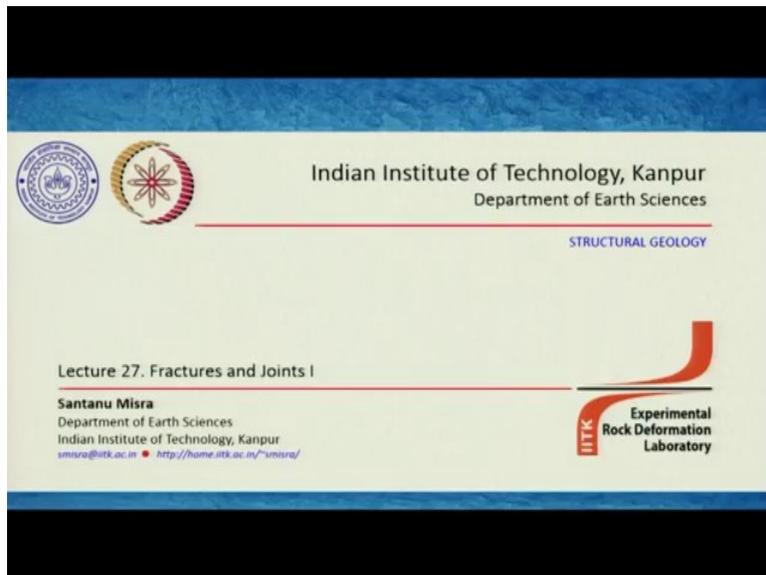


Structural Geology
Professor Santanu Misra
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Lecture 27
Fractures and Joints - 1

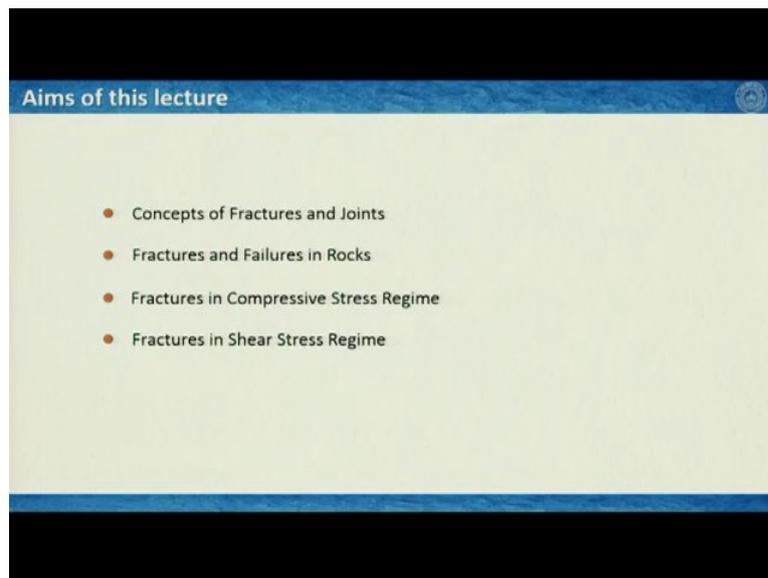
Hello everyone, welcome back again to this online NPTEL Structural Geology course and we are going to start a new week and this week we will mostly focus on the brittle deformation of rocks.

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So mostly we will see fractures, joints and essentially faults, so we will have 3 to 4 lectures. And today we will start with this topic with mostly focusing on fractures and we are in lecture number 27. We already have started this lecture on fractures and so on particularly when we talked about boudinage, but there we also inserted or included the structures like pinch and soils and so on where it is not typically a brittle deformation, but this week we will mostly stay in the brittle domain or brittle deformation domain of rocks.

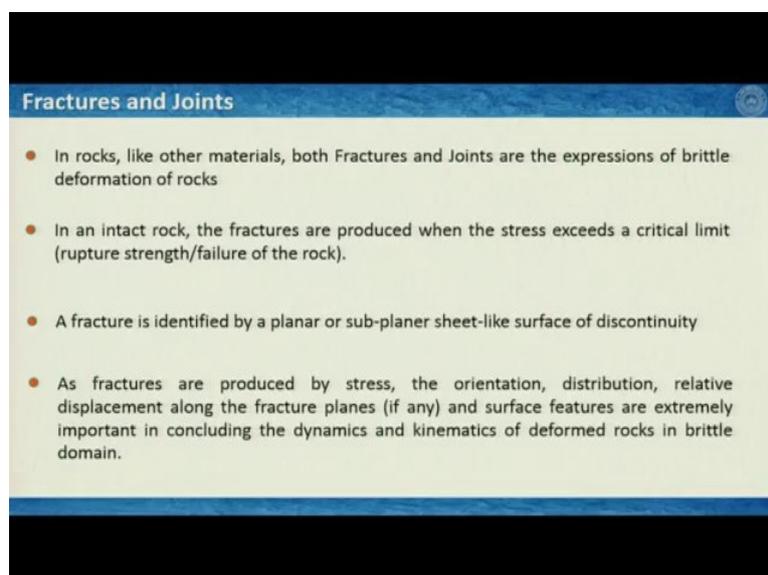
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So, in the first lecture which is today we will learn mostly concepts of fractures and joints, then we will talk about fractures and failures in rocks, then we will see the different kinds of fractures that we produce in compressive stress regime and in shear stress regime. So, these 4 points are the topics of today's lecture and so these 4 are the things we will cover in this lecture.

And then in the next lecture and the following lectures we will mostly focus on joints in particular and then we will see the faults of rocks and we will see what are the different processes that are involved, the mechanisms, different structures, their implications and so on. So, let us start with the concepts of what are fractures and what are joints.

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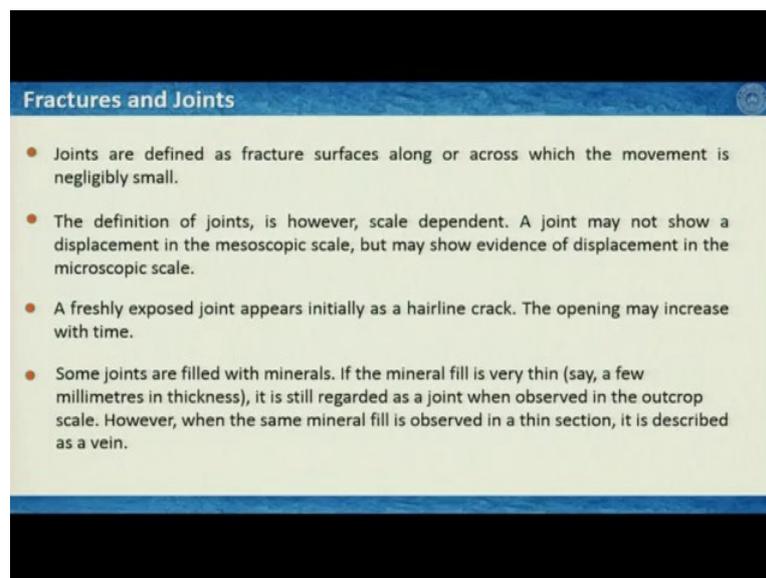
Now, in rocks, like all other materials, both fractures and joints are essentially the expressions of brittle deformation of rocks. Now, in an intact rock, the fractures are produced, you can produce a fracture in an intact rock when the stress exceeds a critical limit and we generally call the critical limit as rupture strength, fracture strength or failure of the rock, we will spend a lot of time on the failure of the rocks in this lecture.

And generally you identify the fracture in the rock systems by mostly a planar, or sub planar sheet like surface discontinuity. So, this is what you see mostly in 2D or 3D, but in 1 dimension or what I mean by these that in sections, in any surfaces, eroded surfaces or it can be a fractured surface itself, we see the fractures like a hairline sort of crack or hairline discontinuity in the rock mass.

And as fractures are produced by stress, because you need to apply some sort of stress to fractured the rock. So therefore, the orientation, distribution, relative displacement along the fracture planes if there is any displacement at all, these are the surface features and these are extremely important in concluding the dynamics and kinematics of deformed rocks in brittle domain.

So whatever fracture you produce its orientation, the distribution, and so on must have some relations with the stress field of this regime. And if there is a relation and we can calibrate this relationship then just looking the fractures, their orientations and so on in the field, we can conclude convincingly the stress regime by which the fractures have formed in the field.

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Fractures and Joints

- Joints are defined as fracture surfaces along or across which the movement is negligibly small.
- The definition of joints, is however, scale dependent. A joint may not show a displacement in the mesoscopic scale, but may show evidence of displacement in the microscopic scale.
- A freshly exposed joint appears initially as a hairline crack. The opening may increase with time.
- Some joints are filled with minerals. If the mineral fill is very thin (say, a few millimetres in thickness), it is still regarded as a joint when observed in the outcrop scale. However, when the same mineral fill is observed in a thin section, it is described as a vein.

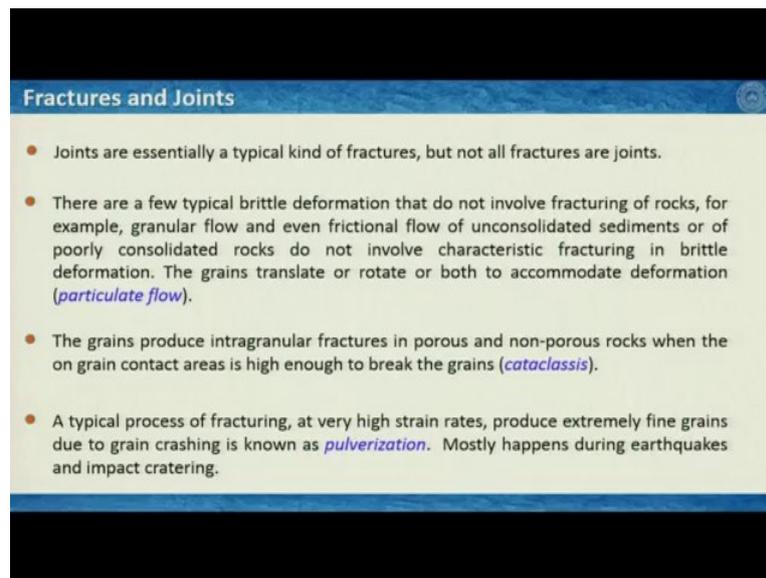
And in this context joints in contrary to the fracture they all joints are generally fractures, we will see that, but they are defined as fracture surfaces along or across the movement is negligibly small. So joints just produce a fracture, but there is no displacement or very less displacement along the fracture planes and in particular because in geology we deal with scales.

Now this definition of joint that I just said that or is written here that joints are defined as fracture surfaces along or across which the movement is negligibly small is essentially a scale dependent statement. Now a joint may not show a displacement in the mesoscopic scale that means in the field scale, but may show evidence of displacements in the microscopic scale. So it is also important that you remember the definition of joint is scale dependent and we generally describe this in the context of field scale or even a large scale.

Now a freshly exposed joint that means that joint just have formed and exposed on the surface appears as a hairline crack, a very thin line. And the opening may increase with time when you have weathering or some other natural processes go on on this joint surfaces, then we see that opening is happening along this surface and eventually the rock breaks and fall apart along the joint planes that happens very frequently and this is quite normal and common. Some joints are filled with minerals. If the mineral field is very thin say, few millimetres in thickness, it is still regarded as a joint when observed in the outcrop scale.

However, we have a different name of the same feature if we see this under microscope and then it is known as a vein and so on. So we will learn all these different terminologies mostly to assign the same processes or same feature, but this is how it is, this is our subject is, we have very similar feature, but depending on the scale at which we are looking at, we name them differently or the way we are observing, it will see some examples in this lecture as well.

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Fractures and Joints

- Joints are essentially a typical kind of fractures, but not all fractures are joints.
- There are a few typical brittle deformation that do not involve fracturing of rocks, for example, granular flow and even frictional flow of unconsolidated sediments or of poorly consolidated rocks do not involve characteristic fracturing in brittle deformation. The grains translate or rotate or both to accommodate deformation (*particulate flow*).
- The grains produce intragranular fractures in porous and non-porous rocks when the on grain contact areas is high enough to break the grains (*cataclasis*).
- A typical process of fracturing, at very high strain rates, produce extremely fine grains due to grain crushing is known as *pulverization*. Mostly happens during earthquakes and impact cratering.

Now, as I said the joints are essentially a typical kind of fractures, but not all fractures are joints and this is exactly what we are looking at today and will mostly focus on the fractures where we have displacements along the fracture planes. So we focus in joints today. But there are few typical brittle deformations because we are dealing with brittle deformations in this lecture or in this week that do not involve fracturing of rocks, interestingly brittle deformation is happening.

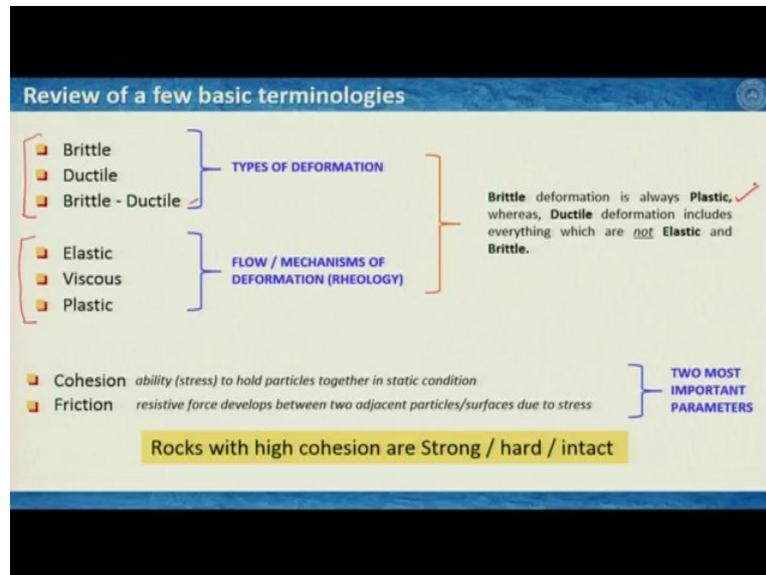
So, for example, you can think of that granular flow and even frictional flow of unconsolidated sediments or of poorly consolidated rocks do not involve characteristic fracturing in the brittle deformation. The grains actually do translate or rotate or both to accommodate the deformation and this is known as particulate flow. We have learned all these things in our deformation mechanism lecture, particularly in the lecture of cataclasis.

And cataclasis is also one of the important processes of fractures and joints, where the grains produce intra-granular fractures in porous or non-porous rocks when the grain are in contact and the areas or the stress you apply is high enough to break these grains and this is known as cataclasis. Now, there is another term which is pulverization, a typical process of fracturing at very high strain rates and that produce extremely fine grains due to grain crushing and this is known as pulverization.

So you have a piece of rock and there is a fracture happened and then this inside these fractures because of the movement of these fracture walls the grains inside they got extremely crushed and eventually remain as very fine grained structure and this process is known as

pulverization. And pulverization you can imagine this can happen mostly when you have an earthquake or an impact cratering on the surface.

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So, let us review some of the basic terminologies that we have learned in the previous lectures. We have a two pairs of terminologies with three terms in each group. The first group consists of brittle, ductile, and brittle-ductile. And the second group consists of elastic, viscous and plastic. Now you already are familiar to these terms, maybe not with brittle-ductile.

So brittle and ductile we know that these are the processes of deformation, if the cohesion is maintained that means the rocks do not produce any visible fractures, then we call this is a ductile deformation. But, if the cohesion is lost then we call it brittle deformation. Now there is something in between that a rock may produce fractures and at the same time it may not lose cohesion at some parts of this rock mass, and then we call it brittle ductile or simultaneously brittle and ductile deformation, if it happens together then we call it brittle ductile deformation.

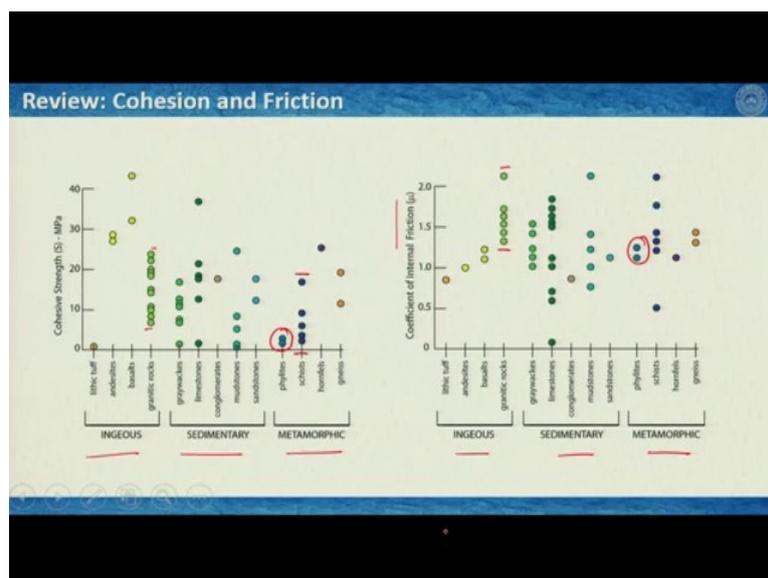
On the other hand elastic, viscous and plastic these are rheological terms, so we can summarize it this way that brittle, ductile and brittle-ductile are types of deformation and on the other hand elastic, viscous and plastic are some sort of flow or mechanisms of deformation or in other ways you can call it rheology. We have also learned that this brittle, ductile, brittle-ductile and elastic, plastic, viscous they apparently do not have any relationship.

However, brittle deformation is always plastic, whereas, ductile deformation includes everything which are not elastic because ductile deformation is a permanent deformation, so it cannot include elastic deformation and of course which are not brittle because the brittle deformation is essentially not a ductile deformation because in brittle deformation we will lose the cohesion of the rocks.

Now we also learnt two other terms and I already mentioned one of these terms, one is cohesion, and another is friction. So cohesion is the ability or stress to hold particles together in static condition that means I have some sand grains kept on a bowl and I make something cover on it and then I just leave it there. So the intra-granular interactions between the sand grains if this is good enough to hold the shape, then we say that yes it is a cohesive material, but if I continue piling up sand on the bowl at one point of time it would fail that means it would not maintain its cohesion in the static condition.

Friction in contrary is a resistive force that develops between two adjacent particles or surfaces due to stress. So, once there is a stress from outside, then the intra-granular forces are known as friction and once there is no stress from outside only the static condition is prevailing, then the intra-granular forces are known as cohesion and these two are very important parameters. I would like to also highlight one point here that rocks with high cohesion are generally strong, hard and intact, we will learn about it soon.

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We have also learned that apparently cohesion and friction these two material parameters they do not have any major relationship. So they are some sort of independent, what I mean

by this if the friction of a rock is high that does not mean that the cohesion of this rock has to be high or low and vice-versa. So here are two plots and we have seen this before, but I would like to highlight it again.

These are the cohesive strengths which are measured in megapascal or the unit is in megapascal and these are some rocks, common rocks, igneous, sedimentary and metamorphic. And in this plot we have coefficient of friction which is mu and we have again the similar rocks in three classes igneous, sedimentary and metamorphic. What we see here that, so let us take the example of granite and we see it has a quite wide range here and again if we come to the granitic rocks, the friction is pretty high.

Now interestingly if we come to the schists here which is a metamorphic rock and we know this is extremely foliated rock, schists or phyllites and so on we see phyllites have a very low cohesion, but once we see phyllites have very high friction and you can compare all the rocks here in this plot and you will see that these two terminologies which are very important in controlling the fractures and joints of rocks have apparently no relationships between them.

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Rock Failure: concept

- In classical rock mechanics, **Rock Failure** is achieved when the rock under stress achieves permanent deformation.
- For **perfect brittle** rocks, Yield Stress is equal to Failure Stress; for **brittle-ductile** or **ductile rocks** Failure Stress is different from Yield Stress.
- Brittle fracturing is commonly described with the **Mohr-Coulomb criterion**.

$$\tau_c = S + \mu(\sigma_n - P_f)$$

τ_c = critical shear stress for fracturing
 S = cohesion of the material
 μ = co-efficient of friction
 σ_n = normal stress acting on the fracture surface
 P_f = pore fluid pressure

We also have learnt about this equation that will that we will learn soon, but in the context of the classical rock mechanics we have to understand that what is the rock failure or when we are going to produce the fracture in the rock. Now, rock failure is generally achieved when the rock under stress achieves permanent deformation. Now, in brittle deformation the permanent deformation is mostly manifested or achieved by the fracturing of rocks.

So, for perfect brittle rocks the yield stress is equal to the failure stress. For brittle-ductile or ductile rocks failure stress is different from yield stress. And we have learnt about it but still I would like to give you a little idea about it. If I am dealing, so this is strain and this is stress and if I am dealing with a brittle rock, then this elastic loading would happen and then the rock would fail like this. So, clearly this is the yield stress of this rock, this is the elastic limit.

Now, if I have a rock in the brittle ductile domain, then it may follow the same path, but it may not produce fracture here, it may go a little bit and then it may produce a fracture and this part here is where you achieve your ductile deformation and then finally it produces a fracture or multiple fractures.

But, if we talk about the ductile range, then even if we have the same yield strength it would not produce a failure, it would not produce a fracture in the rock, and it would continue flowing this and we know from the previous lectures that it can flow with at constant stress then we have to call it steady state, it can flow at higher stress then we call it strain hardening or it can flow at lower stress and then we call it strain softening.

So these are the processes we have learnt and we can see this more in one of the next lectures when we talk about the stress-strain curves, but the brittle fracturing or rock failure expressed by fractures are commonly described by a relationship which is known as Mohr-Coulomb failure criteria. Now, we have learnt about this before where this equation is expressed as shear stress is equal to cohesion plus mu which is the coefficient of friction multiplied by normal stress minus pore fluid pressure.

If you do not have pore fluid pressure then the equation stands like this $S + \mu$ (you do not have to do the bracket here) σ_N , so this is how we figure out that this is the condition, so this is the critical shear stress that you need to have to make a fracture in the rock, make a (failure) fracture failure in the rock and which is a function of the cohesion of this rock, the coefficient of friction of this rock and the normal stress is being applied to the rock.

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Rock Failure: Idealizations and Assumptions

- Rock is isotropic, homogeneous and stress are applied uniformly
- Textural characteristics such as grain size and sorting have no influence
- Temperature and strain rate are ignored
- Intermediate stress (σ_2) does not play any role

These are often violated in rock deformation experiments and all of them have been demonstrated to have significant influences in Rock Failure and Fracture Generation

Now, there are some assumptions and how do we get all these things, the fracture strength, the failure strength, what kind of fractures we will produce and things like that. Because if you remember at the very beginning I told that if we can calibrate the fractures, their orientations, their aggregates or their shape and so on, then it is possible to identify or to understand what is going to be the orientation or what was the orientation of the stress axis, principal axis of stresses or overall stress regime of this area.

And experiments here are extremely useful because we can do experiments in different ways keeping the stress axis differently and then we see what kind of fractures we are producing in our samples. And once we have these ideas then we go to the field and check that what kind of fracture have produced and then we see these fractures, we match it with our experimental results and see and finally conclude, yes, this is a fracture that must have produced under such and such stress domains.

But to do that, (we do) for these type of calibrations of fractures in experiments to the field, we have some sort of considerations and these considerations are very very ideal. So one of these considerations is rock is isotropic, homogeneous and stresses are applied uniformly. The second consideration is textural characteristics such as grain size and sorting have no influence. The third one is temperature and strain rates are ignored, and the fourth one is intermediate stress or σ_2 does not produce any role.

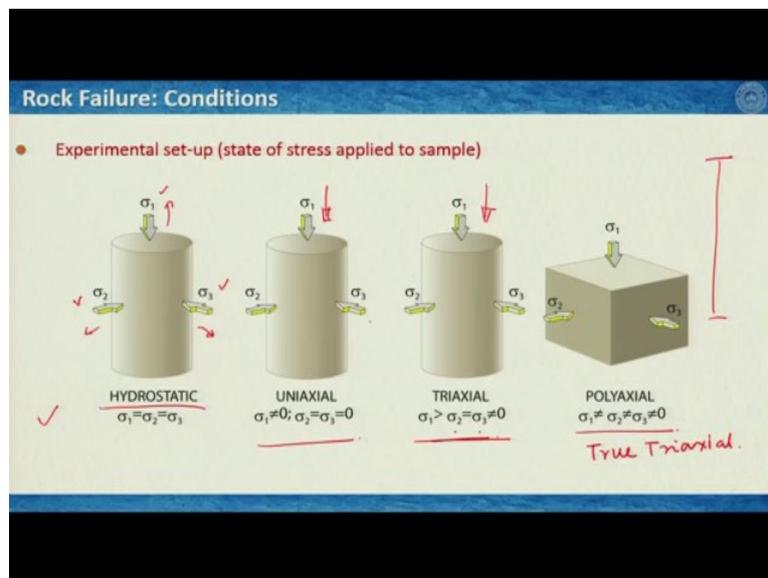
Now, these are very sweet statements, but as experimentalists generally do not try to follow any rule except the basic laws of science and physics, so we generally deviate from this and

this is why this statement is written. These are often violated in rock deformation experiments and all of them have been demonstrated to have significant influences in rock failure and fracture generation.

So that means if I deal with an anisotropic rock it would vary from isotropic rock, if we deal with homogeneous rock it would certainly vary from the failure and other things (from homogeneous) from heterogeneous rock, the textures and grain size and sorting have no influence this is the consideration. But we have seen people have shown from experiments that all these textural characteristics grain size and sortings they do have a significant influence in the strength and failure of rocks.

And similarly, temperature and strain rate we have seen it they have a significant influence. So all these things are not considered in actual rock deformation experiments, but these are some thumb rules that one has to taste at the very beginning to understand the essential parameters that one can vary in rock deformation to understand the fracture patterns and other processes of brittle deformation. As I said that experimental rock deformation has a series of considerations and these considerations we generally do mostly to understand the fracture patterns, their orientations and so on.

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So, here are four examples that experimental rock deformation or rock mechanics people generally do consider in their experimental setup. The first one is hydrostatic state of stress, from our stress lecture we have understood that if sigma 1, sigma 2 and sigma 3 these three

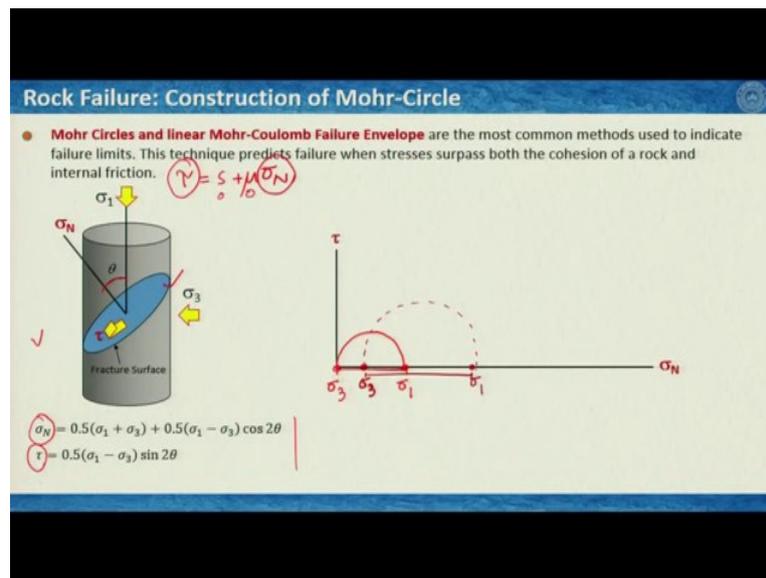
principal axis of stresses which are being applied to the rock samples are equal then it is hydrostatic.

So in that case if they are compressive then the rock will shrink, if they are not compressive but in the tensile domain that means these arrows are in the opposite direction then the rock would expand or it would produce fracture in a different way we will see that soon. Then there is one consideration which is uniaxial deformation or unconfined deformation that means that you do not have any confinement, atmospheric pressure is there or vacuum is there around the rock samples and then you apply a load from the top and bottom or only from the top where bottom is constrained.

So the condition is σ_1 which is the stress you are applying has a value but σ_2 and σ_3 they are first of all equal and they are either in atmospheric conditions or under in vacuum. Then we have another set up called triaxial where σ_1 is as it was we considered here for uniaxial, but σ_2 and σ_3 they are either equal to each other or sometimes they are not equal to each other. If they are equal to each other then we call it triaxial that means σ_1 which is essentially greater than σ_2 and σ_3 , and σ_2 and σ_3 they are equal and not equal to 0. So that means the rock is under confinement and then a $(\sigma_1 : \sigma_2 : \sigma_3)$ stress is applied to the sample.

Polyaxial is sometimes we call it true triaxial stress that means the σ_1 , σ_2 and σ_3 they have three different values and they are not equal to each other. So this is how we considered these four different stress regimes, but there are some other experimental set up as well one can work on biaxial and so on. But these are the standard processes, we work with this, we generally use cylindrical samples for some special advantages in preparation and so on. But for true triaxial we mostly use or polyaxial we mostly use samples of cube or parallelepiped shapes.

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Now the study of rock failure is generally done with Mohr circle. So Mohr circle or a linear Mohr-Coulomb failure envelope is or you can consider that these two generally are considered together so Mohr circle and linear Mohr-Coulomb failure envelope they generally are plotted together are the most common methods used to indicate failure limits, so we will see this soon.

And this technique predicts the failure when the stresses surpass both the cohesion of a rock and the internal friction and this is essentially an expression of this Mohr-Coulomb failure criteria which I would like to write again. So, what you need? You need shear stress and you need normal stress.

So this is an example here is I have shown by a cartoon diagram that if I apply sigma 1 which is the compressive force and then sigma 3 here and then this is the fracture this blue one is a fracture you have produced and this fracture can make an angle with the normal to the fracture plane and with the sigma 1 and say this angle is theta. Now from the stress classes we know that we can calculate sigma N and we can calculate tau once we know sigma 1 and sigma 3.

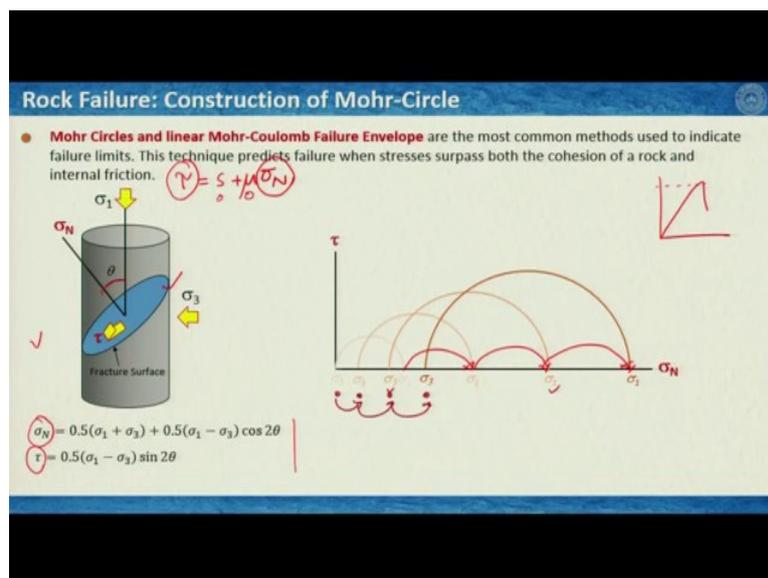
So, to figure out the cohesion and mu we need to plot tau versus normal stress. And if we do an uncontained uniaxial test then it is very very important that at that time your sigma 3 would be 0 and then sigma 1 has a value when the rock is producing the fracture. So if I take these two points like this here is sigma 3 which is the atmospheric pressure or you can say if you do it in vacuum that there is no value and then I can find by rock deformation that what is

the stress at which the rock produced its first fracture. And say this is sigma 1 and we plot sigma 1 here.

Now, it is possible that considering this length along the sigma N axis as the diameter of a circle we can draw one half circle like this and this is your sigma 3 and this is your sigma 1. So in this case sigma 3 was 0. Now, if I increase the sigma 3, say for example, sigma 3 is now I plotted it here that is the value, I applied some confinement, then we know that with confining pressure the failure strength of the rock increases.

So sigma 1 in that case in the second case has to be certainly higher than the sigma 1 when there was no confinement. And then again I can consider this as the diameter of the circle and draw another circle like this, the half circle. And then I can increase again sigma 3 and plot sigma 1, I can again increase sigma 3 and plot sigma 1 at which the rock is producing the failure.

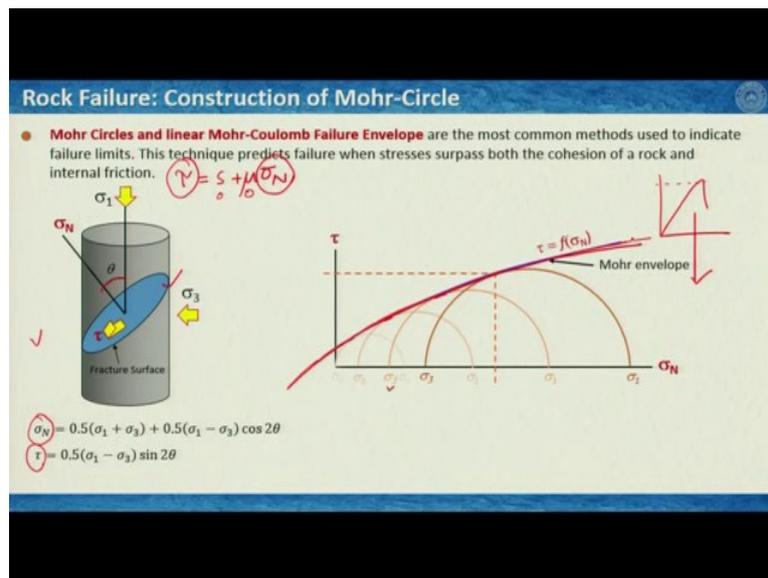
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Now, in doing so we can continuously plot these values and we can see actually that how this evolution of this stress happening. So I do not know if you can see this this is sigma 3 and sigma 1, then the next one sigma 3 and sigma 1, then the next one this is sigma 3 and this is your sigma 1, and then the next one this is sigma 3 and this is sigma 1.

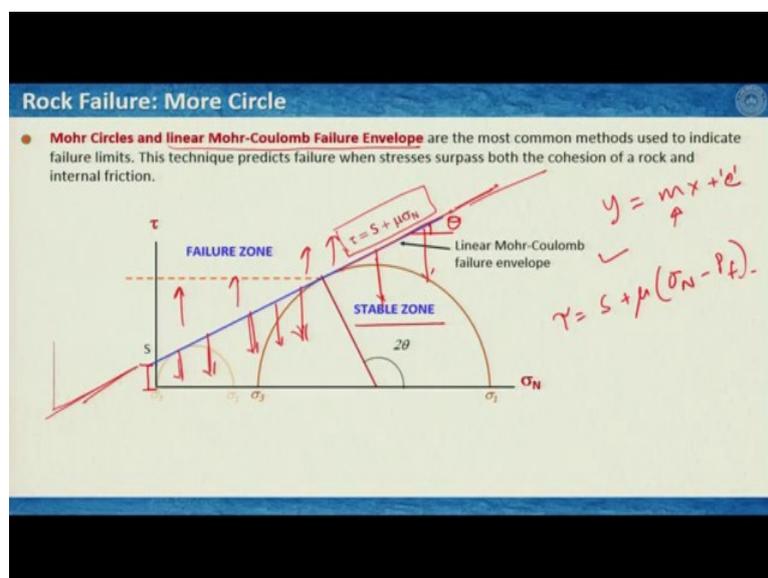
So, what is happening here? At each time I am increasing the confining pressure and as a result the failure stress is increasing from here to here, then here to here and then here to here. The failure stress is at which we see the first fracture is appearing or you can see this like this that this is a stress at which it is failing.

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Now, interestingly this is a plot of normal stress versus shear stress. Now it is possible that I can actually figure out a line which is touching all these half circles and this line which is drawn here with the blue color is known as Mohr envelope. And this, the equation, the expression of this line is essentially where shear stress is a function of normal stress, this is a nonlinear fit.

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Now, once I approximate this non-linear fit to a linear fit for example like this then we call it linear Mohr-Coulomb Failure Envelope the definition is same. Now what happens here, what is the importance of this blue line? In this case you see that this blue line is a straight line and therefore, I can write it in this format and this equation is essentially an equation like y equal

to μx plus c , where c is s , μ is the coefficient of friction. So this value here is the cohesion and this is measured in megapascal and this angle if this is θ then \tan of this angle is the coefficient of friction.

Now, what is the importance of this line that we are drawing or linear Mohr-Coulomb Failure Envelope? If the stress, applied stress stays below this line then the rock is not going to produce any fracture, so this is a stable zone. If the stress is in this side then the rock would produce fractures so or unstable zone. So this line is actually very important to separate out the stable field and unstable field of the rock.

Now, you can clearly understand if I apply pore fluid pressure and start working on then this line would change and they may shift, they may rotate and so on, but you can try by yourself that how it can happen if I apply pore fluid pressure to this considering the fact that $\tau = s + \mu \sigma_N - p_f$. So this is one type of failure criteria that if this line is defining the failure criteria here that if the stress is above this line then we fail the rock or we produce the fracture in the rock and if it is below we do not produce the fracture in the rock.

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Rock Failure Criteria		
Rock Failure Criteria aim to mathematically express the condition(s) at which the failure occurs.		
Failure Criteria	Mathematical Expression	Parameters
Mohr-Coulomb	$\tau = S + \mu\sigma; \tau = S + \mu(\sigma - p_f)$	τ : shear stress
Hoek-Brown	$\sigma_1 = \sigma_3 + \sqrt{mC_0\sigma_3 + sC_0^2}$	$\sigma_1, \sigma_2, \sigma_3$: Principal axes of stresses
Griffith criterion	$\sigma_0 = \sqrt{(2E\gamma_s/\pi a)}$	σ_0 : Critical tensile stress
Bieniawski-Yudhbir	$\sigma_1/\sigma_3 = 1 + B(\sigma_1/C_0)^{0.75}$	σ_0 : Uniaxial Compressive Stress
Modified Wiebols-Cook	$\sqrt{J_2} = A + B J_1 + C J_1^2$	E : Young's Modulus
Modified Lade	$J_1/J_3 = \eta_1 + 27$	$2a$: Length of the initial crack
Ramamurthy's	$(\sigma_1 - \sigma_3)/\sigma_3 = B(C_0/\sigma_3)^{0.75 (0.85)}$	γ_s : Surface Energy/unit area
Tresca's criterion	$ \tau_{max} = 0.5(\sigma_1 - \sigma_3)$	A, B, S, η_1, \dots : Material constants
von Mises Criterion	$0.5[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2] \leq \sigma_y^2$	m, s, μ, \dots : coefficients
Drucker-Prager (Ins. / Cirm.)	$\sqrt{(1/6)[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} = A + B(\sigma_1 + \sigma_2 + \sigma_3)$	J_1, J_2, \dots : Stress invariants

There are many more criteria: original and their modified versions [Rahimi and Nygaard, 2015; IIRMMMS]

Now, there are many other failure criteria and here is a list. The first one is the Mohr-Coulomb failure criteria that we have already learnt and these failure criteria mostly aim to mathematically express the conditions at which failures do occur. Now here are some important failure criteria that people use in rock mechanics or rock fracture mechanics, so Mohr-Coulomb we have learnt.

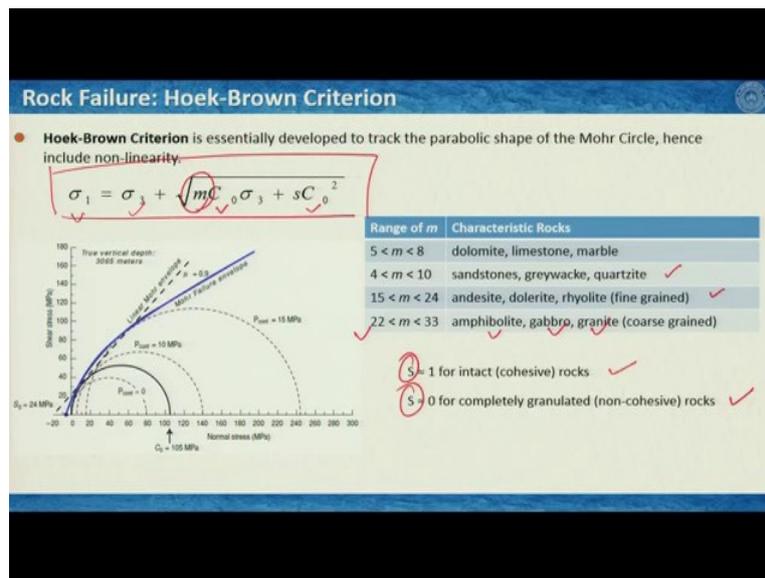
Then there is Hoek-Brown, Griffith criteria, then Bieniawski-Yudhbir criteria, Modified Wiebols-Cook criteria, Modified Lade criteria, Ramamurthy's criteria, Tresca's criteria, von Mises criteria and Drucker-Prager criteria, so it has two inscribed and circumference. These are the mathematical expressions of all these failure criteria and here I have given the explanations of the symbols I have used in these equations.

Now, interestingly let us have a look of these parameters which are actually being used to look at or understand the failure criteria, yield stress, principal axis of stresses, critical tensile stress, I am sorry the first one is shear stress, then yield stress, uniaxial compressive stress, young's modulus, length of the initial crack, surface energy or unit area, some series of material constants, then series of coefficients and the stress invariants.

So we see that all these are related to the stress of the system and at the same time some material constants, material parameters, some material coefficients and at the same time some geometric considerations, length of the initial crack, and so on. So in the following slides we are not going to look at all these, so generally structural geologists or rock mechanics engineer use Mohr-Coulomb, Hoek-Brown, Tresca's criteria and von Mises criteria, sometimes Griffith criterion is also used.

But mostly restricted to a lot of theoretical analysis, however, this list is not complete, if you are further interested you can read this paper which is a very recent paper and there are a series of failure criteria, rock failure criteria and their modified versions and their relationships, their advantages and disadvantages. But in this class we will mostly look at the Mohr-Coulomb failure criteria which we have already seen. Next slide we will Hoek-Brown, Tresca's criterion and von Mises criterion.

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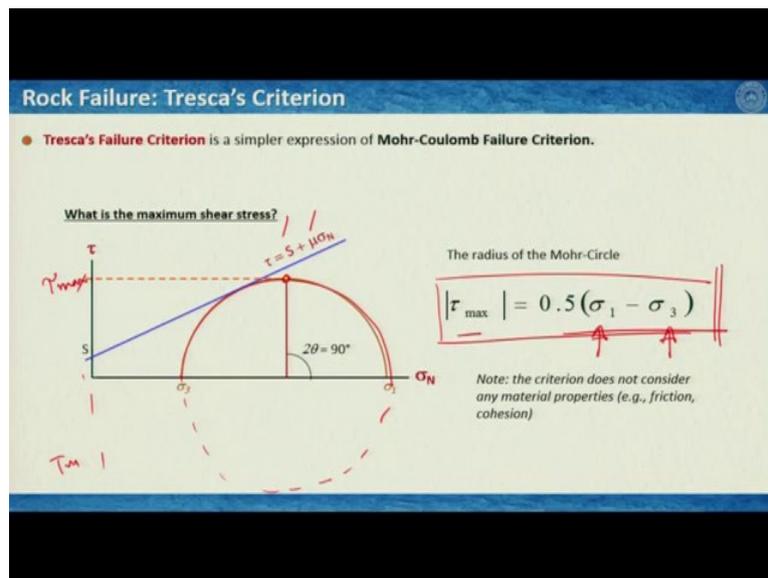


So, Hoek-Brown criteria is nothing but because in our construction of Mohr circle we have seen that the Mohr envelope is actually a nonlinear curve, we approximated it to make it linear Mohr-Coulomb failure criteria to fit in the More-Coulomb equation, but indeed it is a nonlinear fit and to account this nonlinear fit you need to include a non-linear function in your equation.

And this is the expression of this equation and here you have sigma 1 and sigma 3, principal axis of stresses, then you have some material constants C_0 and then you have another parameter which is m . Now m is very very important in Hoek-Brown failure criteria. Now people have done experiments and they figured out that m ranges from 5 to 8 if the rocks are dolomite, limestone, marble so mostly carbonate rocks.

The m ranges from 4 to 10 if these are sandstones, greywackes, and quartzite. m drastically jumps to 15 to 24 when we are dealing with andesite, dolerite, or rhyolite or in other words fine grained intact highly cohesive rocks. And it is even higher when we have m ranges from 22 to 33 when you are dealing with coarse grained amphibolite, gabbro and granitic rocks. Now this s is 1 for intact rocks and s equal to 0 for completely granulated or non-cohesive rocks, so s is the cohesion here and we have learnt later. So this is how they put it in the equation.

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Tresca's failure criteria is the simplest one. Now, if we consider a failure curve like this and this is the Mohr-Coulomb failure criteria so then we can simply figure out that the maximum shear stress here is coming somewhere here, this is the maximum shear stress we can achieve, so this is tau max. And if we are on the negative side then this would be your tau max here somewhere. So, and it tells that it is simply the radius of the circle of the Mohr circle.

So, therefore, tau max is expressed as half of sigma 1 minus sigma 3 and this is the simplest form of Mohr-Coulomb failure criteria. Now, what is very interesting of this failure criteria is that this equation does not involve any material parameter or any material property. Say for example, here we have coefficient of friction and cohesion but it does not include anything only the failure criteria is applicable just based on the principal axis of stresses 2D sigma 1 and sigma 3 and if you go to 3D then sigma 2 comes in the picture.

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Rock Failure: von-Mises Criterion

- The **von Mises Failure criterion** (Maximum Distortion Energy Theory of Failure) suggests that failure of a ductile material begins when the **distortional strain energy /second deviatoric stress invariant** reaches a critical value (Yield Strength).

Yield Strength: σ_y

Second deviatoric stress invariant: $0.5((\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2)^{1/2}$

To satisfy the failure criterion:

Second deviatoric stress invariant \leq yield strength

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 \leq 2\sigma_y^2$$

You can also achieve the same equation by considering the **distortional strain energy** during deformation.

Now von Mises failure criteria is something that really does not deal with fracturing of rocks, but it is one of the important criterion to understand the failure of rocks or in other ways the ductile failure or plastic failure of rocks. We have learnt about it, so I am not going to spend more time on this. But generally von Mises failure criterion or you can call it maximum distortion energy theory of failure suggests that failure of a ductile material begins when distortional strain energy or second deviatoric stress invariant reaches a critical value or the yield strength.

Now, if yield strength is σ_y and second stress invariant is something like that, then von Mises failure criteria is expressed in this way. And you can also achieve the similar equation using distortional strain energy, but we are not going into that part right now.

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Rock Failure: Comparison

- The **Mohr-Coulomb, Hoek Brown and Tresca's Failure criteria** are very similar and one needs only σ_1 and σ_3 .
- The **Hoek Brown Failure criterion** is a better choice as it better-fits the actual Mohr Envelope than linear approximation of **The Mohr-Coulomb Failure criterion**.
- **Tresca's Failure criterion** is further simplified and considers zero friction. Good for metals and deep-rocks, which have yield strength but strength does not increase with confining oressure.
- The **von Mises and Drucker-Prager Failure criteria** include intermediate principal stress (σ_2) and therefore require true polyaxial experimental data, unless boundary conditions are applied.

Data from Shirahama Sandstone, Japan
(Colmenares & Zoback, 2002)

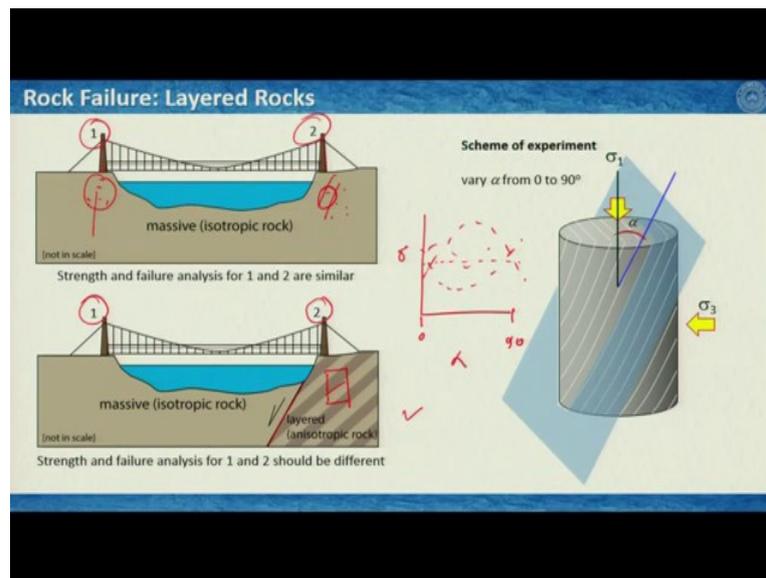
Criterion	C_0 (MPa)	μ	m	S
Mohr-Coulomb	110	0.65	-	-
Hoek-Brown	90	-	9.6	1
Wiebols-Cook	75	0.65	-	-
Lade	85	0.55	-	-
Drucker-Prager (Inscribed)	175	0.50	-	-
Drucker-Prager (Circumscribed)	110	0.35	-	-

So here is some comparisons of these failure criteria that we have learnt Mohr-Coulomb, Hoek-Brown and Tresca's failure criteria together with von Mises failure criteria. Now, what do we see here? These are your some data that for you can get from a sandstone which is I took from this paper and you see it for different failure criteria these values do vary significantly.

And therefore it is somehow important to understand that which failure criteria I should use at which point or which particular application I am going to do. So the Mohr-Coulomb, Hoek-Brown and Tresca's failure criteria are very similar and one needs only sigma 1 and sigma 3, the cohesion and coefficient of frictions do come automatically. The Hoek-Brown failure criteria is a better choice as it better feeds the actual Mohr envelope than the linear approximation of the Mohr-Coulomb failure criteria.

The Tresca's failure criteria is extremely simplified and considers 0 friction of the rocks, good for metals and deep rocks which have yield strength, but strength does not increase with confining pressure. The von Mises and some related Drucker-Prager failure criteria include intermediate principal axis of stress sigma 2. And therefore, require true polyaxial experimental data unless you have some sort of boundary conditions, I mean whether you are doing in 2D then you can exclude sigma 2 and can deal with only sigma 1 and sigma 3.

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Now, is this always true that we talked about that when we have to consider the rocks are always isotropic, rocks are always homogeneous, they are so on. Now consider a situation as a structural geologist you are there to build a bridge across a river. So you can imagine that these are the pillars that we have to build and you have to suggest that how much strength this rock can have to hold the pillar for quite a long time.

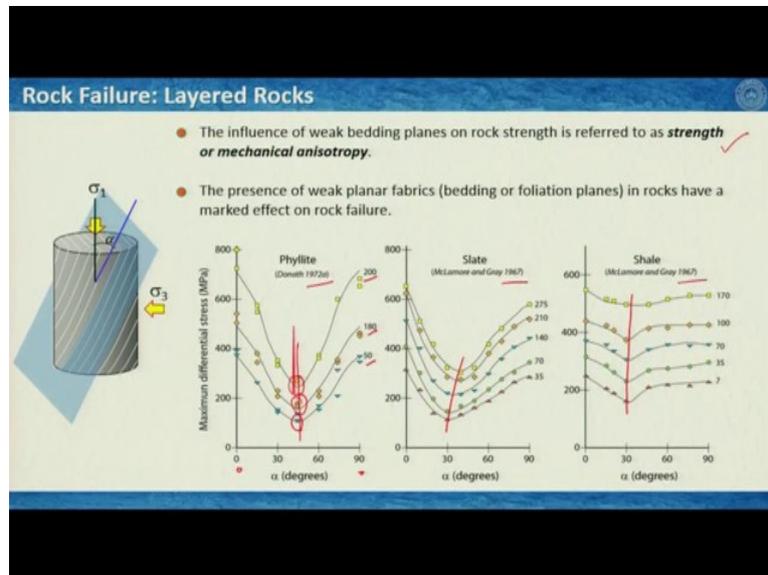
So, what generally you do? You can take a sample from here, you test in the laboratory, you do series of measurements and then suggest yeah this is the strength of this rock, so the weight load of the pillar on this rock should be less than the strength of the rock and there are some other calculations you go with this. And then you also survey here and you see the rock is very similar that you have seen here. So you suggest the similar treatment for pillar 1 and pillar 2.

However, in this case, in the second scenario if you have a fault here and the rocks in this side is layered or anisotropic rock, then the situation here and the situation here for pillar 1 and pillar 2 would be essentially different. And this is where the deviations do come in the, in our understanding. So, what do you do? You actually scheme an experiment where you take this rock from the field and then you vary this angle as I have illustrated here.

When you vary this angle alpha then you can plot actually the strength of this rock, the failure strength of this rock say sigma with respect to this angle 0 to 90 degree and then you see whether the strength is constant, strength is changing like this, strength is changing like this or so on. So how your orientation of the layering or orientation of the bedding planes

foliation or in general planar fabric is influencing the strength of the rock considering that rock is anisotropic.

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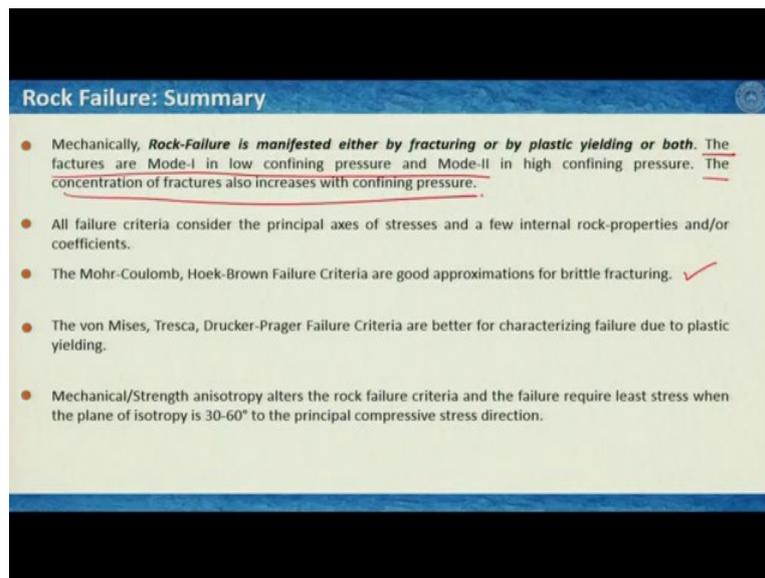


So, people have done a series of experiments and this is how are the results. The influence of weak bedding planes on rock strength is referred as strength or mechanical anisotropy. The presence of weak planar fabrics bedding or foliation planes in rocks have a marked effect on rock failure. As you can see here again these are very old experiments, people still do, continue this kind of experiments.

So these are the alpha, the degrees 0 to 90 degree and this is maximum differential stress where the rock fail. These values are the confining pressure, so at 50 megapascal confining pressure we see that when the angle is about 45 degrees the strength is lowest and this is for the all confining pressure ranges only the strength increased but failure happens at very very low stress compared to the angle, so when it is either parallel or perpendicular to the loading direction.

For shale this shifted towards 30 degrees and for shale here as well in a different shale it shifted around 30 degrees and these are due to some rock properties. But what is the take home message from this slide is that an isotropic homogeneous intact rock may have a strength which is completely different if the similar composition we have but rock is layered or foliated, then the strength of this rock actually or failure of this rock is a function of the orientation of these layerings with respect to the loading direction.

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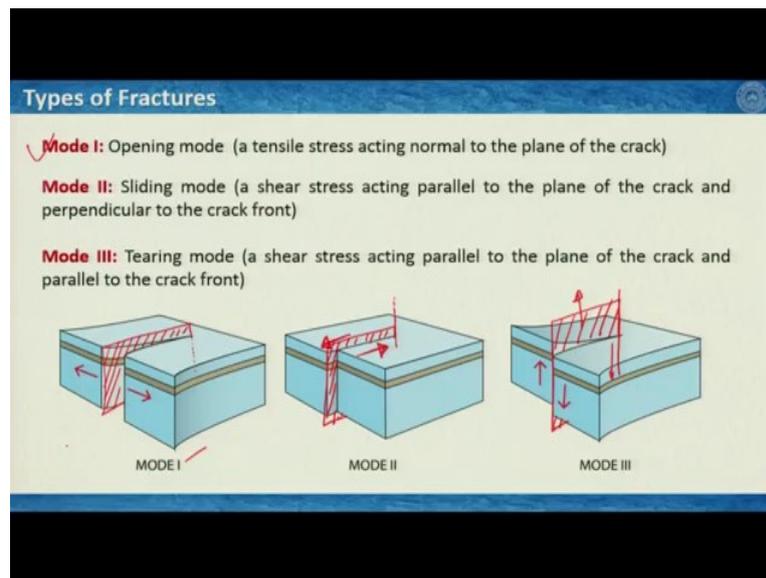
Rock Failure: Summary

- Mechanically, Rock-Failure is manifested either by fracturing or by plastic yielding or both. The fractures are Mode-I in low confining pressure and Mode-II in high confining pressure. The concentration of fractures also increases with confining pressure.
- All failure criteria consider the principal axes of stresses and a few internal rock-properties and/or coefficients.
- The Mohr-Coulomb, Hoek-Brown Failure Criteria are good approximations for brittle fracturing. ✓
- The von Mises, Tresca, Drucker-Prager Failure Criteria are better for characterizing failure due to plastic yielding.
- Mechanical/Strength anisotropy alters the rock failure criteria and the failure require least stress when the plane of isotropy is 30-60° to the principal compressive stress direction.

So, from the rock failure part or that we have learned so far we can summarize that mechanically rock failure is manifested either by fracturing or by plastic yielding or both, but in this lecture we will be mostly concentrating on fracturing processes. The fractures are mode 1 in low confining pressure and mode 2 in high confining pressure, this is something we are going to learn very very soon. The concentration of fractures also increases with confining pressure, again we are going to learn this soon.

All failure criteria considered the principal axis of stresses and a few internal rock properties and or coefficients. The Mohr-Coulomb, Hoek-Brown failure criteria are good approximations for brittle fracturing and this is what we have to consider. However, the von Mises, Tresca and other failure criteria are better for characterizing the failure due to plastic yielding. And finally you have learnt in the last slide that mechanical strength anisotropy alters the rock failure criteria and the failure required least stress when the plane of isotropy is around 30 to 60 degrees to the principal compression stress direction.

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So in the previous slide we talked about mode 1 and mode 2 fractures and here are the explanations. Mode 1 is an opening mode fracture where a tensile stress acting normal to the plane of the rock. Mode 2 is a sliding mode and it is conceived as a shear stress acting parallel to the plane of the crack and perpendicular to the crack front. Mode 3 is a tearing mode fracture where a shear stress acting parallel to the plane of the crack and also parallel to the crack front.

Let us have a look on these three illustrations, this is mode 1 you see here this is the fracture and this is the fracture tip. So our tensile stress acting normal to the plane of the crack so this is essentially the plane of the crack as you can see here. And these tensile stress, these two red arrows are acting normal or perpendicular to the plane of the crack and if that conditions are satisfied then we call it mode 1 fracture or tensile fracture or opening mode fracture.

Mode 2 fractures are shear fractures or sliding fractures where again this is the fracture plane and this is the fracture tip the way the fracture is propagating in this direction it says that a shear stress of course a shear stress is acting so because this is going this way, this is going this way along the fracture plane of the crack and perpendicular to the crack front. So this is the crack front and this is acting perpendicular to the crack front.

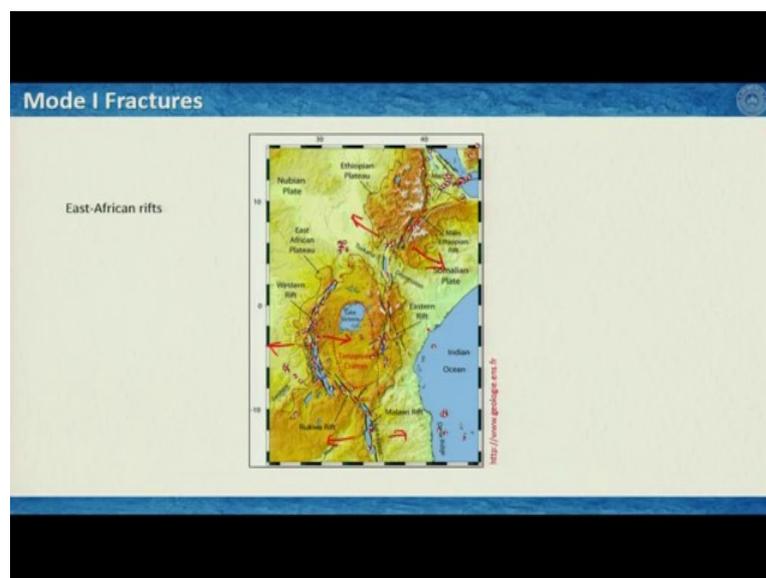
The tearing mode or mode 3 on the other hand again this is the fracture plane I just do this here to demarcate this is a fracture plane and what it says that a shear stress acting parallel to the plane of the crack so it is acting parallel to the plane of the crack as we can see and also

parallel to the crack front, this is the crack front and it is acting also parallel to the crack front unlike the sliding or shearing mode.

So, mode 1 fracture is opening mode you open it, you open the fracture. Mode 2 is sliding or shearing mode something like that and mode 3 is tearing mode something like this. So in mode 1 we generally open space between the two fracture walls. In mode 2 and mode 3 we generally, typical mode 2 and mode 3 fractures you generally do not open a space between the two fracture walls.

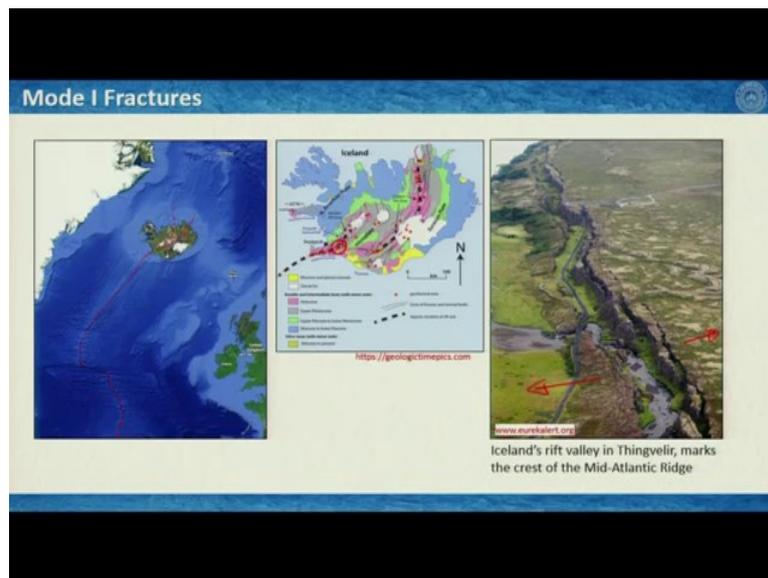
Now, there are many geological examples of mode 1, mode 2 and mode 3 fractures. And these examples range from very very large scale to micro scale. I am not going to show you all of them, but I particularly focus on mode 1 fractures and in the following slides we will see how these mode 1 fractures we can actually observe from a very large scale to a very small scale. Mode 2 fractures we will see anyway when you will be dealing with shear fractures.

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So here is the large scale example of mode 1 fracture and this example is from East African rift. As you can see here this is the eastern part of the Africa continent and this is actually opening, so what we see here these are demarcated by lot of lakes or water bodies and along this this continent is actually rifting. And therefore, we have a continental scale mode 1 fracture produced here.

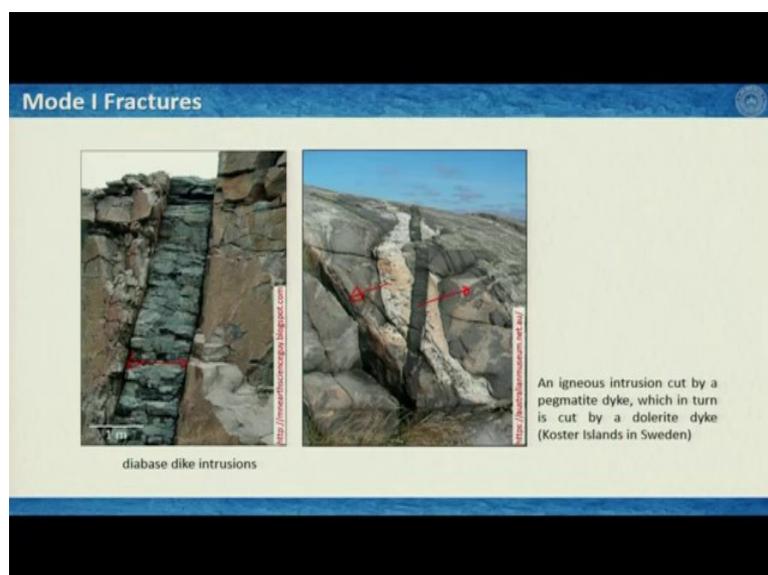
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We would like to see another example and we would go to Iceland, what do you see here? This you see is the mid-oceanic ridge in the Atlantic and it passes through here and then it goes here and here and so on, so this is known as the hinge zone of the Mid-Atlantic ridge. And if we see the map of the Iceland we see that the ridge is coming like this, this black dotted lines, then it is one going here, then there is another one which is going like this.

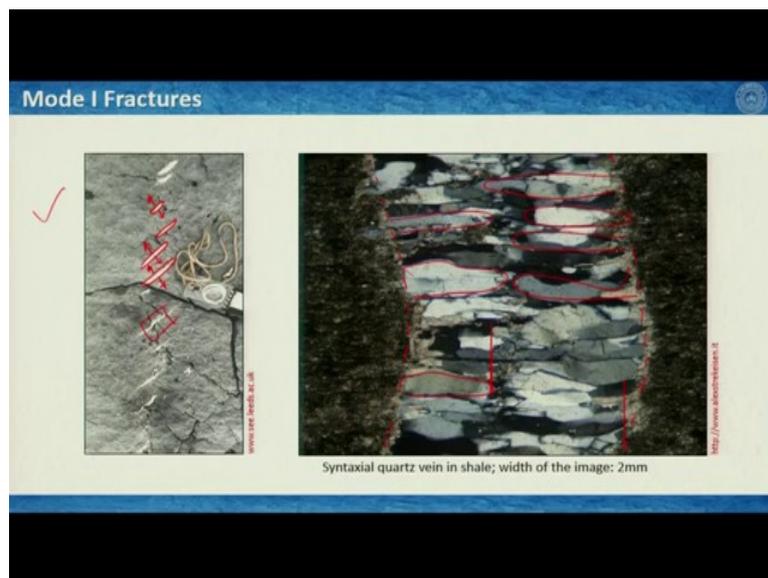
If I take you somewhere here then you see it is like this and this is essentially a mode 1 fracture where it is rifting this side and this side. So you see a space is being created, a river or whatever is flowing through this and this is Iceland's rift valley that actually marks the crest of the Mid-Atlantic ridge and this is essentially an expression of mode 1 fracture.

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In the field scale, yes, we see dikes and these are one of the classic examples of mode I fractures as you can see a diabase dike intrusion here in this rock this one and here there are two different dikes at two different generations, the first one is a pegmatite dyke and the second one is a dolerite dyke the black one. So this example is from Sweden, so you can see a tensile domain is remaining as a tensile domain and it happened in two different generations and it is continuing fracturing it at least in two different stages.

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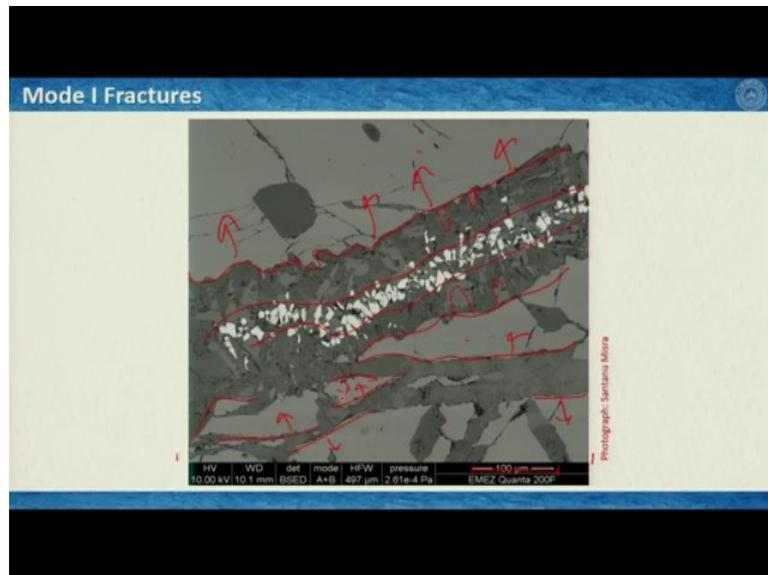
So these were the examples from the field scale or mesoscale. Now let us see some examples also on the field scale and that the microscale at the same time, what do you see here in this image, that you see this little white marks here these are actually tensile fractures, we will see it soon how does it happen. But clearly you see this these little things, these small fractures they have some sort of opening.

So the fractures were opening in this way. And these are typical initial on or initial and fractures generally happen due to shearing of the rocks, we will learn about it soon, but these are examples of mode I or tensile or opening mode fractures. Now, if you make a thin section of this kind of features then you will see under thin section that these are the host rock or the country rock which is in this case shale and this opening fracture is filled by this quartz fibers and these we do not call like opening fractures or something like that.

Here in this case as I said this we call vein or something like that which is filled by some sort of minerals. In this case this is quartz, but there are many many veins which are filled by

economic minerals and therefore these are also very-very important to study fractures in the structural geology.

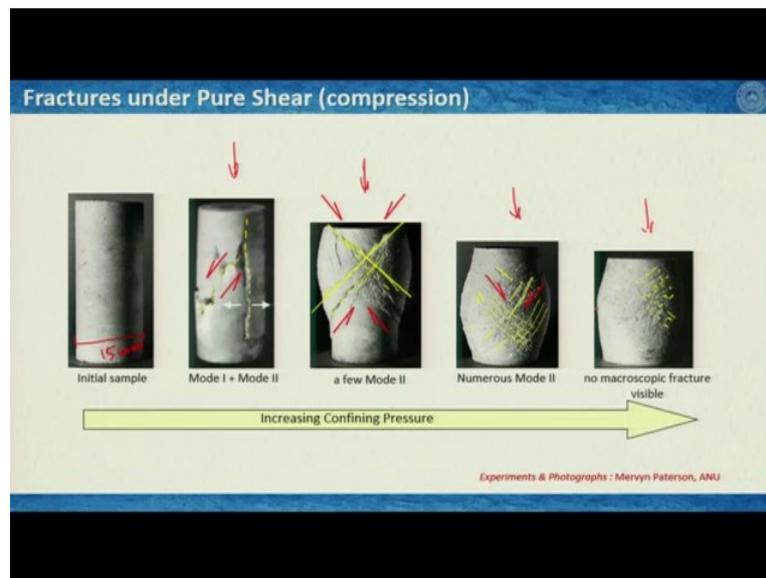
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And this is a even further micro scale so this is the scale is about 100 microns so you can imagine that the entire width of this image could be close to 500 microns and what do we see here that this is a host matrix, a single grain and you see this grain got fractured in different ways so these are essentially opening mode fractures. And in a very similar way that we have seen in the quartz we see that poly mineralic deposits happened here and at the middle we have some oxides.

Now, people study this for different purposes but here we are trying to understand the mode 1 fractures and we are trying to see this in different scales. So these are the opening mode and it happen and in different ways maybe same time or in different times and this is what people generally do observe and do research on this.

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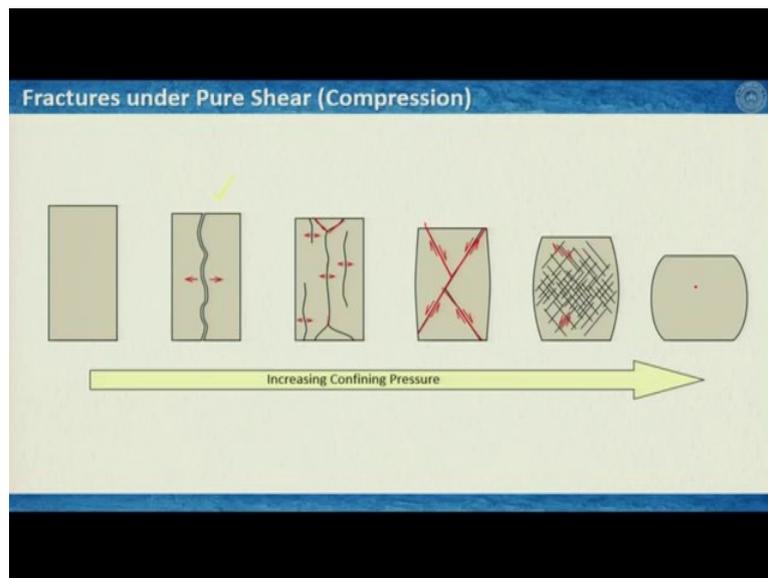


Now, we will switch to the next topic of this class which feature fractures under pure shear or under compression and then fractures under simple shear and we will see what are the different ways the fractures do form. The image as you see here in this slide are the classic examples of rock deformation experiments performed by Mervyn Paterson. So these are Carrara marble samples and this is the initial sample the diameter of the sample was 15 millimetre.

And from here the experiments, different experiments were conducted with increasing confining pressure and as you can understand from the shape of the samples that these samples were compressed, what do you see here when the confining pressure is very very low? Then we see that opening mode of fractures are appearing, opening modes fractures here and shear fractures here and they are less in numbers with little more increase in the confining pressure we see that mode 1 fractures are gone from the system and we mostly see mode 2 fractures in two different sets one set is like this, another set is like this.

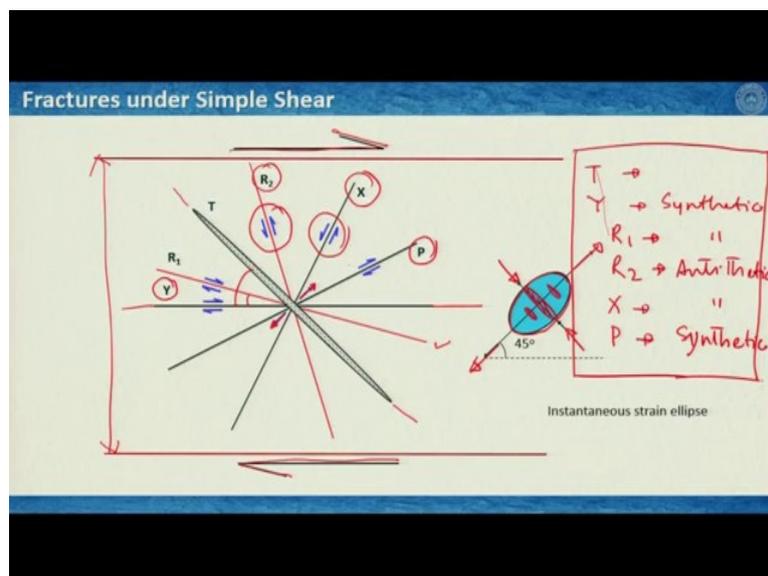
With further increasing of the confining pressure we see numerous mode 2 fractures as you can see here from this little yellow dotted shades, when we go with further confining pressure a higher confining pressure or highest in this range of experiments you hardly see any macroscopic fracture. However, a very close look would give you an impression that a series of very tiny small-scale fractures in the sample. So there is a transition from the fracture patterns with the confinement of the sample.

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And if we try to summarize it in a different way by sketches we can figure out that when the confining pressure is low or no confinement then the rocks would produce mostly tensile fractures as we have seen here. When we have a little more confining pressure then we see a combination of tensile and shear fractures with further increase of the confining pressure we see that conjugate sets of shear fractures do appear in the sample with more confining pressure and numerous number of shear fractures in conjugate sets and at highest confining pressure we hardly see in the sample scale any shear fractures or any conjugate shear fractures. However, under microscope if you make a thin section of this you may see some sort of very-very densely packed conjugate shear fractures.

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The scenario somehow changes a lot when we go with simple shear, so a rock is being deformed under simple shear and in brittle domain in that case we produce or there is a possibility of production of number of different shear fractures one set of tensile fracture and the shear fractures would have different sense of movements with respect to the bulk shear.

So, let us have a look if this is the brittle piece of the rock and we are applying a dextral sense of shear or clockwise shear then it would produce primarily a tensile fracture in this orientation because once you have setting like this then your instantaneous strain ellipse would take a shape like this and you can figure out that this is your extension direction and this is your compression direction.

So clearly perpendicular to the extension direction you would produce tensile fractures, series of tensile fractures you would produce. And if you remember in one of the slides we have seen in one of these type of fractures. So these are opening mode of fractures in sheared rock deforming in brittle domain. One set of fractures you can expect which is parallel to the bulk shear direction and these are known as Y shear fracture.

The sense of displacement in the Y shear fracture is synthetic that means the sense of shear is very similar to that of the bulk shear, then you form a very low angle shear which is marked by this red line and this is known as R1 or low angle riddle shear fracture, this angle is typically 10 to 20 degrees and classically at 15 degrees. The sense of shear is also synthetic that means the displacements happening along this shear fracture is very similar to that of the bulk shear.

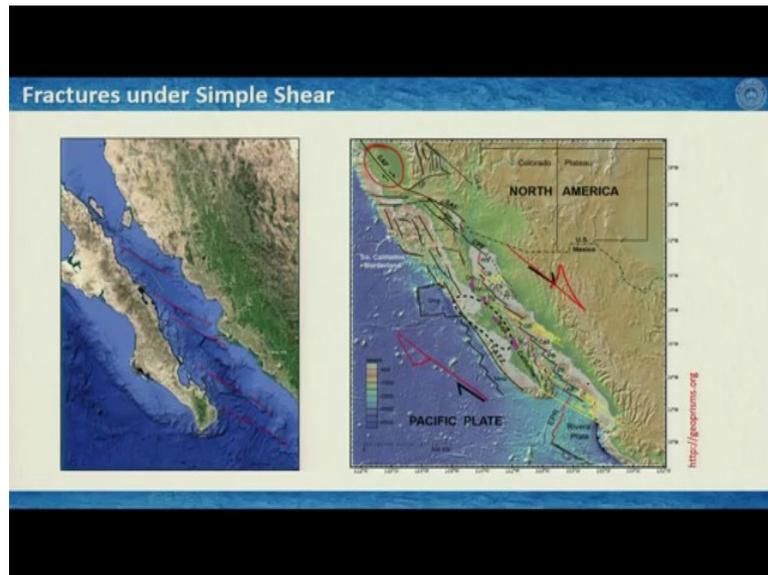
You form another set of shear fractures which are known as R2 or high angle riddle shear fractures this angle is typically 75 degrees and here interestingly the sense of shear is reversed that means it is antithetic. So the shear sense is here sinistral, but bulk shear is dextral.

Some sort of mirror image of these two fractures form on the other side of the shear zone or brittle shear zone. One is P shear fracture where the sense of displacement is synthetic similar to the bulk shear direction and then we have another set of shear fractures X shear fractures where the sense of shear is opposite to the bulk shear direction or this is antithetic.

So if I try to list tensile fracture which is generally at 45 degrees then Y shear fractures which is synthetic, then we have R1 which is synthetic, we have R2 which is antithetic, we have X which is again antithetic and P which is synthetic. So there are a lot of possibilities where we

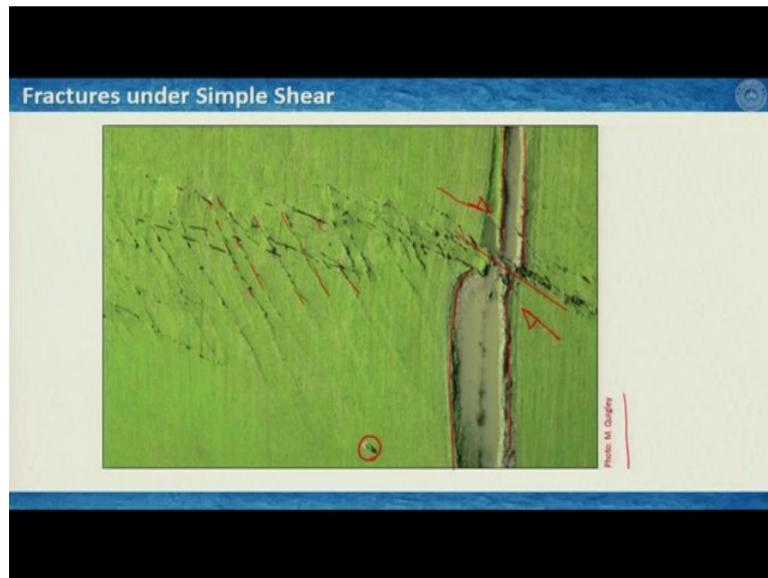
can form all these 1, 2, 3, 4, 5, 6 types of fractures in a brittle shear zone, but interestingly it is very rare that you see all these fractures in a single place. So here I would like to give you some examples again that how do these shear fractures do happen in large scales in small scales and then what is the general implications of these shear fractures and their mutual interactions with the local and global stress regime.

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The first example I would like to take you to the Gulf of California, so what we see here this is again a kind of rift zone, but it is with a shearing mode and you can see here this little fabrics and these are apparently your low angle riddle shear fractures here is a map so this North American plate is moving in this way and Pacific plate is moving this way and this is tearing this the San Andreas Fault is somewhere here, so these are all low angle riddle shear fractures and they are being connected to each other and this produce a lot of earthquakes.

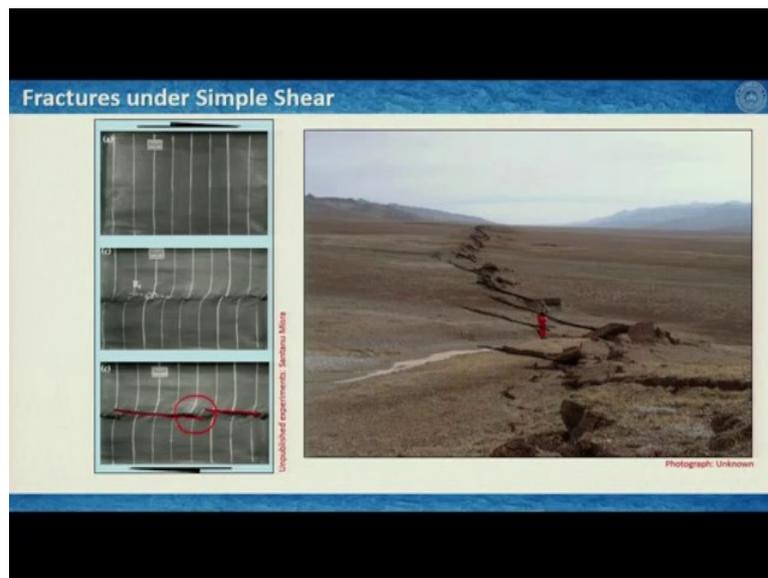
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Now, this is a very important or interesting photograph this is an aerial photograph, if I do not tell you it is not possible for you to understand what it is but what we see here this is a canal right and you see this got a shift along this I said this is an aerial photograph so this is a field and this could be a cow or something like that you can consider as a scale and this photograph is taken by Mark Quigley of University of Canterbury in New Zealand and these typical structures were produced during the 2011 earthquake in the Canterbury.

And you can clearly see the two sets of fractures here, one set is like this and another set is like this. Now, based on this if I ask you that look at this image and figure out what was the bulk shear direction it will not be something I would like to ask you at this stage and you try to figure out and send me an email or to the TAS or posted in the discussion forum that what is the bulk sense of shear in this structure at looking at these shear fractures what you can figure out, what was the sense of shear in this area.

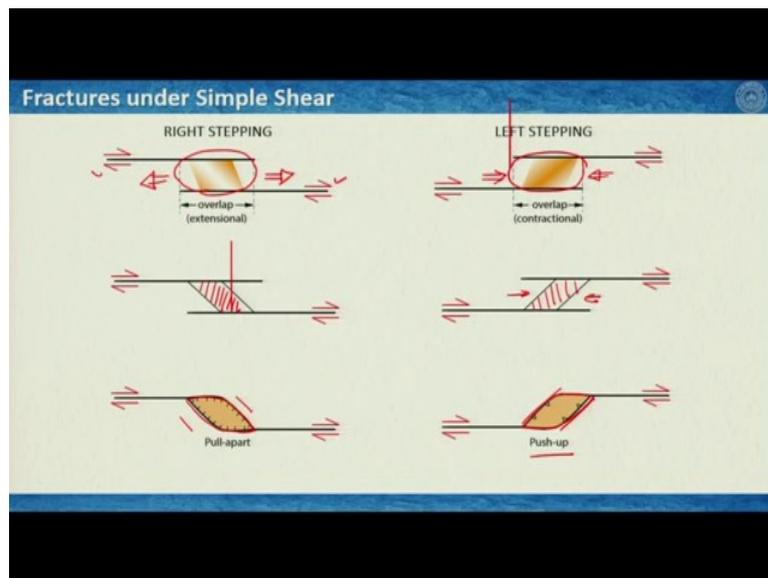
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Now, not necessarily these shear fractures are continuous so when you produce this low angle riddle shear fractures they generally make some step overs. So this is an example that I performed with the clay models and you see that we have shear fractures one set like this, another set like this, one set like this and so on and this you also see in the field, you see one is here, one is here, another is here and here, here and so on, so this is how it happens.

So you have series of shear fractures at low angle or high angle or different ways and they together define a fracture zone a shear fracture zone, but it has an excellent implications when these steps or these shear fractures do interact with each other what I mean by that you see this was a fracture here and this was another fracture and from the shadows here you can figure out that this part got elevated and we will see that why and how does it happen.

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So we have two possibilities one it is right stepping and another is left stepping what do I mean by this that you have two shear fractures and this is their overlapping zone and this part as you can see is moving this way and this part is moving this way because of the sense of shear in this side. Interestingly if you have a left stepping which is similar sense of shear dextral, you can see this is a compressing here and this is also compressing here.

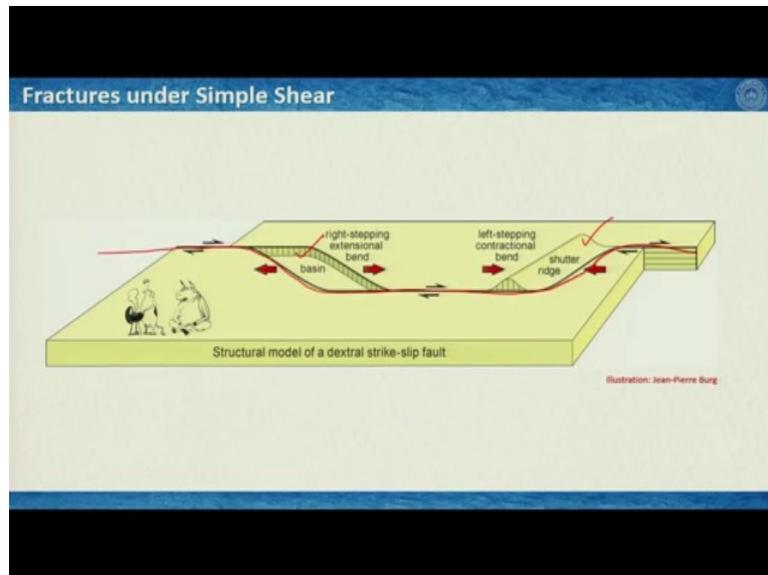
So this domain is under compression and this domain is under extension, this overlapping zone. When they connect eventually you form an area something like this in this particular case this is under extension and in this particular case this is under contraction. So what you finally come out that here you form a basin that this part is moving this side and this side and these are characterized this boundary is characterized by normal faults and in this side you have oblique normal faults, we will learn about what is normal fault, what is oblique normal faults later.

And we will also connect these when we learn large scale processes particularly in terms of the strikes defaults and other places. Interestingly this side because we are compressing this so this place would get pushed up and therefore it is known as push up, so these boundaries would be characterized by reverse or thrust faults and we will have oblique reverse or thrust faults here.

So you see that the same process in one setting if it is right stepping in the overlapping zone it is possible to form depressions or pull apart basin and if it is left stepping then in the

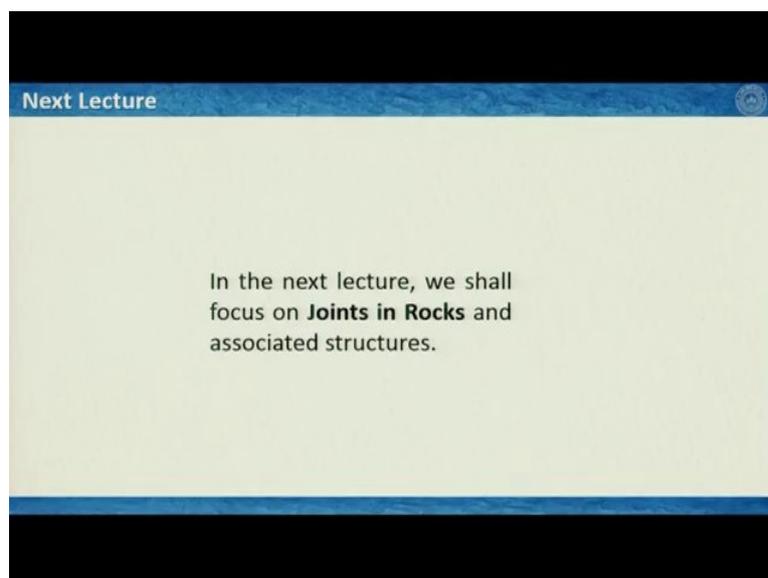
overlapping zone instead of forming a basin we can form a mountain or a hillock or topographic elevation due to push up.

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Jean-Pierre Burg came out with a very excellent illustration and I did not reproduce it. So this is from his lecture notes as you can see here the same sense of shear this is your master fault and here you form a basin and here form a ridge or some topographic elevation and known as shatter ridge, so this is associated with a dextral strike-slip fault, we will learn more about it. But it is important to understand that when the fractures to interact they can form the series of different structures in between. With this note I conclude this lecture.

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And in the next lecture we will talk about Joints in Rocks and associated structures, thank you very much, see you in the next lecture.