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

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Lecture - 25
Application of Fluid Inclusion to Ore Forming Environments (Contd.)

Welcome to today's session of inclusions in minerals. We have been discussing about the application of fluid inclusion micro thermometric data to ore forming environment to understand the origin and the path of evolution that the ore fluid actually passed through. During different stage identifiable stages of mineralization in any mineralizing system where a hydrothermal fluid is involved. As you have said this literature on the hydrothermal ore deposits and fluid inclusions especially in different types of hydrothermal systems, a wide spectrum of hydrothermal systems are actually too fast.

We will just take some examples and then go through the fluid inclusion characteristics the rational that is developed in linking the entrapment of different generations of fluid inclusions; in different host minerals in accordance with the established or identified stages of mineralization in a particular deposit. It could be a single episode of fluid activity which could have given rise to mineralization in different locales. Or it could be multiple stages of hydrothermal activity with multiple sources which would have given rise to mineralization of metals in different locales as has been exemplified in some of the cases, like the like the volcanogenic massive sulphide deposits the and in cases like the one which was the Indian example which was described.

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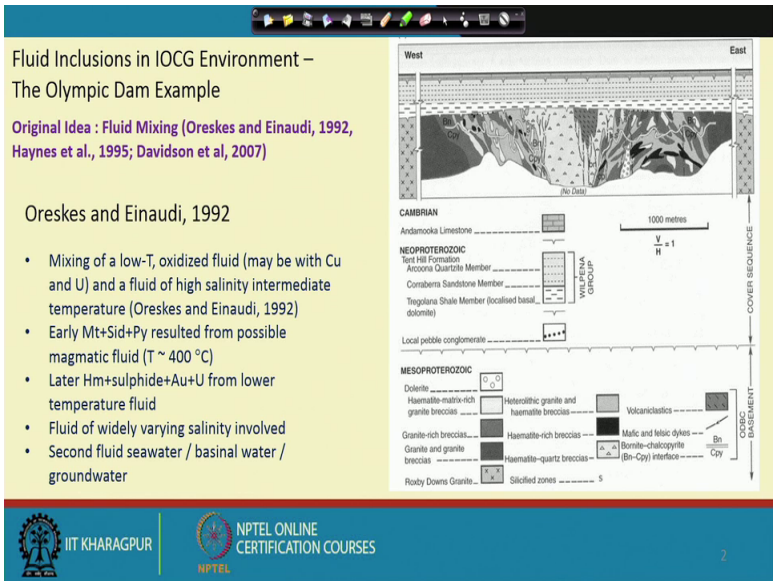

So, we will continue with one important type of one important class of hydrothermal deposit that is known as the IOCG deposits. The iron oxide copper gold deposit and this particular deposit with its origin to the discovery of the giant, Olympic dam deposit in eastern Australian south eastern Australia in the Gawler Craton. And since, then there has been because this is the very first time that breach mineralization of copper uranium and gold was discovered in a zone brachiated zone in a granite of continental interior.

During mostly during the middle Proterozoic time within about 1600 million years to 13 15 or 1400 million years' time. And this discovery of this deposit was a major breakthrough and it gave rise to many further exploration programs in other continents. And over the last 32 years of there about 3 decades of discovery of this particular deposit, there are many more such deposits record have occurrences reported from other parts of the world which are also named as iron oxide copper gold deposits based on the association.

But, we would confine ourselves when it comes to the fluid characteristics and the evolution of the fluid or the inferred path of evolution of the fluid. By taking the Olympic dam joint deposit or rather the IOCG province in this in South Australia and the Gawler Craton. And so, let us just have a look even though it is not intended to discuss the genetic ore genetic aspects in detail about this particular deposit, but we will try to see how the ideas have evolved or what was the original idea regarding the origin of the

hydrothermal fluid and its evolution in this particular classic deposit. If we look at this diagram taken from the book of John Ridley and the ore deposit geology where a cross section of this Olympic dam deposit in a Gawler Craton is shown. And we very peculiar the peculiarity of this particular deposit that it is covered by younger sediments and this constitute the Proterozoic ensemble rock ensemble constituting of the rock speed of granite. And a zone of brachiated granite and the mineralization is confined to this brachiated zone where we also do have representative of the contemporaneous Gawler range organics.

And what we could see here that this represent the particular cross section of a mineralization zone where there is a depth wise variation in the middle assemblage at depth you get mainly pyrite dominated and then gives rise to chalcopyrite bornite, chalcocite covellite type of sulphide mineral minerals and also associated with rich gold and pitchblende mineralization. And this is being interpreted in a way that the sulfidation state decreases towards the, from bottom to top and the interesting facts about this deposit is that the mineralization is mostly within the (Refer Time: 05:43) complex. So, by later stages of cementing within the within the brachia or is later cross cutting veins.

And one of the important aspect of this deposit is that the host means there is no abundant proper and host mineral a quartz, in all the different stages in mineralization to extensively studied the fluid inclusion characteristics, but there are other associated can minerals like fluoride and boride which do help in concerning the fluid characteristics in floored different stages of mineralization. If we look at the fluid inclusion characteristics which was first studied by Oreskes and Einaudi and it was published in 1992 and the what is interesting is that this brachia do have initially magnetite as well as hematite. And the magnetite hematite coating on these brachia, so one which could be this the placement sedimentary rock or the valid material itself.

Then there are some alterations which are also observed like Chloritic or Serisitric alteration which do which does indicate that within this stages, during the which this iron oxide deposited precipitated it must have happened in, kind of a reactions which would have given rise to acidic alteration of the material there. So, the first I want to reduce a kind of fluid evolution path of fluid evolution was way back in 1992 and from this mineralization did what Oreskes and Einaudi started. So, they also interpreted in terms of

a early magnetite siderite pyrite type of mineralization, which was later imprinted by hematite sulphide gold and uranium mineralization from low temperature fluid.

So, the interpretation from the extensive fluid inclusion study is present in quartz fluorite and barite from the different stages like is shown from the early pyrite, stage pyrite, magnetite stage which could be more into kind of a current kind of stage. And then later on giving rise to a sulphide stage which have been interpreted in differently by different authors as we see later this kind of interpretation is absolutely mine.

And the initial interpretations made by the authors are that there was mixing of two different types of fluids. Because they do they did see that one component of the fluid represented the low saline low temperature oxidized fluid. And the other one is a moderately high temperature going up to four hundred degree centigrade which they thought could be possibly from a magnetic fluid. And the mixing which was deciphered was that this low temperature oxidized fluid carried the copper and maybe uranium and on its mixing with this moderate temperature fluid where which contain the iron.

So, the iron undergoing the kind of copper oxidation reduction reaction giving rise to deposition of iron oxide in the form of hematite and liberated such kind of reactions which also we saw in the case of the malanjkhand deposit fluid mixing. Similar kind of situation was deciphered, but here giving rise to mostly hematite. So, the fluid which was a relatively moderately saline in the high temperature fluid was speculated to be of a magnetic derivation.

And the low temperature fluid have its origin source from some kind of a basinal fluid or could be seawater or the basinal fluid or could be ground water that that what was deciphered. Because this wall was purely based on the fluid inclusion assemblages reading to the microthermometric data without much of isotopic or any in situ micro analytical data on the fluid inclusions.

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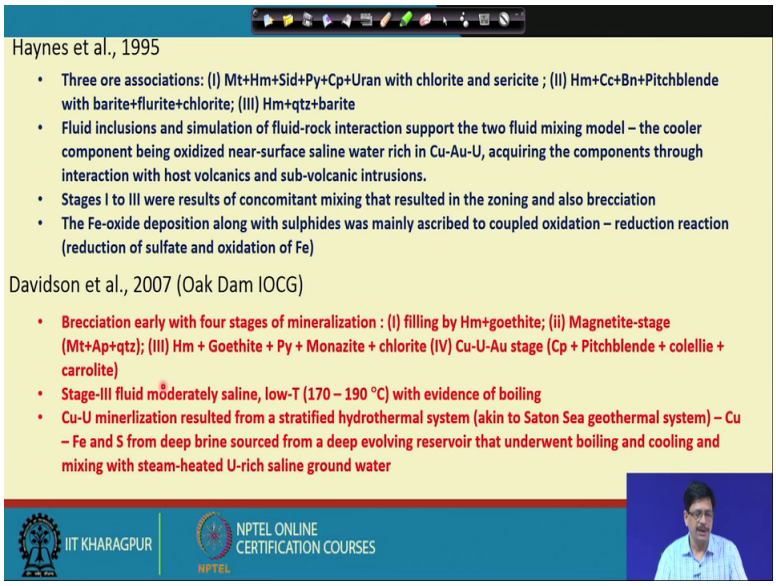

So, later on in 1995, hence it will also they decipher three ore associations. The first one is the magnetite hematite, siderite, pyrite chalcopyrite, and uran pyrite with chlorite and sericite. And the second stage was hematite dominant chalcocite and boronite where we see that the mineralized a the sulphides are basically giving rise to a more with boronoite kind of mineralogy with pitchblende.

And the latest stage was the hematite quartz and barite which was kind of a non-sulphide bearing stages. So, this stage 2 is the most important mineralization event. And they did combine their result of fluid inclusion study with water rock or simulation of fluid rock interaction by picking hypothetical a meteoric water and then titrating with the mineralogy of the (Refer Time: 10:44).

And in similar such calculations they also deciphered that the conclusion about the fluid mixing which was earlier deciphered, by I know the no discuss on in their work was corroborated was supported. And also it was concluded that is iron oxide deposition along with sulphide was mainly expect to a coupled oxidation reduction reaction like the one which was discussed before. And this stage 1, 2, 3 the results upon contaminant mixing that resulted in the zoning and also vegetation they described the vegetation to also contaminant fluid mixing and boiling phenomena.

Although this remains a little bit of a unnatural issue as to how this recreation could have been brought about. But it according to a hand settle 1995 this was more of a

concomitant mixing and zoning of the way the zone zoning in the mineralization at different sulphide association has have been shown. The later on Davidson et al in 2007 they studied a locality which is just in the within the same IOCG province of eastern Australia. The oak dam deposit which is little east southeast of the Olympic dam deposit and they interpreted that this brocciation was early with and the total four stages of mineralization.

One was the feeling very hematite goethite and then magnetite states with magnetite hepatite and quartz then hematite goethite, pyrite, monazite, chlorite. And then the copper uranium gold states with the pitchblende and charolite and cohelite and carolite deposition. And they deciphered from their fluid inclusion studies that these stage 3. Which is basically the stage in which much of monazite hematite goethite and monazite it was specifitated was a moderate this aligned low temperature 170 190 degree centigrade which also indicated boiling.

And they deciphered that copper uranium mineralization that resulted from a stratified hydrothermal system like what we observe in a certain geothermal system this copper iron and sulphur. So, here as far as the different propositions are concerned the first model of mixing ascribed most of the copper and uranium to have come from the low and temperature oxidized fluid. And the high temperature contributing to iron and this view sometimes get changed in this case the copper iron and sulphur is both copper iron and sulphur suppose are disappear to ensures from a deep circulating fluid.

Which are essentially a deep able thing reserve here which undergoing boiling and cooling and mixing with steam heated uranium rich saline ground water. So, the here the other component was deciphered to be estimated and uranium reach oxidized fluid because in order to have uranium the fluid random dissolved it has to be a oxidized fluid. So, that it could carry uranium and a fluid mixing is has to be evoked n in order to get the uranium deposited in the form of plus 4 insoluble oxide form.

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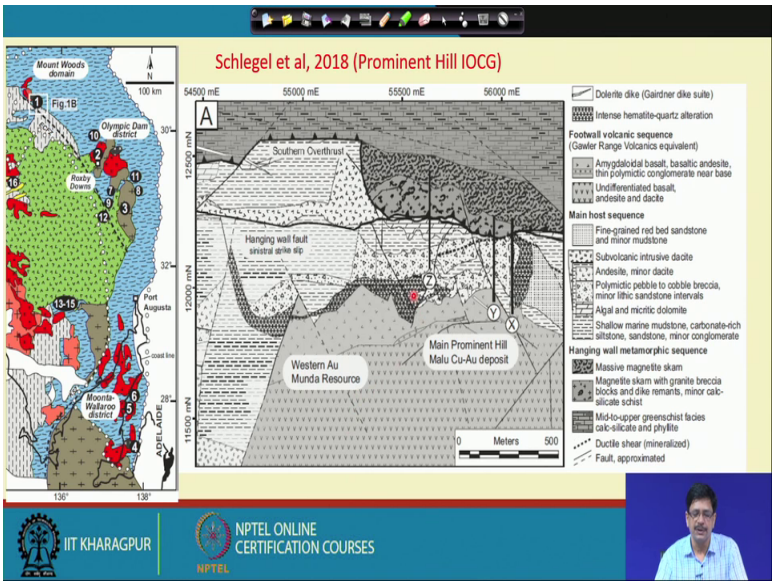

Now, this recent work from squeeze a little 2018, they gave they had studied from they also studied the IOCG from the this prominent hill iron oxide copper gold deposit I shown here. So, this is a map of the IOCG province in southern Australia this is the this 2 is a from Olympic dam. The number seven is the wok dam which is just described as Davidson et al 2007. And one can one can see that the total ensemble here this is the on the green is the column arranged volcanics. And the red ones are the later inclusives like the garnet which is described occurring within the Olympic time deposit there are earlier pages of garnet.

And the whole assembly shown here which constitute the iron ore coppt iron oxide copper gold mineralize province. Now coming to the prominent hill IOCG the a plan a map which is shown here, it is quite clear that. What is actually we are seeing from the magnetite rezone is essentially could be thought of as a earlier scan type of mineralization zone with some amount of pyrite. And then later on the it the sequence actually was in the order of this creation of this magnetite I is brachia here. And then later on this brachia fillings and the deposition of the sulphides in different stages; so, here is the massive magnetite's come and this is the sedimentary horizon, brachia and the is that the calcelicate (Refer Time: 16:30) rocks here.

And there are as usual there are some structural complexities which helped in the hydrothermal fluid that circulated. And these zones are the intense hematite quartz zones

and these are the zones which is represented by the politic pebble to kobo brachia with minor elliptic beside. And the sense would with this sandstone intervals and these are the this marine mersenne. So, this entire sequence shows the Proterozoic basement sediment along with the metric units the volcanic or protonic unit and these represented by the valcanics.

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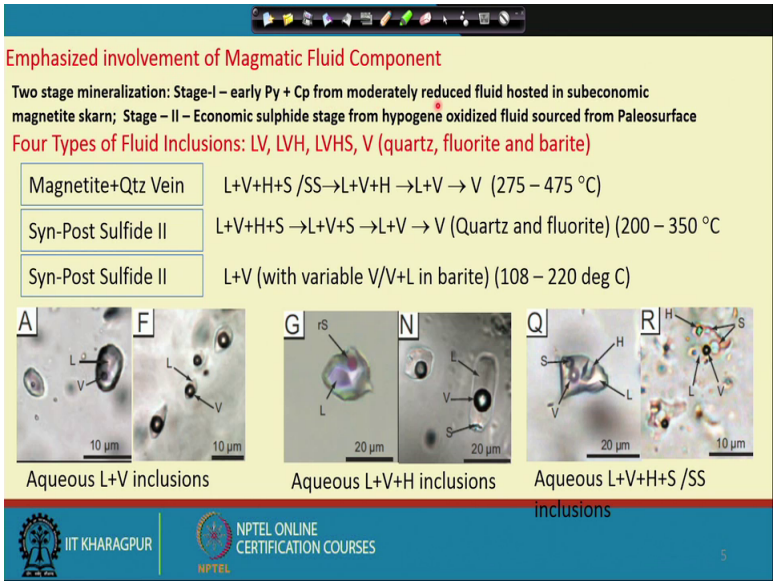

So in this work the authors they decipher they two stages to mineralization the stage one is the pyrite chalcopyrite or directly reduced we go straight to be sub economy. It is these are all the post magnetite one which is the scan stage. And this stage two economic sulphide stage from hypogeum oxidized resource from the failure surface. And here also the fluid inclusion was done from different types of hosts and as I said that in the recent literature on any of such mineralizing systems. The what we see is that we get to see some good quality, good resolution fluid inclusion images.

And also in addition to that the fluid inclusion micro thermometric data are actually supplemented with some good analytical data including the in situ non-destructive like analytical data as well as isotopic data. So, the conclusions that are derived is actually by combining or collating synthesizing all information which is obtained from different sources. So, confining or restricting ourselves to the fluid inclusion characteristics and the fluid inclusion data micro thermometric data that was synthesized by these authors.

So, they studied the magnetite cause when the same post sulphide and the post sulphide to hence, where they found the inclusion types where the aqueous biphase, inclusions with variable liquid vapour ratio. And the aqueous liquid plus vapour plus halite kind of inclusions. Here there are some kind of inclusions which contain some red minerals, but maybe it could be some iron oxide or sometimes some apex. And these represent the most saline of the fluid components which component multiple constituting or consisting or including some multiple daughter phases along with halite.

So, in this case this the liquid vapour the solid plus more than one solid kind of inclusions which are obtained from the magnetite quartz, when there have a homogeneous range of 200 to 75 to 475. And the inclusions which are containing a single solid phase or halite and liquid vapour inclusions had temperature homogenization from 200 to 300 50 degrees Celsius. And the liquid vapour homogenizations liquid vapour inclusions which are present in the quartz in the infilling of the brachia and they represented in the both disulfide the deposition stages; where having homogenization temperature within the range of 180 to 220 degrees Celsius.

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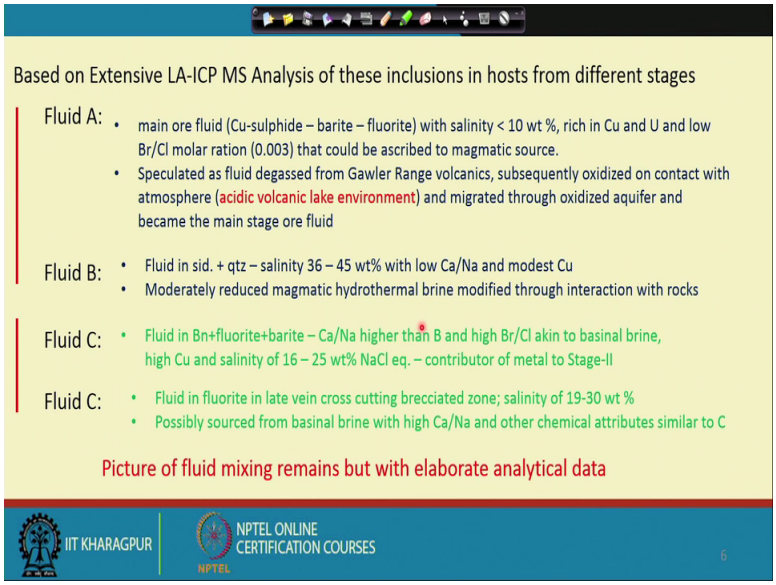

So, now, we see that this data where supplemented by extensive analysis of fluid inclusions of these different generations this liquid vapour inclusions, the liquid vapour plus halite inclusions or the liquid vapour and the constituting or having more than one dotted crystals. So, synthesizing all the data the authors they proposed floor fluid

components, so these three components were essentially based on the chemical data. One of the major chemical one of the very important chemical parameter for discriminating or distinguishing these fluid types was the bromine by chlorine molar ratio.

And the fluid A which is a which is this I have took then main ore fluid in the copper sulphide ores present in barite and fluoride. These are the salinity a moderate salinity or rather low lower to moderate salinity of 10 weight percent NaCl equivalent, this particular fluid came out to the reach in copper and uranium. And have a very low bromine by chlorine molar ratio of 0.003 that is actually the characteristic which is assigned to a magnetic source.

So, they deciphered that this fluid a is essentially is a mathematically sourced fluid. And their speculation was that this, but this fluid is actually not by and normally what happens in a chromatic magma fluid which is absolves from a crystallising protonic body. Rather this is a fluid which actually was resulted from the degassing of the Gawler range volcanics and these degassed fluids subsequently got oxidized in contact with the atmosphere.

And then it formed with kind of an acid volcanic lake environment and that fluid later migrated to the oxidised aquiver and become the main stage ore fluid. So, here the distinction even though this fluid is of low salinity and also lower temperature. The or it is based on some of the key parameters like the molar bromine and chlorine ratio. It is a assigned it is ascribed to a magnetic source, but the magnetic source which is of a little different than what generally happens in normal mineralization associated with magnetism. So, the fluid B was in the siderite and quartz the salinity is high I represented by the liquid plus vapour plus halite inclusions.

And they have low and also along with this chlorine and bromine into chlorine moral ratio elemental species like potassium rubidium led and cesium, were also routinely analyzed by these workers and the inclusions of all the different stages different types. And there were minor variations in the ratio also and one of the ratio was important ratio was the calcium by sodium in the fluid.

So, this particular fluid with have a very low calcium by sodium ratio and if you go from a from fluid A A to fluid B fluid b turned out to be a little higher than its calcium by sodium ratio and modest concentration of copper. So, this particular fluid was again

inferred to be reduced magnetic hydrothermal brine modified through interaction with rocks, but. It remains uncertain whether this particular fluid is actually exalt from the any of the younger valid member that we see in the deposit geology.

And the fluid C is actually fluid is in the boronite fluorite barite association and mostly from the barite. Here the calcium by sodium ratio is higher compared to the fluid B and also have higher bromine by chlorine molar ratio and which cannot be ascribed anymore to a magnetic magnetically sourced fluid. So, the option was that it could it could be it could be or could be thought of more close in characteristics to a basinal fluid basinal brine with high copper. And salinity within the range of 16 to 25 percent equivalent that is expected in kind of a cornet to fluid a basinal brine.

And fluid D are is actually in the fluorite in the late rains cross cutting the brachiated zone. The salinity was of the range of 19 to 30 weight percent and these are possibly source from also from basinal brine based on their highest obtaining calcium by sodium ratio and. So, these this kind of read with their copper concentration, which was also high we are mostly have similar characteristics to what we see in case of the copper deposit in stratified sandstone like the cooper shipper kind of fluid. So, if we could if we see here then fluid A and B are essentially could be clubbed to one category of a magnetically derived fluid and fluid C and D; where I can to can be clubbed together to be fluid which is derived from a basinal source.

So, what we see is that and these authors also did ascribe the mechanism of the deposition to be coupled redux oxidation reaction and reduction of iron and deposition of the sulphides. But the same conclusion was we arrived at with much more elaborate chemical data in situ the extractive chemical analysis like laicpns analysis. And though which many of the important chemical parameters come out to help us and better identifying the source of the fluid and also the evolution the way the fluid evolved.

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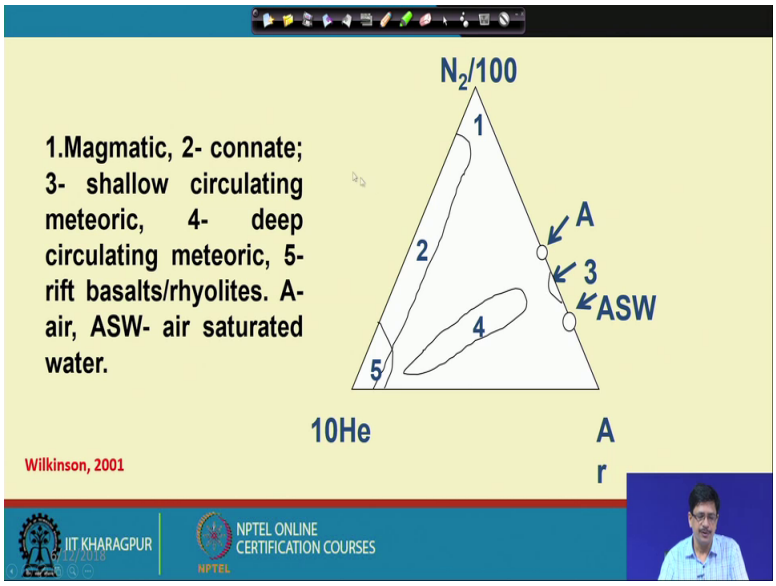

And in this context it would be worthwhile that what is happening or what exactly some other important characteristic with of course, concluding our discussion on the application of with the inclusion data to mineral deposit of the thermal or environment. This diagram which is also taken from Wilkinson 2001 would see is a nitrogen helium and argon a diagram. In which we see that there are some field like this is field the q is the field of magnetic fluid 2 is the fluid of t 2 is the field of cholotrite and 4 is a fluid of d circulating deep circulating meet to the water 5 it is for if basinal rivelites.

And then this a is for air and the three is for circulating meet to the water and this ASW is air saturated water. So, if we have an analytical facility to actually extract the fluid or the gas released from the field inclusion cavity and if we could analyze from these nitrogen helium and argon the fluid ancestry also could be ascribed to. These are these also will help us a lot in addressing this were fluid origin and evolution.

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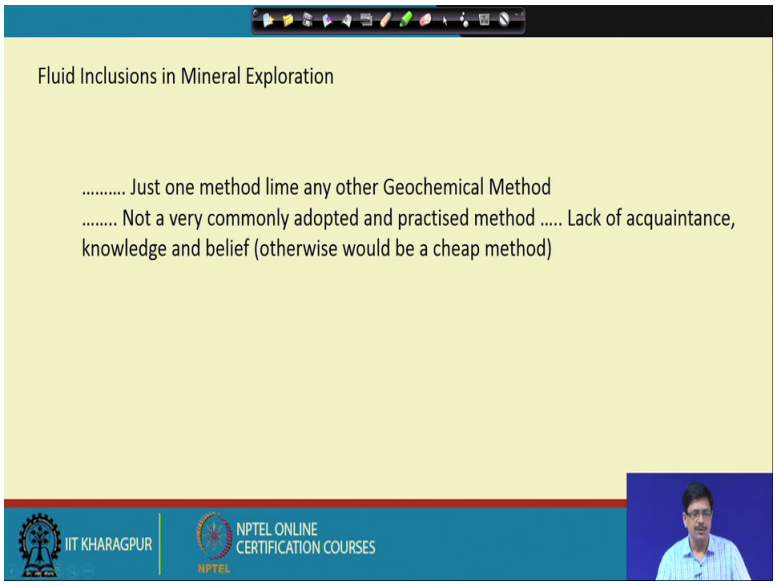

So, now we will conclude our discussion on the application to mineral deposit environment, hydrothermal environment, by adding a little bit of idea on whether fluid inclusions or fluid inclusions microthermometric data or fluid inclusion microthermometric assets could be helpful in mineral exploration. Now, before we look into any of the one or two case studies are examples, we should keep it in mind that this is just another geochemical method.

And any successful discovery doesn't come out of only a single method and it is just it also involves a little bit of and as it happens in many of the practice of exploration. A success in one particular area cannot directly be extrapolated to another area, because these are much specific to the kind of geology and many other essential constituent of the mineralising system. And which these days we say a kind of mineral system approach, but these can always be very successfully applied or could be tried as any other method. And since, a successful discoveries always is a combination of many techniques and many methods results put together.

And so fluid inclusion technique will always can have a component which can add two successful delineation of ore bodies, in different areas. And here they should be also more applicable to areas what we call as a, where ore deposits are there or in a particular ore district to two augment or two discover some more such mineralizing mineralized ore bodies in an existing ore district which is basically known as the broun field exploration.

So, the problem is that this is not a very commonly adopted and practiced method they may be sometimes because the lack of facilities or the lake of acquaintances and knowledgeable. And also to have that much of belief in this particular technique that it will also help in exploration that it is a cheap method and if it is adopted it will definitely give valuable information or valuable input for successful mineral exploration.

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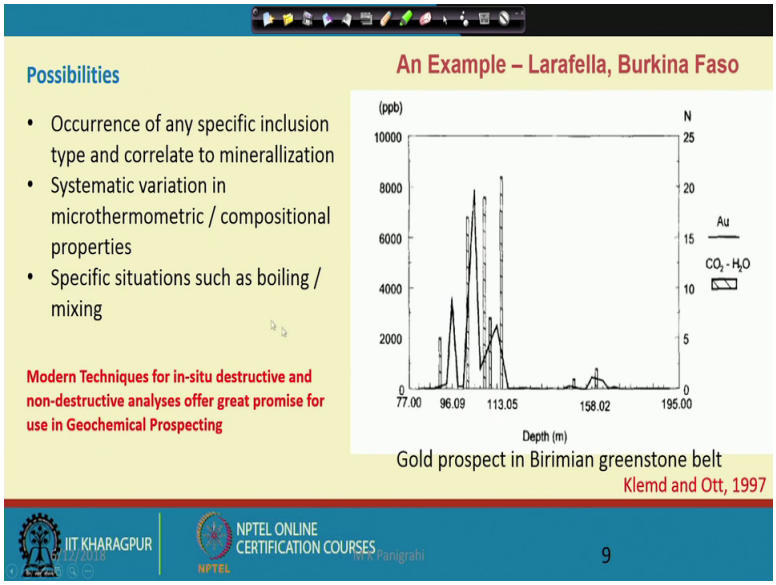

This is just an example, so while discussing fluid inclusions for mineral exploration as a Wilkinson has put it that it could either be that occurrence of any specific inclusion type that quite indicate occurrence of a particular type of mineralization. Or it could be a systematic variation in micro thermometric compositional property which might indicate the direction in which particularly an ore body is occurring or a ore bearing fluid could be more productive in a inspection time, or a specific situation such as a boiling and mixing which we have seen in many cases.

That boiling is a very efficient mechanism for beginning about the position of ore metals from fluid which is transporting the metals. And also the mixing points like discussing the tin bearing garnet pegmatite system and the bastor craton we also saw that a mixing when it is identified will always indicate stanifous pegmatite compared to a situation in which rigor of the fluid to be present. So, many of the situations can be taken into consideration while applying or try attempting to apply fluid inclusions to mineral exploration. There is one example this is from the larafella mineral prospect from

Burkina Faso in not north-western Africa. So, here this is a very quick and the small example that these are this represent the black line black curve represents the gold grade in PPM.

And this is PPB let us say gold grade in PPB 2000, 6000, 10000 and these are the points at which the depth at which the deal code has been logged in terms of the gold grade. So, this we can see and these bars represent the abundance of aqueous carboning inclusion carbon dioxide water bathing inclusion. So, what is observed here is that wherever there is a what carbon dioxide bearing inclusion the it is a immediately preceded very high concentration of gold. So, this gives us an idea that in areas, wherever we do the drilling and without even before going to the determining the actually the grade of gold by any elaborate method.

One can quickly see the fluid including characteristics and can find out or can conclude whether there is would be a gold rezone within the within the immediate vicinity or immediate. And sometimes also as you just have seen in case of the organic gold deposit the methane concentration of the carbonic fluid is also a good indicator of gold reached zones those can also be very effectively utilized.

So, the modern techniques of in situ destructive and non-destructive methods like (Refer Time: 32:20) and which we will be discussing ha in the subsequent classes. And these are also come up to produce some quick data which would be useful in any kind of a mineral prospecting exercise.

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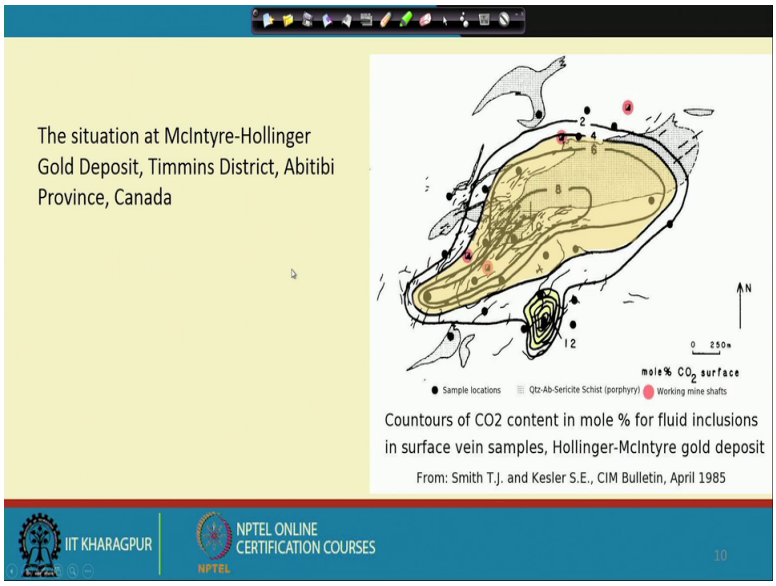

And this is an example from the famous Macintyre Hollinger goldmine from the Tinnins District Abitibi Province Canada which is way back in 1985 done by Smith at al. And this is a very interesting diagram where one can see. So, these particular contours are based on the mole percent of CO 2 on the inclusions. And we could see that the mineralized province actually is or the more with each mineralized zones are basically falling on the contour which is actually more than 5 a particular say more than more than a particular value of the mole percent of carbon dioxide which is 5 percent, 5 mole percent of carbon dioxide which can say.

So, these numbers which are shown here are the occurrence the location of the mineralized bodies in this particular ore district. So, this is another good example of how if the fluid inclusion characteristic would correlate with the reach mineralized zone.

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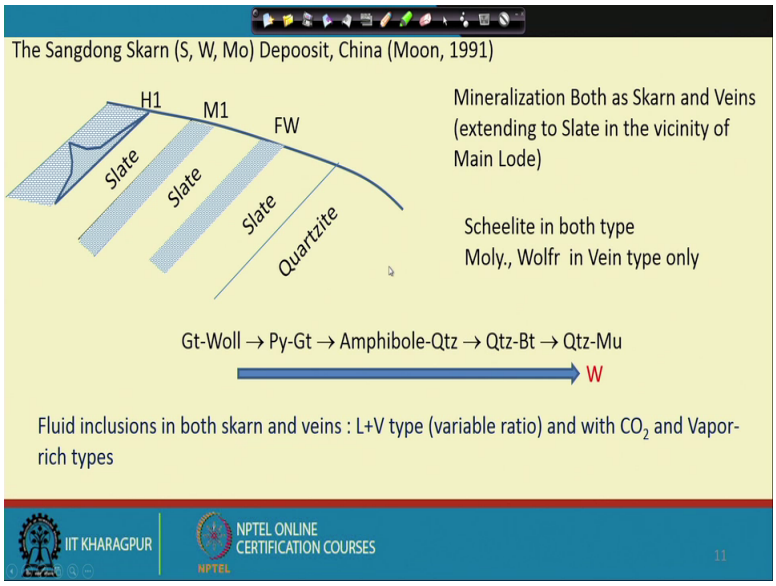

So, one last example this is from the shangdong akarn a deposit in china where the mineralization occurs in form of the ore bodies which is shown as the hanging wall. The main ore body and the foot wall there in the carbonate rocks they are essentially these skarn type of mineralization, which is later on overprinted by veins containing molybdenite and the wolframite.

So, the mineralization both is skarn and veins and the scheelite both in scheelite in both the types and the molybdenite wolfinite. And the vein type and the in any particular ore body the ore body is exhibits a typical zoning from garnet wollastrolite to pyrite, pyrite represent garnet to amphibole garnet to quarts partite and quartz muscovite with the tungsten percent is increasing.

Especially shown this quartz muscovite zone is the central part and is surrounded by the quartz biotype and fuel quartz and the garnet pyrite pyrites and garnet and the (Refer Time: 34:25) garnet or wollastrolite zones the. It is essentially that they must have been the response to a inclusive felsic unit which is somewhere in the sub in the at depth which is given rise to this original or the primary skarn mineralization which was later on over printed by the vein type tungsten mineralization.

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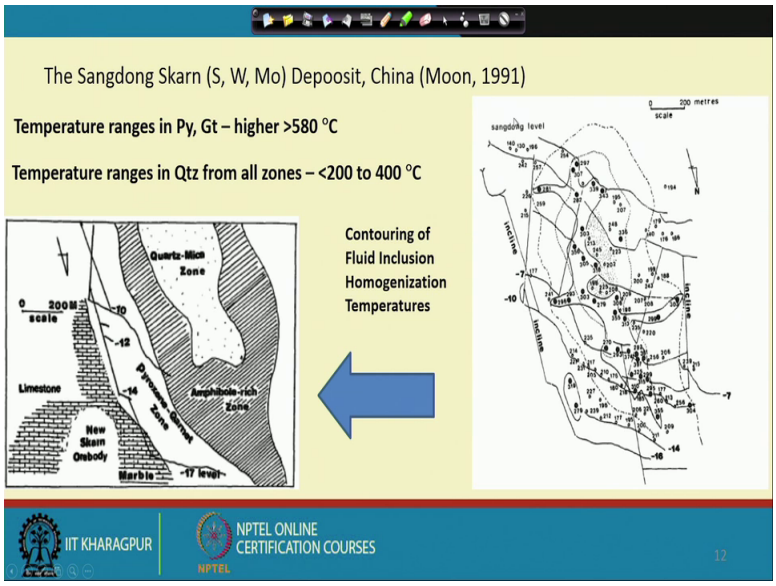

So, quickly if we could see that while doing to fluid inclusion where the microthermpometric data which were taken on pyroxene and garnet and also quartz from all the zones of mineralization and a contouring of the fluid inclusion temperature has been done here like shown here. The high temperature zones like shown here generally coincide with the highest grade of the ore in terms of the highest tungsten grade. So, while doing, so it was observed that there is another kind of a zone which also showing a high temperature characteristics of the ore fluid.

So, it is certainly very empirical but, then on further exploration and drilling it gave rise to a new skan ore body which is very near to or which was earlier unknown to the existing. And which could only be brought out by systematically looking at the fluid inclusion microthermometic data and their presentation in the form of contours this is also a very interesting example as to how it was done.

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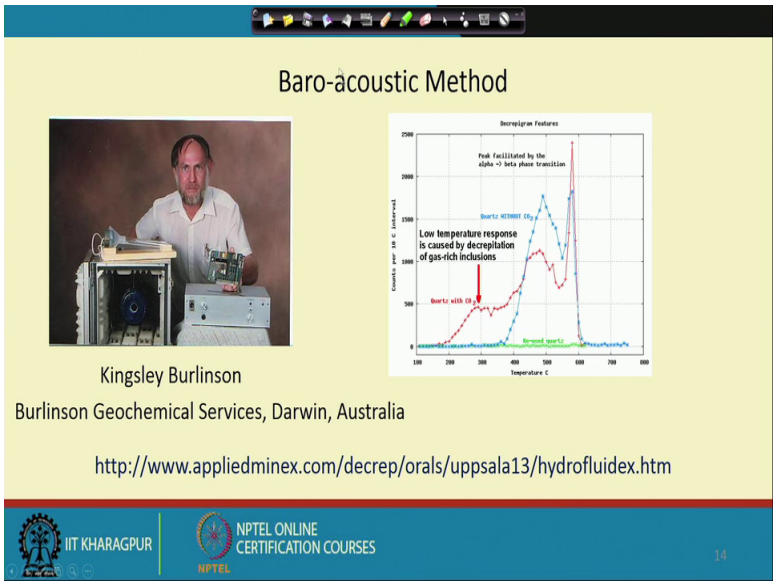

So, to conclude I would again also including the discussion of a one interesting kind of methodology which is also used for mineral exploration which is being done by Kingsley, Burlinson who is having his own Burlinson Geochemical, Services Darwin. So, what he exactly does is he uses the decrypitation of the samples and put them into a furnace and then using some amplification of the sound that is generated with which is very much computerized. It generates these kind of graphs with these graphs which is shown as a temperature versus counts per ten degree interval.

So, these peaks essentially indicate the temperature at which there is majority of the inclusions which decrypted or burst because of increasing temperature. And as we all know that the from the free fundamental idea that we had about the fluid inclusion types with the aqueous carbonic inclusions generally if when they are heated up the because of the building of high internal pressure.

Exceeding the yield strength of the hosts mineral the they decrypted the bursts and during the decrypitation whatever sound that is produced because of this decrypitation, this is amplified and recorded in something which is called a decrypitogram. And this is extensively used or this can be used and correlated with the like as I have been shown before, like the in terms of the gold grade and having a correlation of the decrypitation peak.

So, which are the samples were depending on where the decrypitogram peak is obtained some delineation of the ore body, and they reach mineralization zone could be delineated as is being practiced by this method. Further consultation on this particular methodology and many other examples that he sites that on many deposits across the world; which Kingsley studies for this decrypitation behaviour and presents them in the form of decrypitogram here can be consulted from this link that is provided here.

So, we conclude our discussion on the application of fluid inclusion microthermometric to ore forming environment. And as I have said that the original literature that will be sited necessarily have to be consulted for a better and greater detailed idea about what has been proposed here. And essentially it is just to get the trick of the trade that how the fluid inclusion types their entrapment in different host minerals linking them to the different stages of mineralization have to be very judiciously established.

The inclusions have to be studied from different hosts and then such kind of synthesis of this information can be made to understand the origin and evolution ore fluid in any mineralization system and also to be to apply them to useful outcome like mineral exploration.

Thank you.