Fluid Inclusion in Minerals: Principles, Methodology, Practice and Application

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Lecture – 29
Application of Fluid Inclusion to Deformation, Metamorphism (Contd.)

Welcome to today's lecture, we have been discussing about the Applications of Fluid Inclusions in different areas of geology. And you will please note that we the in this see in this part of the lecture series; the attempt is to bring in sight as many case studies as possible to impress upon the fact that; the imprint that is left by the fluid in course of its activity in crustal processes, can be retrieved and interpreted in terms of it is own in various geological processes.

And although, it is not possible to give exhaustive coverage of the application of fluid inclusions in these areas, in which the fluid inclusion data can be effectively utilized, but attempt has been made to cite as many case studies as possible and keeping in mind that the Indian examples are also discussed um. So, in that context we just started to discuss a one of the important aspects of fluid inclusion studies in application to understand, understanding of deformation in rocks; that are brought about by different tectonic forces.

And as we see them, analyze them in different situations like collagen, collagen zones, orogenic belts and mobile belts ancient as well as the modern, where the theta dine evolve by vary by multiple processes of such activities. And the discussion we just started to understand about how the concept of fluid inclusion planes is being applied to unravel or the, to understand the deformation process. And at the same time how the fluid has assisted the process because in all in invariably in many situations in the crust the processes that take place in a fluid present situation.

And the fluid plays and plays an important role in such processes. So, we just quoted at one of the work that is referenced here.

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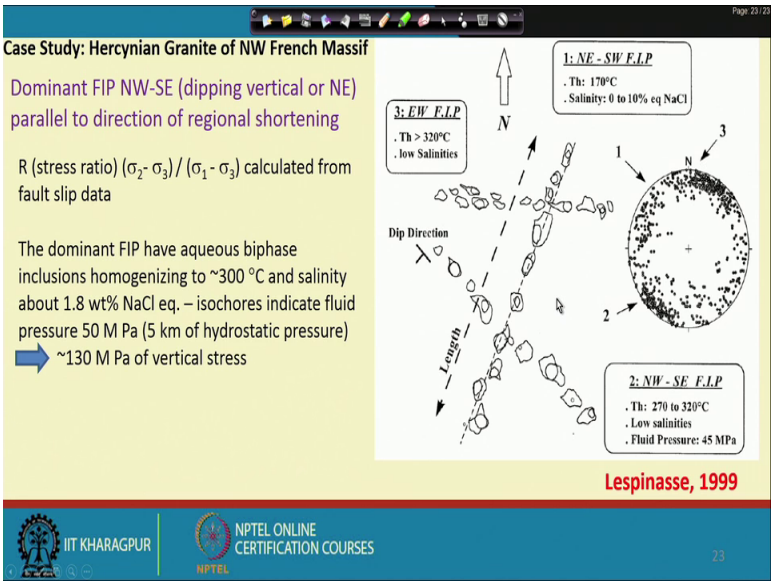

And as emphasized that fluid inclusion the work on fluid inclusion plane or fluid inclusion planes do have a very good future. And need to be applied or need to be studied in many different terrains, where they have not been done. So, that many important conclusions and many important and interesting interpretations can be made to understand the process better.

So, here continuing with the point from where we left in the last class; taking up the same case study is the Hercynian Granite in the northwest French Massif, where these authors presented their work using fluid inclusion plane to understand the stress, analysis these conditions of stress during the deformation process. And needless to mention that the fluid inclusion work have to be adequately backed up by analysis in the study as well as in the laboratory, on deciphering the directions of the nature of the far field stress conditions, which are essentially represented in form of the principle stress axis the stress ellipsoid.

The maximum intermediate and minimum principle stress axis represented by sigma 1, sigma 2, sigma 3. And those kind of calculations are also made from the structural data obtained in the field from the slip of on the fault plane and many other kind of features that are measured in the field.

So, even restrict our discussions to as and when the fluid inclusion have been considered. And the fluid inclusion study has contributed to this particular piece of work. So, during

their study in the French Massif they, it was interpreted that it was essentially a northeast southwest compressional external force that was that acted in the region, which manifested there are if this diagram it represents that there are many different there are many different fluid inclusion planes oriented in maybe different directions. Out of which the northwest southwest southeast of fluid inclusion plane with almost vertical to sub vertical deep are the most prominent fluid inclusion plane.

Although, there are later episodes of hydro fracturing or the brittle fracturing and opening up of the fracture mode one kind of fracture and giving rise to fluid inclusion planes and later stages, but for the for the time being concentrating on this particular set of fluid inclusion plane, which are associated with the main deformation phase was considered. So, here the background analysis has been done. These stress ratio is known, and this particular fluid inclusion plane was found to have a dominantly aqueous biphase inclusions, which homogenized in the range of 270 to 320 of almost an average of 300 degree Celsius.

And the salinity depression in freezing point was about minus 1 degree Celsius, which would be calculated to roughly about 1.8 weight percent NaCl equivalent. So, as we know that many of the situations where the deformation takes place in the presence of a fluid. There we do not have an exact quantitative idea about the effective vertical stress because the pour fluid pressure plays a role. So, then here the fluid inclusions they help us in having some idea at least a range can be interpreted in terms of a range that; what would have been the fluid pressure.

So, if these inclusions could considered, the temperature of homogenization and the salinity from which the densities could be calculated and the isochores could be plotted. And the taking on this kind of an average a value for this isochore and the authors here they interpreted that was giving kind of a 50 roughly about 50 plus minus 10 mega Pascal. So, 500 bars of pressure which could be interpreted from analysis of this particular fluid inclusion plane.

And if this particular depth the 50 mega Pascal is converted to considering that it will have to be a hydrostatic condition. Then it would be translated into a depth of about 5 kilometer from the surface. And that 5 kilometer from the surface if you if the taking out the granite Tectonium, where the rock is essentially granite whose specific gravity is

known. Then the Lithostatic pressure could be also calculated which could have been a give an idea about the vertical stress there, which come out to be around 130 mega Pascal of about 1.3 kilo bar.

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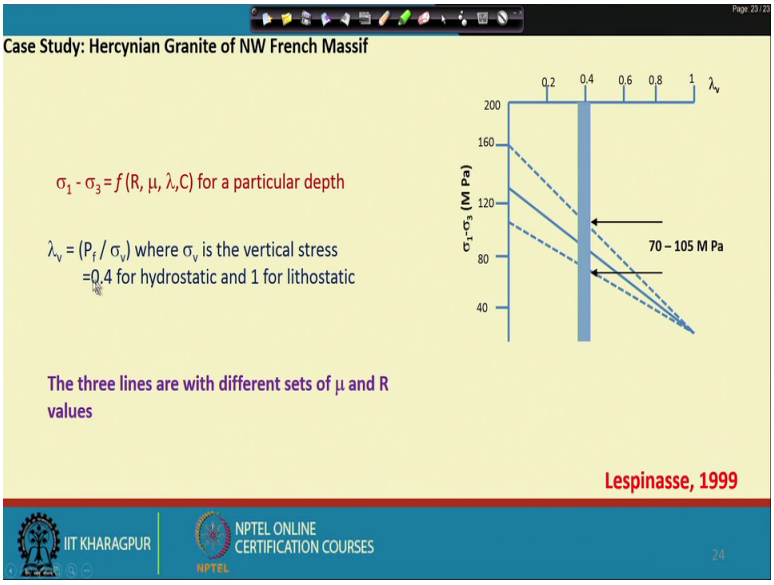

so normally, we are interested in actually getting the value of the sigma 1 minus sigma 3 that is the difference between the maximum principle stress and the minimum principle stress values, and that actually is an important parameter in understanding the deformation process in any segment any crustal rock.

So, that happens to be a function of this parameters such as this; ratio with this ratio is essentially the ratio of a sigma 1 sigma 2 minus sigma 3 divided by sigma 1 minus sigma 3. And that ratio as i mentioned before could be calculated from the stress analysis data, and this mu is the static friction and the lambda is kind of an effective um stress which is essentially the ore fluid divided by the vertical stress here, which takes on a value of 0.4 if the stress is the stress is hydrostatic and it becomes 1 if it is it is a lithostatic.

So now if this under this condition this diagram shows that; this is a on the on this plot of sigma 1 minus sigma 3 versus lambda v. Here if we take a range of take a value of consider the value of hydrostatic pressure and take the value of lambda v is 0.4, then these extreme lines represent the lines which are constructed by taking different sets of value for this friction and the values of the R that is a ratio stress ratio. And then some

kind of a range in the sigma 1 minus sigma 3 could be constrained from the value of a R and the a mu this will be the friction and the stress ratio this is calculated.

So, if we if one considers the lambda v to be able to 0.4, and then it actually gives an idea that the value could be around 70 there is the indicated by this arrow here, between 70 to 105 mega Pascal included in the condition of effective stress the that would reacted in the process of deformation. So, these are the ones which essentially is can be it could only be possible made possible, by looking at the few fluid inclusion planes and then having the calculation.

So, it is the accuracy of such kind of values will always be depending on the calculation of the densities isochores of the fluid inclusions and the constraining of the pressure value from the isochores. The better the constraints R the more accurate is the final value of this parameter that we can get.

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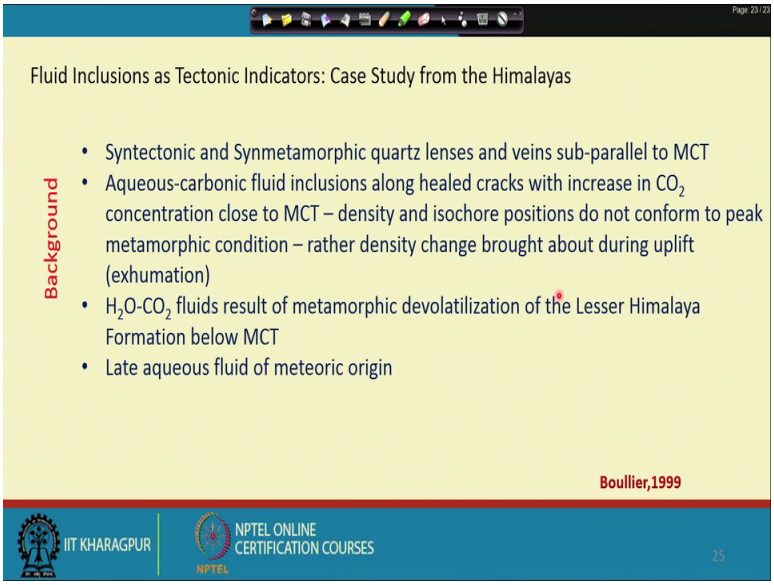

to take it would always be interesting to cite some of the case studies which have been done on the Himalayas. And one such description it is a it is not been very regular rigorously analyzed, but some description of fluid inclusion planes and correlating it with regional tectonics, can be cited from the work of Boullier 1999.

And as i have said a list of all these references will be provided at the end of this which lecture for the details to be refer to, but this is only here we intend to give up give a

broad overview and brief idea. And being home the point the about the importance or the implications useful and important implications of the study of fluid inclusions in understanding crustal processes. So, the background is we all know it is a series of sulfured and dipping thrusts, sorry not were the dipping thrust and the sulfured thrusting of the different segments. The segments of this different types of sediments of the um lesser Himalayas, the simple Himalayas crystalines and so on.

So, this what was done in this particular work is the Syntectonic and the Synmetamorphic quartz lenses in the rocks, around the MCT from below and above the sediment piles of the m MCT were studied. And here the direction and the proper care has been taken for the proper referencing of the volunteer samples, on which the fluid inclusion planes could be very well reference with respect to the original stress direction.

Aqueous so, what was the observed was that they were aqueous carbonic fluid inclusions along healed cracks with increased C O 2 concentrations to the as it as the MCT is rich, which will be shown in the next slide. Density and the isochore positions do not conform to the peak metamorphic condition, rather density change brought about during uplift and exhumation. So, this particular fluid inclusions that were studied, and we are not exactly confirming to the peak metamorphic conditions and this H 2 O C O 2 fluids the result from the metamorphic devolatilization of the lesser Himalayas.

So, the aqueous carbonic inclusions that was seen in the fluid inclusion planes in the in the from the Synmetamorphic quartz lenses, that were sampled. They are they are presumed to be the result of the metamorphic devolatilization of the lesser Himalayan formations below the MCT. And the late aqueous fluids where of meteoric origin were interpreted view of meteoric origin.

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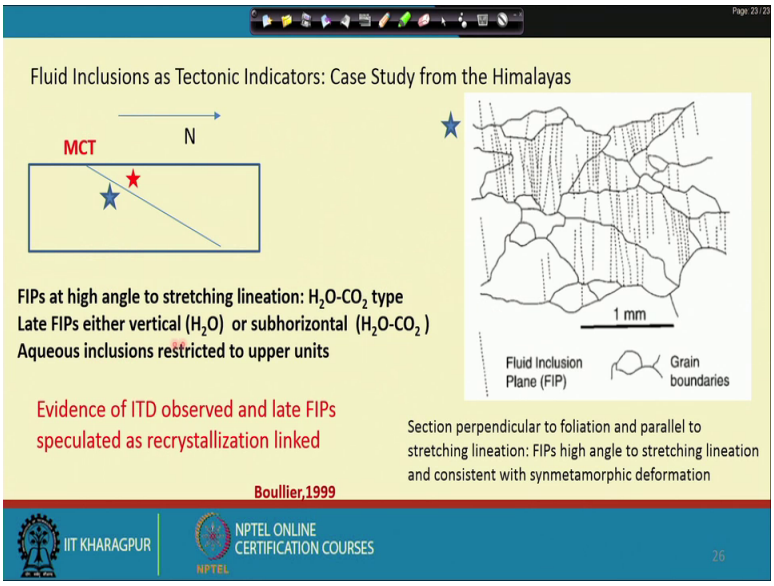

So, this was the situation here if this is the MCT, then samples which are taken from below and above. So here mostly the FIPs; that were taken, where, H 2 O-C O 2 type and the late FIPs with on the vertical fluid inclusion planes. So, this FIP the which were having the aqueous carbonic inclusion type are mostly on planes which are parallel to the foliations defining the MCT in the in that region. And, but the late the FIPs where the they are populated of by aqueous inclusions H 2 O rich inclusions, were having at vertical or sub horizontal and aqueous inclusions restricted to the units which are above the MCT.

So, what was shown here was that these dotted lines represent the fluid inclusion planes, and they were mostly emanating from the grain boundaries. And this particular section is perpendicular to the foliation and parallel to the stretching lineation, the FIPs at high angle to the stretching lineation and consistent with the synmetamorphic deformation.

So, here what was observed was that the fluid inclusions they confirm to evidence of isothermal decompression that was observed in the late fluid inclusion planes and were speculated as they are linked to the recrystallization. Like the situation which we discussed before in case of the Sardinian examples, where the earlier inclusions which are trapped in the subhorizontal the fluid inclusion planes containing the H 2 O CO 2 type. The they were later on recrystallized with the recrystallization of the host quartz and evidence of the isothermal decompositions were observed in them.

So, they were no much of microthermometric data or VB takes data and isochores that are presented in this particular work, but it was qualitatively shown that with the progress and towards the later part of the exhumation history, this isothermal decompression. We are also imprinted in the form of the differently oriented aqueous inclusion, and the original homogeneous aqueous carbonic fluids were entrapped in the fluid inclusion planes which are indifferent at a high angle to the grain boundaries.

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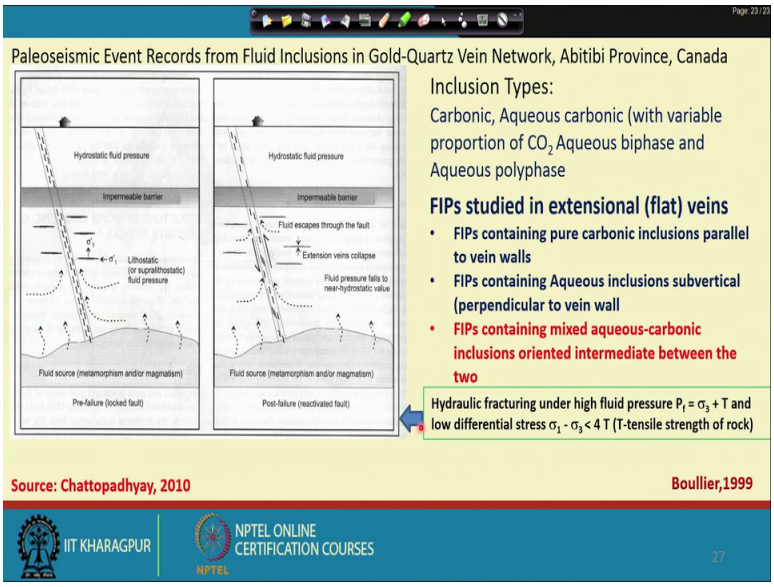

This particular case study is from an orogenic gold deposit in Abitibi province Canada. Now this is interesting case study that was presented in this again by Boullier 1999. So, we could possibly just have a little bit of a background idea about what exactly happens in a orogenic gold formation system. So, what is essentially is that; the regional far field stress operates on a horizontal direction it is a compression axis, it is a compression from horizontal compression that operates there with the maximum principal stress direction is horizontal.

And the system evolves in this way that; there is an impermeable bar barrier which makes the fluid to be confined within this particular region, and the fluid which is generated in the process of devolatilization of the rocks. The volcano sedimentary pile the green stones which are generally the rock types in orogenic gold systems. There the fluid which is essentially will be a homogeneous aqueous carbonic fluid, that fluid is generated here. In this particular compressive region it keeps on accumulating and

because of this impermeable barrier this fluid is not able to be channelized through the through whatever is available as it could be a fault system.

And within that that process the fluid is actually the fluid pressure exceeds the lithostatic pressure, and which is called as the super lithostatic pressure. And during that kind of a period because the fluid is developing a super lithostatic pressure to withstand the load of the overlying rocks data. And is this particular structure is an unfavorable structure for the fluid to move through. So, it waits till the time that there is a seismic rupturing or a failure, through after which the fluid escapes through this channel ways and there is a drop of the fluid pressure. And the operating stress system undergoes a change in their orientation.

So, during the process in which the super lithostatic pressure builds up, there are generations of this kind of sub parallel sub horizontal kind of vein systems or the flat vein systems. Because of the hydraulic fracturing that takes place this particular process, it is it has been presented by many in the in the literature; that it keeps on in a repetitive manner concomitant manner that with, initial phase of the rupturing and the release of the fluid decreasing of the fluid pressure the fluid escapes through this particular zone and then deposits the meta the quartz veins along with the with gold.

And then after this particular this particular zone by the deposition of the quartz veins gets sealed up. Again it leads to the development of the super lithostatic pressure the within in the fluid which is again below that. So, it keeps on happening in a cyclic or a repetitive manner, which is been presented as the seismic pumping or the fault wall mechanism and the veins which form in this processs, they are being described is a crack seal kind of a processes.

So, what is expected here is that there will be one state in which this super lithostatic pressure will create hydraulic fracturing and generate this kind of flat veins by little failure. And then it will be alter then after the fluid has escaped the fluid pressure is dropped it the stress condition will change and there will be vertical shortening that will be in this kind of frame. So, these veins will experience; initially there will be a generation of hydraulic fracturing and opening up of this a under a particular stress condition and sigma 3s will be vertical. And then when the there is escape of fluid and collapse of this structure in the and there is vertical stress.

So, these veins will give rise to vertical hydro fracturing and crack seal kind of process. So, by looking at the veins they always exhibit very complicated pattern or structure repeat. So, this repetitive structure of hydraulic fracturing and then collapsing of these veins and again, and another set of hydraulic fracturing and then vertical type of veins sometimes accompanied by formation of some late hydrothermal minerals like Tourmaline.

So, this keeps this kind of veins give very interesting microscopic features from which; such features could be deciphered. So, this with this at the background, in this particular work the fluid inclusion planes were studied in. So, here this particular design represents here or here which is a also been shown here, these 2 stages; that here these there these veins will be the shear veins, their orientation will be different from the veins which are here even though there will be kind of aborting against the main plane of shear or the fault here.

And as it will been shown here, there will be extension vein collapse during the time at which the fluid pressure is dropping. So, one would expect then in this case this 2 different. So, this cyclic manner this flat vein would preserve episodes of initial stage where there is because of the building up of the lithostatic pressure and the hydraulic fracturing and the generation of this veins, in which sigma 3 will be vertical and the other case when sigma 3 becomes horizontal.

And so one you definitely would look we will see many series of such fluid inclusion planes. At least one dominant plane would be during the process of the during the first phase. And then there will be almost perpendicular to that there will be fluid inclusion planes. So, such fluid inclusion planes in this kind of veins in this part in this cold province Abitibi province of Canada, there are some selected gold deposits from where the veins were sampled the shear veins as well as the flood vents.

So, they were populated with carbonic, carbon dioxide rich and aqueous rich inclusions with variable proportions of carbon dioxide. So, the author is classified them to be carbon, carbon dioxide dominant and water dominant and intermediate inclusion types which variable proportions of carbon dioxide and water. So, the f FIPs studied in the extensional and the flat veins, this FIPs containing pure carbonic inclusions parallely vein walls. And the FIPs containing the aqueous inclusions or subvertical the

perpendicular to vein wall as is expected in the phase in which the fluid pressure is dropped and this phase conditions has just reversed.

And the FIPs containing the mixed aqueous carbonic inclusions are oriented also intermediate between the 2 for which, the exact mechanism is not very well known. So, here the hydraulic fracturing under a high fluid pressure this kind of situation takes place, where the fluid pressure will be equal to sigma 3 plus the tensile strength of the rock. And the differential stress would be low which will be less than 4 times the tensile strength of the rock.

So, there is what the general condition which applies to such kind of fault fall mechanism of formation of this kind of shear grains and the associated flat veins that is observed in many such orogenic gold mineralizing system in many of the areas, many of the granite instance Archaean granite instant terrains in many different cationic blocks, which we discussed before.

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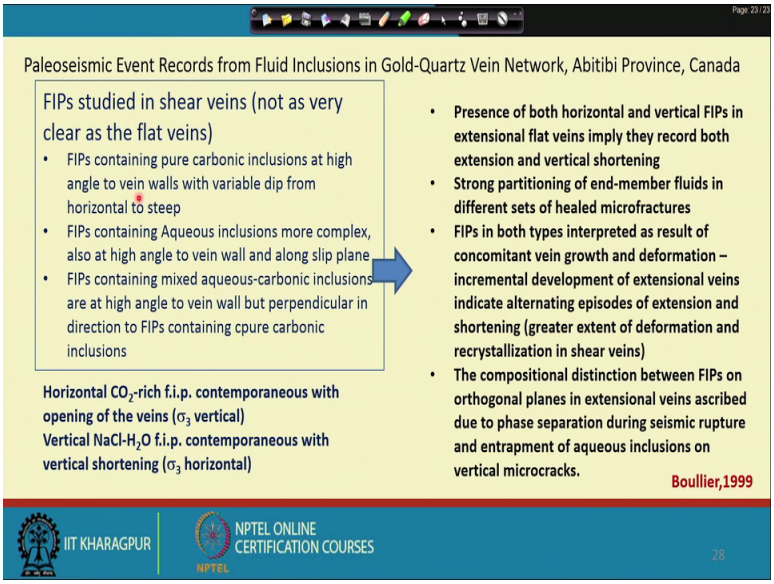

So, FIPs which you are studied in the CR veins; not is very clear as the flat veins because they have undergone more of recrystallization through the different phases of shearing with these flood veins actually survived.

So, this shear veins, they exhibit greater degree of recrystallization boundary migration. So, there were as discussed before; there are grains which are inclusion free are the more

recrystallized polygonal veins and many kinds of features as discussed before was also observed here. The fluid inclusion planes containing pure carbonic inclusions at a high angle to the vein once this as in the case of the flood veins, here the also they are at high angles to the vein wall.

FIPs containing aqueous inclusions are more complex also at high angle to the vein wall along the slip plane. And the FIPs containing mixed aqueous carbonic inclusions are at high angle to the vein wall, but perpendicular in direction to the FIPs containing the pure carbonic conclusions. So, the horizontal carbon dioxide rich fluid inclusion planes were contemporaneous with the opening of the veins where sigma 3 is vertical, as has been shown here. And the vertical NaCl H 2 O fluid inclusion panes contemporaneous with the vertical shortening as has been extend is has been shown here, and which are likely to give rise to this kind of moved on type of cracks, which will be sealed by deposition of quartz veins there.

So, the implications of these the presence of both horizontal and vertical fluid inclusion planes in extensional flat veins imply; that they record both extension and vertical shortening. Strong partitioning of end member fluids in different sets of healed micro fractures. So, what is actually interesting theories that; these process actually keep happening in a continuum concomitantly with the seismic rupture or failure, then again buildup of the fluid pressure above the lithostatic pressure in a and that we say is a super lithostatic pressure.

And then another phase of seismic rupturing and the dropping of the fluid pressure. So, that the vertical shortening takes place. So, they are essentially seen depositional of or rather than being post, I mean the these kind of deformations are not actually they do not post a deformation of the veins, but actually they keep on happening during the growth of these veins in different phases, which are very clear from the microscopic observations of these veins and also from the fluid inclusion plane.

So, what is interpreted here is that; during the super lithostatic pressure where the fluid is actually is a one phase mixed it is H O C O 2 fluid. And they are the ones which dominate the fluid inclusion plane which are parallel to the vein walls, and as and when there is a there is a collapse of this wall and generation of this kind of walls which are perpendicular to the vein wall. They are the H 2 O component which is are mixed from

the parent fluid, and as discussed before possibly because of their at more accurate wetting angle. So, those are the ones which actually populate the perpendicular set of the fluid inclusion planes.

So, FIP in both types interpreted as a result of concomitant vein growth and deformation, incremental development of extensional veins that indicate alternating episodes of extension and start shortening. And the compositional distinctions between these fluid inclusion planes on orthogonal planes it can be expressed can be explained as due to the phase separation during the seismic rapture and entrapment of the aqueous inclusions on vertical microcracks.

So, this gives us this here the fluid inclusion study of the fluid inclusion plane is gives a very good complement to the analysis that was done from the, from the micro structures of the quartz veins, which in which show evidence of growth in multiple phases. And also gives the as expected the different fluid inclusion planes. The fluid inclusions there being of compositional different type is also very much explain a very well explainable on the basis of the switching over of the stress conditions in this cyclic process. So, we will continue discussing in the next class.

Thank you.