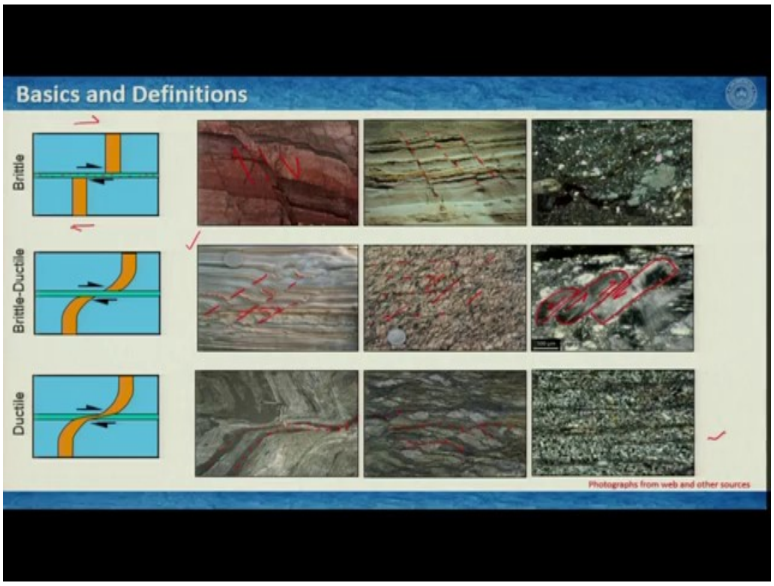

So as we talked about brittle deformation, so the brittle deformation we learnt that it does not retain or it does not maintain the cohesion of the rock. So if this was intact initially this orange marker in this blue matrix, then because of the shearing you see that the entire rock mass did not deform but it just deformed along this narrow zone. And therefore this got shifted and it lost its cohesion. And we can see here some examples, so this is a large scale field example, we can see that slip happened along this narrow zone.

And here we see that we have a series of planes along which the deformation localized and here as well it is a microstructure where we see that because of this brittle deformation the rock lost its cohesion and it is almost brecciated. Now another extent is of course as we learnt is the ductile deformation where this orange marker zone did not lose its cohesion. So it remained continued and therefore we see that some examples here, for example this black layer you can see that it is going like this. Or this one as well it is going like this. So it did not break, it maintained continuity.

If we see in a different scale, we also see that these things are maintaining their continuities. It is not some sort of fracture processes and so on and this is the image of the microstructure. Now this brittle and ductile, these two are the end members of deformation processes. So whatever happens in between brittle and ductile we call it brittle-ductile deformation.

So that means it receives some sort of ductile deformation and also it receives a significant amount of brittle deformation. Now how much brittle? how much ductile? is a question, is observation that we have to do in the field or in the laboratory. Now whether brittle came first or ductile came first, this is again a question of research and observation of specific areas. But if we focus on this brittle-ductile part and particularly on this image, we see that these layers they are little bent, they are a little bit curved and that indicates that these layers at one point of time suffered ductile deformation and later it produced the brittle deformation here.

We can see here, it is a microstructure, so these are some brittle fractures but at the same time it is producing some other features. We will learn more about it in our shear zone lectures. But these are evidences of brittle-ductile deformation. Similarly we see that here in the matrix dynamic recrystallization is going on but this large clump we have seen this image before that these clumps they were broken and they are slipping past each other. So it has both brittle and ductile deformation in this. So based on this idea we will now try to define what is a fault.

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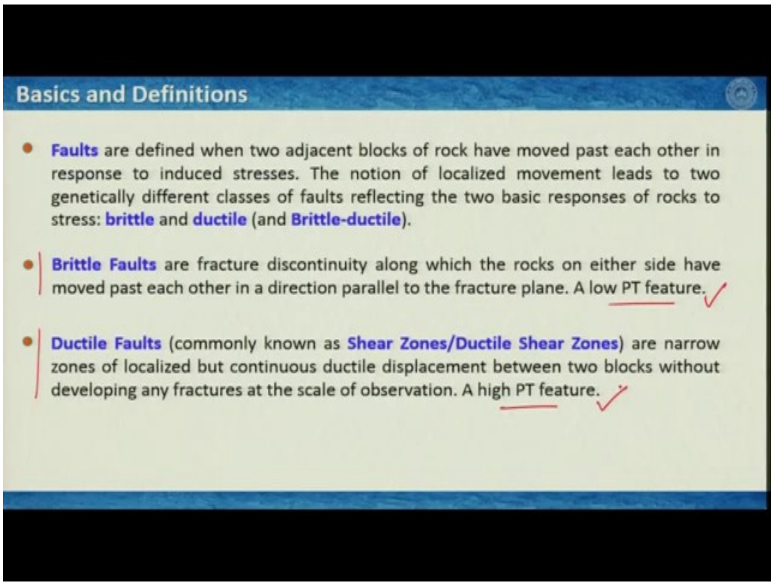

So faults are defined when two adjacent blocks or rock have moved past each other in response to induced stresses. The notion of localized movement leads to the two genetically different classes of faults reflecting the two basic responses of rocks to the stress. One is brittle and another is ductile and whatever stays in between is brittle-ductile. Now brittle faults which is commonly known as faults, we generally refer, faults as brittle faults, they are fracture discontinuity, so there must be some fracture. So cohesion must be lost to define the discontinuity.

So fracture discontinuity along which the rocks on either side have moved past each other in a direction parallel to the fracture plane, and because it is a brittle type of deformation, it is a brittle fault, so it is a low pressure temperature feature. On the other hand ductile faults we do not say it ductile faults, we mostly call it shear zones or ductile shear zones commonly. These are narrow zones of localized but continuous ductile displacement between two blocks without developing or producing any characteristic fractures at the scale of observation. If that happens then this is a high pressure temperature feature.

And we learn about ductile faults or ductile shear zones in the next week. And this week we will focus on brittle faults or faults as we commonly talk about. Now how these things do happen in nature? How do we understand that where we expect brittle faults, where we expect ductile faults? And as it is mentioned here this is a low pressure temperature feature and this is a high pressure temperature feature.

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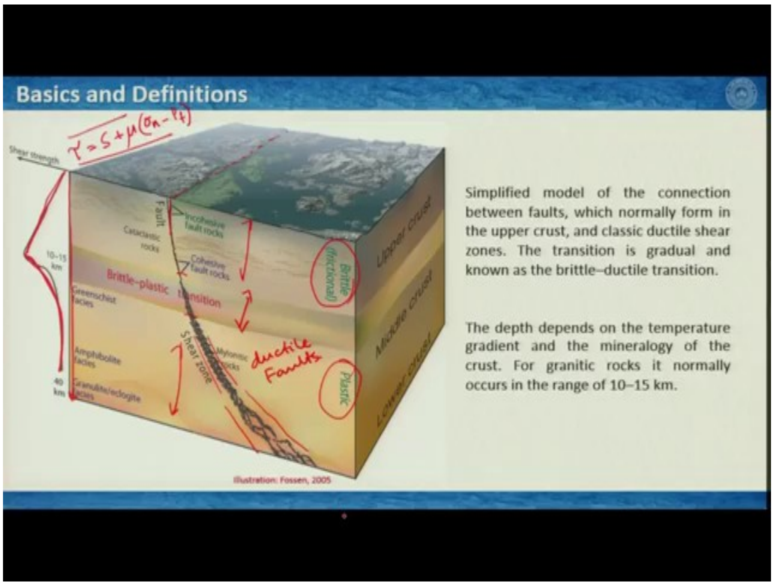

So professor Fossen came up with a very nice illustration that on the surface of the earth or on the subsurface of the earth, we have faults. So this is the expression of the fault on the surface and if we see on the deeper side, at the subsurface we have incohesive fault rocks, that means the cohesion got lost. And slowly we reach to the cohesive fault rocks and then we arrive the brittle-ductile transition and finally we see here mylonitic rocks. We will learn later what is mylonite in the next week. But these are your ductile faults.

And then it anastomoses and widens its depth and so on. So we have brittle deformation here, we have ductile deformation here and whatever stays in between it is brittle-ductile deformation. So this is exactly what is written here and we also have learnt deformation mechanism, so we can figure it out that in this part this is mostly defined by frictional way and this is mostly defined by plastic way and when you define the frictional way, we know that we have derived the law Mohr–Coulomb failure criterion, that was shear stress was S plus friction multiplied by normal stress minus pore fluid pressure.

Now this is a linear equation, so the strength here increases linearly. But here we remember if you remember the power law, then power law was exponent dependent. So therefore this is now linear and this particular pattern of the strain profile shear strain profile of the earth through depth is known as the rheological profile of the earth. We learn about it later but this is how the faults are distributed at the surface. These are brittle, at the depth these are ductile and in between we have brittle-ductile type of deformation.

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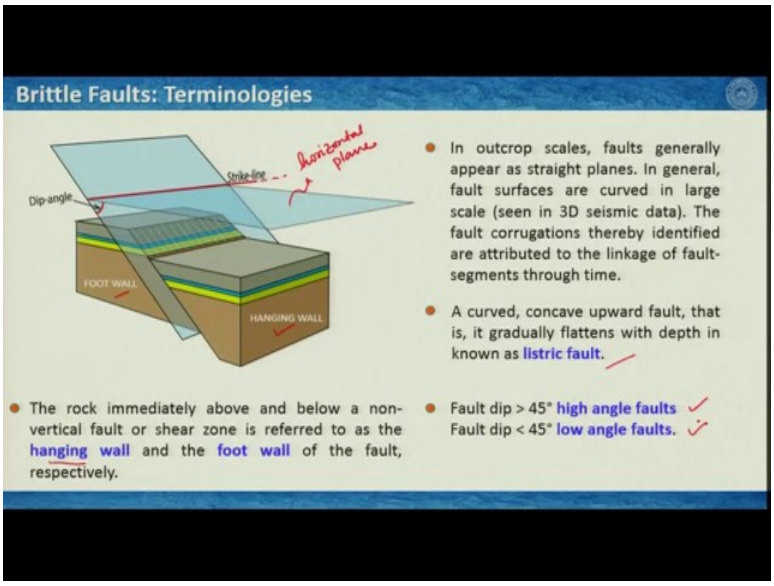

Now let us talk about the brittle faults and their terminologies. Now faults we know that as we have defined that it is a fracture discontinuity. So the discontinuity must represent a plane and if we have a plane, then as a structural geologist the first thing first is we have to understand what is the strike and dip of this particular plane. So the fault surface itself defines the fault plane and if it is a plane then we can measure the strike. So in this case this is a plane and this is intersecting with the horizontal plane. So this is your horizontal plane.

And where this horizontal plane intersects the fault plane, this blue plane is a projection of the fault plane. So that defines the strike line. And the angle it makes is the dip angle. We have learnt about it. Now there are very interesting terminologies related to fault rocks or faulted rocks. So the rock mass which is immediately above the fault plane and that tells you that fault is not vertical. That means the dip is not 90 degrees. In that case anything above the fault plane we call it a hanging wall and anything below the fault plane we call it foot wall.

And these hanging wall and foot wall, these two terminologies we will use continuously and also professionally if we continue geology or specifically structural geology. There are few other terms. Let us talk about in outcrop scales. Faults generally as I said, that these are mostly straight planes, however faults are really large scale features and in general, they are curved in large scales and these are mostly revealed by 3D seismic reflection data.

These fault corrugations thereby identified and attributed to the linkage of fault segments through time. So when the fault is curved and concave upward, then it gradually flattens with a depth. That means the dip generally reduces with depth, then this is known as listric fault. We will see the diagram soon. If the fault dip is greater than 45 degree, then we call it high angle faults. And if the fault dip is less than 45 degree then we call it low angle faults.

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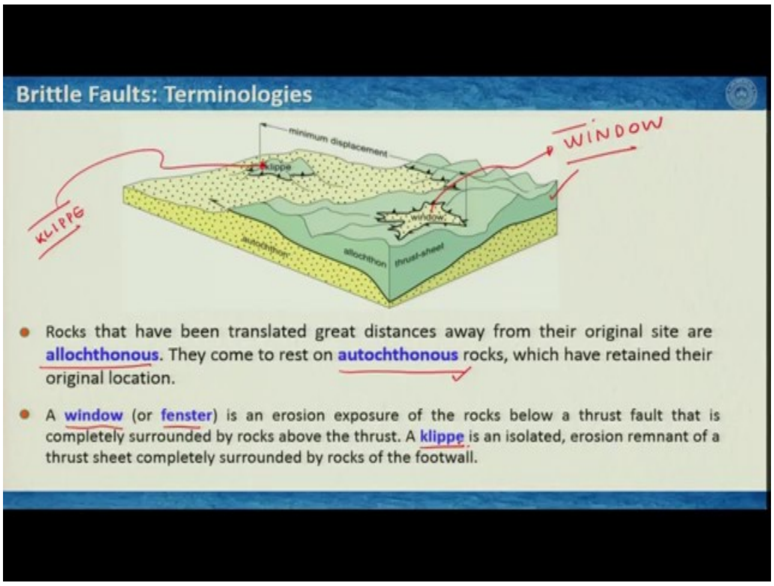

There are some other terminologies. As you can understand that fault is some sort of, you have to have a displacement along the fracture surface and there it is different and it is exactly where it is different from joints because in joints we do not have any displacement along the fracture surfaces. But in faults, yes we have displacement along the fracture surfaces. Now imagine if this displacement is large enough then where actual rock was originated can travel kilometers after kilometers and rest in a different place. If that happens, that rocks that have been translated great distance away from their original site, these are known as allochthonous.

And then they come to rest on some rocks, those are actually resting on their original location. And these are known as autochthonous rocks which have retained their original location. Now in this context there are two other terminologies, one is window and another is klippe. So imagine that this one of the fault blocks travelled a lot and staying somewhere as an allochthon. For example, this bluish material here and now this can get eroded and can expose the autochthon rock in between. If that happens then this is known as window.

And similarly, if it stays in a little higher topography and stays in an isolated manner and erosion made it staying isolated then the sheet is completely surrounded by autochthonous material. What we see here, these are known as klippe. And these are terminologies generally those who work in large scale orogenies they use. But it is important that we know what is allochthonous, we know what is autochthonous, we know what is window or fenster and we also know what is klippe.

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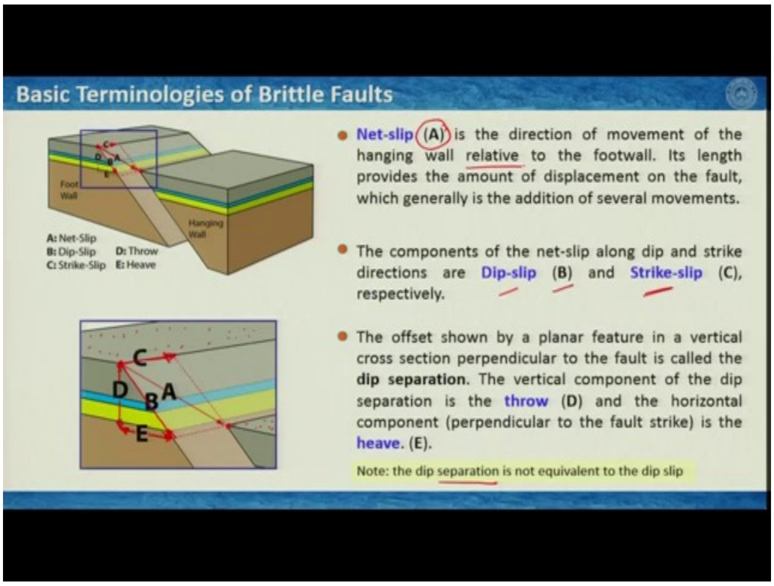

Now there are some other terminologies associated to the faults and these are mostly kinematic terminologies and this is what we are going to learn now. First I define this, I read these texts or I just explained to you what it is and then we will look at this diagrams. So net-slip is the direction of movement of the hanging wall relative to the footwall. This term relative is very very important here.

The length of the net-slip provides the amount or magnitude of displacement on the fault which generally is the addition of several movements. So what we see here, if we just have this example, so we see that this point and this point, they are together at one point of time or before the fault happened. Now fault this displaced this point from here to here. So these two points which were neighbors at one point of time now they stay far away.

Now along which this displacement happens is a vector and this vector is known as net-slip which is A. You can see here, a zoom diagram here, so this was, these two points were together, now they are separated along the fault plane and the vector of this displacement is known as net-slip. If this net-slip happens along a particular direction, then it is possible that we can resolve the component of this net-slip vector along the strike of the fault plane and along the dip direction of the fault plane.

So these are B and C. So the components of the net-slip along the dip and strike directions are dip slip which is B in this image. So its component along the dip direction and then strike-slip which is C, the component of the net-slip along the strike direction. And these are known as dip slip and strike-slip. Now we have also an offset because of this fault. So when we see a planar feature, for example this surface we can consider, this horizontal surface is a planar feature. Now this horizontal surface is now resting here. So it moved down.

So the magnitude of the movement if you measure vertically, then this is known as throw. So in this case is this distance which is marked by B. And the horizontal displacement if there is any, then this is known as heave which is marked by E. Now clearly we can see that the fault movement can be in the sense that you can have dip slip 0 and you can have only type strike-slip. At the same time you can have zeroth strike-slip. And you can have the dip slip component only.

So net-slip can vary from the strike-slip to dip slip along a fault plane. Now sometimes we use another term which is called separation, we will talk about it later. And this is very important but at this time please understand that dip separation or strike separation are not equivalent to the dip slip or strike slip respectively. We learn about it soon.

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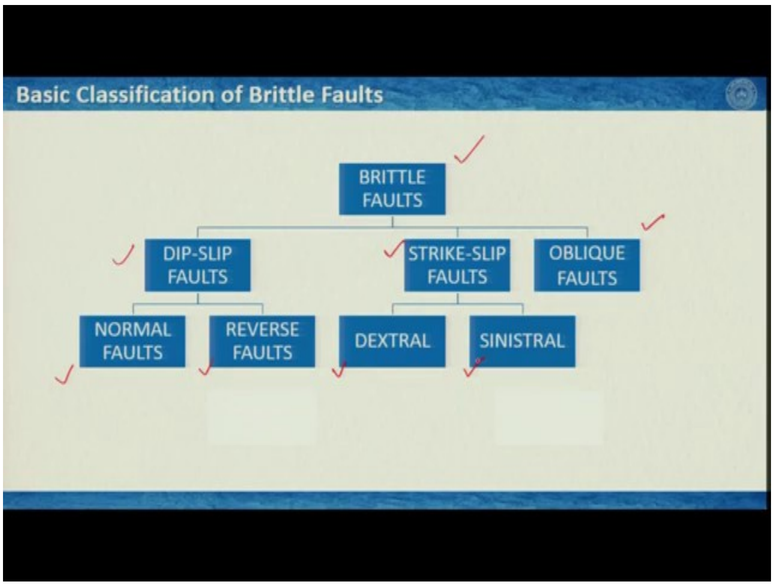

So slip on the fault plane we can define the faults in three major categories. The first category of the brittle fault of course is dip slip faults. The second category is strike-slip faults and third category is oblique faults. We will learn their definitions very soon in the next slide. Within the dip slip faults we have normal faults and reverse faults. Within the strike-slip faults based on the sense of the displacement, sense of the strike-slip displacement to be specific, we have dextral faults and we have sinistral faults. So let us look at their definitions.

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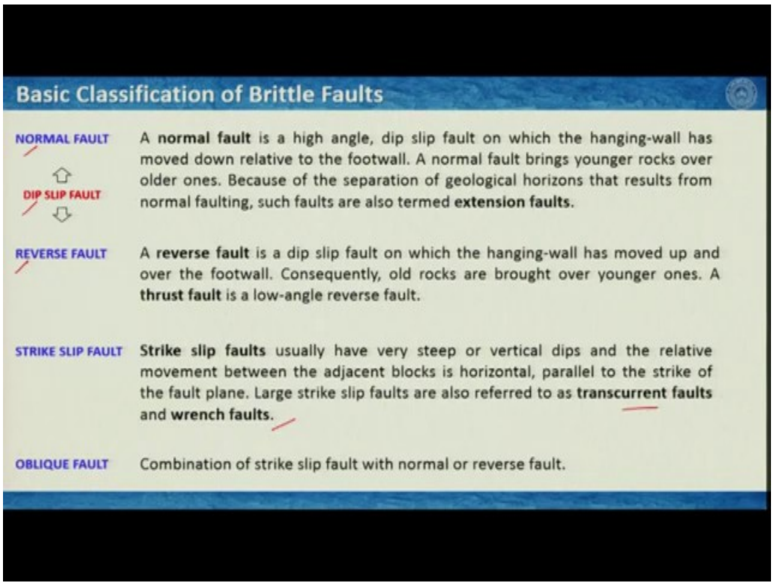

So as I said that dip slip faults are classified in two sections. One is normal fault and another is reverse fault. So normal fault, we can define it now, is a high angle dip slip fault on which the hanging wall has moved down relative to the footwall. We will see that drawing soon. A normal fault brings younger rocks over older ones. Because of the separation of geological horizons that results from normal faulting, such faults are also termed extensional faults. We will see that.

The reverse fault is on the other hand is a dip slip fault as well on which the hanging wall has moved up over the footwall. So, consequently older rocks are brought over the younger rocks. A thrust fault is low angle reverse fault. So, generally the angle is 30 degrees. If the fault dip is less than 30 degrees then we call it thrust faults and if it is more than that, then we call it reverse fault. The strike-slip faults usually have very steep or vertical dips.

And the relative movement between the adjacent blocks generally is horizontal, parallel to the strike of the fault plane. Large strike-slip faults are also referred to as transcurrent faults and or wrench faults. We will talk about it later, this transcurrent and wrench fault. Then oblique fault is something that combines the dip slip and strike-slip fault, so it is a combination of strike-slip fault with normal or reverse slip components. Let us see what is the normal fault.

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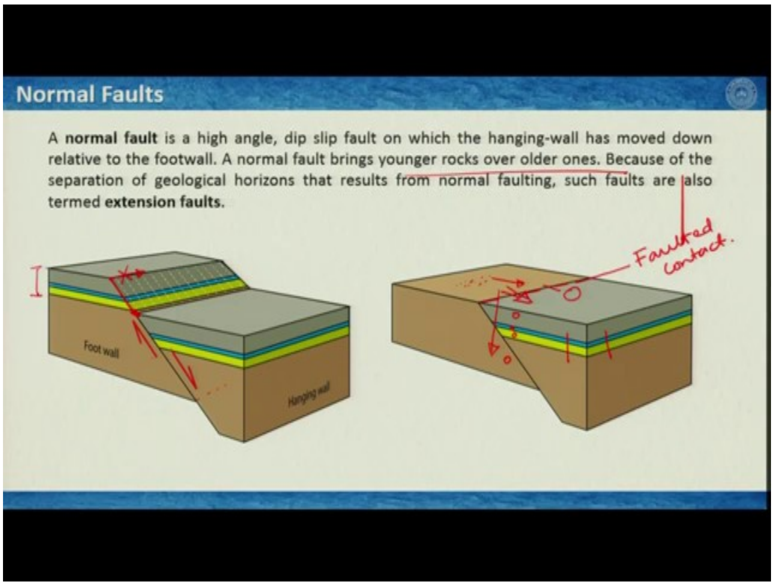

A normal fault as we have defined is a high angle fault on which, hanging wall moved down past the footwall or relative to the footwall. So this is the hanging wall. So first define the fault plane. This is the fault plane here and it is going down as well. So this block has moved down in this direction relative to the footwall. So this is the sense of displacement as it is marked by the red half arrows. So this is a normal fault. Now, we see that this is a pure dip slip normal fault because it does not have any strike slip component.

Or in other words, if I considered, try to draw the net-slip here, the net-slip is moving like this because this point and this point were together at one point of time before the fault. So this displacement happened or the slip happened along the dip direction of the fault plane. And therefore it does not have any strike slip component. So therefore this is a pure dip slip fault and in that case the hanging wall moved down relative to the footwall. Now talking about this younger rock over the older ones, we can see it here but let us do it in other ways.

Because this has gone down so this would be a topographic high in the system and if this is topographic high, this would erode with time. And if it erodes then it would stay like this. Now if you do a fieldwork, you can figure out that you are walking in this rock and then if you walk along this side then you encounter a contact with another type of rock which is younger than this. So your younging direction, you may plot in the field like this way but this is not a true lithological contact. This is a faulted contact.

The lithological contacts are actually here. So you have to look here and there to figure out that whether this is a true lithological contact or this is a faulted contact. There are some features here that actually would tell you that this is a faulted contact but not a lithological contact. So this is a kind of unconformity. But what I wanted to say that if you drill a log here, you will see that this is younger rock then younger rock then younger rock and then older rock. So it brings the younger rock over the older ones. So it maintains the normal stratigraphy of the rock.

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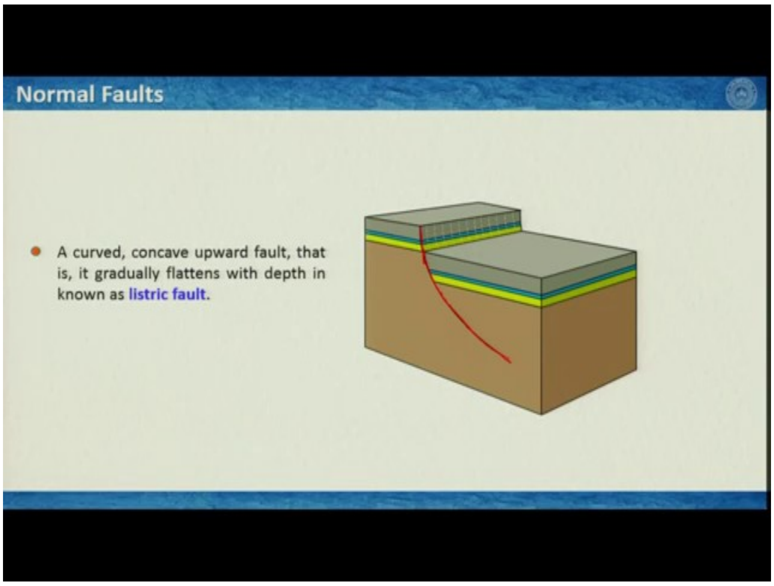

As I talked about the listric fault, you can see here that if the scale is very very large then it is not just a straight plane. At depth the dip of the fault changes or in specifically dip of the fault reduces. So the fault in section appears like a curved line and this is known as listric fault particularly applicable for normal faults.

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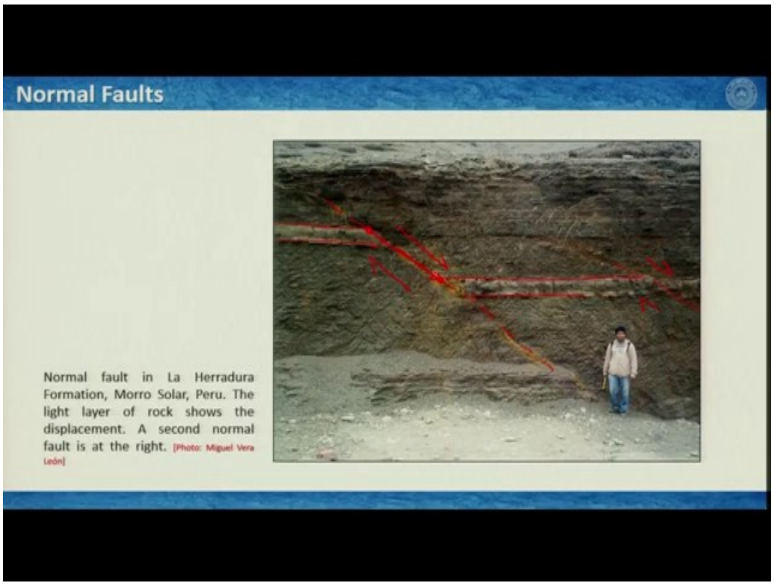

So, here is an example or field photograph of normal fault from Peru. And you can see here these are the horizontal bedding planes, the traces of the horizontal bedding planes and this is separated by this fault line. So we are seeing this in a vertical section. So the beds were horizontal, bedding planes were horizontal and this got separated this way. We see also another normal fault here but not as spectacular as it is because of the slip. So it was here and the net slip from this we can calculate from here to here. So this is an example of normal fault.

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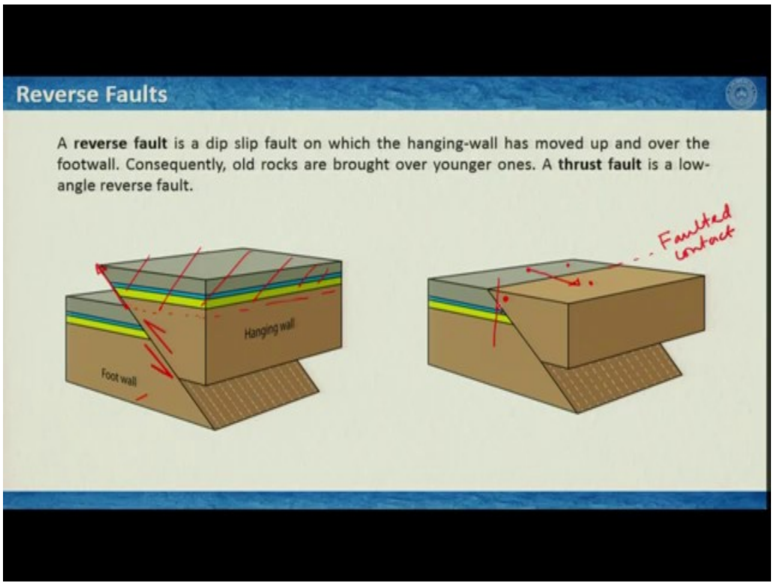

Reverse fault as we learnt that it is a dip slip fault essentially on which hanging wall has moved upward and over the footwall. So this diagram illustrates that. So we have the same footwall but hanging wall unlike normal faults instead of going down it moved up. So that is why the arrow is given, half arrow is given this way. And the footwall relatively moved below the hanging wall. So when the hanging wall moved upward relative to the footwall, the fault is a reverse fault and again you can figure out that there is no strike slip component.

Whatever component it has, so it was here and now it went here. So you can figure out this is the net-slip and this net-slip here is entirely dip slip. In a similar way as we have looked at in the normal fault now this is a topographic high, this region and this can erode out. And if that erodes out then we have a feature like this. And again if you start walking from here and do the fieldwork you may find an older rock because you are here on the younger rock and then you arrive to an older rock and then there are some features by which you can identify that this is a faulted boundary or faulted contact.

This is not a lithological contact. Interestingly if you drill here, you make a bore hole. You figure out that you have first older rock and then you arrive to an younger rock here or here. So that is the characteristics of reverse faults that it brings older rocks over the younger rocks.

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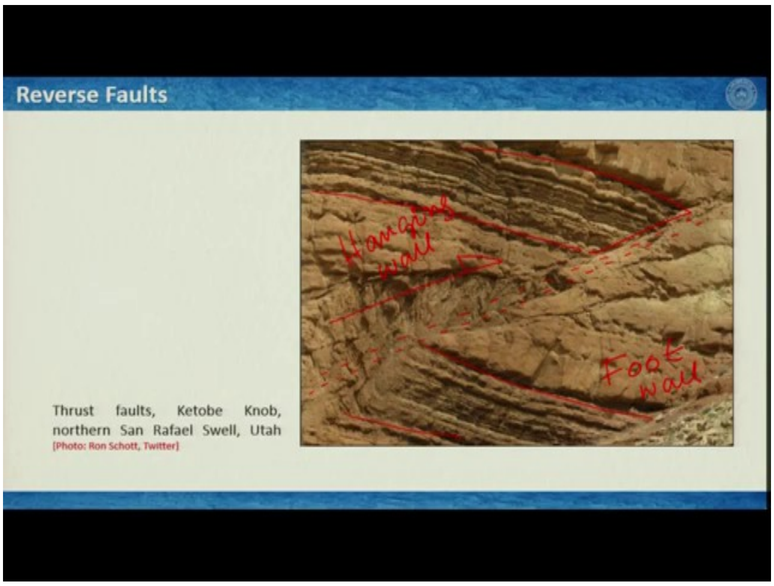

Here is an example of a spectacular thrust fault from Utah. So you see here that this is the fault plane, most likely it goes like this. It is not a single line here. So this suite of layers now it is here, so it moved this way. So this is your footwall and this is the hanging wall of this fault and hanging wall moved upward with respect to the footwall and therefore this is a reverse fault.

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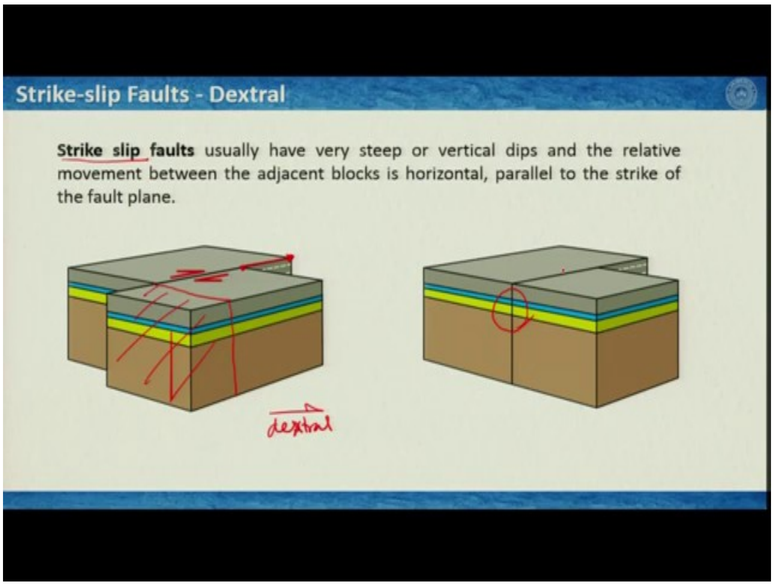

Strike-slip faults as we talked about at the dip of the strike slip faults are generally steep or it is almost vertical. And the relative movement generally happens along the strike. And what we see here that this is an example, this is an illustration of strike-slip fault and here the movement is dextran. That means if I stand here and try to look at it, then I see that the block away from me is moving towards the right side.

And when that happens this is we called dextral displacement or dextral sense of shear. Now what we see here that this point and these two points were, so this point and this point they were together before the faulting and now this point has moved to this place, right? So this is the net-slip and there is no dip slip component. So entire slip component is strike-slip component and therefore we assign it as strike-slip fault.

Now because the marker this bedding planes in this case they are horizontal, if this part gets eroded though this is not topographic high but for the sake of argument let us consider that this part is eroded. Then it would look like this and you do not see any offset on the vertical side because it is strike-slip fault. However if the beds were at an angle, then you could figure out that this is a strike-slip fault. We will see this later.

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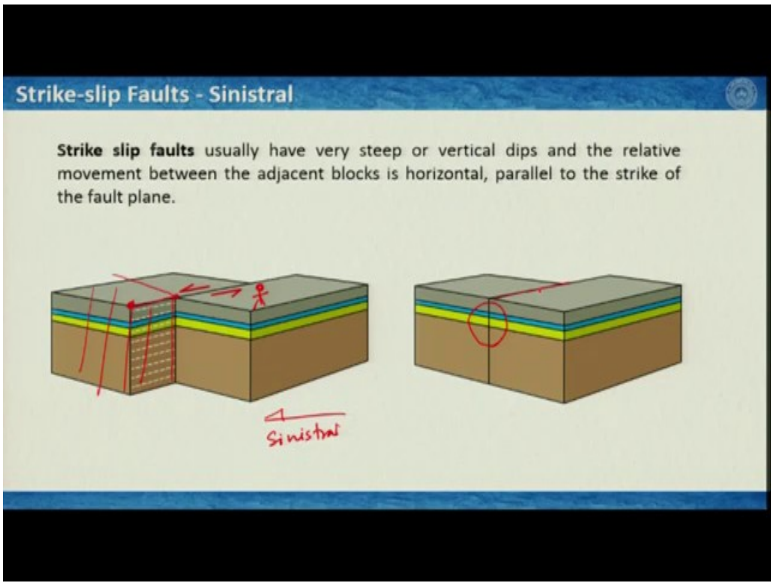

The sinistral strike-slip fault is exactly opposite. So this point it was here and now it moved here but here that sense of displacement is sinistral. Again if I stand here and I look the far away block is moving in which direction then I will see it is moving towards the left. And if that happens then this is sinistral. Relative to me it moved towards the left side and therefore this is a sinistral fault.

Again I can erode this part and we will see more or less the same feature that we do not have any vertical or dip slip component. And we also cannot understand any strike slip component though we know there were deformation but because we do not have any marker planer or maker line we cannot understand that at least from the fieldwork that this was a strike-slip fault. But there are ways, we learn about it soon.

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So here is an example of strike-slip fault and as we can figure out that if I stand here then I look at the further part, then it moved left side. So this is an example of sinistral strike-slip fault. And why I am, I understand this, that this part has moved relative to this way because I have some marker lines here. So, these marker lines show me the offset is like this. So this is from an earthquake from California and photograph from US GS. But you see here how does it work.

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Now, I will take you to another spectacular place where I used to live at one point of time. This is Wairarapa fault and this is near Wellington in New Zealand. And this is one of the large active faults in New Zealand. And it was responsible for the massive magnitude 8.2 earthquakes, it happened in 1955 and almost shaken the north island of New Zealand and this is one of the largest recorded earthquake in the New Zealand.

What we see here, first of all we see a fault scar. So this fault is not a true strike-slip fault but it is mostly strike-slip fault with a little, very little dip slip component. But what we see here, so this red dot here, dotted line here that defines the fault plane, what we see here that this is the river right now which is flowing like this which is continuous. If we consider that this part is fixed and this part is moving in this direction, then what we see that this river was initially here and it was flowing like this and then the river in this side got moved. Then it was flowing here and now it is flowing here. So the river is continuously shifting and this has been dated to be of pre-1855 earthquake and this is a classic example of dextral strike-slip fault. And why this is dextral? Exactly because if you stand in this side you will see that this is moving towards your right side.

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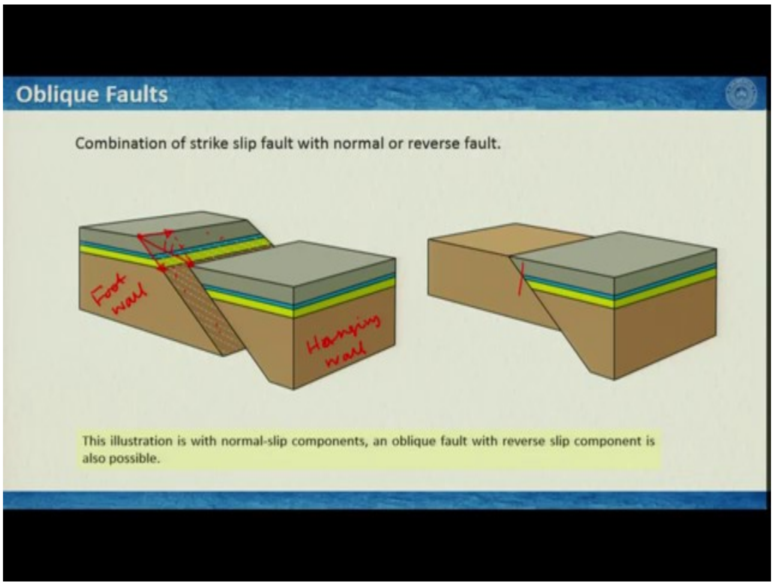

Now, oblique faults, when you have both strike-slip and dip slip component in your system. And it can be either normal dip slip component or reverse dip slip component. So here the illustration is for the normal dip slip component. So, if I consider this is the fault plane, this one, then this is the hanging wall and this is the footwall and these two points were together before the faulting, it moved this way. So, we can figure out that this is the strike-slip component and this is the dip slip component.

So it combines, its net slip combines both strike-slip and dip slip component. Therefore, this is an oblique fault and here we see if we can erode this topographic relief and also this side, then it appears like this and we see that because it is a normal oblique fault, so we see it bring the younger rock over the or above the older rocks. But if it is a reverse dip slip fault, then it would make the opposite scenario. That means it would bring the older rock over the younger rocks.

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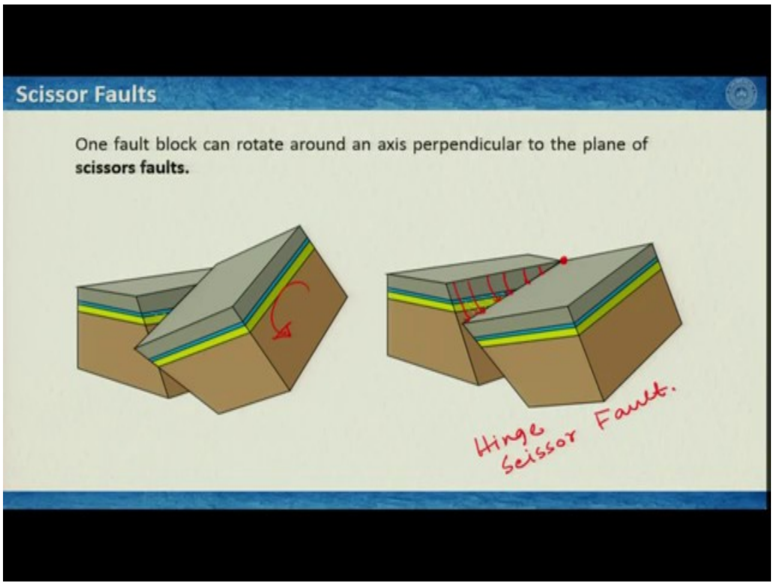

Now, there are few other typical faults and these are known as scissor faults. So, this one is a scissor fault that one fault lock can rotate around an axis perpendicular to the plane of the scissor faults. So, for example, this one, so there could be an axis and this block actually rotated over it. So it does not have any typical fixed net-slip, so the net-slip could vary.

And this is you can, this you can geometrically analyze by the rotational displacements or movements. But these are scissor faults and if it happens following a hinge point then these are known as hinge scissor faults. So you can see that net-slip is varying from the hinge and as you go far away. So this is known as hinge scissor fault.

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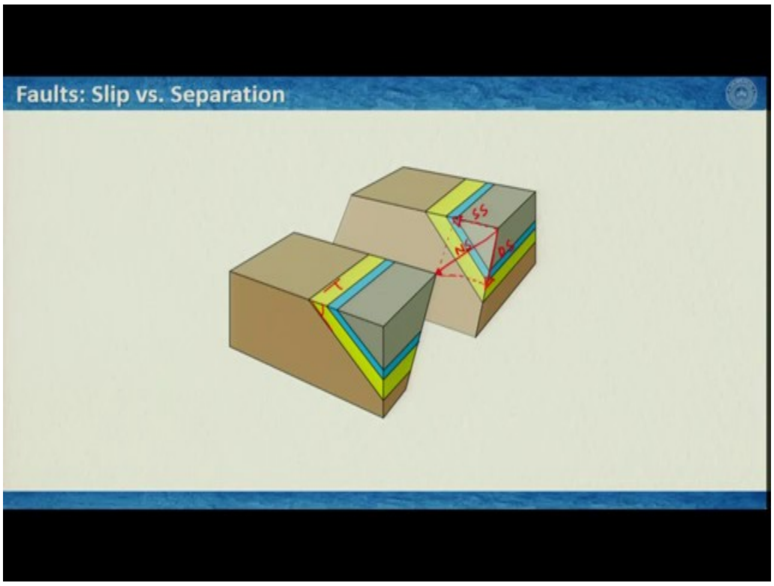

Now, let us talk about what are the very important parts that I mentioned before. That whatever we learnt so far this normal fault, reverse faults, strike-slip fault, scissor fault and so on, these are known as mostly marked or mostly classified separated by their slip movements based on their kinematics. And if you go back and see all these illustrations, the bedding planes were always horizontal but not necessarily has to be the case always.

The bedding planes because of some pre-deformation fold, fault, or so on, could be tilted. And if the tilting happens and the faults do move either in normal or reverse or in strike-slip manner, the separation of the bedding planes may not show you what is dip-slip; what is strike-slip and what is your net-slip component. And therefore, it is important that in the field to study if possible three-dimensionality when you particularly look at the fault.

And when you look at this illustration we will figure it out how dangerous it is just by looking at the separation concluding the kinematics of the fault, that whether this is normal, reverse or strike-slip. So, what we see here first of all, that in this illustration the bedding planes are not horizontal like before.

So, here the bedding plane has a dip and this is the strike of the bedding plane and this is the dip of the bedding plane in this case and if this rock block displaced by a normal oblique slip movement then we know that this would be its strike-slip component and this would be its dip slip component. So you just write strike-slip, this is dip slip, ds and this is ns net slip.

Now imagine that this fault with time, this part got eroded and then we here doing fieldwork on the surface.

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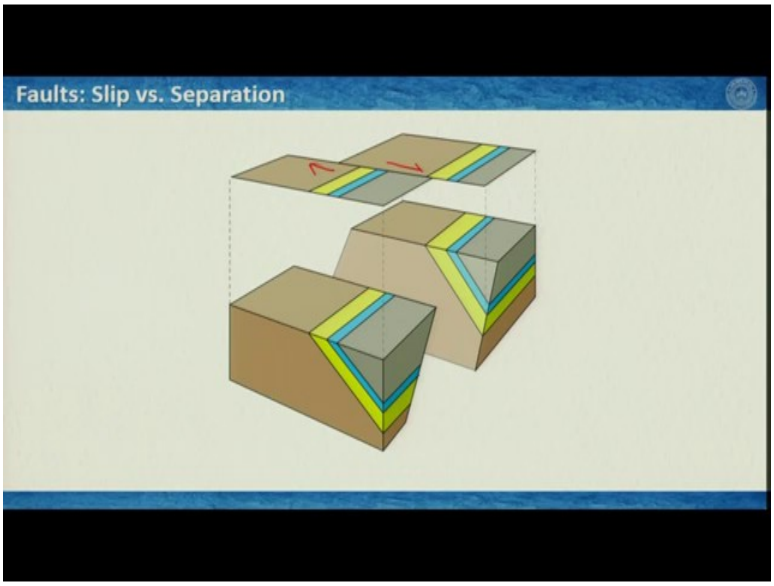

So, if I project this on the surface, I would see it something like that. So, on the surface you see this strike-slip separation, right? And if you just look at the surface, then you may conclude the fact that the fault is a strike-slip fault without any dip slip component and looking at these 3D illustrations it is clear to us that this is not only a strike-slip fault but this is an oblique fault. Now, say this fault got an exposure by some river cut or so, something like that or an erosion and this vertical surface is exposed.

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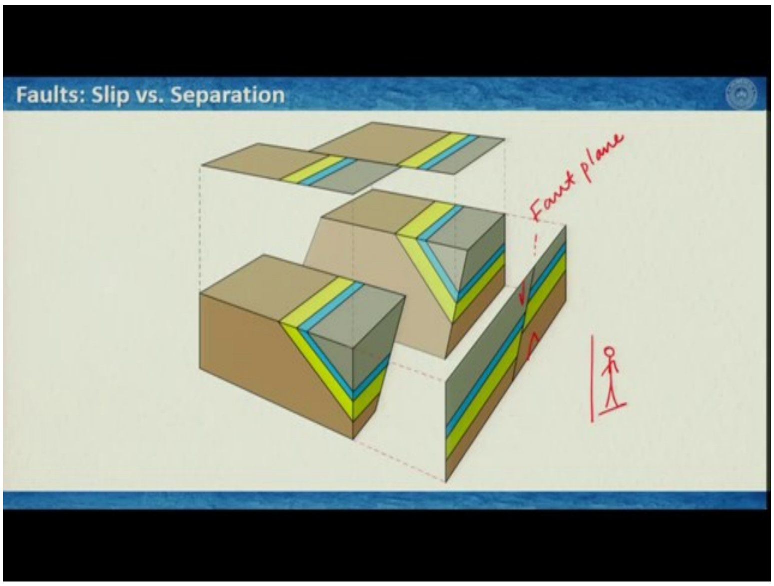

If that happens then we may see it on the vertical section like this where this is the fault plane, or trace of the fault plane, let us, and we see that it is showing a normal slip component, normal dip slip component. And if the top surface is not exposed, say it is topographically very high, we cannot reach there, then just by looking at in the field I can conclude that this is a normal fault. But again this idea is wrong.

So the message I would like to give you with these illustrations, these two particular illustrations that just do not look at the separation. So this is known as separation that when you have a planar feature is offset by the fault movement, so this offset is known as separation but that necessarily indicate that it offset is also the kinematic parameter or it does not lead you to conclude about the kinematics of the fault surface.

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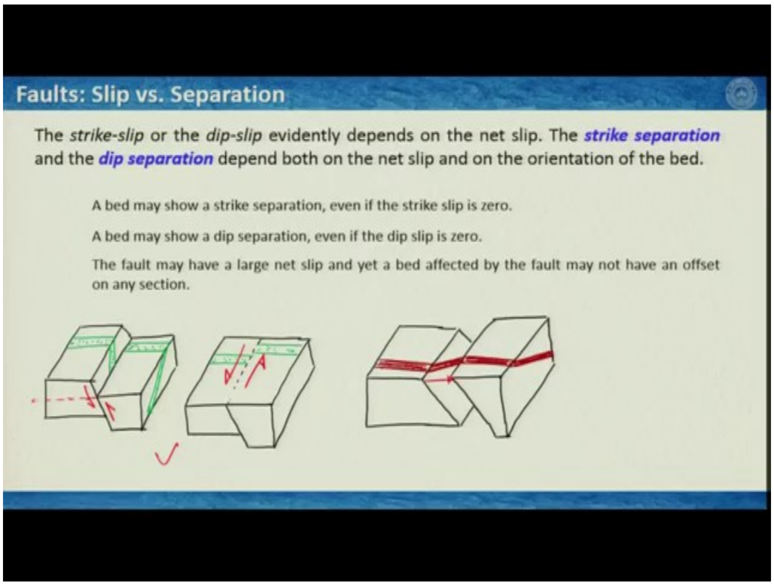

So, the strike-slip or dip slip evidently depends on the net-slip that is for sure. But the strike separation and the dip separation depend both on the net-slip, and at the same time orientation of the bed with respect to the fault plane. For example, a bed may show a strike separation even if the strike-slip is 0. I try to draw it but you can also try it by yourself. So, for example, I can consider a fault like this. I draw a normal fault.

So, if there is no marker, nothing, this is a normal fault. No problem. But if I have the bedding plane something like this and here say then it would go this way, is something like this, that means the bed is inclined and has a dip. And again if this part gets eroded like this, then what we will see in reality or in the field, this is the trace of the fault plane and on this side we may have something like that.

But the vertical side is not exposed, so the horizontal side what you see that it is, so you see that this is indeed a dip slip fault. This is a normal fault without any strike-slip component but you see here this is showing a strike-slip fault. So be very careful. Now, again a bed may show a dip separation even if the dip slip is 0. So, for example, you are having a strike-slip fault and it is showing a dip separation. So we can try this drawing.

Even if you can have a dip slip fault, but you do not see any dip separation, so all these things are possible. And the fault may have a large net-slip and yet a bed may not be affected by the fault and it may not show any offset or any separation on either sections. So, I have given you just an example and you can try these all possibilities. Try to draw that which way the bed should be oriented and how this can happen. I give you one more example.

For example, I have again say, for example, an oblique fault is happening. I am not going to complete the entire demonstration. This is for your idea. So we know that this is the net-slip, okay. Now, we can figure out if your bedding plane is dipping exactly the way slip happened, so it is parallel to the slip direction, then you can guess that if this part gets eroded you do not see any separation.

So but you have a significant magnitude of net-slip. So this you always remember when you look at faults in the field. So these are beautiful structures, look at it, try to interpret it but when you conclude about the kinematics that what is the dip slip, whether this fault is normal fault or strike-slip fault or reverse fault, do not do it just looking at separation unless you are confirmed by a third dimensional observation.

Now, we will see some special type of normal faults and we will sort of name them that how do they occur in nature. So, normal faults we have seen so far that it is one-sided but it is possible that normal faults may happen either converging to each other or diverging to each other and both of them could be normal faults and they can stay there as conjugate sets.

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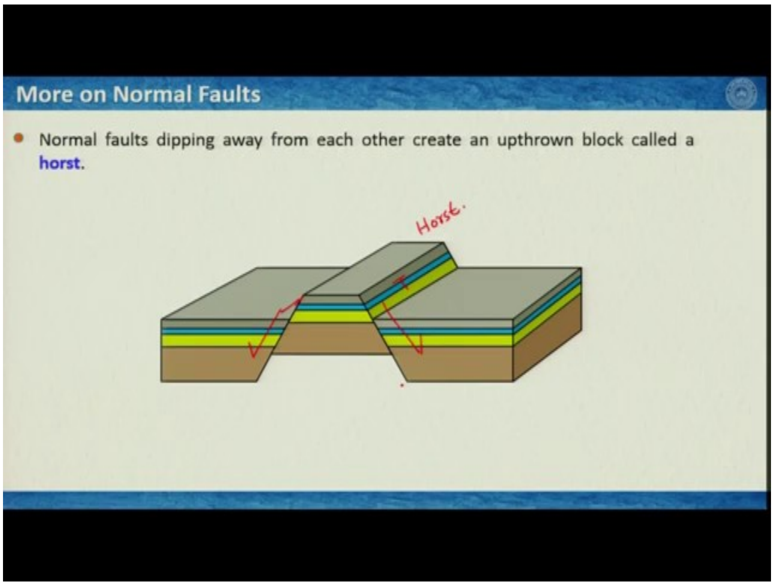

Now, when the normal faults dipping away from each other and then they create an upthrown block, this is called horst, so as we see in this illustration so it was initially a straight layers and then it had a normal fault in this side and another fault in this side and they are dipping away from each other or their dip directions are opposite. So here it is dipping this side and on the other side it is dipping in this side. And this particular feature is topographic elevation is known as horst. And these are conjugate sets of normal faults.

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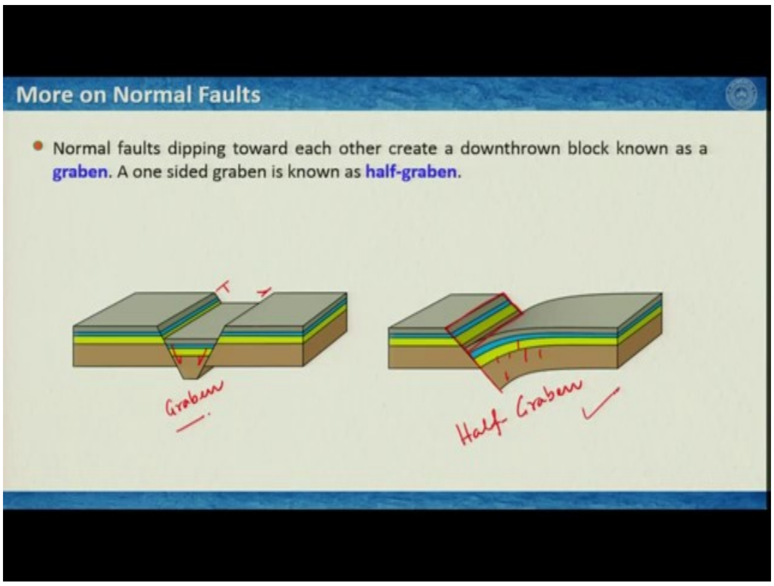

If the opposite happens that means the normal faults dipping towards each other, then they create a downthrown block and this is known as graben. So again you see that this part went down this way and this part went down this way. So these are two normal faults again in conjugate sets. But they are dipping towards each other, so this fault is dipping this way and this fault is dipping this side. And therefore the block in the middle pushed down.

And this is known as graben. You can also have something called half-graben where you do not form the other conjugate set but one set is extremely prominent and these are known as half-graben. You may see some sort of subsidiary faults here but the major or master fault is this one. We will see this soon. So this is known as graben. And this is known as half-graben.

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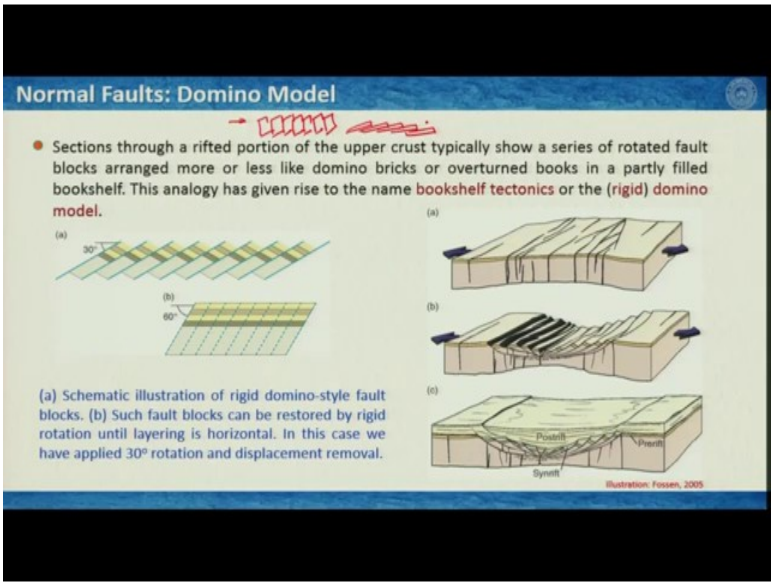

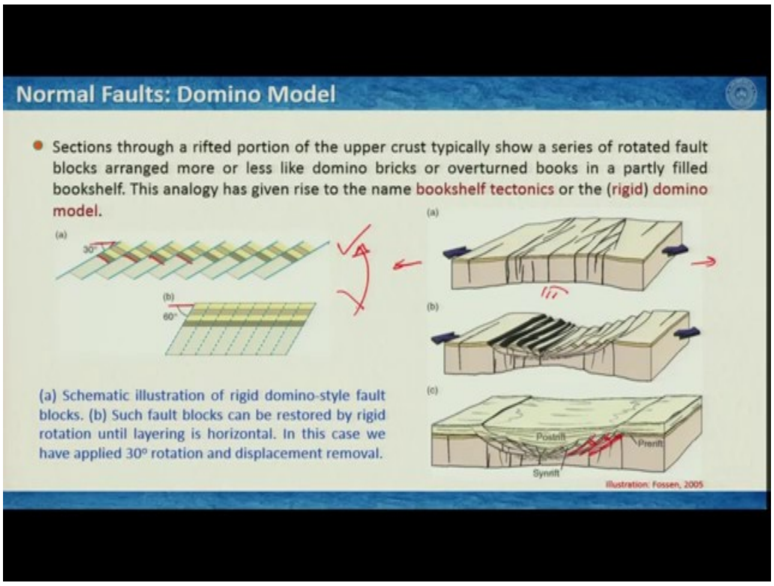

Now there is also one very interesting nature of normal faults and we call it, domino model. Now domino is something that kids do play or even adults play as well. So you remember that we have little blocks like this, we align it like this in a different way. And then you push from this side and they slide and they stay like this. So this is called domino or dominos. Now in normal faults it happens in a very similar way. So sections through a rifted portion of the upper crust typically show a series of rotated fault.

So that means you are having normal faults one after another and the fault blocks arranged more or less like the domino bricks or overturned books in a partly field bookshelf. This analogy has given rise to the name bookshelf tectonics or the rigid domino model. So you have books in the bookshelves, there you make them space in between and then you arrange one after another and then if you tilt from one side then the books will rotate past each other and they will make a shape something like this.

So this is a rigid domino style fault block. So initially it was like this and then it can take the shape of like this and in the other way you actually can tilt them back, so now it is 30 degrees but you can tilt them back to match this layer with this layer and this layer and so on. And then you can figure out what is the initial orientation or initial angle of the original deposition.

Now this also happens when in large scale tectonics particularly where when you have riff tectonics. So here we see that maybe a plume is coming here or some extensional tectonics is happening. So it produces large number of normal faults and eventually they tilt and they produce features like this. And these are all kind of domino structures that are characteristics of normal faults.

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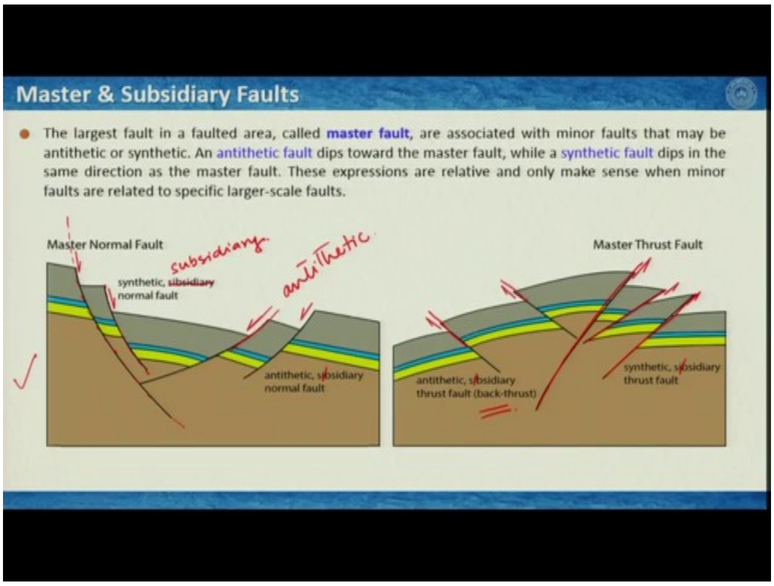

And then we have as we talked about, we can have master and subsidiary faults. So once you have a normal fault and then the other block may or may not show some sort of rotation. And if it cannot rotate properly, it produces a series of subsidiary faults. It can happen both in hanging wall and also in footwall. It can happen both in normal faults and also in thrust faults. So the largest fault in a faulted area is known as master fault.

And these are associated with minor faults that may be antithetic or synthetic. An antithetic fault dips towards the master fault while a synthetic fault dips in the same direction as the master fault. Now these expressions are relative and only make sense when minor faults are related to the specific larger scale fault. So it can happen in a different generation. In that case we have to be very careful to name them as either antithetic faults or synthetic faults.

So the first example here, first illustration here is a modified version from professor Jean-Pierre Isbouts illustration. What we see here that this is the master normal fault and then it produced a synthetic subsidiary normal fault. So this spelling is wrong here. It should be subsidiary. Everywhere it is wrong and then you see that we have normal faults but the dip is on the other side. So therefore these are antithetic with respect to the master normal fault.

In the thrust fault it can happen in a very similar way. So this is the master fault you can consider and then we have same dip of, same dip direction or similar dip direction of this synthetic thrust faults. But on the other side, we have antithetic faults where the dip direction is opposite to that of the master fault. And these are sometimes known as back-thrusts. So these are very-very important in a fault system that you have to identify what is master fault and then what is subsidiary faults and whether they are synthetic or antithetic.

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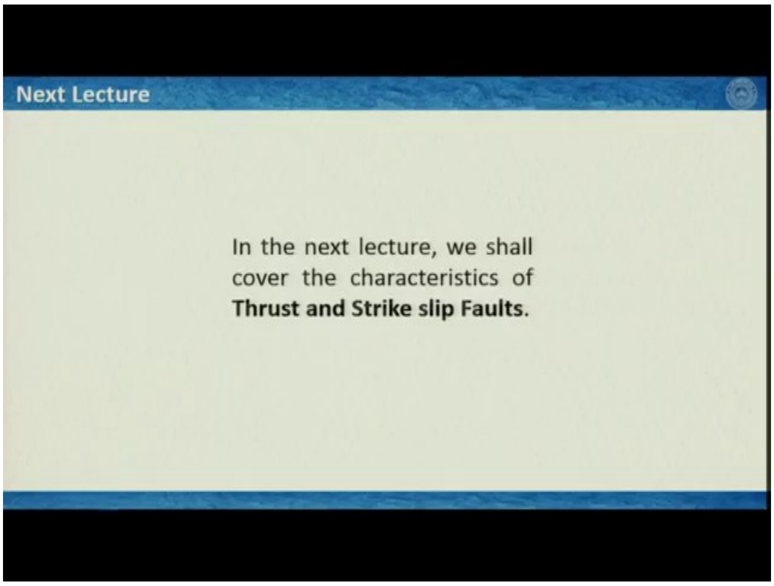

So with this I conclude this lecture and also this is the last lecture for this particular week. If you have complain that whole week was very-very long, so what I decided that a thrust and strike-slip faults, we will spill to the next week in the lecture week of shear zones. So we will start with this thrust and strike-slip faults in the shear zone week and then we will go to the shear zone lectures. So till then have a nice time. I will see you in the next lecture. Thank you very much.