Structural Geology
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Lecture - 11
Rheology – II (Complex Rheology)

Hello everyone! Welcome back again to this online Structural Geology course under NPTEL and today we are around lecture number 11 and we are studying Rheology. Today we are at our part 2 of the rheology lecture. In the last lecture i. e. in lecture no.10 of rheology we learned the three basic the 3 n members of rheology: elastic rheology, viscous rheology and plastic rheology and today we learn combined or complex rheology.

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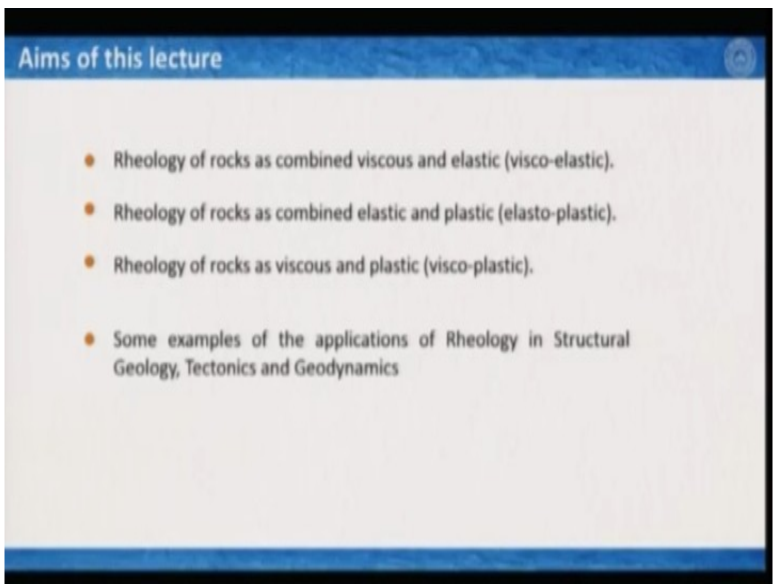

Now in this present lecture, we will cover rheology of rocks as combined viscous and elastic materials. So we will call it visco-elastic rheology. Similarly we will combine elastic and plastic that would be elasto-plastic rheology. We will also combine viscous and plastic. That would be your visco-plastic material, and then in the next lecture we will cover some examples of the applications of rheology in structural geology, tectonics and geodynamics. Now we start with a first the visco-elastic rheology but before that let us have a look that what are the different applications of this combined rheology.

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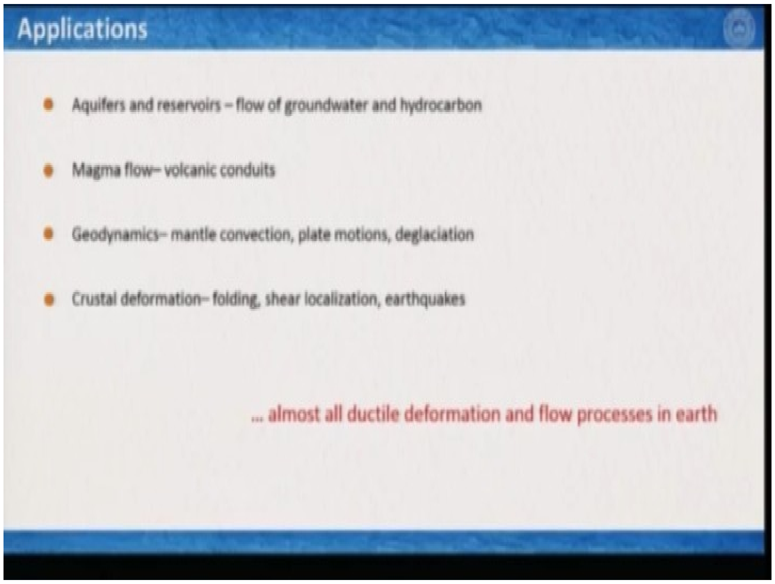

So in aquifers and reservoirs so flow of groundwater and hydrocarbons to understand their flow behavior, flow mechanisms. It is important that we use a complex rheology or combined rheology there, magma flow in volcanic conduits that also requires complex rheology to explain the flow mechanisms. In geodynamics there is mantle convection, plate motions, the deglaciation phenomena. All these are explained by complex rheology and if we come to the crustal deformation, the structure we generally see in the field, the ductile structures, folding, share localizations and also earthquakes which are not ductile but these are all explained by complex rheology.

Accordingly you can consider that almost all ductile deformations and their flow processes in earth can be explained by using the complex rheology. So, the complex rheology or combined rheology basics is very simple that we will see that elastic, plastic and viscous be it linear or non-linear these are often found to be too simple to model and explain the deformation behavior of rocks under certain conditions.

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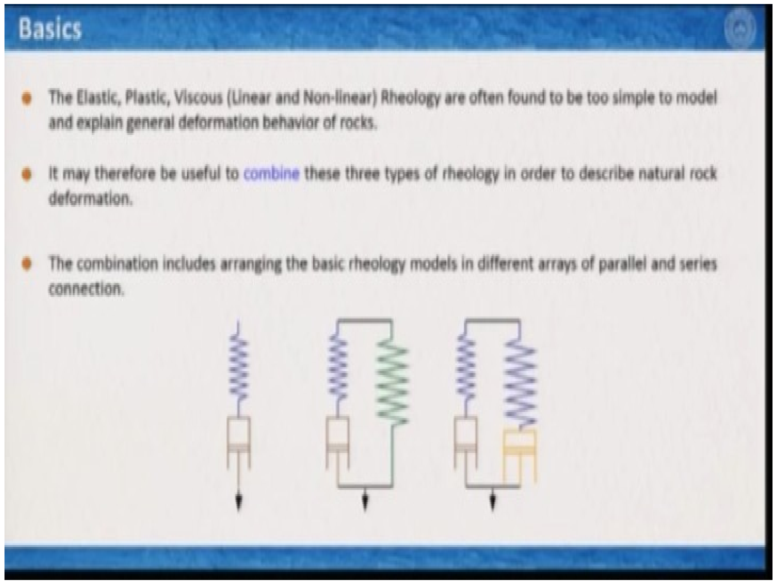

In this context it is important that we combine these 3 types of basic rheology in order to describe the natural rock deformation and the combinations. The possibility of these combinations are many so as you can see here, I have added a spring and a dashpot, then I have springs of 2 different properties and then a dashpot, 2 different springs, 2 different dashpots. So you can array them in parallel and series and then again parallel and series and so on.

We are going to learn today is the very simple combinations in parallel and also in series particularly for visco-elastic rheologies and then we will see how to explain what would be their stress strain curve, what will their stress versus time strain versus time curves and why these are important for understanding better the deformation of rocks.

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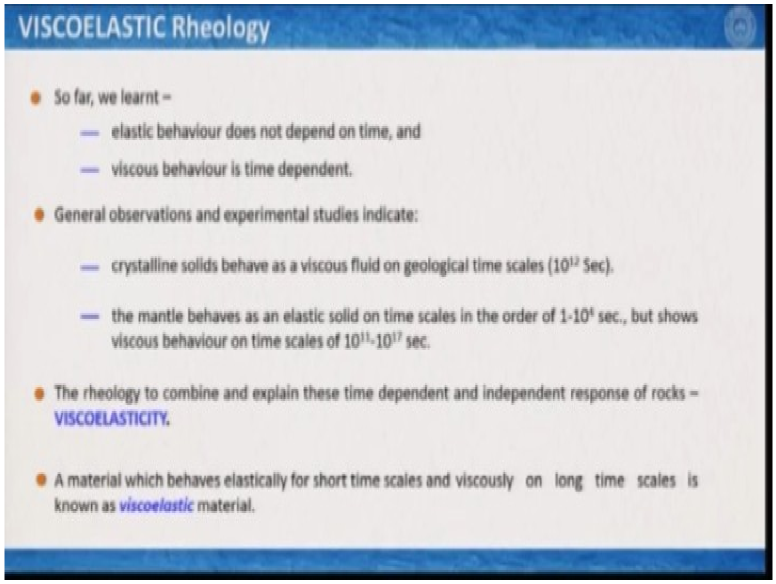

Accordingly we start first with visco-elastic rheology. In the previous lecture we learned that elastic behavior is not time dependent. That means it does not depend on time and we also learned if we consider viscous rheology then it is time dependent. It is strain rate dependent. Now, if we have to combine these 2 observations that one rheology elastic is time independent and another rheology viscous which is time dependent. How can we explain this in terms of or how can we apply this in our earth systems?

Now the general observations that we have seen from different type of long-term, short-term measurements that crystalline solids when it deforms it behave as a viscous fluid in geological time scales like 10 to the power 12 seconds or so on but the mantle behaves as an elastic solid on time scales very when it is very small so 1 to 10 to the power 4 seconds but it shows a viscous behavior on time scales when it is very high 10 to the power 11 or 10 to the power 17 seconds.

So, in general if we try to understand that if the deformation is short time, then the rocks respond as elastic manner, but if it is very long time, then it responds as viscous manner. So this is a spot or this is a range where we can apply the visco-elastic rheology the combinations of elasticity and viscosity. We have combined them together in different ways and then we can apply this visco elasticity to explain the behavior of the deformation and the materials that do have the property that in short time scales they behave elastically and long timescales they behave in disgust manner are known as visco-elastic material.

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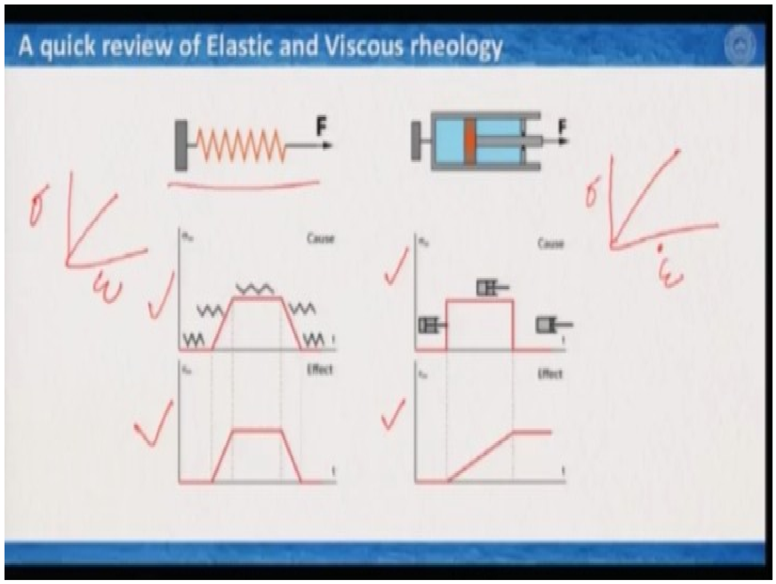

Now let us have a quick review of what we have learned for viscous and elastic rheology. We know that elastic rheology is explained by a spring and the stress strain curve is like linear something like that. This is your stress, this is your strain and this is the stress versus time and strain versus time response, this one and this one for the viscosity is explained by dashpot and then here we generally explain it stress versus strain rate curve.

And it is like this for a linear viscous material and this is your stress versus time and strain versus time curve with time is corresponding to stress and strain. Now you can combine these 2 rheology either in parallel or in series. When you combine them in parallel, we see a different behavior when you combine in series we get a different behavior and both of them have applications in structural geology or geodynamics in general.

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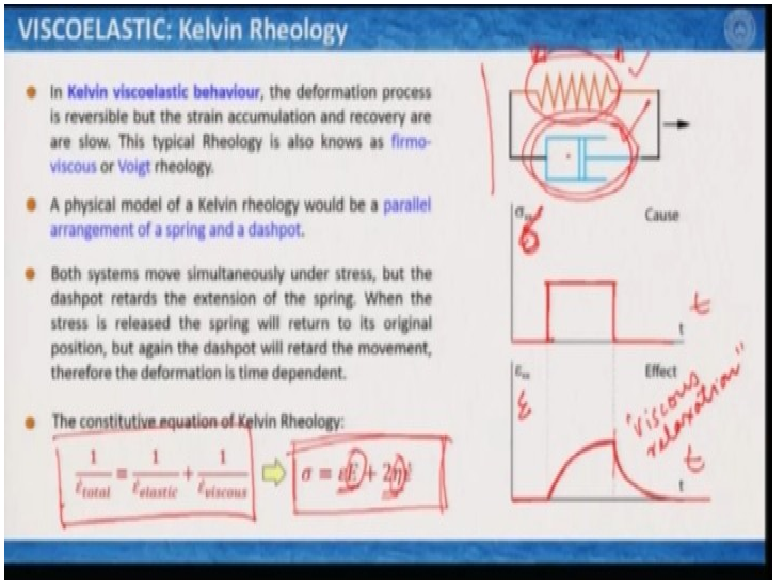

So, let us first have a look, the first visco-elastic component that we will be talking about is known as Kelvin rheology. Since Kelvin visco-elastic behavior or Kelvin visco-elastic materials the deformation process is reversible, right? That is the first thing to get but the strain accumulation recovery are extremely slow. It is not like plastic materials and this typical real rheology, this Kelvin rheology is also known as firmo-viscous or Voigt rheology. Now, generally this Kelvin rheology is explained or we model it when we add spring and the dashpot that means elastic and the viscous in parallel arrangement, what we see here that I have spring and in parallel I have a dashpot.

Now the first statement that we made in this slide the deformation process is reversible, you can clearly figure out if we stay within the elastic domain of this spring does not matter how far I stretch this it has to come back to its original position because there is the spring. So this response of viscous part is important in determining that how much time it would take to come back to its position because when it comes back to its position or when it responds this way, it is not a function of the spring anymore. It is a function of how much this fluid is allowing this entire system to come back to its original position.

So both the systems, in this case, the spring and this viscous dashpot, they move simultaneously under stress, but the dashpot retards the extension of the spring. So when the stress is released, the spring will return to its original position. It will try to return to its original position very quickly but again the dashpot will return this movement. Okay? So therefore the deformation is time dependent though the entire deformation is recoverable. So you can again see this with the stress versus time and strain. I am sorry. This is stress and strain versus time plot. The application of stress is very similar that we have applied to our elastic elements.

Therefore we apply instantaneous stress which is here to here and then leave it for a while and then release the stress instantaneously and then it stays at 0. The strain response is very interesting. So when the stress is 0, the strain is 0 at the beginning but when we instantaneously apply the stress, now because it has both spring and dashpot in parallel, the strain increase is somehow nonlinear. Even if the spring is linear and the fluid here is a linear viscous fluid because we are combining them and once we release the stress again, the recovery is nonlinear and time dependent. So it comes back to its original position in an asymptotic manner and this part, this release of strain very slowly is known as viscous relaxation.

Viscous relaxation has many applications in structural geology and geodynamics. We will not go into that part but you just remember that when you, when you are dealing with this kind of rheology, Kelvin rheology in the release of strain after the load is gone is nonlinear and it is extremely slow and it is known as viscous relaxation. So clearly I have the equation for this. A spring known is Hooke's Law and viscous is also known is the flow of the Newtonian but As they are parallel so the total deformation would be following the equation of parallel combinations of elements.

In this context if I have to go with the strain rate, then I know that 1 by strain rate should be equal to 1 by strain rate of the elastic element which would be added with the inverse of the strain rate of the viscous element and if we expand this equation or resolve this equation, then we simply get this equation where your total stress is equal to strain multiplied by the elastic element and then viscosity is multiplied by strain rate of this viscous element and this is how, so this is Young’s modulus and this is viscosity.

So this is how we explain the Kelvin rheology where the strain is recoverable or the entire deformation is reversible but entire process is extremely slow. What would happen if we add this elastic and viscous elements instead of parallel if we add them in series? Then what we get is known as Maxwell rheology.

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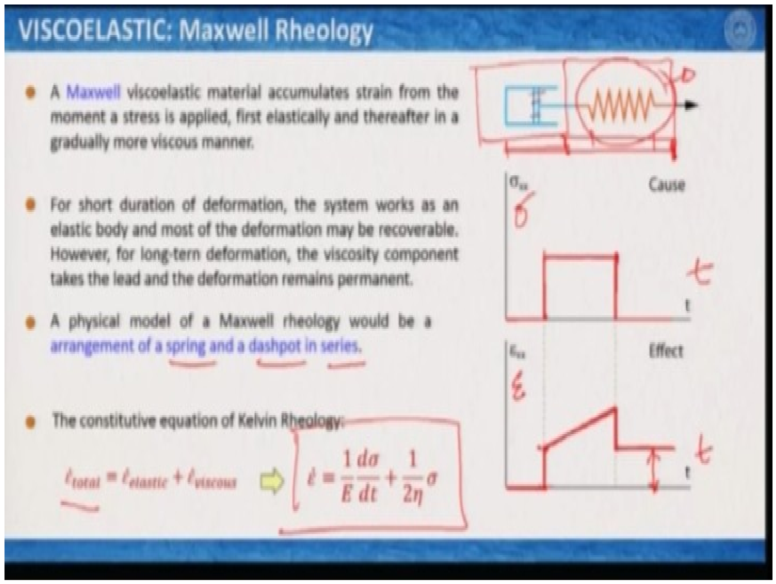

So here we have the viscous element here, we have the elastic element and they are added in the series. Accordingly a Maxwell visco-elastic material accumulates strain from the moment a stress is applied because it is independently deforming, it can deform independently this spring, the deformation of the spring does not depend initially on the deformation of this viscous element, right? So it deforms immediately the moment a stress is applied. First elastically and then it goes to gradually in viscous manner.

So therefore, for short duration of deformation this system works as an elastic body, but later this goes to a viscous manner. During this short duration of deformation in most of the cases is recoverable because then it is independent of the dashpot but the spring then only plays the role. However, for long-term deformation the viscosity component takes the lead right because then we discuss viscous material starts flowing through the porous spaces of this piston and then it remains permanent and if it becomes permanent, then your deformation is permanent and you cannot recover it.

Or in other way, you can recover the deformation of the spring but you cannot recover the deformation of this dashpot. So the total deformation therefore is not coming back to its original position once you release the stress. So the deformation is not totally recoverable and this is the physical model of Maxwell rheology where you can arrange it a spring and a dashpot in series.

Now, once we do it in series, the equation is very straightforward. So total strain rate is the sum of the total strain rate of elastic and thus total strain rate of viscous components and if we expand this equation or resolve this equation, then it takes this little complex shape and here again, we have sigma and time and here we have again strain and time curve and what we see here? Let me explain it. I should do it before that we have 0 stress, no strain then instantaneously, I apply the stress, the strain increases instantaneously because of this elastic element.

So, this deformation is essentially because of the spring this one, and then I add the viscous part when I keep it for quite a long time. So, then viscous strain increases slowly. Now, when I release the stress instantaneously the elastic part released but viscous stream stays, it does not come back to its original position. But again, this happens very-very slowly however in linear manner. So this is visco-elastic rheology and we learned that we have Maxwell rheology and we have Kelvin rheology. Maxwell rheology when we add viscosity and elasticity in series and Kelvin rheology when you add specificity and elasticity in parallel.

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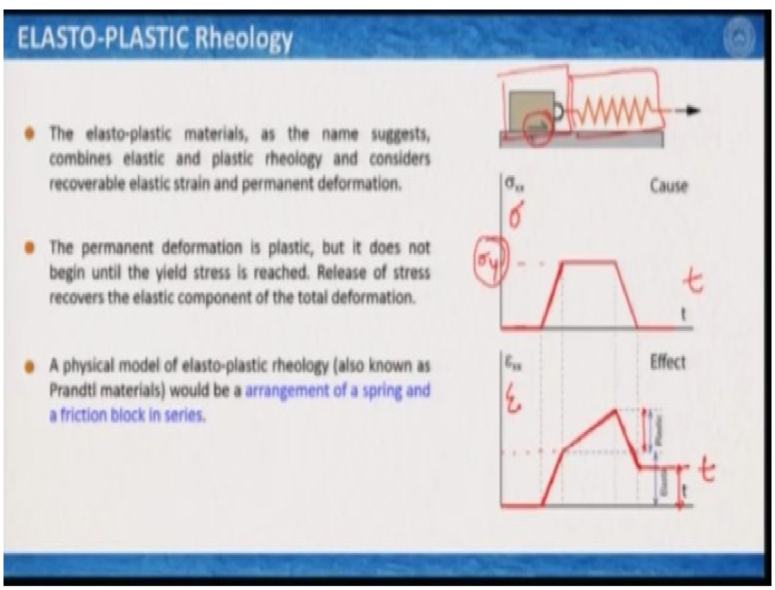

Let us talk about another one which is elasto-plastic rheology. The elasto-plastic materials as you can guess from this name that it combines elastic material, elastic element and plastic element, right? So it considers recoverable elastic strain from the elastic element, but non-recoverable strain from the plastic element. So, therefore, the total deformation is not recoverable. The permanent deformation as I talk is plastic, but it does not begin until the yield stress is reached. Release of stress recovers the elastic component of the total deformation and the physical model we can in a simple way we can see it when you add them in series.

Here I have this spring block. I am sorry here I have the spring block and then I have the friction block here and if I pull it, the spring, the spring slowly expands because of the force I am applying and when this spring also gives the load to this, cooling load to this friction block and when this friction is overcome by this force, pull force, pulling force the list friction block starts moving and when the stress is released then this spring comes back to its original position but not the friction block. So, we can have an idea from this behavior from stress versus time and strain versus time curve. So, here when the stress we apply there is no stress, there is no strain.

Then I slowly pull this spring. So, I increase the stress, strain is also increased linearly the way I increase the stress but then when I start moving this spring, so this is your elastic sigma Y is your yield stress, then this friction block starts moving and if I release the stress in the elastic strain, I recovered, I can recover the elastic strain and then the plastic strain continues. So this strain is equivalent to this strain. This is your plastic strain, which you cannot recover. This model has significant applications or it is in a simpler form we apply it mostly to predict the or understand the behavior of the earthquakes and we will see it later.

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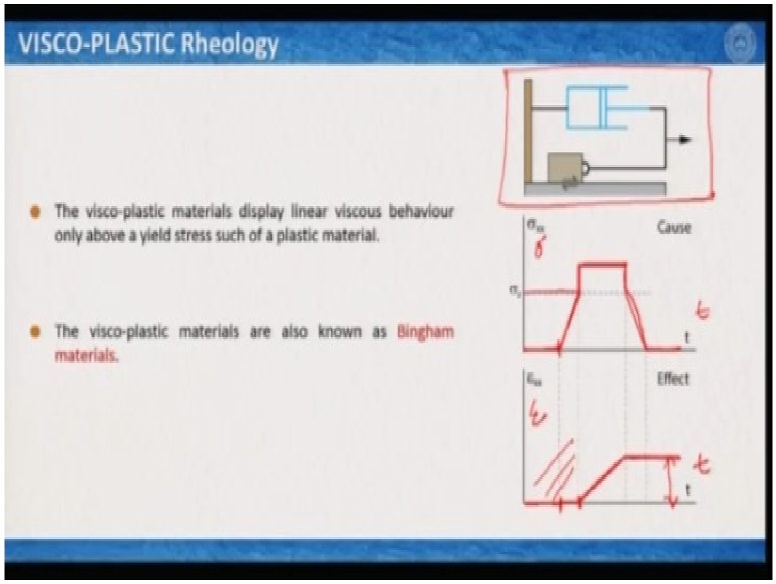

So now we will see what is visco-plastic rheology. As you can understand it has viscous element and plastic element and in this case the visco-plastic materials display the linear viscous behavior only above yield stress of a plastic material. Now, visco plastic materials are also known as Bingham materials or Bingham plastics and a typical visco-plastic rheology is generally shown by the parallel arrangements of friction block and dashpot, which is shown here. So what is happening in this case?

If I add the, if I try to understand these 2 elasto plots, this is sigma versus time and strain versus time. So in the stress is 0, strain is 0 and then I start slowly applying the load. Once I am applying this load, interestingly I cannot move the dashpot till I reach the yield of this friction block. Right? So there would be no deformation. There will be no strain, even if there is some sort of stress and when I reach the yield stress then I instantaneously move this spring block and then stress goes this way and then I leave the stress.

So in the entire time the strain continue continues increasing but it does not matter if I release the stress the Strain remains permanent because of the friction block and also viscous element. So, I repeat, the visco plastic materials display linear viscous behavior after the yield stress or only above the yield stress of when you are dealing with a visco-plastic material. So, therefore, if I do not look at this part this behavior is essentially behavior of linear viscous-rheology.

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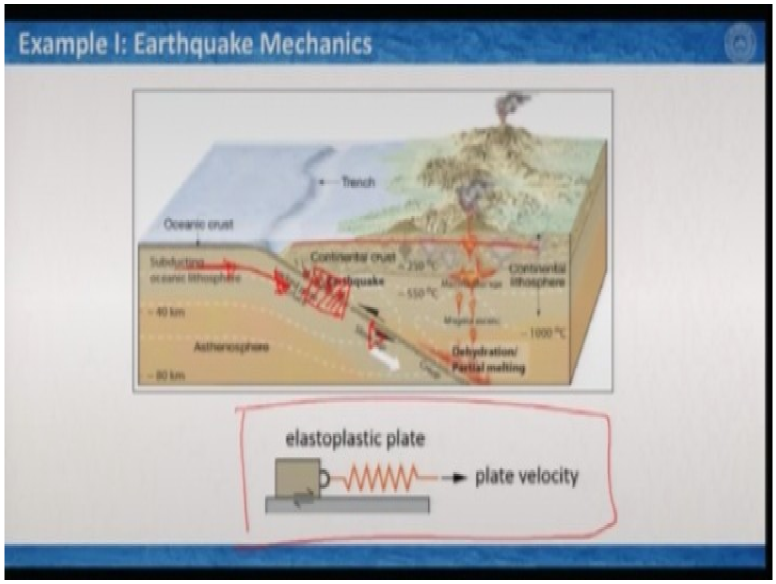

Now we will see 3 examples of where and how in large-scale processes we apply this complex or combined rheology. The first one we take over is earthquake mechanics. Now we know how earthquakes do happen right? That most of the earthquakes do happen along plate boundaries or to be very specific in the convergent plate boundaries where oceanic plate goes down below the continental plate and here is an illustration where this oceanic block is continues to subduct under this continental crust and we know earthquake happens somewhere here what we call Benioff Zone at some depth.

So at this place there is a significant amount of friction. So there is some sort of resistance. Now when this block is continuously pushing to go down because of this resistance it cannot move immediately if there is no creep happening. Now, in such a setting at this region, this plate is accumulating significant amount of elastic strain. At one point of time when you accumulate this elastic strain, it releases very suddenly, in a very similar way we have seen in our friction block. We overcome the yield stress and then it starts moving instantaneously.

When this strain here, the elastic strain here is released in forms of catastrophic or seismic event and therefore we have an earthquake. Now, this we can very simply model using this elasto-plastic rheology. I just remind you that actual process of earthquake or microphysics of that is extremely complex and it is not always advised to explain it using this model, but this is the simplest way you can explain the earthquake mechanics in rheological context.

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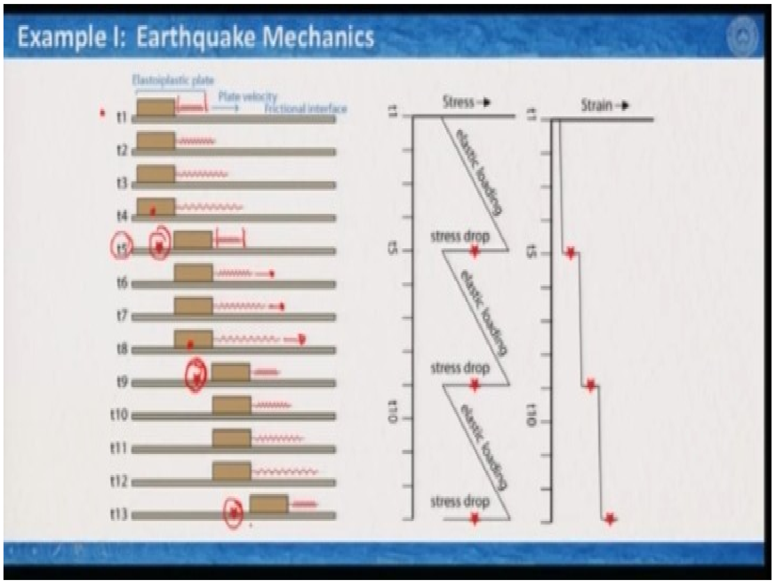

So what we see here, I am trying to provide here an illustration. Here we are considering that this spring and the friction block together form the elastic plate. The pull I applying to this spring is the plate velocity and this frictional interface is your contact between continental plate and oceanic plate. So, at t1 things are very stable. Now the plate velocity has been applied to this spring so spring is slowly expanding as you can see and when we overcome this frictional resistance here, this block suddenly moves to its forward it moves forward suddenly and that happens at t5 and when this sudden move happens you have a release of energy and this is an earthquake.

Interestingly when that happens it actually shrinks the spring back to its original position. So, I have this spring here and I have the spring here. So, I have accumulated the strain but my elastic element comes back to its original position, not the plastic element, but plate velocity continues. So the same thing do happen here, I am again stretching the spring, again stretching the spring, again stretching the spring and again when I reach the elastic, this friction of this block, then this block suddenly moves forward and produce another earthquake and so on.

So, I have one earthquake , second earthquake here and in a similar way I have third earthquake here with accumulation of more strength and it is happening in a zigzag manner, like it takes time to accumulate the strain, then suddenly it releases, then again it takes time to accumulate the strain suddenly it releases and so on. This is very similar of what we call earthquake recurrence that in a place if you have an earthquake, then it comes back in time. That could be in 100 years, 200 years or several million years it depends on the frictional resistance. It depends on many other parameter, the composition, the fluid content and so on.

We are not going to that part but this behavior of an elasto-plastic body is excellent to understand, up to primarily first order understanding of an earthquake phenomena. So, you can see that you have doing elastic loading in the stress and then at t5 you have a stress drop because it brings comes back. Then you have again elastic loading, you have stress drop each stress drop is characterized by an earthquake. So, this is a very simple model but one can understand the earthquake mechanics using a very simple combined elasto-plastic rheology.

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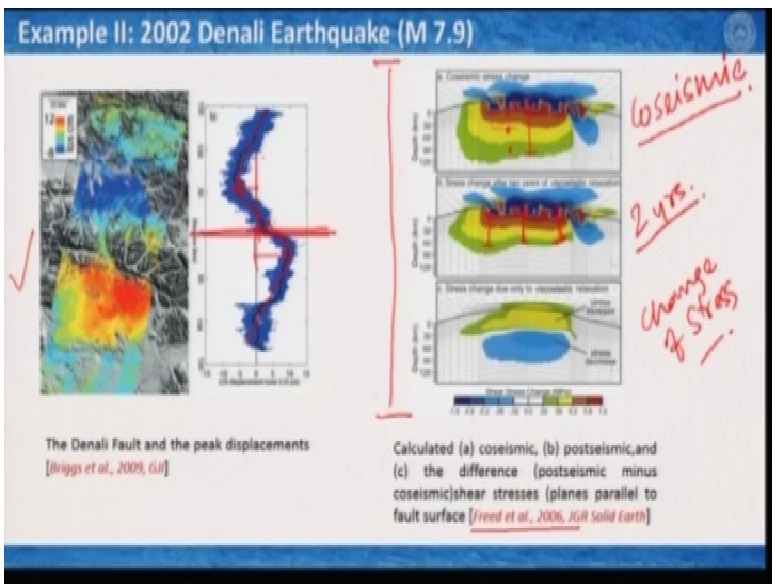

Let us have a second example and this example is from 2002 Denali earthquake the magnitude was 7.9, it was a huge earthquake, but it happened, you know Denali is in US, the northern part of US in Alaska. No one died, but it was a devastating earthquake close to 50 - 60 million was the damage that happened in this earthquake because of many many landslides. So this diagram here on the left side shows the displacement of this earthquake, maximum displacement.

This is where this line of the slip so you had this magnitude of; I am sorry this is your magnitude of maximum slip that happened in this earthquake, which is pretty high in terms of this earthquake that happened on the surface because this was a very shallow earthquake it was, if I remember correctly, 12 13 kilometers depth it happened on the surface. Now what is interesting of this earthquake? Now if I have an earthquake, the earthquake is not an isolated process because the top part of the plate is also attached to the mantle below which you have learned is somehow viscous.

So when you have this huge displacement of several kilometers of these plates then mantle also gets affected by these deformation. So instantaneous deformation of this crust that produced an earthquake also provide an instantaneous deformation in the mantle and this is what is shown in this diagram. So this is co-seismic stress change. What do you see here that this is this yellow then, sorry orange, then yellow, then green. These are your stress accumulation immediately after the earthquake and then the second illustration shows same place after two years and we can clearly see that at least visualize, I am not going into the detail but if you are interested, you can read this paper Free Little, 2006. I think 2006 A, they have 2 papers on this.

Accordingly what you can see here that the justified considered this affected area or affected depth has reduced from the co-seismic time to next 2 years and this third is showing the change of stress. That means if you subtract from this to this and this clearly indicates that we are recovering the stress and this is an excellent example of Maxwell rheology that when you have instant deformation, like then the spring takes the lead but in long-term the dashpot comes into the picture to recover or not recover the strain and so on. So, this is an excellent application of visco-elastic rheology in explaining earthquake processes in earth particularly the mantle deformation during the earthquake.

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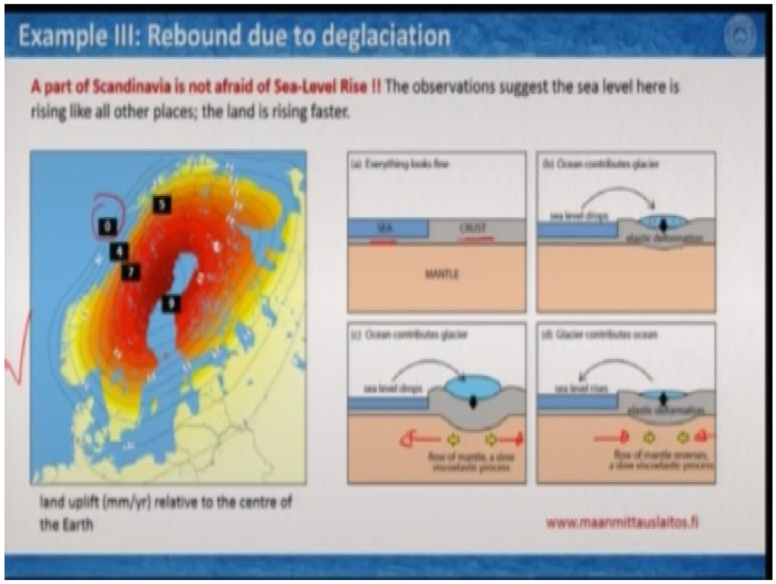

The last example that I would like to give is related to be deglaciation and rebound due to deglaciation. Now, we know, that most of this lands that, the continents are under the threat of the sea level rise but there is one place in the world where sea level is going down. Now this is very interesting and this is a very important geodynamic problem that people had to solve and helping solve again by the study of complex geology combined rheology. So that land is rising, sea level is lowering down.

It is the only phenomenon that is being seen in Scandinavian parts so it is Norway and other places, Finland, Norway and these places but however the observations suggest that the sea level rise phenomena is also there, so with respect to the center of the earth, if we measure the sea level at different times, then sea level is certainly rising in this region but interestingly the rise of the land is faster.

So therefore, the relative rise of land you can see there. Now, what we see? Let us have a first look in this image. At the core of this area, so this is the Scandinavian countries and these contours that we see here, these are your land uplifts. So at the core the land uplifts with a rate of 9 millimeter per year and then it slowly reduces to 0 almost when you reach the sea. Now, this is explained by a combined rheology, this behavior that is why land is rising up in this region and why also the maximum rise is at the core of this area.

So these 4 diagrams actually very-very simply describe how this can happen. So when we have a very standard setting we have sea, we have crust and below that mantle so these parties, you can consider, this is your thick continental crust. You have thin oceanic crust above which you have the sea and then below you have mantle everything is rest and everything is in peace, but earth is a dynamic system so probably during some sort of pulling age, pulling time. The sea level dropped because it contributed to the formation of glacier in this region.

Now this glacier which is this blue area is heavy ice so ice is loading the continental crust and therefore it is deforming elastic way the continental crust so it is going down. Now it continues the glaciation and then the size or volume of the glacier increased. Therefore weight also increased and the continental crust deformed further. Now, when you deform further elastically, of course, it has to displace the mantle below.

So, the mantle below, very slowly move away from this place because it has to accommodate the sinking, elastically sinking, continental crust. Now, till this part it is fine. We have glaciers in Finland and Norway very good, but later when the deglaciation started the sea level rise happened because the water from the glacier goes down, comes back to the sea. Acordingly the elastic deformation that we had in the continental crust is now recovering the strain so it is coming back to its original position and the mantle is also coming back to recover the fill up the gap.

So this is exactly what is happening during due to deglaciation this continental crust is coming back all pushing up and this is happening mostly because the deglaciation also the push from the mantle below and this is also an excellent example of using combined rheology in explaining the rebound due to the glaciation in Scandinavian places.

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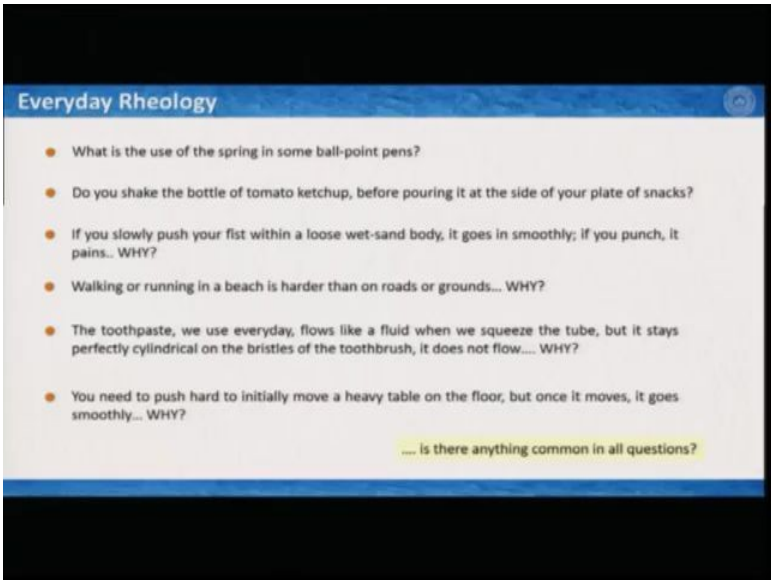

We are almost at the end of the lecture and of this rheology and I would like to show you the, one of the first slides where we have cited some of the everyday use of rheology examples like the ballpoint pens, then why do you have to shake the bottles of tomato ketchup or running on a beach is harder than running on roads and so on. Now I request you to review all these questions or all these facts and I am sure you can now answer them or you can now understand the processes of all these mechanisms in terms of rheology.

So, I repeat whatever we do most of the things where we have some sort of forces required to move something best way to explain is using the 3 basic rheologies or combinations of them. So with this I finish this lecture but we are not done with rheology.

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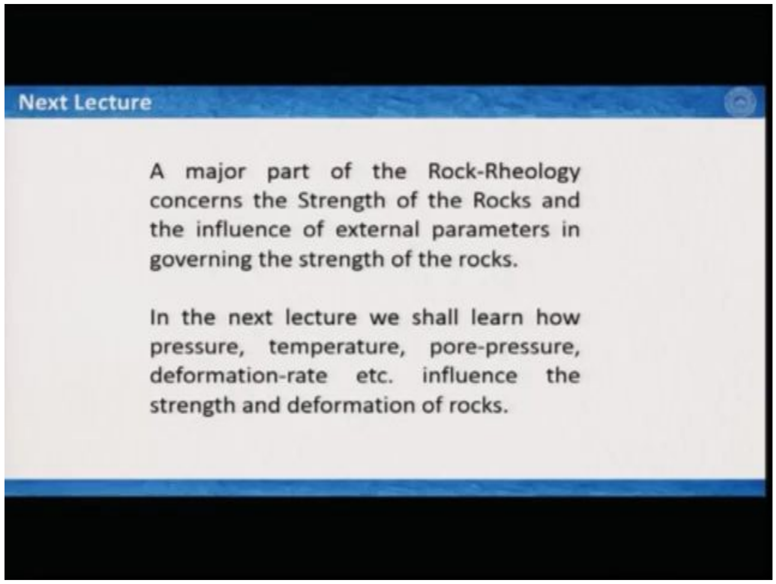

We will have a short lecture to understand that what are the influences of the different external parameters in governing the flow or strength of the rock. So, we are going to learn it in the next lecture. Thank you very much.