Structural Geology
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Lecture 14
Deformation Mechanism
Part 2 Cataclastic Deformation

Hello everyone! welcome back again to this online structural geology NPTEL. Today, we are in our lecture number 14 and you are learning deformation mechanism of rocks. Since, in the previous lecture we learned about different types of crystal defects. And, today we will mostly focus on cataclastic deformation which generally happens at the surface, or shallow part of the earth.

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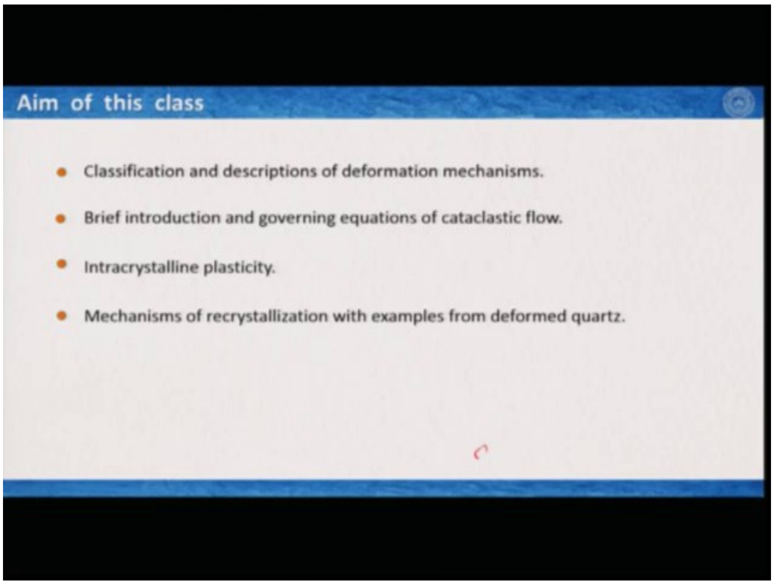

And we will follow intra crystalline plasticity and then mechanism of recrystallization with examples from deformed quartz in the next lectures. Now, in this lecture I will classify the deformation mechanism. And, then we will mostly spend the entire time on discussing the different processes of cataclastic deformation, or brittle deformation. Mostly, we will focus in the microscale processes or grain scale processes.

Before discussing on the actual process and classifications let us have we have learned about some basics. So, the deformation of rocks as I told in the last lecture is achieved by various processes. And it is now a quite obvious and well established, that does not matter how large is the scale of the deformation. Deformation do initiate at a very very small scale in the crystal scale. So, large fault if you consider it initiates with a very tiny fracture or number of tiny fractures.

Accordingly, either the tiny fracture propagates in response to stress, or lot of tiny fractures the cordless; and then propagate together to give rise scale faults. So, now all this process at least today, we will learn cataclastic processes.

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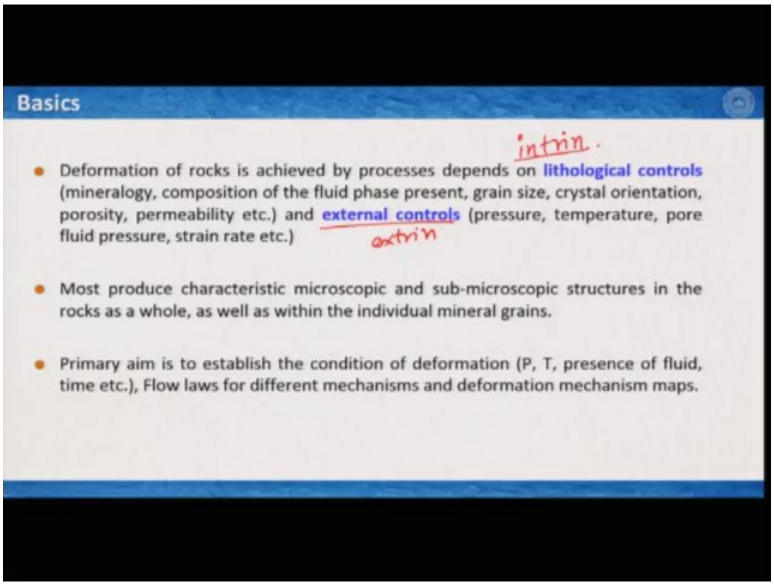

This is mostly achieved by different process and these processes are functions of measuredly two parameters. One is the lithological controls, or sometime we call it intrinsic parameters. So if i write it like intrinsic parameter and then another is external control so, that is known as extrinsic. Now, within the intrin sick or lithological controls you may think of the parameters, which are inherent of the rock. So, that is mineralogy you can think of composition of the fluid that you have in the rock or different grain sizes, crystal orientation, porosity permeability etc.

On the other hand external controls are the ambiance where the rock is being deformed. So, there you can think of pressure temperature, pore fluid pressure, the rate of deformation or strain rate etc. Now, while this process are this parameters are controlling the deformation process And, while the deformation do happen under the different controls, than they produce characteristic microstructures and submicroscopic features.

I want to say that a brittle rock or a rock that has undergone brittle deformation, would have a very typical micro structure to that of a rock has under gone a ductile deformation. And this you probably have seen in thin sections, if you have at all studied this. We will learn more about it in the next lecture; will have some photograph of these thin sections, in this lecture as well particularly relevant for brittle deformations.

But, the point is that looking at the microstructures you can certainly figure out, that the mechanism or the process of deformation was different at different regimes, if you consider this whether brittle or ductile. Now, based on that people do study deformation mechanism of rocks, primarily to understand or establish the ambiance and at the same time different internal controls.

So, it could be the grain size or the mineralogy and so on. So, we generally get all this information through experiments and then we match it with natural deformation, natural deformation rocks. So, we vary pressure, temperatures and we change the composition of different fluids. We deform the rocks at various times etc. So, we do all these sort of things and then we plot them in different ways, may be it stress verses strain or maybe it strain rate verses stress, pic stress verses strain and with the control or pressure temperatures and so on.

We have seen this one of the last lectures and then out of this curves we infer different parameters, rheological parameters. And, based on these rheological parameters we find the constants. So the final aim is to figure out that what could be the flow law, that what sort of rheological law is applicable to this kind of studies? And therefore we theorize it by experiments. And then the people who do numerical modeling, or even analytical modeling.

They use these sorts of parameters or some basic equations to fit in their large scale numerical model and get the bigger picture. So this is how the different disciplines of structural geology if you can think our different ways of looking at structural geology. Someone goes to the field collect rocks in sections then someone does the experiments and someone does numerical modeling. And as a hole we get a comprehensive idea of the entire process.

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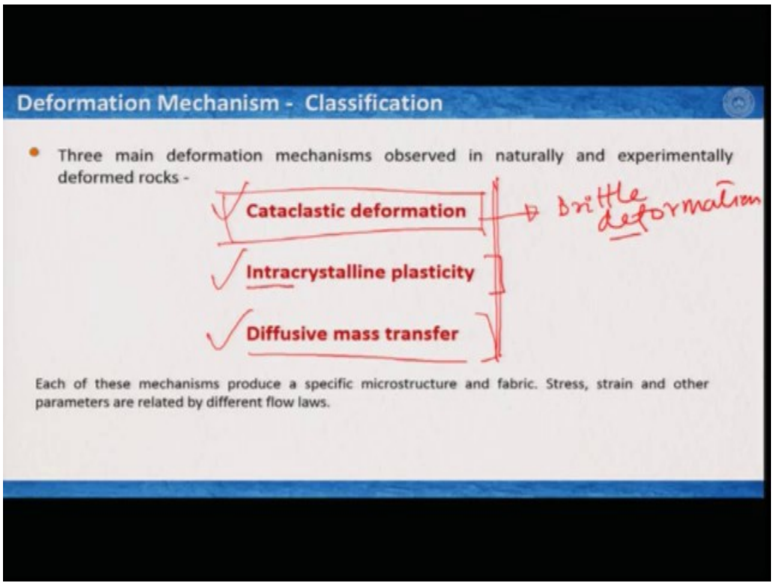

So, if we try to classify or the deformation mechanism that we are talking about. Then there are three major categories or three major classes of deformations mechanism. And, this is mostly derived by observing the naturally and experimentally deforms rocks. The first one is cataclastic deformation, second one is intracrystalline plasticity and third one is the diffusive mass transfer. As, the name suggest we can figure out that.

Cataclastic deformation is mostly considers brittle deformation. Where rocks do fracture the intra crystalline plasticity is something where we consider the deformations of grains and this deformation of grains do happen at high pressure and particularly are high temperature. Where all these defects that we have learned in the previous lecture, do influence or do govern the deformation. So, it is a deformation within the crystal so, please remember this terms intra crystalline not intar crystalline.

And then of course the diffusion is one of the very important process of deformation and we learn about it in our lecture number 14.3. So, today we mostly focus on cataclastic deformation. And as I said in the previous slide that each of this, be it cataclastic be it intra crystalline be it diffusive mass transfer.

If you look microstructure they are characteristic for each and every process. So, they produce different types of fabrics, different types of appearance of the rock under thin sections and so on. And, people do study not only under optical micro scopes but, electron microscopes particular scanning electron microscopes and transmission electrical micro scopes are now a days very useful.

And in recent days, there are some other tools that you can use even though or check the atomic scale process using atom prop tomography and so on. So, again the primary aim of studying these three mechanisms is to figure out the different relationships between stress strain and other parameters. That how they are related and how we can put them together in different flow laws.

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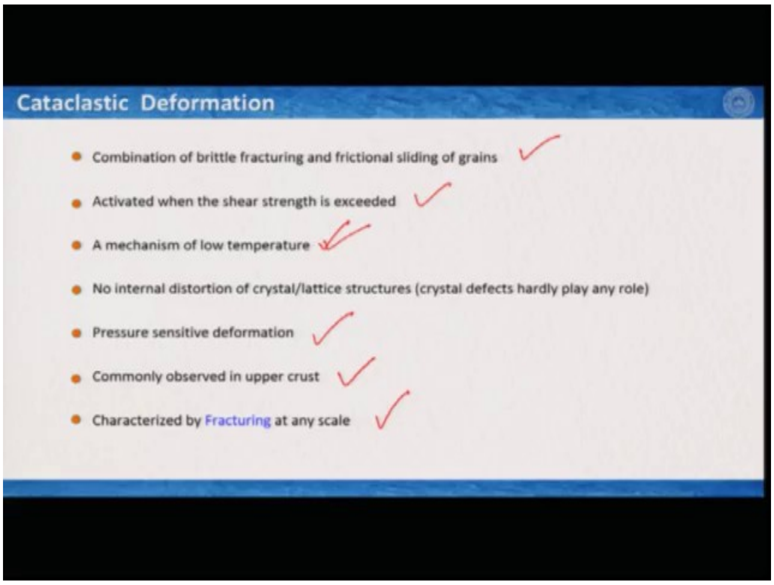

So, let us start with cataclastic deformation mechanism. And, we will first learn that what are the characteristic of cataclastic deformation? So, I have given a list here in this slide. Cataclastic deformation is nothing but, when your grains do fracture or you have sort of fictional sliding of the grains. So, it is the combination of brittle fracturing and frictional sliding of grains. And if you have fracture or frictionally slide the grains from one past to another. Then it is activated only, when you exceed the shear strength of the rock, or shear strength between two grains, we will learn about it later.

Brittle deformation or Cataclastic deformation as we have learned that, it has to be a low temperature process. Therefore, we mostly see this either on the shallow crast or on the surface. As I said that there is no internal distortion of the crystal or lattice structures during cataclastic deformation. So, crystal defects hardly play any role in cataclastic deformation grains. Just do fracture they rotate, they break, they just slip us each other. But, the internally the crystals do not show any special type deformation.

If, that happens then it is intra crystalline plasticity which we will learn about it next lecture. The deformation is not that temperature sensivity, as I talked about in this point, that it is a mechanism of low temperature. But, pressure do play all sort of pressures, you can think of the confining pressure, you can think of the port fluid pressures. They do play a very important role in controlling the different process of the deformation mechanism under cataclastic deformation. If you recall we have learnt that the strength of the rocks do very greatly.

When we vary the pressure and poor fly pressure. So, as I said that this is presensitive and at the same time it is low temperature deformations. So, we commonly observe at the upper crossed, or on the surface or at the shallow surface of the earth. And essentially it is characterized by fracturing at any scale. But, today we mostly look at the fracturing at grain scale. Now, we can classify the entire range of cataclastic deformation in three basic ways.

The first one is localized deformation sometimes we call frictional flow, with a special characteristics, second one is granular flow and the third one is cataclastic flow. So, in the entire lecture actually, we look at these three basic process of cataclastic deformation. As you can see it is not typical flow but, rock do deform. They move from one point to another point.

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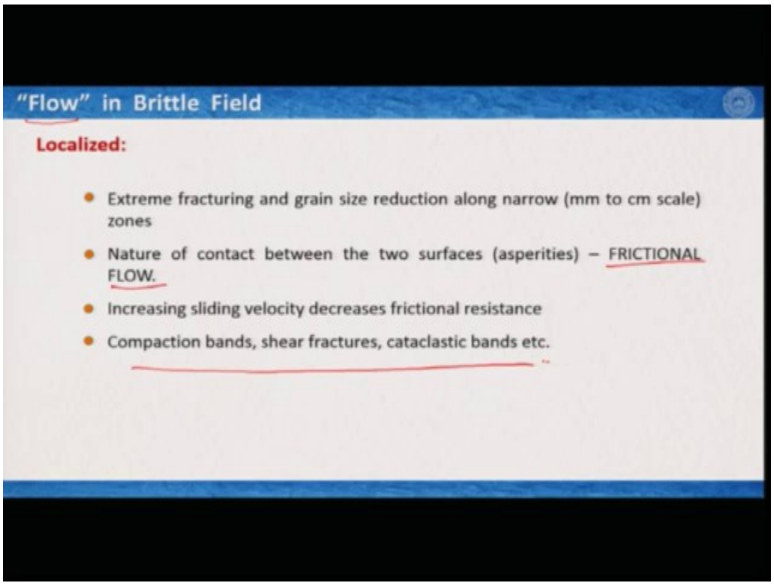

Therefore I used this word flow here but, within inverted commas. So, let us look at the first process which localized cataclastic deformation. Generally, the characteristic of this localized this cataclastic deformation includes, extreme fracturing and grain size reduction along a narrow zones. So its extremes fracturing and grain size reduction along narrow zones. And when I talk about narrow its millimeter to centimeter scale. Now, this fracturing or grain size reduction may happen by compaction, or may happen by shearing.

So, sometimes the nature of contact between the two surfaces, which we will learn later, is called asperities. If, that type of flow do happens, that means one is sliding first to another in grain scale, then sometime we call them as frictional flow. Now, clearly if you increase the sliding velocity, or if we increase the strain rate, that decreases the frictional resistances. So, therefore the sliding velocity or the force if you have more than, you quickly deform the rock.

And as an example of localized deformation you can sight many. So, compaction bands are there shear fractures are there. And, sometimes cataclastic bands are also included in the localized type of cataclastic deformation we learn all about this in the following sides.

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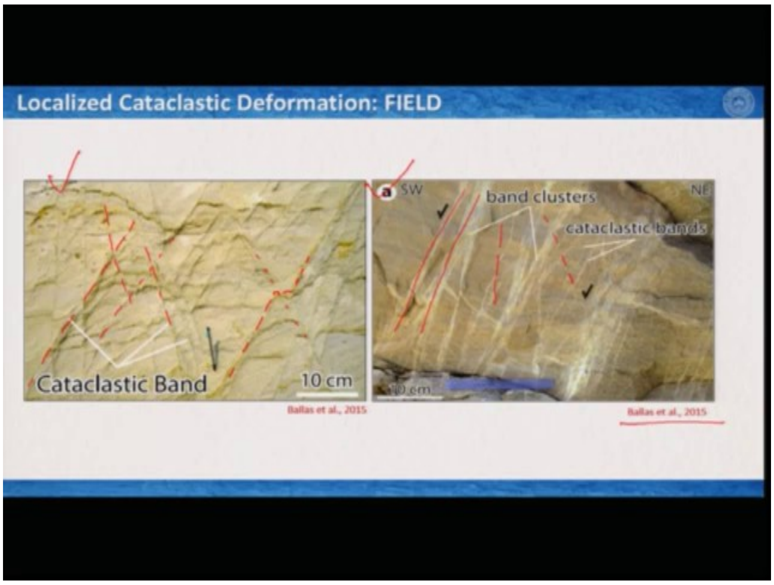

So, here are some examples of cataclastic deformation in the field. So, in both examples if this one and this one the host rock or the country rock is sand stone. This I have taken from a various publications from ballast 2015. And what do we see here we have learned the conjugate fracture if you remember. So, we see that two sets of fantastic conjugate shear fractures are there. And these are known as a compaction or cataclastic bands. So, we will see the micro structure of this soon.

And, this case as well you can see that, dominantly one set is there going like this. And at same time we have one very quickly developed another set but, it is at an angle with the previous one. So, these are the look of the deformation bands, or cataclastics bands, or localized bands, localized cataclastics bands in the field. This is how they look alike and i am sure you have seen it when you go to the field. Particularly, in sand stone rich torrents which are deformed a while.

Now, you also see that this shear bands or cataclastic bands also displaced by the next generation of a fractures. So, we will see that these are what are the grain scale process of this in some of the following slides?

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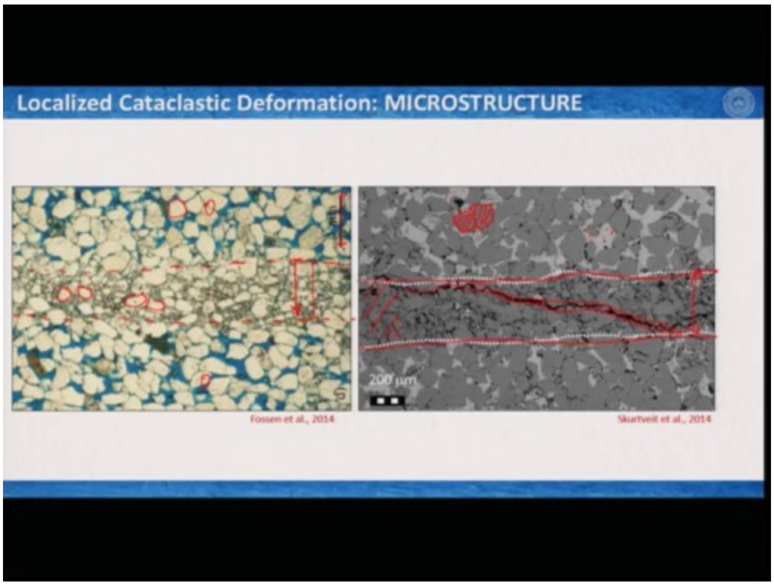

Now, this is how it looks like in we see them under microscope. The first one is an optical microscope image. So, we can see that this yellow things are your sand size grains and then the background is blue coloured this are your porosities. And, you clearly see that there is a zone at the middle running from west to east. Where, there is an animal so this part is little heterogeneous, compare to this area and this area. What do you see here apparently, if we measure statistically the grain sizes is here are little reduced from what we see from outside.

And, at the same time the porosity has also reduced and the number of small or finer grains along this narrow zone is quite significant. And as I said this length is about one millimeter. So we are looking at this about one millimeter scale. So, this are very narrow or thin zone. You can also see the second image. This is a scanning electron microscope image that is why it is in grey scale. What do we see here more or less very similar feature. We have larger grain outside this are sand sized grains.

And then we have this so what we see here this dark grey grains are sand size grains. And then the lighter grey are the cements which field the matrix. Now, again we see in the middle running from west to east. This zone here it is again little anomalous with respect to the top and bottom of this image. And the grain size is here got reduced sort of we can think, they got pulverized and compacted together the cement are almost absent in this area. We also see a very typical fracture or opening here along this.

So, these are all characteristics of localized cataclastic deformation. That happens at a very narrow zone here and here. Where the grains do compact or they move fast each other by producing some fractures within the grains and they just compact together.

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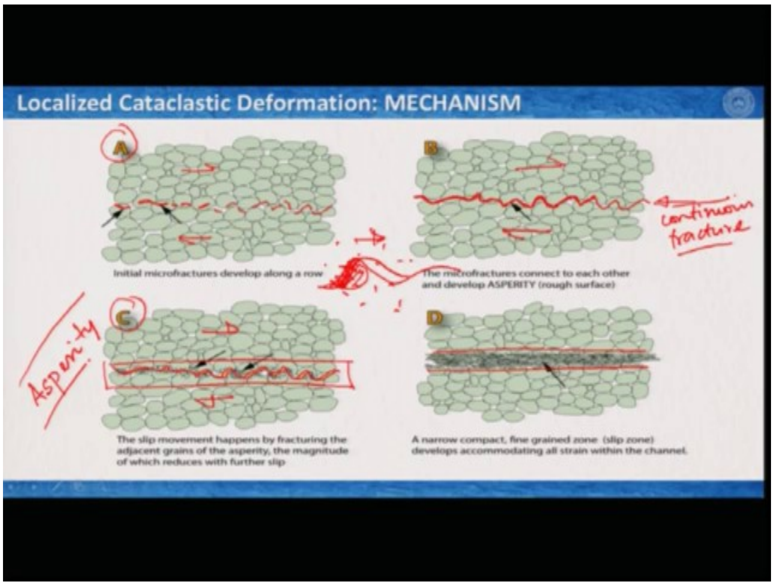

So, if we try to figure out the different processes that how do it happen? Here is an illustration of the different process that you can think of I have given four elastration here. And, this is mostly applicable for frictional flow. So, in the first image which is A, what do we see here that we have an arrangement of grains with some porosities which are white here. And, then this red areas are some tiny little fractures that developed due to application of some sort of deformation. So, you can think of may be deformation is going on this way.

And, now these little red lines they can connect to each other, as I was talking about and they can produce a continuous fracture. Now, this continuous fracture does act as a weak zone. So if the shear continuous, then this fracture along this fractures these two blocks are separated now. And, they try slide first each other. Now, what do we see here? Now, because of this red area red line here is not very straight. So, you can clearly see that if try to draw it, here this is a fracture. And I have some grain here and I have some grains here.

Now if this one moves in this side. So clearly you should have an opening like that and then it tries to qualies here this way. So, you generate an enormous force here so, the grains here do fracture. And, this exactly what is happing here this area along this narrow zone we are producing lot of fractures. Particularly on the contact zones so, we have a rough surface defined by a very tiny fracture which is continuous. And, this rough surface this roughness is known as asperity as we talked in the other lecture and also in the previous slide.

So, ones this starts further moving then this fractured grains it is much easier to deform it. And, therefore you eventually end up with a very narrow zone. Where your grains sizes get significantly reduced the porosities as well. So this how the localized cataclastic deformation is achieved particular in the context of frictional flow.

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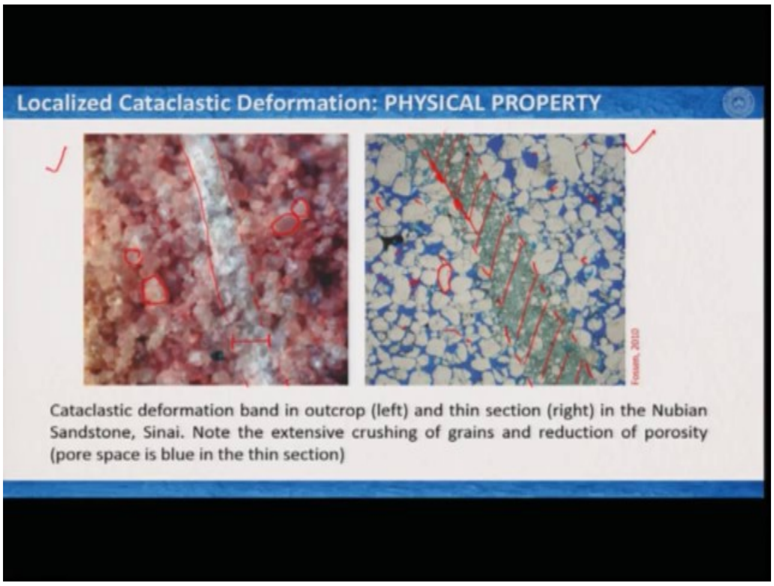

Now, let us have a look of some of some more natural examples. That, what why we should be concerned, or why should concerned about this kind of narrow localized brittle or cataclastic deformation. What do we see here, this is a field photograph and this is a thin section of the same area. Now, we will see that this is about one millimeter later in the later image. So, what do we see here you can clearly image very nicely the photography is taken by the professor foison.

You see this are the little grains here, and then along this narrow zone we have something but really crushed which is just sort of pulverized here. And, the thin sections also are revealing the same feature so now here we see the individual grains. Separately the blue areas are you porosities the open spaces. But, along this zones you can clearly see that within this zones the grains are crushed they are highly pulverized. Grain size got reduced and porosities also is also extremely less.

This is the very interesting area where you can see that probably it was like this some it just got some cut from here because, the shearing deformation. And, again this are very narrow area Very narrow zone, along which the intra deformation accumulated the rest of the area of section is virtually un deformed. And, not affected by the deformation at all. But, we still have to answer the question why we should be concerned about this kind deformation.

So for we have seen that whatever examples we look at, that along this cataclastic deformation bands the porosity got reduced. Can we have example otherwise that is whether we can see that know the porosity can also increase along this the deformation of bands and the answer is yes.

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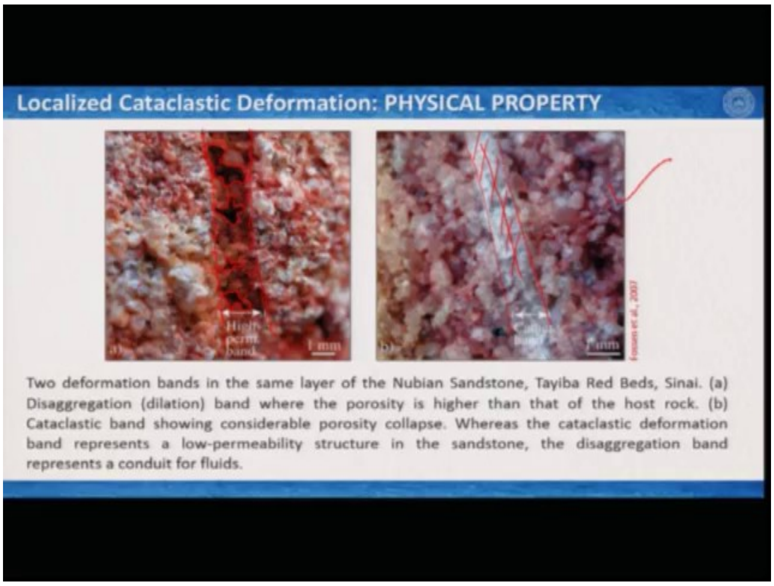

So, this image is exactly what we have seen in the previous slide where you have seen that porosity got extremely reduced here along this narrow zone. However, in this exposer here the rocks are little compacted compare to this. But, this deformation band that we see here. Here you can large openings. At least from the field photograph you see so, we hardly see this opening outside therefore, here we can conclude that in this image we got porosity reduced and in this image along this localized cataclastic band we have porosity increased.

Now, if porosity increases therefore the permeability also do increase. So, the take home message from the slide is that. You may have a porous rock which you may consider that this is a good permeable rock. But, if this rock has cataclastic localized deformation bands which are compacted like this. Then your flow or permeability would be significantly reduced, even if the host rock is extremely porous or permeable. On the other hand these narrow channels this image could be an excellent avenue for following the fluid even if the rock is compact.

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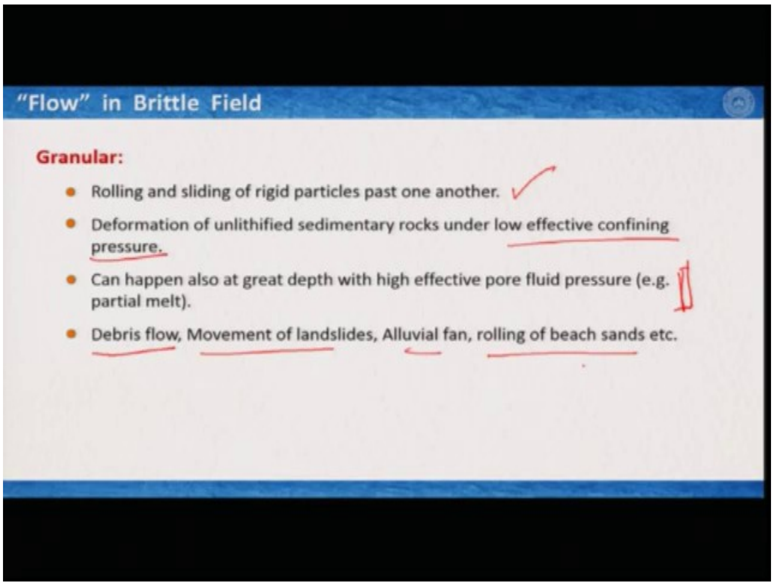

So, based on that, we will see later that, what are the different ways that we can classify this localized deformation bands? But, before that we focus on the granular flow of the cataclastic deformation. So, the granular flow unlike the cataclastic localized deformation bands are characterize by rolling and sliding of rigid particles passed one another. We will see the examples soon and this is very interesting type of deformation mechanism under the cataclastic domain.

We mostly say these sort deformations in lithified sedimentary rocks where the confinement is extremely low. What I mean by extremely low, or low confining pressure low effective confining pressure will understand we will see the examples. However, it can also happen at great depth where, the effective pressure is also reduced if, we have good number of or good volume of partial melt in the system. So, therefore as we have learned in one of the previous lectures. That if we have pour pressure significant compare to that of the confining pressure.

Then your effective confining pressure reduces so, therefore you see or you can consider this as very low effective confining pressure. And, that can happen when you have a rock with partially molten features. But, these are very rare and let us we will not explore this particular feature in this lecture. And, this type of granular flow that you are talking about under the cataclastic deformation are described or example you can think of a debris flow movement of landslides, alluvial fan, rolling of beach sands etc. We will see these examples.

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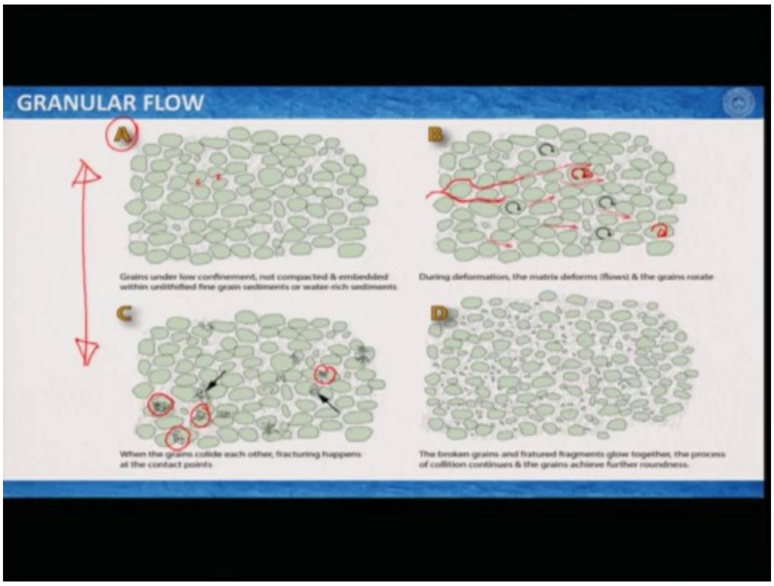

But, first have look how does it work? So in a very similar illustration I had shown you, how it works. So, this is illustration a where the grains are under low confinement they are not compacted, so they are not lithified. And, they are imbedded with unlithified also unlithified find grain sediments or water grain sediments which are he little dots, as you can see that grains are because they are no lithified they ample spaces between the grains.

So, if the deformation is being applied and the overall confinement is very low that happens this fluids or this fine particles, or fine sediments, fine matrix they try to flow around the grains. And when that happens individual grains as you can see, here indicated by black circular arrows the grains tend to rotate. Now when they rotate now when this grain do rotate of course collide each other along a certain point and when this collision do happen then this grains produce fractures along their contact points.

So, this is how the fractures are coming along the picture. That the grains are rolling and why they are rolling they are touching each other and when they touch each other they produce fractures along their contact zones. And, tough this little tiny grains they also contribute to the matrix. And, therefore the overall grains size reduces and the flow continues and then the grains again do collide further grain size reduces and so on. So, this is the process of granular flow that you have learn that what is a mechanism.

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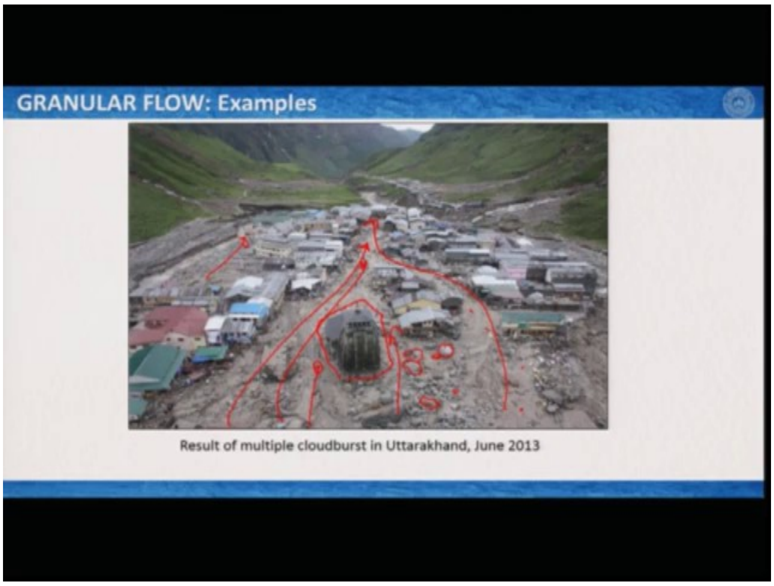

Now if you think of the examples, one of the recent devastating examples I can site you which you can see in this image. Is the multiple cloud burst that happened in June 2013 in uttrakhand India. What do you see here in the middle standing the kedarnath temple. And you can figure out this various boulders, tables, and so on sand size grains all over they flew with the aid of water along this direction. Now, the water is gone and this is how it looks like. So, this is classic example of granular flow.

So, this all this boulders, tables, or sand size grains when they are flowing with aid of water they rotated, they collided, each other they reduced their grain size and so on. Now, the same process does happen in a beach. When the waves do come the sands they just flow in the side, again they come back flow again towards the beach side, and again they flow towards seaside. So, a continuous rolling is happing and this is why if, you are interested in sedimentology you probably know that beach sands are very well sorted and they are also very rounded.

And, this is why the mechanism of doing so is the granular flow. They continuously role and become spherical or rounded. There is now sharp edge if, you are sampling the beach sand or some sand stone with very nice roundness, then you probably can infer this are the beach sand deposits.

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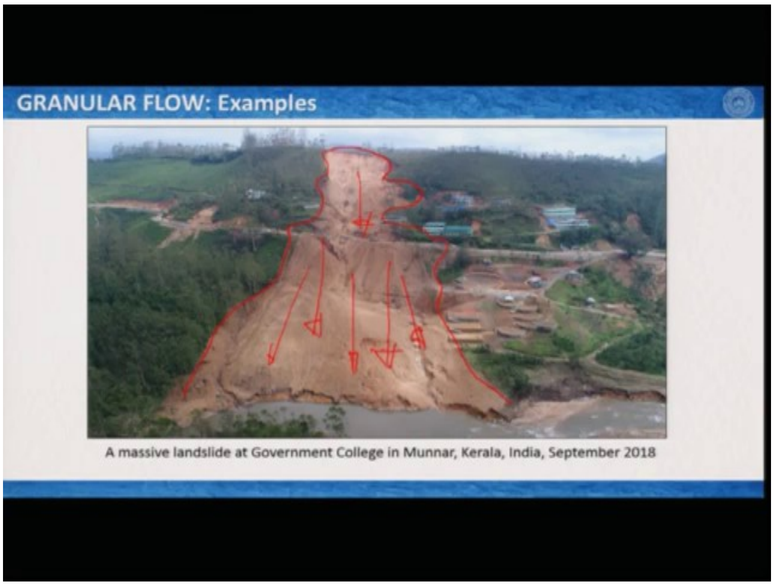

Now, another example is also very recent in Kerala. Last year we had significant flood there and that flood was associated with landslides devastating landslides. So, this is an image which I have collected from the government of Kerala website. And, this you can figure out that this is one landslide. So, materials form the top flew towards this direction, they just role to this direction. So this is the place near Government College in Munnar Kerala and that happen in September 2018. What do we see here, that these materials actually sort of just came down like sliding and rolling.

So, this you can part of this flow can be described as debris flow but again there is no confinement the grains or boulders or tables they were free rotate. Free to move and while they were moving, they actually did the job of granular flow, they contributed to the entire flow of this landslide.

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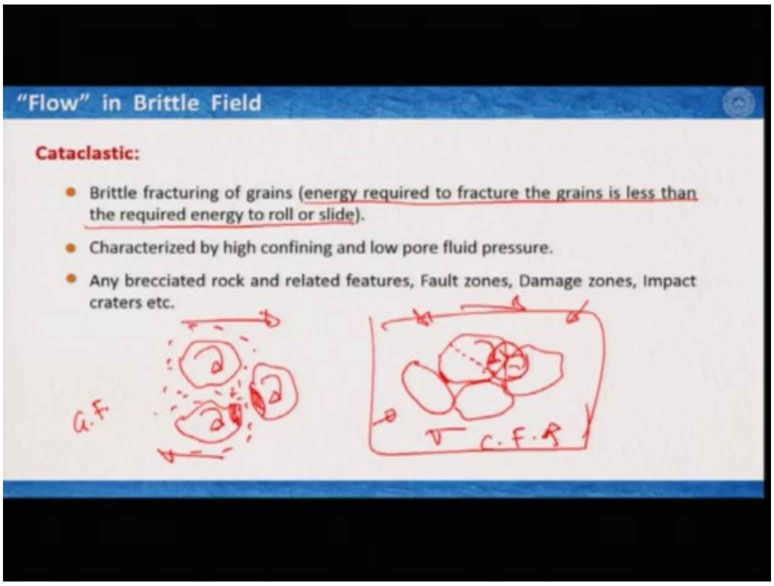

Now, we will look at the last one that is cataclastic deformation in the brittle field. Now, cataclastic deformation is very similar what we have learned with localized deformation. Now localized deformation do happen along a narrow zone. But, cataclastic deformation does happen in a very large area large scale but, the mechanism is more or less same. However, in cataclastic deformation if you have to compare granular flow, cataclastic deformation does happen act or under very very large confining pressure.

So, it is brittle fracturing of grain as it has to be where you have to have some energy required to fracture the grains which is less than the required energy to roll or slide. We will learn about it later. And then it is characterized as I talk about by high confining pressure and low fluid pressure. So, fluid is absent in this kind of deformation or extremely low. And examples you can site for this type of cataclastic deformations are brecciated rock or some related structures fault zones, large fault zones, damaged zones and certainly impact craters.

And now before we go to next slide on this elastration or similar elastration. We have seen with a granular flow or localized flow. So, what happens I just try to give you the difference or try to sight you the examples or sight you does it work. Since, granular flow we have grains like this which was filled by soft sediments unlithified sediments and fluids. In cataclastic deformation we have grains under high confinement and fewer fluids. So, therefore the grains are touching each other unlike this.

So, this is granular flow and this is cataclastic flow now, if there is deformation say for example a shearing is happing in this way in both cases. Now here the grains finds it easier to accommodate the deformation just by rolling. And, while they roll they probably touch each other, they fracture as we have seen in this image, so in the previous slide. So, they just fracture here and there and this how the grain sizes reduces. But, in this case this is exactly what mention here is, energy required to fracture the grains is less than required energy to roll or slide.

Because, this is under significant confinement, it the grains define is impossible to roll. Because, the frictional contact here here and other places are extremely high. So, instead of rolling or slide just other grains. The grains do prefer to sacrifice themselves by producing, some sort of fractures along the contact germs. And when this fractures happens they get again compacted because, there is now scope at porosity to could stay there unless the grains themselves produce some sort of strong network or strong frame work.

Then again these tiny small grains try to rotate but, they cannot because of huge consignment. They again produce fracture and this is how we achieve cataclastic flow or the cataclastic deformation. So you see in the next elastration.

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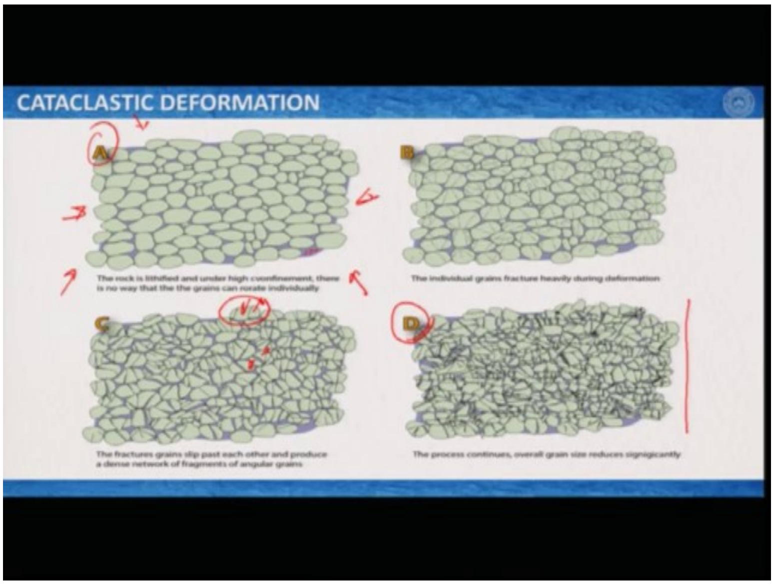

What do we see here this four elastration in A, we have some compacted matrix this dark grey and this greenish grains. Now, when the deformation comes in this sort of settings, which is highly compacted lithified and it has significant confinement than the grains cannot rotate. So, therefore they produce fractures within themselves. And, then this fractures are easier to either open or slide here in this grain, you can see that you have some sort of sliding going on, we have some sort of opening going on here and so on.

So, all these process do happen but, what is important you see by this fracturing the grains size got significantly reduced. And if that continuous what we finally achieve is you see in the elastration D. So, the overall grains size reduces significantly the grains unlike the granular flow are extremely angular. They are not circular grains, or their ages are not rounded there extremely angular. So, this is some of the characteristics of cataclastic deformation. And, if wee this kind of structures either in field or under microscope this are known as breccia or brecciated rocks.

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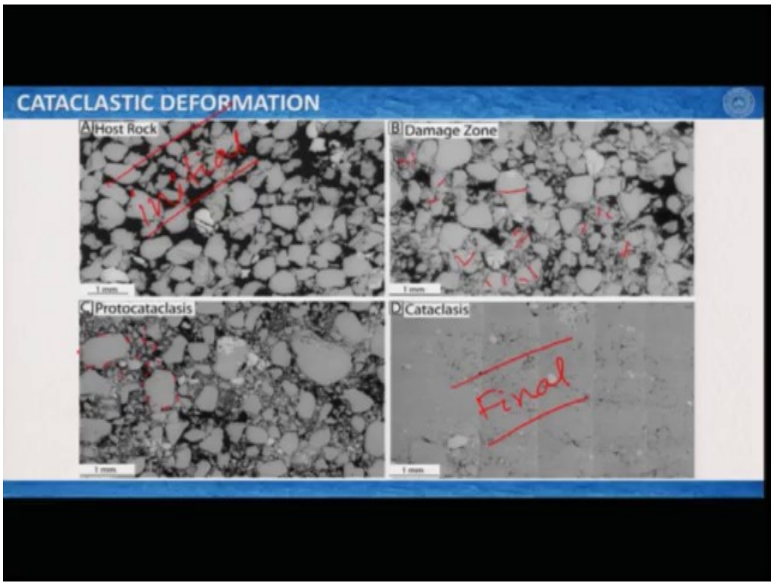

Accordingly we will some examples now; here is one very good micro structural study. Scanning electron microscopic(SEM) images. So this is the host rock that is sort of undeforming rock this grey areas are the grains and the black areas are your porosity. As you can see when the deformation comes, then we produce some damages along the grains. So, you can see that this grains are getting fractured here here heavily, like they are getting crush like someone hammered it. And, then this grains do rotate by themselves. But, they cannot so they produce further fractures and they got some sort of sorting.

So, you have large grains here and here which is field by finding matrix it further deformation what you see that it is like a crushed mass. Where there is virtually no porosity now you compare this was your initial and this was your final. So, grains size reduction is something very important for cataclastic deformation. We learn later that, why the rocks do have to reduce their grains size to accommodate energy or to accommodate deformation.

Now, the mechanism here at least in cataclastic deformation is extensive fracturing of the grains. So, rocks are the grains or the crystal, they produce fractures within themselves. And, therefore the porosities and another things got reduce significantly. But, it can happen in otherwise as well we will see it later.

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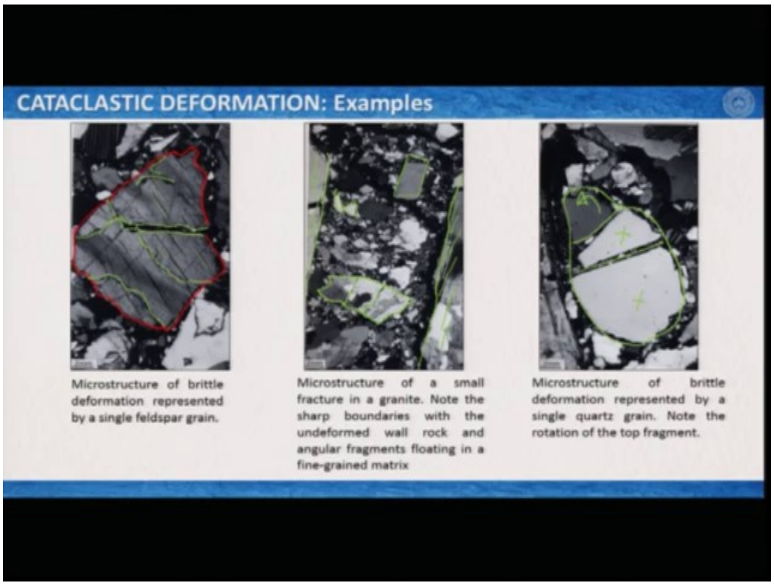

Now, here I try to give you some examples, that when you look at the thin sections under microscope optical microscopes. You can have some sort of ideas that you are looking at cataclastic deformations. So, this is a single fails per grain as you can see here. And you can see this are the cleavages of the grains you can figure out. And, you can see this grains is characterized by some sort of fracturing here and so on. So, this are the characteristic of cataclastic deformation.

In the next image you can see that, it is a micro structure of a small fracture in granite. So, you see that you have a very short boundary here and here. And, in between you have a lot of grains which are angular in nature. And, you can also figure out that the grain size here on this two boundaries and the grain size in the middle are significantly different. You probably, can see the fracturing process is going on, so this was the large grain. And then you see the fracturing is happening along this so grain.

This grain is divided in three equal pieces, now this is again quartz grain and I tell you it was a probably single crystal like this. And, then it produces fractures here and here. So this is also cataclastic deformation and we see it in microscale. Now, the color or here and here are very similar. But here it is little different so, you can asked that how do you say that this is a single grain. And, this can happen that even a single grain after fracturing may show a different color at least in this case shades.

And this is because the grains may have rotated therefore, we see within a single grain you see a different color because, it has rotated and therefore its orientation got changed and we see a different coloured. This is you must have learned in your optical mineralogy lectures.

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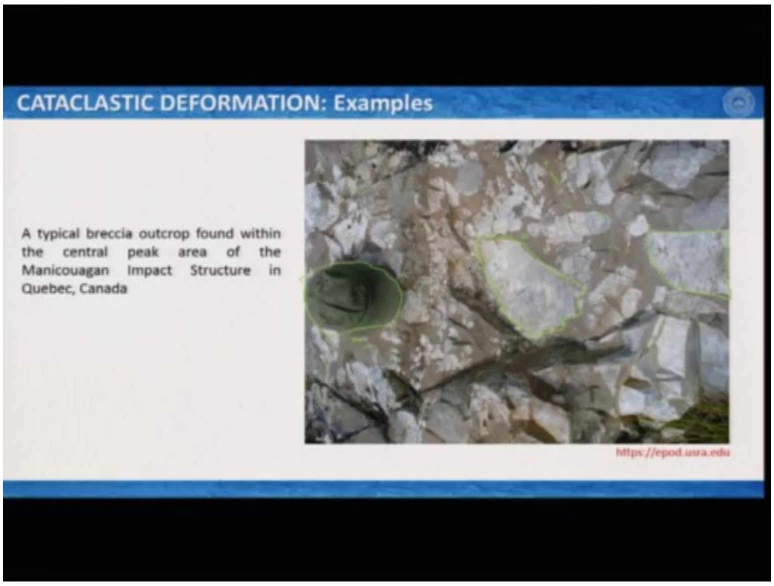

Now here are some other examples, so this is typical breccia outcrop and this is in Canada. And, you can see this hat is the scale and you see here these angular grains here or this are not grains actually this are clast. So, and they are hosted within the fine grain matrix. So, this is an example of cataclastic deformation. Please note this is not localized deformation because, when have an impact clatter. A huge mass is impacting and then everything is getting fractured. So, it is not a localized feature, at least the scale we are thinking of.

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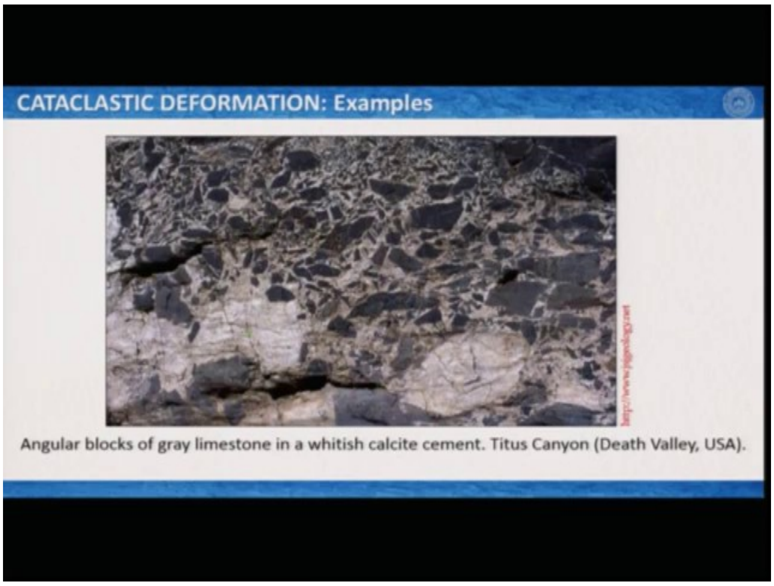

And this is another example again form USA from Death Valley. And you see these black things which are actually limestone clastses and this are within the calcite cement which are white. And, you see prolific angular clastses and this is the very typical impact induced breccia. This is how it looks like and this an example of cataclastic deformation.

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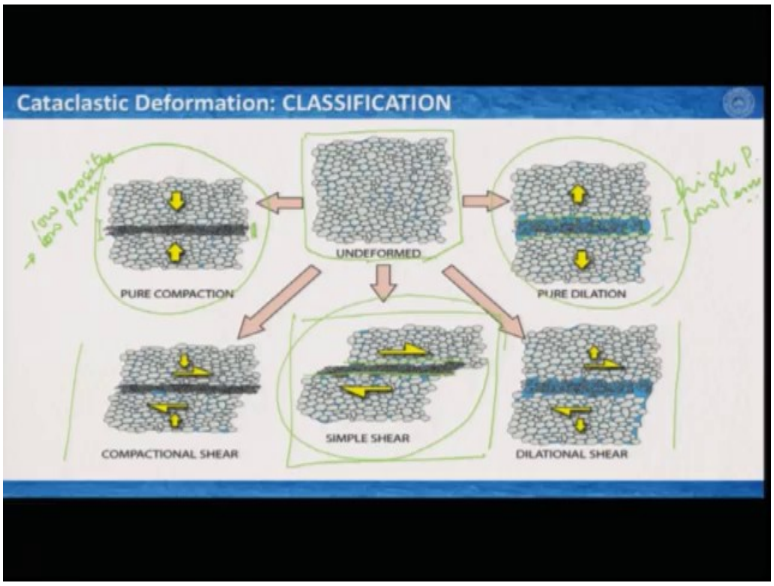

Now talking about this porosity reduction or permeability reduction etc particularly applicable for localized cataclastic deformation. Here I try to give you a summary diagrams some sort of classification diagram. Say if I considered this one as an un-deformed setting of grains and this blue things behind are your pore spaces. Than you can have pure compaction without any shear component the rocks can deform. And, then it can form the localized cataclastic deformation.

On the other hand you can have pure dilation, where rocks are experiencing uniaxial tension or something like that. And, instead of uniform or homogenous distribution of deformation. Somewhere, it just opens up the grains produce fractures and you have an opening. So, clearly hear this area is of low porosity. And therefore, most likely of low permeability but, here it is essentially high porosity and low permeability. But, if the shear comes in the picture which is this one which is simple shear.

See it also produces something like that where you reduce the porosity and permeability. Now if compaction and simple shear, they do combine together than you have something called compositional shear. And, if shear simple shear and dilation they combine together, then what you get is dilatational shear. So, this are the five N members, or I would say these three are the N member pure compaction, pure dilation and simple shear and any combination between them can happen.

So, within three N members you can have the localized deformation, localized cataclastic deformation. And, based on the way the rocks are deforming whether it is compaction dilation or simple shear porosity and permeability of the rock would vary accordingly. Now let us have some ideas or some basic concepts on the failure criteria, that what are the conditions when the rocks would produce fracture? As you have learned that when you are discussing about this cataclastic deformation fracture is produced when the shear strength is exceeded.

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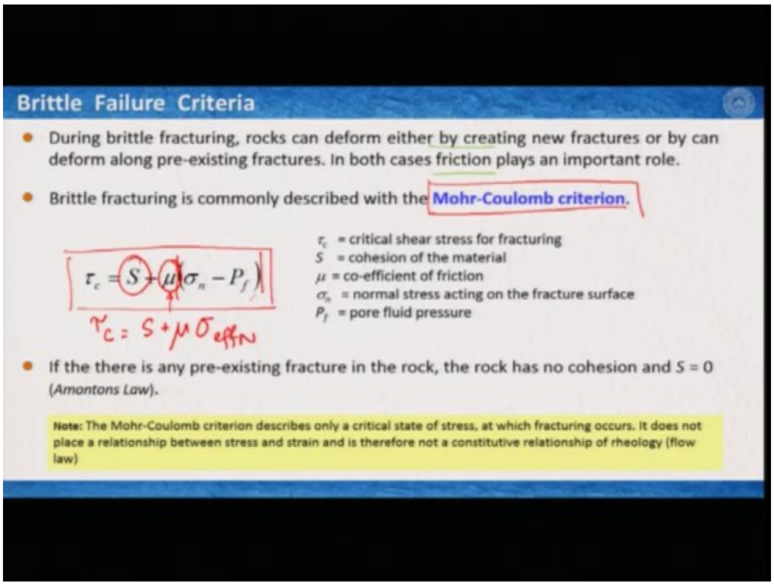

During the brittle fracturing therefore the rocks can deform either by creating new fractures, or can deform along a preexisting fracture. And in both cases we have said about it quite a lot of time the friction place a very important role. So, the fracturing process that involve friction one can give or one can theorized it by Mohr coulomb failure criteria. A Mohr coulomb failure criterion is expressed by very simple equation. Where, shear stress or critical shear stress for fracturing is equated to this which is cohesion of the rock you're talking about.

The mue is the frictional coefficient or coefficient of friction, sigma is in normal stress and Pf is the pour flawed pressure. So, eventually this sigma S minus P gives you the effective fluid pressure or effective I am sorry it gives the effective normal stress. So you can write it actually TC equal to S plus mue sigma effective normal, which is equal to sigma normal minus pore fluid pressure. Now we will discuss about this two terms cohesion and friction in the next slide.

And, in the slide after we will see that how does it work with different rocks. But the cohesion is something if you have some sort of preexisting fracturing in the rock. Then there is no cohesion. I also tell that this equation is one of the most important equations in brittle fracturing or brittle deformation and extensively used in rock mechanic studies. And I repeat this is known as Mohr coulomb failure criteria. I also like to remind you that this is not a flow law.

Because, what we have learned in one of the previous lectures. That flow take cares of three major parameters one is dynamic parameters second which is a related to kinematic parameter and they equal or they are balance by constant or rheological constant.

Now in this case this is not such an equation so, this is not a constitutive equation but, a law of failure or a criterion of failure. We can take of this way. Now what is cohesion and what is friction. Now we talk about this term very frequently. Now cohesion is something i just try to give the feeling.

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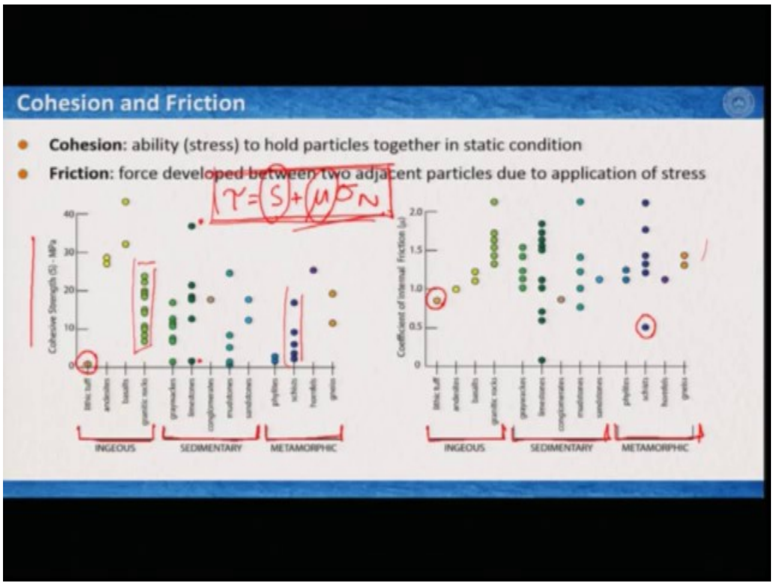

When you have your material in rest that is in static condition there is now external force is being applied, then this particles can still stay together. And this ability of staying together of particles under static conditions is cohesion. We can think of that the sands the loose sands. If, you make them set them somewhere they will lose and fall apart so, the cohesion is low. But, if you compacted by your hand and try let it be there it may stay for a while but, and then it will fall. If you add little bit of water and compacted by your hand it will stay for a while.

And, if you add cement and water then it may stay for a quite long time. Note there is no external force is being applied. So, in that case the cohesion from loose sand to compacted sand to wet sand to the sand with cement the cohesion is increasing. So, it is an ability to hold the particles together under static condition. Friction on the other hand if, you try to understand physically it is force that is developed between two adjacent particles due to application of stress.

What I mean by this that friction always requires, to define friction it is always important to have an external force or stress. And when you have that then this two grains would like to stick to each other but, because of this external force they cannot or what is the resistance. So, that they can stick together is measured by a parameter which is known as friction. Then the previous equation we have seen that we wrote the equation. In general tau equal to cohesion plus mue by mue multiply it by sigma N.

This is the equation we have figured out this is Mohr coolant failure criteria. Now the question is there in relationship between cohesion and friction. So, people performed experiments and they measured equation strength of different rocks. So, we see a series of igneous rocks here we see a sedimentary rocks and here is the series of common metamorphic rocks and this is your cohesive strength. Which is in the unit which is mega Pascal. Now this is lithic tuff the cohesion is extremely low for granitic rocks this green ones the cohesions are quite variable.

Then limestones from very low to extremely high and so on. So, for different rocks it does not matter it is igneous or sedimentary or metamorphic or we see that the values redistributed. If you look at the coefficient of friction mue which is dimension less quantity this are the same rocks igneous, sedimentary and metamorphic. And, we again see a various a wide distribution of this. Now what do we see here which is very important message i would like to give you from this slide.

That the rock is highly cohesive, that does not mean that its friction would be high and vice versa is also true. For example this lithic tuff it has very low cohesive strength. But, it is frictional coefficient is quite significant. Similarly shiest its cohesion is pretty wide but its frictional coefficient is even less than the lithic tuff. So, cohesion and friction they apparently do not any relationship however this equation we see now in the light of experiments and mini rocks.

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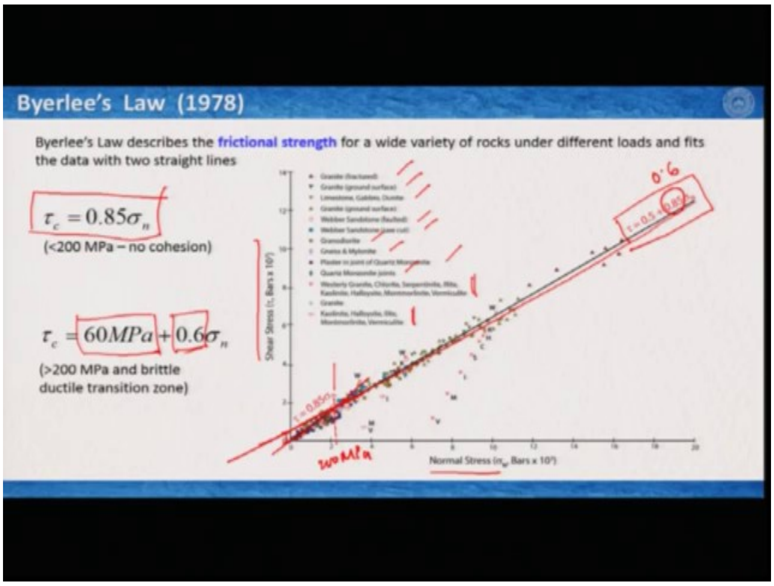

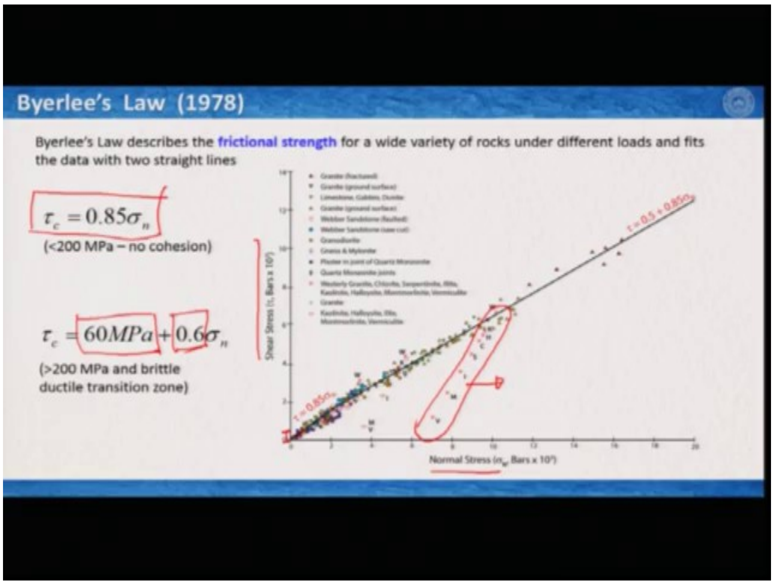

What we can figure out form this slide is very famous plot from Byerlee and this is known as Byerlee’s law. So, Byerlee’s law actually do describe the frictional strength for a wide variety of rocks under different loads. And, then he try to fit the data with two straight lines. So, how does it work so, what he has done? He deform the rocks he measured the shear stress at different confinements so, this are your normal stresses the confinement and then he calculated or he from the stress and curve the pic stress.

And, there are number of rocks variety of rocks he has used and I am not sure if he can read it but, form the slides, the pdf files I had given you and you can figure out. So, it has granite fractured, granite ground surface it has lime stone, gabro, dunite, sand stone then different types of sand stones. So, faulted socket sand stones gadolinite nice and milonite then quartz monzonite, quartz monzonite with joints then westerly granite and lot of clay minerals and here as well.

Now we can see that interestingly all this values of shear stress verses normal stress, they more or less do follow line. The first take home message from this plot is that, the composition is not a function of determining the frictional strength and the cohesion particularly. However it is a function of normal stress. If, we zoom this part then we would see that, here it is going through the center. And, then this line if you connect this line its coming through the center it is coming somewhere here.

So, up to this around 200 mega Pascals confining pressure byerlee proposed that below 200 mega Pascals rocks hardly have any cohesion. And, this slope gives the coefficient of friction so he got this equation. That at low confinement rocks has coefficient of friction average 0.85. However, this is about 60 mega Pascal this slop if we continue doing like this. And, here he found this equation that, where the cohesion is about 60 mega Pascal and coefficient friction is about 0.6, I am sorry this is written wrong this should be 0.6.

So, this is how we can figure out that the friction or strength of the rock is not function of the composition of the rock. Now, you can also figure out that there some rocks or some minerals which do not agree with this plot and this are this rocks. And, if we see this are mostly sapentinite, elite, kelinite, hallucinate Mont Moro lite vermiculite and so on. Now this do not agree on this plot of byerlees law. And, there are sort of outliers. And there are mostly clay minerals it has the significant meaning. That why they are outside and why studying of this sort of clay minerals are important but, we will not talk about this later but, this are significant for earth quake studies.

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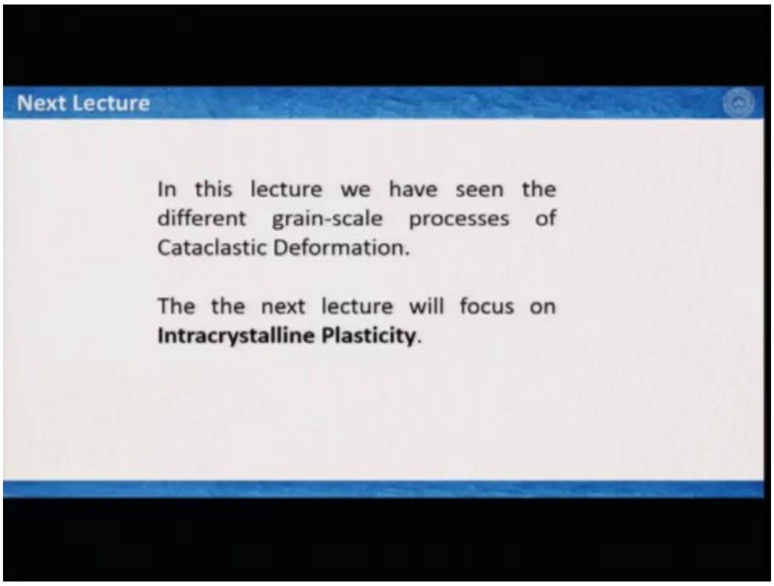

So, we complete this lecture and in the next lecture, we will learn about intra crystalline plasticity so, in this lecture we mostly have learned the cataclastic process. Where the mostly look at the grain scale process but, without looking at the features that you have learn in the first lecture of deformation mechanism. These defects or dislocation or grain boundaries which have no influence in cataclastic deformation. But, they play significant role in intra crystalline plasticity and dynamic recrystallization. So, we are going to learn this in the next lecture number 14.2 thank you very much.