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

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Lecture – 26
Application of Fluid Inclusion to Deformation, Metamorphism

Welcome to today's section of Fluid Inclusions in Minerals. In this week, we intend to have a glimpse of variety of topics in which fluid inclusions are applied. They would range from conditions of very low, conditions of pressure temperature in digenetic environment to medium and high grain metamorphic environment to deformation in different types of regimes tectonic regimes.

And being a non expert in all these subjects that I have mentioned, I will only give you a broad idea as to how the fluid inclusions can be a looked in, can be looked at, how interpretations could be made which will be useful to the fields in which we have chosen the problem to address of the characteristics of the fluid, the fluid evolution and how the fluid assisted process when around in giving rise to various types of phenomena the processes that we are considering.

So, the each of these particular topics that I have mentioned, requires a good background of the fundamentals of those subjects. And only they will be so, the fluid inclusion characteristics in the fluid inclusion data will only be used in conjunction with let us say for example, if someone is interested in understanding the, the in metamorphism, so the metamorphism in terms of what happens with increasing pressure temperature conditions, to identify different types of annual assemblages something arising out of a reaction texture, some breakdown or some equilibrium, assemblage and to decipher in terms of the changing a paragenetic sequence of the different metamorphic assemblages which generally come into existence with the changing pressure temperature conditions and also more importantly the fluid there is present there.

And so, one need to have a good understanding of the chemo graphic and the principles of application of heterogeneous phase, equilibrium chemical thermodynamics in addition to the P V T X relationships in fluid mixtures so that the formalism can be very effectively applied to quantifying, to quantitatively understand the process of metamorphism. Similarly, when it comes to deformation, it is it is very essential to understand from very microscopic level of the minerals, the way they deform there with respect to the different crystallographic planes, the slip planes and the rules that divide by the deformation of these minerals.

And what happens exactly if there are fluids present in the fraction species and how they facilitate the deformation process. In addition to the understanding of the broader aspects like the operation of for field stress, conditions and the development of the different types of fabrics, in rocks a proper identification of them and are trying to put them in conformity or in accordance with what is observed from the fluid inclusions.

Today, we would just give a brief introduction. So, is it when it comes to the then the application of fluid inclusions to the study of deformed rocks, deformed and metamorphic rocks as we find them in ancient and present day, modern day orogenic environment, the colligenal belt, the mobile belts where we see different many generations of metamorphism and deformation that the rocks would have undergone.

And so, the fluids will eventually be getting interrupts within the host minerals either during the process of their primary growth or during any recrystallization that goes on in between and will be interrupt in those minerals and we can, we only see then when there exposed to the earth surface and this for kind of process which make them exposed on the earth surface is definitely some kind of process of exhumation or an roofing which whatever happened to bring the rocks to the surface from down below in from great depth in terms of 20 Kilometers, 25, 30, 10, 15 Kilometers from the surface.

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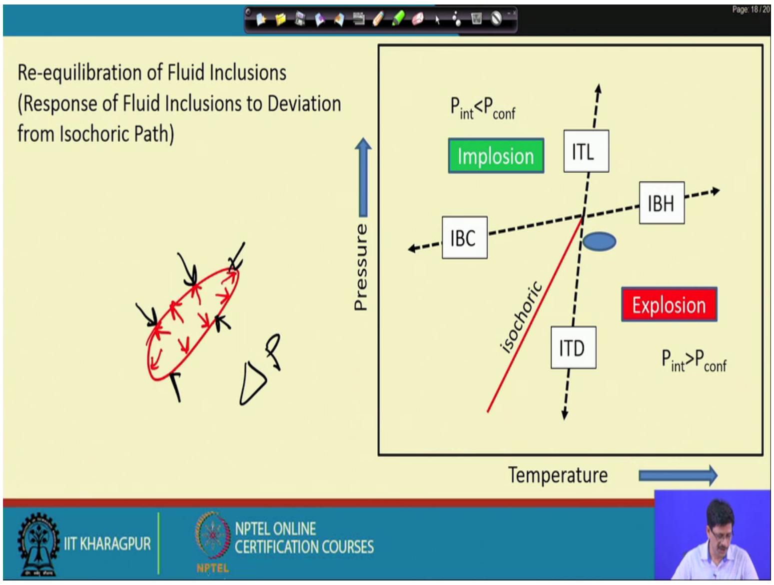

So, just to begin the discussion, it is not only important to understand the fluid characteristics, the mechanism of their entrapment, the pressure temperature conditions in which the fluids are entrapped and it is also equally important to understand that what exactly happens after the fluid is entrapped in the form of inclusions in the solid mineral lattice.

is it, is it happens many of the situations like; now here, on this diagram there is a there these schematic pressure temperature diagram on which one hypothetical fluid inclusion is shown with this filled blue ellipse and the red line is indicating it is isochoric path of evolution. What is essentially understood by the isochoric path of evolution is that depending on the composition of this fluid and the density which is actually is out of the temperature at which it formed and the because we have our assumption is that the fluid after it is entrapment will follow a isocompositional, isodensity line or maybe a curved path which will be which will call as the isochore.

And we presume that the right from the conditions of it is entrapment at great depth corresponding to high pressure and temperature condition with the exhumation of the rock, it would have followed a path where any change in temperature would have also changed the internal pressure within the inclusion cavity and if that internal pressure it we have which is withstood by the host mineral, then the inclusion can follow this isochoric path and can be can remain, can survive or can remain unchanged with it is restrain composition, at the condition at which we are seeing them either depending on what the chemistry is where very laboratory seen whether it is a it is a water rich solution of whether it is water plus carbon dioxide and other gaseous species depending on that, we would be seeing this inclusion as a biphase or a triphase, sometimes with more than one liquid.

Now, the situation is that what has been shown here; the different inclusion has formed in these particular conditions corresponding to the pressure temperature, then there are possibilities; for example, in a as we as we have said that in a [may/many] many corresponding to situation like for example, when this particular rock has formed here and the constituent mineral happens to be a phase in an equilibrium assemblage and has interrupt, a packet of fluid in the form of a fluid inclusion.

Now, it is not necessarily that the geological condition or the conditions of evolution of this particular segment of the crust here who follow exactly as dictated by it is isochore, rather there are more possibilities is, rather a ruled then exception that the pressure temperature conditions of evolution might deviate very significantly from the path which we can call as an isochoric path.

So, the possibilities as shown here; the first possibility is that that it could follow a situation where the there would be a sharp drop in pressure with minor or negligible variation in temperature which you can call as an iso, near isothermal decompression path which is very common in orogenic belts in a clockwise path, in an orogenic belt as it happens. For example, a something in a essentially in a clockwise path, something if it starts from here, then it follows initially a loading path and then there is a increase in temperature with a isobaric heating kind of path and then there is drop in pressure and then, so this essentially constitutes a tool what is use a clockwise pressure temperature time path which is observed in many of the orogenic belts.

So, there are situations in which, this is a strong possibility that there will be a change significant drop in pressure with very negligible change in temperature because the temperature for the equilibrium temperature distribution to reach it will, it takes time because of the poor conductivity of the rock layers. So, when it have when it happens in such a way so, what is expected here is that the fluid inside the inclusion cavity would tend to expand because of when fall in the pressure and because of the higher coefficient of expansion of this particular liquid. This liquid will sorry, because of the because of expansion of this particular fluid with decreasing in pressure.

So, what exactly would happen there is something that if this is the inclusion, it is of course will be in it is one phase condition because the temperature and pressure that is shown here would only be a miscible one phase fluid whether it is a pure water or water plus carbon dioxide. So, what will happen is that with decrease in pressure, this inclusion fluid will keep on exerting more and more pressure on the on it is wall.

And this particular pressure and then, are the pressure which is the external pressure on the inclusion wall will be less than the pressure which is exerted by the inclusion and that is what exactly has been shown here that here the P internal which is shown by this red arrow here, this P internal would be more than P confinements, if we are considering a litho static pressure at any particular point within the earth crust, if the pressure is litho static and the confining pressure, that pressure is less than the pressure which will be exerted by the fluid on the wall of the inclusion.

So, if it of the depending on the rheological property with the ductility of, the rheological property of the host solid mineral, it will undergo deformation. This inclusion will the shape of the inclusion will change, it might then there are some possibility which might happen depending on the this del P that is in terms of in terms of mega pascal, the what is the difference of this the difference of P internal and P confined?

So, this will give rise to so, if this happens, there are possibility that the inclusion will change. It is original morphology the geometry and there are also possibility that the inclusion might undergo change in it is density depending on what is the extent of this difference. As compared to that, if we think of a situation where there is a rock which is formed here and then this because it might be depending on the kind of the tectonic process that is taking place, this particular rock will experience and an isothermal loading, sometimes it is dependent as isothermal compression or ITC.

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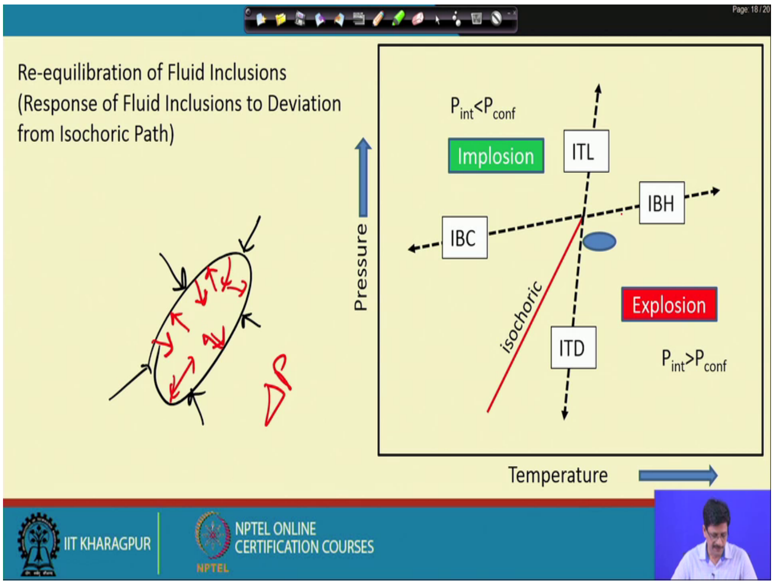

So, it will have a process which will be isothermal loading in which case, they in this case, if this is the entrapped inclusion, then the pressure here is the confining pressure and the pressure that will be exerted on the one of the inclusion here. The situation will be exactly opposite to what we saw in case of an isothermal decompression path in which the P internal will be less than the P confined. So, it would as if this inclusion would tend to collapse because of this del P which is a opposite of what was happening in case of isothermal decompression path.

See the other possibility here, that this particular rock which is formed here with the entrapped inclusion will undergo a isobaric heating, the pressure of almost remaining same. There will be some extra input of heat in form of any possibility could be there, they could be under plating of some magmatic body or some excess production of heat because of some reason where the system will undergo a isobaric heating. So, isobaric heating would have this almost a similar kind of situation as isothermal decompression because here also, the P internal would be greater than P confined and it is also likely that the inclusion will exhibit some change in it is shape and some textural change is expected. And it might depending on the rate at which it might happen, that the inclusion might get re equilibrated to a completely new set of shape or morphology.

And similarly so, this the opposite of that, it could be isobaric cooling in which case it is the P internal is greater than and less than the P confined. So, the two paths; isobaric heating and isothermal decompression will be where the P internal would be greater than P confined will give rise to the features which are, which are classified under the change in the textural characteristics which is due to explosion in the fluid, inclusion cavity tend to explode because of the expansion of the volume.

And the reverse situation is it happens in case of an isothermal loading and isobaric cooling, the where the inclusion cavity tends to flunk because of the higher confining pressure. So, this also give rise to some kind of texture which is implosion known as the implosion type of texture. Now, over the past two decades or so, we have been coming to know about, then got some very good idea would exact exactly what might be happening through experiments which are conducted by experts in the field and I will be just quickly browsing through some of the results which is, which was obtained in this as reported in this reference which is shown here.

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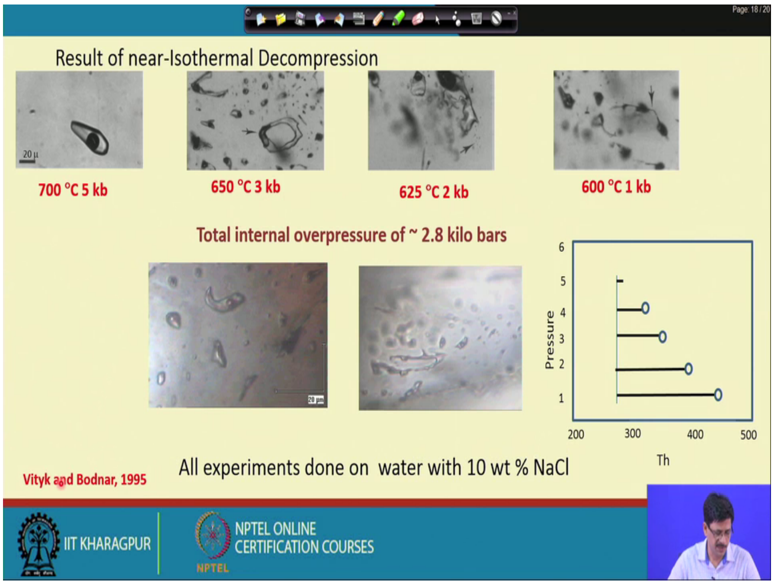

So, the experiments were done exactly on this kind of four different kind of paths ITD, ITL, IBH or IBC and then, we can have a look as to what kind of textures where observed. So, these experiments were actually done by these authors on synthetic inclusions and synthetic inclusions are actually the ones which are trapped in Brazilian Quartz by creating fractures in them and then putting them into a hydrothermal apparatus where the fluid of desired chemistry can be trapped, as inclusions are sealed in the fractures and those inclusions which we routinely uses the synthetic inclusions in many of the laboratories.

So, the first situation where the inclusion was trapped was synthesized. So, this series of experiments which are reported were done on a 10 weight percent NaCl water and this is this is an example of a inclusion, original inclusion which was trapped at a condition of 700 degree centigrade and 5 kilo bar pressure. If we need to simulate the isothermal decompression means we are going to change or the pressure has to be dropped systematically and within the experimental conditions in much shorter intervals of time compared to what exactly happens in terms of only few hundreds of hours compared to what happens in nature.

So, if you could see here that this particular series where the this inclusion is re equibilated at a condition of 650 degree centigrade and 3 kilo bar and then subsequently at 2 kilo bar and 1 kilo bar of pressure, you could see clearly the change that is brought about in the inclusion geometry. And the notable thing here is this; there is the inclusion tends to take the shape of an annular ring with a change, with a drop of pressure about 2 kilo bar and then, these kind of features which we can only say it is kind of explosion feature where there are this inclusion cavities likely to have decrepitated and smaller such satellite inclusions just should have interrupt in the near in the vicinity. Also another important thing to observe here is that where some moderately large size inclusions are showing. So, this could be as a hook shaped inclusion, this is an annular inclusion whereas, there are other inclusions which are of smaller size that seem to be a intact and this shows the extreme conditions.

So, in these kind of a situation where the total internal overpressure where the P internal is greater than the P confined starting from conditions of the, I mean the inclusions which were not subjected to any re equilibration experiment, originals original trapping conditions of 700 degrees centigrade and 5 kilo bar. By the time it comes to 600 degree centigrade and 1 kilo bar, there is a difference about 2.8 kilo bar is, del P a is of the order of 2.8 kilo bar and we see the kind of extreme case on explosion texture which is observed here.

And this possibly recall these inclusions being shown before in when we were showing the drivers types of inclusion morphology and sizes and shape that can have, this is a typically hook shaped can be imagine which is taken from the Eastern hours mobile belt, one of the samples of magnetite. This is also a case where the inclusion is also has a standing towards attaining a annular shape. And so, these kind of textural features give as some idea that the rocks that we are looking at is likely to have undergone such kind of exhumation process.

And here, what is shown here in this diagram is that is the change in the temperature homogenization. So, when there is a original fluid which is subjected to an isothermal decompression and there is expansion of the inclusion cavity and if it results in a brittle failure decrepitation or of this particular inclusion that essentially since it is not the, the salt content of the inclusion is not changing and if it is getting and trapped again or getting sealed again at a at a at a lower density condition, then it is temperature of homogeneity is also likely be higher, then the temperature of homogenization in undeformed inclusion.

So, it is shown here as this as this is the original situation of 5 kilo bar and 700 degree Celsius. This homogenization was around 300, for the undeformed one. So, for the deformed one, the temperature of homogenization could vary in great ranges and so, that gives us one of the ideas that when we do study fluid inclusion micro thermometry in such kind of rocks, the range that is operating the temperature of homogenization could lead us to suspect that some we have whether we have actually sampling or we are taking there on some of the inclusions which are earlier leaked.

Although we have discussed then that how to identify them and how to avoid taking inclusions runs up such inclusions, but on the other hand, to get some idea about the conditions for the techno metamorphic evolution of these rocks, it gives us some very valuable insights.

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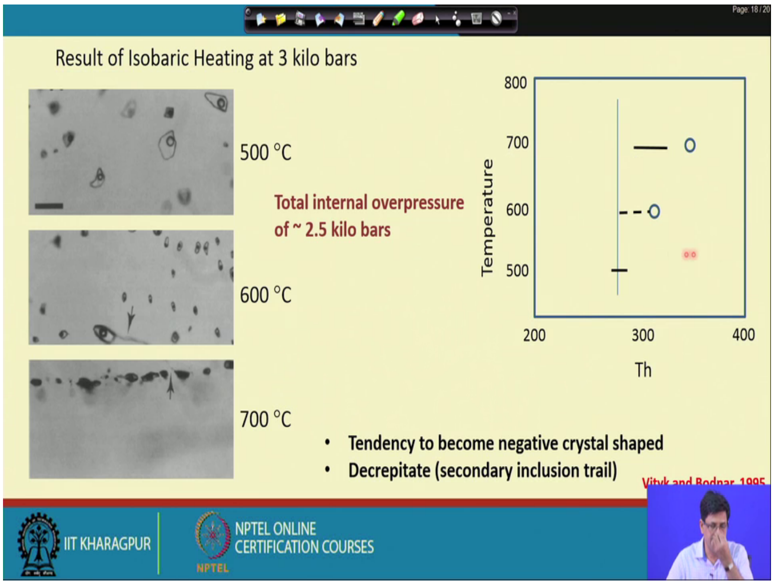

So, here is the situation where the result of isobaric heating, it is also explosion texture where the experiments were done on two different conditions where the pressure was kept constant at 3 kilo bars and the heating was from 500 degree Celsius to 700 degree Celsius. And as expected before, in these conditions also when there is an explosion texture, the as the temperature is at higher and higher temperature, the spread in the temperature of homogenization this why this circles actually indicate the theoretically calculated what could be the temperature of homogenization, but since all the inclusions are actually not re equilibrated, so we might get a ranged in the temperature of homogenization of these inclusions which we either can call them as re equilibrated or more confidently, we can say that those inclusions which actually have responded to such kind of a non isochoric path of the revolution.

So, in some of the situations, it is speculated that actually tend to become tend to attain a negative crystal shape because maybe because of dissolution re precipitation of the host mineral and from energetic considerations because if the temperature is kept at a higher value, than the original trapped condition, then it might tend to attain negative crystal shape. But generally, you there are certain derivations that we also see natural assemblages.

And they do also decrepitated as is shown here in the last diagram; they do also do it decrepitated in form secondary inclusion fails whenever the content of the original inclusion is expelled out from the cavity.

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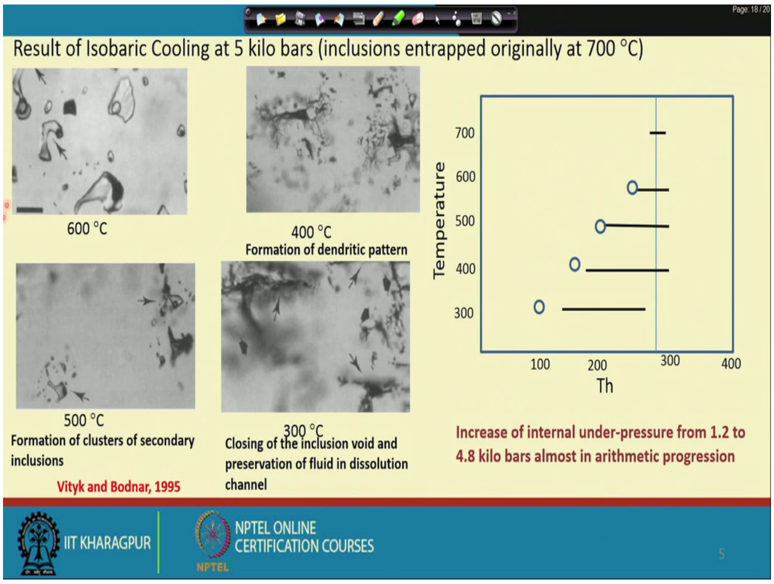

This is the situation corresponding to inclusion. So, this is the experiments which are conducted or the inclusions were trapped at originally at 5 kilo bars and they were cooled from 600 to 300 degree Celsius temperature. And here, the increase in the internal under pressure, it went on from 1.2 to 4.8 kilo or almost arithmetically, the temperature going from 600 to 500 to 400 to 300.

And what we see here that the inclusion texture, here also the cavity sort of collapses and we could see satellite secondary inclusions as shown by the pictures they taken from this particular reference. And the ultimate case almost happens in a way as if the inclusion the, the fluid from the inclusion cavity is totally lost and later on, you know they are preserved in fluids in the dissolution channel like shown here.

And here, the temperature of homogenization because here is the situation where the density of the inclusion fluid is actually changing in a reverse manner, so the original inclusions homogenization temperature we get a value which will be lower.

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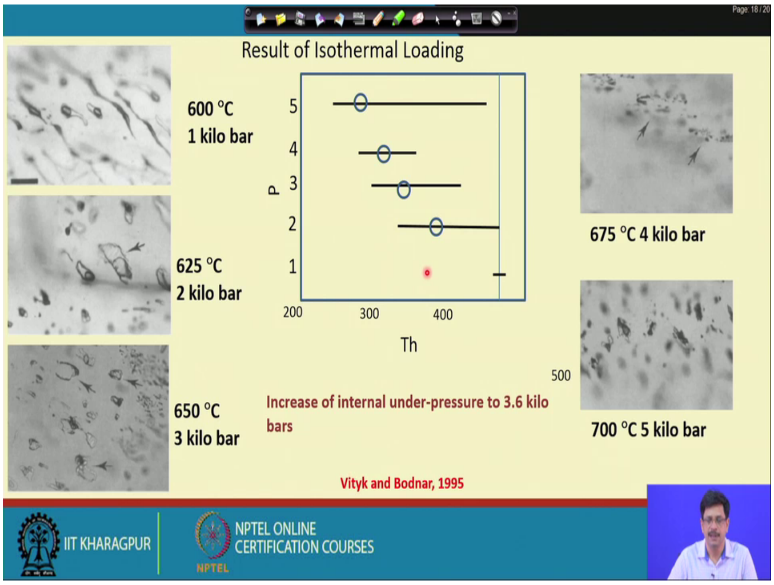

And this are also is an example of the process of implosion right because of isothermal loading where the P confining is more than that of P internal. And here, the temperature which is kept around 600 degree Celsius and the pressure is varied from 1 kilo bar to 5 kilo bar and it is calculated by the authors that the internal pressure give the del P a and go to as high as 3.6 kilo bars which is enough to bring about such kind of changes in the inclusion morphology and their texture.

So, what is more interesting here is that what was shown as the hook shape or the kind of annular shape; at some pressure temperature conditions, intermediate values of the isothermal loading which is about 3 kilo bar, such kind of annular shape is also observed. In addition to and then finally, those kind of annular shape actually the disappear when the with the loading is much higher of the order of 5 kilo bar. Of course, this is are the situations in which the experiments have done and also the same situation, the these are the expected ranges of the observe ranges in the homogenization temperature and the circles representing the expected homogenization temperature decrease in case of inclusion.

So, other than the fact that this implosion also sometimes give rise to annular or hook shape inclusion which coincides. Ideally speaking, the textures that is produced by implosion and those produced by explosions are essentially, they must be distinctly different from each other barring such kind of a exceptional case.

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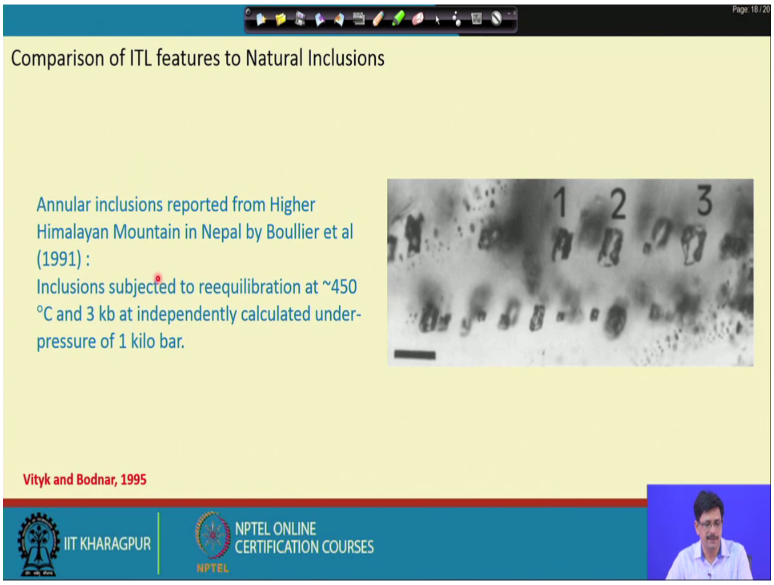

And so, this it is always essential or it is always implied that we would always try to compare the results that people have reported from their experiments to what have been reported from natural rocks.

So, here is an example of a inclusions showing this kind of annular shape that is taken from the higher Himalayan, mountain of Nepal by Boullier et al 1991 where such kind of annular shape of the inclusions where shown where they interpreted the inclusions were subjected to re equilibration of about 450 degree centigrade and 3 kilo bar at independently calculated under pressure of 1 kilo bar. This kind of pressure the del P a of change in the in the in a pressure condition can be calculated independently from other structural considerations and this is just an example.

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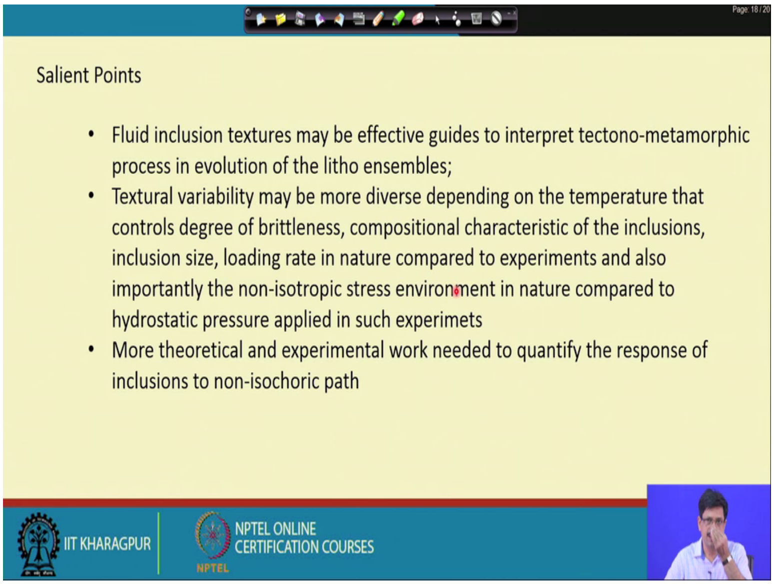

So, the points that we can make from here that fluid inclusion textures may be effective guides to interpret techno metamorphic process of evolution in the different litho ensembles mainly where when we go and examine rocks in the orogenic belts like the Alpine Himalayan belt or and as we know that the more ancient originic belt is, the more difficult would be to interpret in terms of the unraveling the history of the evolution.

because certain old mobile bears like eastern guards whose many of the instances have shown the inclusions from some of the rock types there, they speculated to have undergone several cycles of such assembly and rifting and they do record several such cycles of Orogenic activity. And when we see such kind of textures in those rock ensembles, we really have to interpret them very carefully through which phase, which stage of the evolution the duty present, but definite they give very useful inside to us.

So, the textural variability may be more diverse depending on the temperature will situation, the only limitation here is that the experiments are conductated very limited conditions; for example, this discrete values of the temperature and pressure and the application of the pressure, the rate at which the pressure is applied is far faster than what happens in nature. There are a degree of brittleness of the host mineral also is a function of temperature, the compositional characteristics of the inclusion is also important; for example, what is shown in case of the pure water NaCl like 10 weight percent, NaCl water the behavior of that inclusion is definitely going to be different from a inclusion which is pure carbon dioxide where the d P by d t slope is much lower and the kind of overpressure or under pressure that will be experienced by them is likely to be less.

Even though, we could still if the pressure if the conditions are so drastically different, there is also no reason that why they should not be behaving this kind of inclusion, this kind of morphological characteristics. So, the strain rate and the an another important situation is that these experiments like the one whose results have been cited here where done under isotropic stress environment but in reality in nature, this trace is anisotropic.

So, there are the stresses of deviatoric nature. Some of them will be discussing little bit. And so, definitely is it looks like, so they need to be more of experimental work and theoretical analysis that should be done to really mimic the natural conditions and to make the correspondence even more and definitive so as to make our interpretations better.

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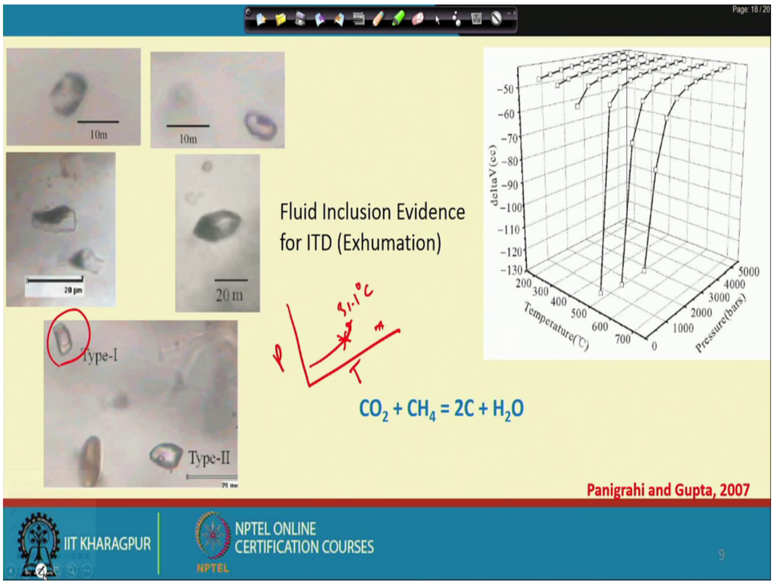

So, just an example that I am showing from again the Eastern guards as well as the one of the schist belts in the work at all.

So, when we see, so this is a situation in which we get such kind of inclusions and we interpret them to have to be a result of this isothermal decompression process. Here, it is an inclusion in which we see there is an aqueous liquid even with a vapor plus this black particle which are identified as graphite. In this case, this is taken from the one of the schist, a schist sample from the Hutti-Maski schist belts; this one is without any vapor phase. So, it depends exactly the pressure temperature condition at which the corresponding to what we will just be discussing.

Here, it is a situation in which an aqueous fluid with graphite, with about more, with about any vapor bubble. This is an inclusion which is purely a carbonic liquid and graphite and here, it is showing that a that a pure carbonic biphase inclusion, liquid rich biphase inclusion, pure carbonic inclusion is going this thing with a pure carbonic vapor rich inclusion and micro thermometry showed where this inclusion homogenized into vapor stage and this inclusion homogenized into liquid stage. And as we know that, if we look at the say for example, if we if we see the condition corresponding to the critical temperature of carbon dioxide, then any entrapment process on the solvers to give rise to such kind of a situation can simply be ruled out.

So, what can be interpreted here is that that, this inclusion which is a vapor carbon vapor carbonic inclusion here must have been trapped somewhere at a high temperature and very low pressure in the vapor stable field of carbon dioxide and this inclusion must have been trapped at a at a later time and such we have already discussed what exactly happens and during re crystallization process which can always be brought out by a Kathryn luminescence image of the host mineral where there are there are domains of re crystallized quartz which generally come out around such kind of later and trapped inclusions.

So, the situation is that when we see water plus graphite or carbon dioxide plus graphite, situation then when we try to understand what could be the possibility; one of the possibility that comes out that this must have been, they must be representing inclusions, the carbonic fluid which had dropped with variable proportions of carbon dioxide and methane. If the carbon dioxide and methane are of exactly equal proportion, then they will react out to give rise to carbon and water. If the proportions are different, then one of the phase might get consumed. So, we might get water plus graphite or carbon dioxide plus graphite. In case of carbon dioxide graphite, there is as always a possibility that there will be a ream of liquid, ream of liquid water which would have gone undetected.

So, now the relevance of this with call with as regards to the isothermal decompression or the exhumation kind of process that we know that, when there is there is a isothermal decompression, the fluid inside the inclusion is exactly more pressure. So, P internal is greater than P confined. And this, when this it exists the yield strength of the host mineral the inclusion the inclusion cavity explorer, so there is a brittle deformation goes on happens or some part of the inclusion can actually get out in terms of satellite inclusion and of a high of a lower density.

Now, if we if we have in leave of that, if we have a reaction where there will be a substantial change in volume; that means, a negative volume change, this product side will be having much less volume than the reactant side, then this particular explosion can possibly be inhibited by reaction, by this reaction which gives rise to graphite and water and the volume expansion is actually counter counteracted by such reaction which results in a net volume change, net negative volume change.

So, to prove that this particular reaction, this particular reaction has been the volume change of the reaction is worked out from thermodynamic data and is plotted here on a 3 Dimensional plot here the temperature pressure and the change in a volume, what we could see here that the at higher temperature conditions and also from higher pressure conditions when we change the pressure from 5 kilo bar to up to 3 kilo bar or suddenly when it comes to about one kilo bar or so, there the change in the volume of this reaction is substantial.

And the as a, I mean what we can observe from this particular diagram that this proposition of the exhumation resulting in such kind of inclusions which give rise to various proportions of graphite plus water plus carbon dioxide plus or minus methane could be a, if this kind of a reaction mechanism is very feasible and the calculation of the volume change of the reaction actually supports the fact that there could be substantial change or reduction in the volume of this particular fluid mixture and that is all.

So, these kind of situations when we see in the fluid inclusion assemblage that also gives us some indication that an isothermal decompression phenomena must have taken place. So, these are some of the examples that that I that I could say, but there could be many more and there are many other case studies for example, from the alpine belt also, there are some classic studies will exactly talk about and also this situation which I depicted here that this carbon in vapor inclusion. So, what so, the situation here is that there are two things which happens that the some when the inclusions which are already trapped in the host mineral.

So, either you can have a situation that the inclusion is trapped in the host mineral or the fluid which is presenting the inter granular species or the fraction species and this particular ensemble is undergoing exhumation. So, the already trapped inclusions will undergo changes like the one which is shown here and the fluid which is present say for example, if a carbonic liquid, carbonic fluid in it is liquid state it is present when the conditions, the pressure temperature condition was high pressure was high and as the pressure dropped because of an isothermal decompression, it where it goes into the carbon dioxide vapor field and this carbon dioxide is later on trapped is a carbonic vapor.

So, these two situations actually correspond to this kind of this phase changes is post entrapment phase changes in response to isothermal decompression whereas this kind of entrapment took place after the isothermal decompression has taken place and the fluid, the carbonic fluid actually entered into it is vapor stability region from the liquid stable field with decrease in pressure. So, these are some of the interpretations that can be made from fluid inclusion characteristics and from the micro thermometric data which could be a very useful significance to understand the techno metamorphic evolution in such kind of terrains. So, we will continue our discussion in the next class.

Thank you.