Structural Geology
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Lecture No 12
Rheology – 3 (Role of External Parameters)

Hello everyone! Welcome back again to this online Structural Geology NPTEL course and we are learning rheology and we are in the lecture number 12.

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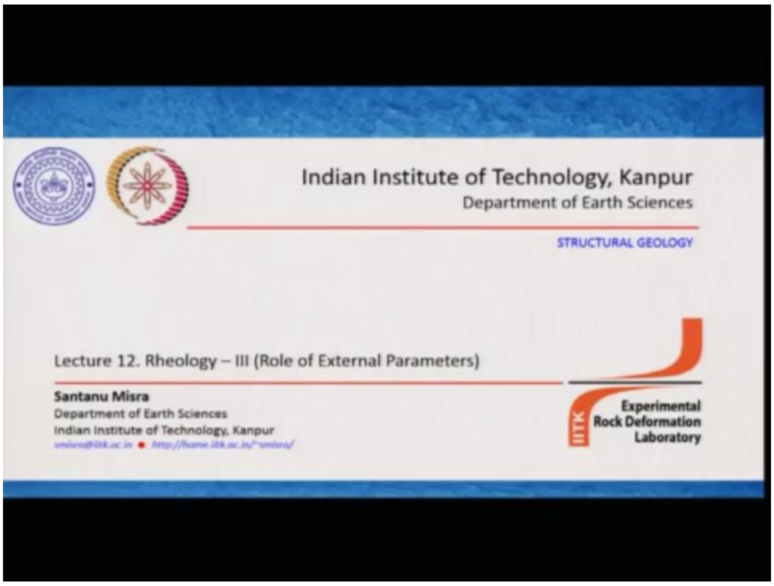

The last lecture of rheology we have learned elastic, viscous and plastic rheology. Then we have learned elastoviscous, elastoplastic and viscoplastic rheology. We also discussed some of their applications in terms of structural geology and geodynamics will continue with the rheology throughout the lecture whenever we learn fold, fault, lineation foliation all these things, we mostly learn in the context of light of rheology along with some other parameters but this lecture particularly focus on the role of external parameters in response to the strength and deformation of rock materials.

This particular topic that what is a role of external parameters in governing the flow or strength of the materials you may not consider is a typical part of rheology or integration of rheological studies but for rock deformation studies, for structural geology these are very very important and therefore I decided to include it in the course of rheology.

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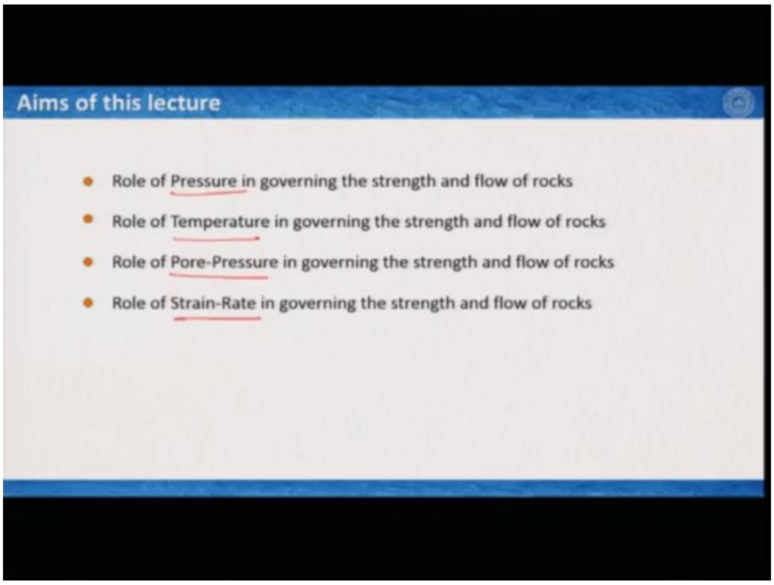

Now we will cover mostly 4 different important parameters one is pressure and then 2nd one is temperature, after that we will look at the pore-pressure and strain rate, so these 4 parameters and their influence in governing the strength and flow of rocks. Now we know that pressure and temperature as I go deeper of this earth they do increase. Pore-pressure is something which is mostly applicable for reservoir rocks where the porous spaces of the rocks are filled by either fluid it could be water, it could be gas, it could be hydrocarbons and so on at more or less shallow depth and in deeper earth it could be the melt, in partially molten rock and so on.

The pore pressure has a very important role in determining the strength and flow of the rocks in general because if I have rock at say 20 megapascal confining pressure then if I add pore pressure to the rock, the effective confining pressure reduces, we will learn about it later when we learn deformation mechanism because pore-pressure exerts an opposite force to the wall of the rock and therefore the total confining pressure reduces, so we will see that how the pore pressure place the role in governing the strength of the rocks.

And then strain rate is also very important because the earth though the process is extremely slow but even within in the range of slowness, there are many varieties, many ways or many possible strain rocks to deform, so pressure temperature these are extremely important on finding the behaviour of the rock under stress at the same time pore pressure and strain rate.

So we will look at these 4 and the expression of these 4 terminologies or 4 terms or 4 external parameters in governing the strength and the flow of the rock are mostly derived from experimental observation, so there are many different ways of running experiments which is not the part of this course but something is very important to consider right now before we start the actual slides where we will see the role of pressure temperature, pore fluid pressure and strain rate.

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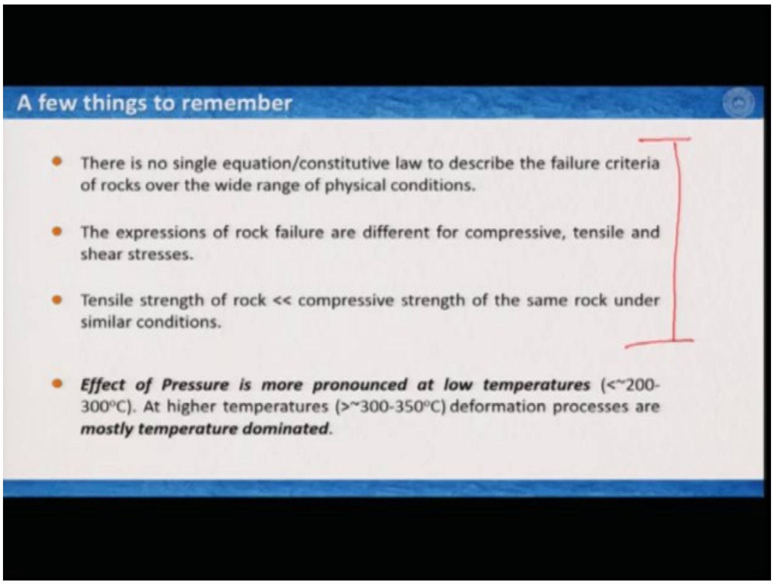

It is important to understand very very clearly that there is no single equation or constitutive law to describe the flow or failure criteria of rocks in wide range of physical conditions and therefore we had to have these different kinds of rheology and whichever fits with my observation I will use it without breaking the laws of physics and science in general and it is also important to understand the expressions of behaviour of the rock and the failure pattern, failure mechanism are essentially different on the regime of the stress you are applying that means if you are in compressive domain, the behaviour is different to that of tensile and shearing domain and there is also one very important thing to remember that if you are applying compressive stress then the strength of the rock is much higher than the tensile conditions.

So all these parameters constitute or all these statements are some sort of prerequisites in understanding the flow of rocks at different pressure and temperature. I am talking about pressure and temperature, we know that at surface or subsurface conditions the temperature is not very significant, we can go up 200 maximum degree centigrade temperature but at depth we have much larger, much higher, much greater temperature and the general observations from experiments or from the behaviour of the rocks that we see frozen in the field that effect of pressure is much more prominent at low temperature, so that is below 200 or 300 degree centigrade.

Temperature does not play much role in governing the deformation of the rocks at low temperatures but pressure yes but at higher temperature in terms of rock deformation or rock rheology or deformation structures temperatures are the key parameters, so above 300 or 350 degrees the effect of pressure is not that much when we talk about or when we say this in the context of deformation structures and rheology.

The pressure has some other effects but deformation behaviour is essentially govern by temperature at depth and therefor at higher temperature regimes, so based on these 4 ideas we will not move to our findings on experimental findings we learned that how the pressure temperature, pore pressure and strain rate influence the deformation of rocks.

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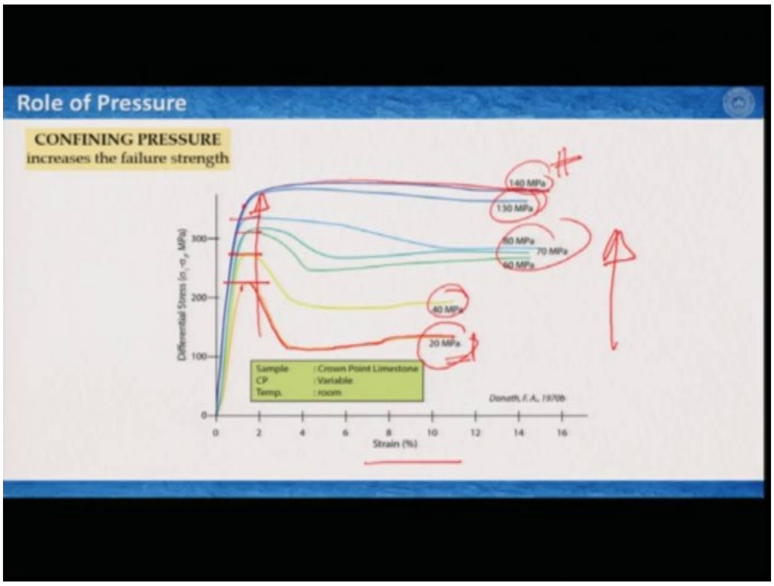

The first one we take is confining pressure and in all slides we will see this kind of curves where the vertical axis is stress or differential stress or the dynamic term which is plotted against kinematic term strain. Now what we see in this plot that different curve, so the sample was a crown point limestone that was deformed at room temperature at variable confine pressure that means the sample was taken to different pressure, different isotactic conditions and then it was deformed, so the isostatic pressure or confining pressure at variable…it range as low as 20 megapascal 2, 1, 40 megapascal.

You know what is the pressure conversion with the depth and you can consider or you can think that what corresponds to 20 megapascal, what depth it corresponds and what depth it corresponds to 140 megapascal. If we look at all these curves stress versus strain curves at different confining pressures where the temperature kept constant and the deformation rate as well, the strain rate we see that it has an extreme variable behaviour under stress.

At low confining pressure it goes to its elastic limit and then it weakens what we call strain weakening, we learned in the last lecture, then it does little bit of strain hardening and flow steadily whether as 140 megapascal, it reaches it yield strength somewhere here and then it flows steadily, so deformation mechanism or flow behaviour is different at different pressures but this is not what you are going to look right now.

What we see that strength of this rock, the peak value of the differential stress at different confining pressures, this crown point limestone has achieved… has a relationship that with increasing confining pressure the strength of the rock has increase and this is more or less constant for any of the rocks we think of. So in general we can say that confining pressure increases the strength of the rock.

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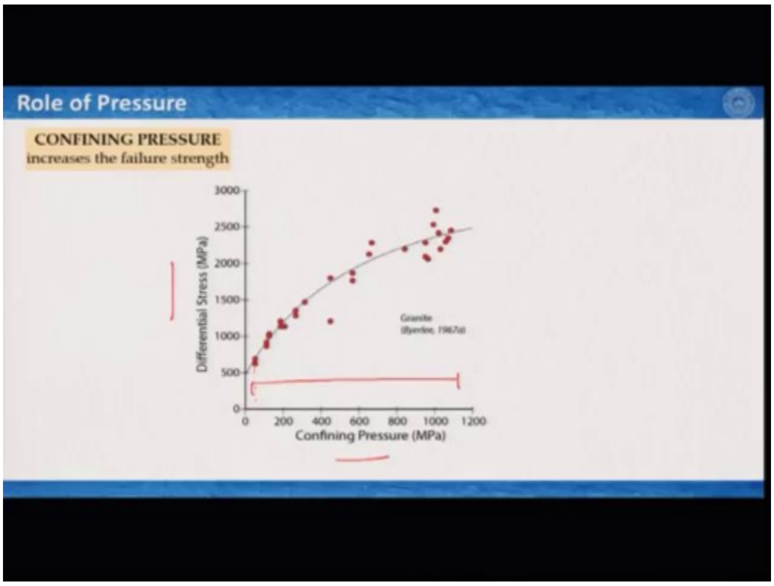

Now we can see it in a different way, so this is another experiment on granite performed by (())(10:04), so in this side again we have different shear stress and this side we have confining pressure and we see that the strength of the rock increased gradually and in this case, these are performed at different experimental conditions maximum up to 1000 close to 1000 megapascal and lower up to this may be 40 or 60 megapascal, so in this wide range of experiment we see the strength of the granite that (())(10:36) has used increased and it got more or less increased non-linearly, so the strength increase is not a linear with confining pressure.

Now, I must stay here that most of the examples that I am going to cite are very old experiments just to show some sort of my respect to all these great experimentalist and structural geologist who thought of running experiment and contributed to our understanding so most of these experiments that we will see these are very old publications but they are very relevant today and we will also use it. There are many new experiments on similar lining but to deal with a different problem I did not pick them up I pick the old ones, some way to show my respect to all these great scientist.

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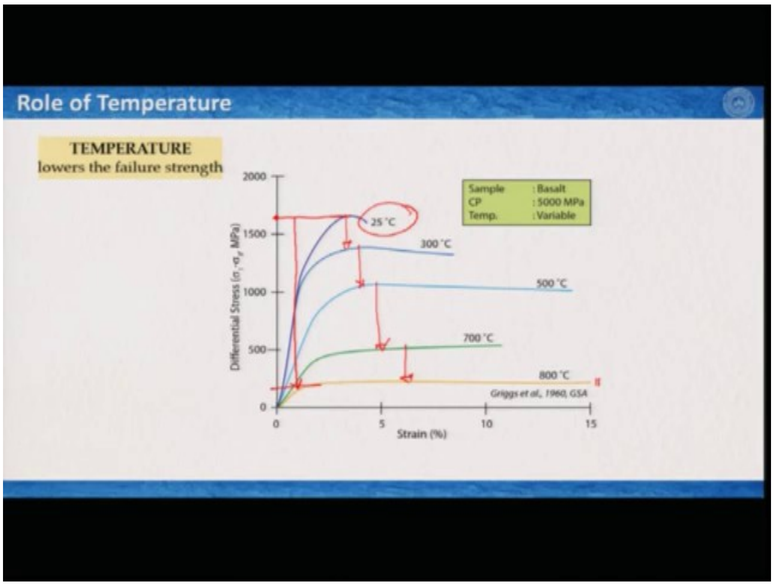

Now if you look at the temperature and then again it is performed by Griggs in 1960 and this sample he used was basalt, so in this case the confining pressure was 5000 megapascal or 5 kilo bar. The strain rate was constant and temperature was variable, so he wanted to check the effect of temperature on the strength of this basalt, so it clearly see that at 25 degrees centigrade the curve looks like this, this blue curve and at 800 degrees centigrade the curve look like this, so here the peak strength is close to 1600 megapascal and here it is probably 150 megapascal.

So 1500 megapascal strength is reduced by raising the temperature from 25 degrees centigrade to 800 degrees centigrade and this is remarkable, you can see it and in between we see that temperature gradually decreases the strength, so 25 to 300, 300 to 500, 500 to 700, 700 to 800 the strength or the flow stress of this basalt slowly decrease with the temperature, therefore you can conclude from this plot that rocks have lower failure strength when you increase the temperature or it flows at low pressure, low differential stress when the temperature is much higher.

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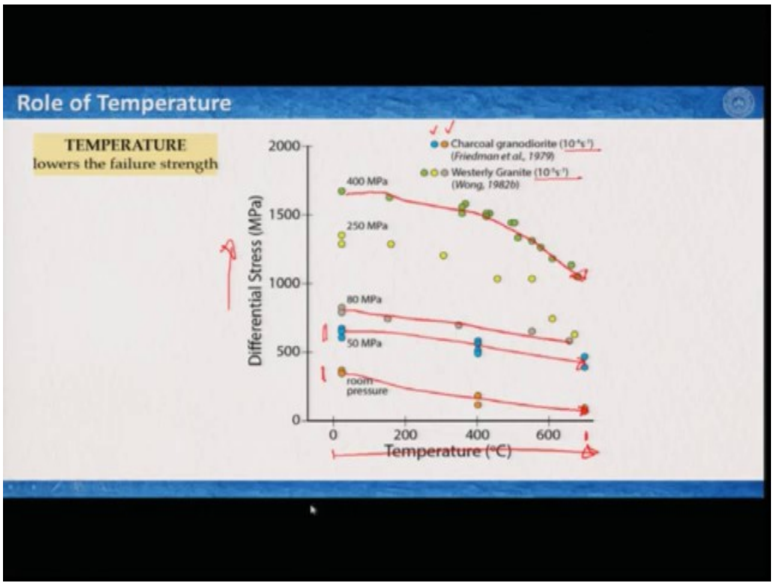

We can also see in a different plot again these are pretty old work one is this blue and orange, so these are granodiorite rock and rest are granite, westerly granite. This granodiorite were deformed with the strain rate of 10 to the power minus 4 per second and the granites were deformed with the strain rate of 10 to the power minus 5 per second and what we are plotting here differential stress versus temperature and the authors plotted the peak stress, the peak value.

And you can see that the temperature from 0 to 700 degree centigrade here if the temperature got increased then at room pressure the temperature decrease, the strength decreases like that at 50 megapascal the strength decrease like that whereas in westerly granite when dealt with 400 megapascal confining pressure, the strength decrease again little nonlinearly but at 80 megapascal it was more or less linear.

So this kind of behaviour, relationship one can obtain that okay I change the temperature but I observed it at different confinement that means at different depths if I increase the temperature what is going to be the behaviour of whether the strength change or flow stress changes is linear or nonlinear and so on, so this is another way of looking at the role of temperature together with pressure in governing the strength of the rock but the conclusion or take-home message from this plot is yes the same temperature lowers the failure and flow stress of flow strength of rock.

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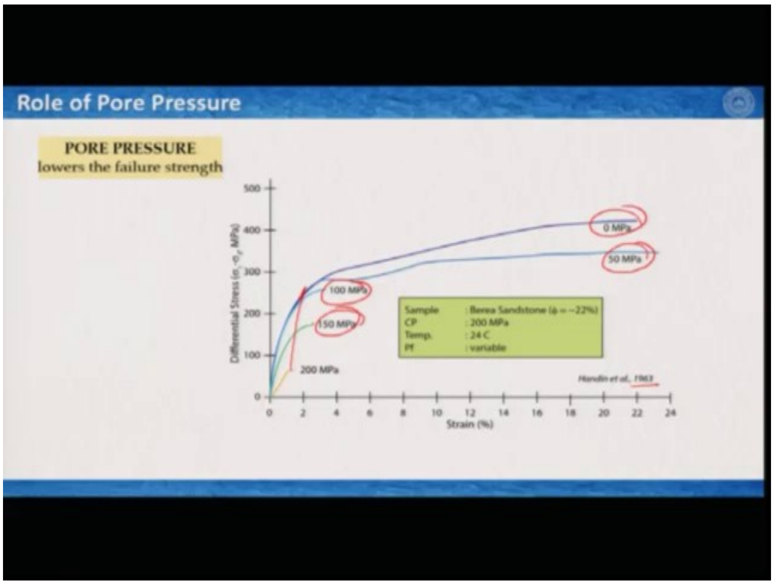

Now let us look at the pore pressure, so these experiments were done with Berea sandstone and performed by again another great geologist (())(15:19) the paper got published in 1963, so Berea sandstone is a sandstone that has porosity is a very consistent porosity from 15 to 25 percent, so these sandstone typically have 22 percent ferocity. The confinement was 200 megapascal, the experiment was performed at room temperature and what he did, he varied the pore pressure, so these values here at the bottom of the curve these are your pore pressure values at 200 megapascal, so when the pore pressure is equal to the confining pressure so that means the rock is almost at room pressure because 200 minus 200 comes to 0, close to 0.

So here we see that the strength is very-very low right this orange curve but when the rent got increased from… When the pore pressure decreased from 200 to 150 megapascal, 50 megapascal decrease of pore pressure increase the strength of the rock from 150 to further decrease t0 100 megapascal further decrease to 50 megapascal and further to 0 megapascal we see that strength and flow of the rock has increased, so pore pressure effectively lowers or decreases the strength of the rock. This was one of the first experiment where (())(16:54) showed this typical phenomena of deformation behaviour.

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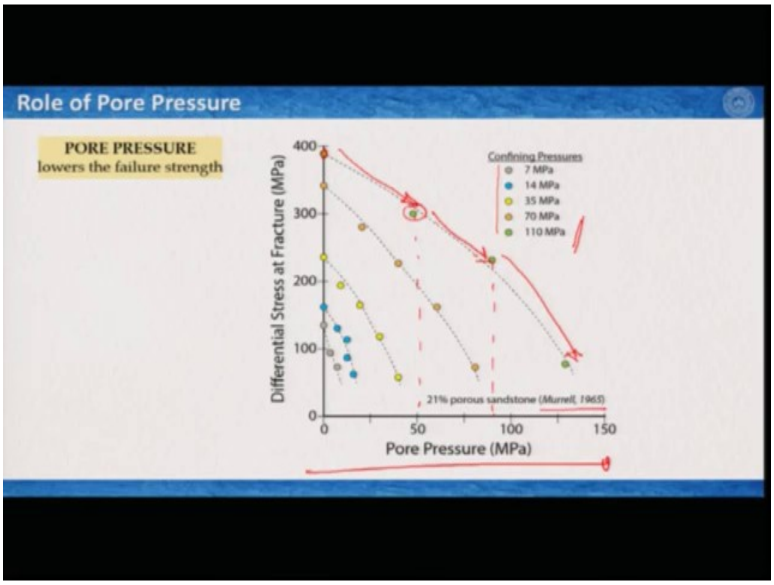

Now this is another way of looking at how pore pressure plays the role in governing the strength or flow of the rocks. So these are again done by a porous sandstone and this time the experiment was done by Murrell in 1965 and here the porosity was 21 percent, so different circles here of different confining pressure that applied and in this X axis we have different pore pressure, so what we see for example if I take this green circle where the confining pressure was 110 megapascal.

So at 0 pore pressure the strength was extremely high close to 400 megapascal but close to 50 megapascal pore pressure the strength reduces to 300 megapascal, so increasing more pressure is reducing the strength of the rock and then probably at 75 or 80 megapascal pore pressure it further reduced and again it further reduced when the pore pressure got increased and this is obvious for all other values but at different confinement. The take-home message again from this plot is that pore pressure reduces the flow and failure strength of rocks.

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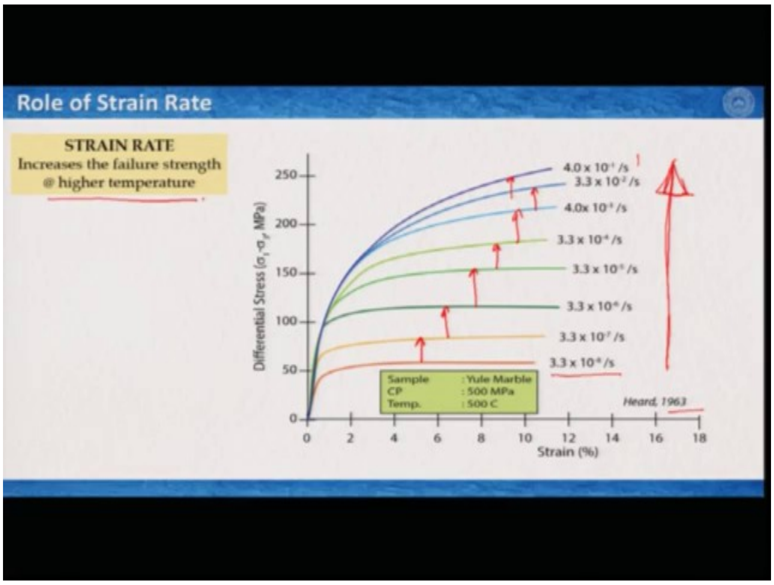

Now let us have a look of this very important series of curves that we are going to see that what is the effect of strain rate, deformation rate that means how fast the rocks are being deformed and these experiments again performed by another one of the great experimentalist Heard it is a paper in 1963 and he worked with Yule Marble, the confining pressure was 500 megapascal and temperature was 500 degrees centigrade, so these 2 were kept constant and he varied the strain rate from 4.02 10 to the power minus 1 to 3.3 into 10 to the power minus 8 per second was the strain rate, so clearly we can see that from here to here strain rate is increasing, so with the magnitude here is 8 then 7, then 6, then 5 and so on.

So with the order of magnitudes which once can change in an experiment and this is how the strain rate has increased and clearly from all these curves we can see that with increase in strain rate each and every step the flow strength or flow stress of this rock this yield marble has increased, so you can conclude that strain rate increases the failure strength. Now one term is written here at high-temperature, so this is watchable only at higher temperature, if you increase the strain rate, the strength increases and this is probably due to the viscous behaviour of the rock so you achieve viscosity and therefor you increase the strength.

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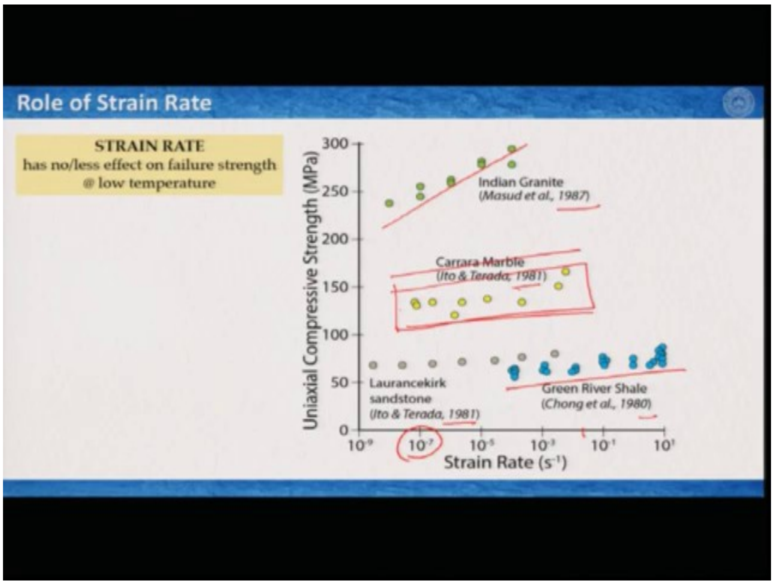

But at room temperature or at low temperature people run experiments again these are pretty old experiments but here we see that increasing strain rate, with increasing strain rate, the strength of the rocks are not increasing the way we saw with the yield model, for example we can consider another marble which is very famous marble that people use for experiments is Carrara marble. Here the strain rate got increased from the order of 10 to the power minus 7 2 almost 10 to the power minus 2 and the flow strength was more or less constant, so strength at low temperature is not a function of strain rate.

So strain rate and high temperature it increases the strength but at low temperature it hardly has any influence in the deformation of the rock and this is most likely because at low temperature rocks to behave in elastic manner and elasticity we know does not depend on strain rate but we still see with some granites For example this is Indian granite and this is a kind of shale where it is increasing slowly even with Carrara marble and this is because these rocks are not ideal elastic material, so it has some sort of other components of the rheology maybe viscous, maybe plastic a little bit and therefore the strength do increase but it does not increase the way we saw with the yield marble in the previous slide.

As a result this role of pressure temperature, pore pressure and strain rate in determining the rheology of the rocks are extremely important and when we observe the real examples of structural geology when you put the field and you learn about fold, fault, application and so on these things are extremely important, so keep this in mind. We will recapitulate of this session, and we will cover a different topic in the next lecture.

So we learned that the effect of rheology on the deformation of the rocks which we have to learn, we learned strain, stress, their relationships that what are the different possible ways a rock can deform but what is the response of a rock when it is deforming in a fix viscous manner, when it is deforming in plastic manner, when it is deforming in elastoviscous manner, when it is deforming in elastoplastic manner that what are the expressions of the rock and I tell you like we say that drops of water makes an ocean, very similarly most of the deformations initiate at the crystal scale at the very very minor minute scale, so either it nucleates at a single point and then it propagates to make it a very large event or many little events do nucleates at different places, they (())(23:54) and they form again a very large event.

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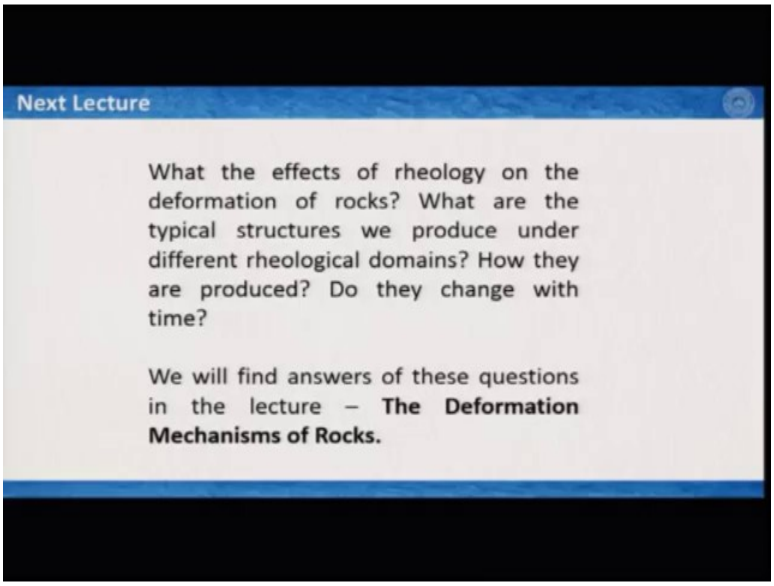

So how does it happen like what other typical structures they produce under different rheological domains, how they are produced and most importantly if they are produced they stay as they are or they change with time and we will answer all these questions in the next lecture with the deformation mechanism of rocks. Thank you very much.