

**Mineral Resources: Geology, Exploration, Economics and Environment**  
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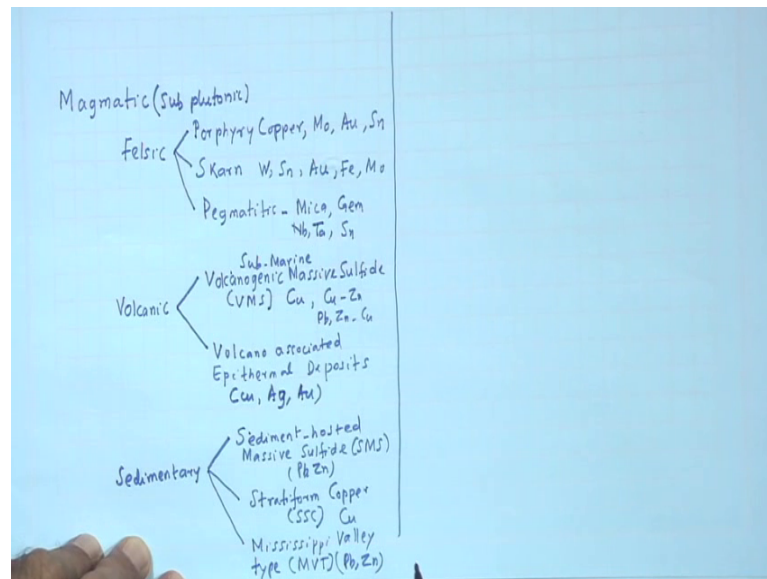
**Lecture - 17**  
**Hydrothermal Processes (Contd.)**

Welcome to today's lecture. We have started to discuss about the hydrothermal processes and the resultant deposits, which are broadly known as the hydrothermal deposits. These deposits occurring in wide diverse spectrum of geological environments, and of almost all metals that we have discussed so far, bearing a few exceptions and as far as these hydrothermal deposits are concerned, when we try to study them and the hydrothermal processes. We ask ourselves some fundamental questions as to where from the fluid has come, what is the source of the fluid and also the source of the metal and other essential constituents which are responsible in giving rise to such mineralizations. Let us have a look at the spectrum of hydrothermal mineral deposits, the magmatic hydrothermal systems.

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We can look at the magmatic deposits in the sub plutonic environment, and when the magmatism is dominantly a Felsic magmatism, like a calcalon magma generated in the convergent plate boundary. So, these we can classify as the Felsic systems, the deposits which we have dominantly the porphyry copper, molybdenum, gold and tin .

We do have the Skarn environment, mostly giving rise to tungsten, tin and sometimes there are gold and iron molybdenum Skarns which are also known, there a very distinct class of deposits and we have the pegmatitic environment, which pegmatites are major sources of a dominant industrial mineralize mica, and they are the storehouse of the gemstones, and sometimes also rare metals such as niobium, tantalum and do some pegmamites are also tin barring and.

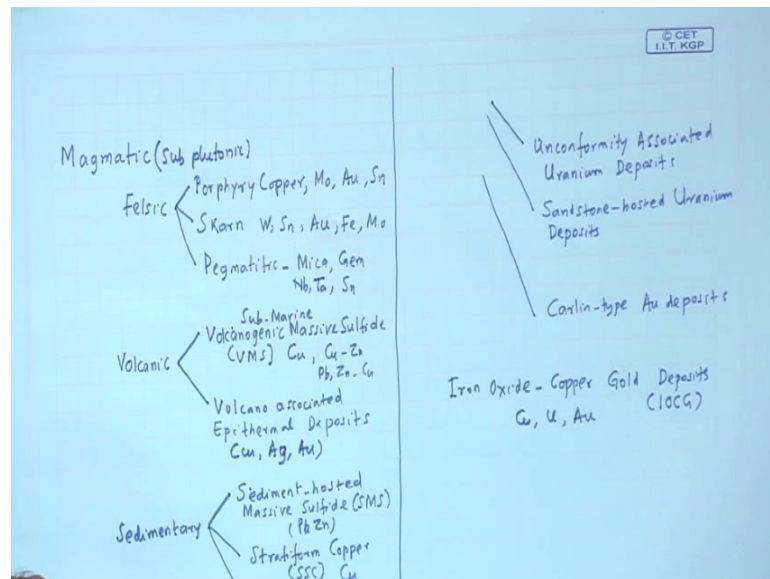
So, when we go to the volcanic system. Here we may not make a distinction between the compositional varieties; like mafic intermediater Felsic. We make them as the, classify them as the volcanogenic massive sulphide deposit or the vms. There are a spectrum of deposits with copper dominant to copper zinc and led, zinc, copper mineralization. They occur in the divergent plate boundaries; like the present day analogs what we have seen on the, in the form of the sulfide chimneys and black smokers .

These are essentially these volcanogenic I said sulfide deposits could be broadly cluster under the submarine, and the metal deposits, the hydrothermal deposits which are associated with young volcanic Islands; they are the volcano associated epithermal

deposits. They give rich sources of copper, silver and gold. All are distributed on the fringe of this Pacific in the of fire.

Here in the Chilean andes region, in some of these regions here, here and in these regions they are, the deposits which distributed this, volcano associated epithermal deposits, we will see their variants. Then we have the sedimentary environment, we have the sediment hosted, massive sulphide deposit or the SMS to give to the rich sources of lead and zinc. We have the stratiform, sedimentary stratiform copper; the SSC, they are rich sources of copper, the Mississippi valley type deposits; m v t. They are the rich sources of lead and zinc and then we have the deposits of uranium.

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So, we can still broadly classify them under the sedimentary class, where we have the, and we do have; we can also categorize under this sedimentary associated deposit; the Carlin type gold deposits, which are essentially associated with a cresson zone in the continental margin, like in the western, in the state of Nevada in United States, and recently they have been a donor active crustal extension, and they give rise to a very complicated set of processes given rise to these gold deposits.

So, these are the deposit types which we will be, and there are some special type of deposits; such as the iron oxide, copper gold deposits or the IOCG. They are certainly come out to be very rich sources of copper, uranium and gold, exemplified by the Olympic dam deposit in Australia. So, these are the spectrum of deposits that we are

going to discuss in the course of this lecture, and especially on the deposits broadly under the class of hydrothermal deposits. We will be trying to address the processes in terms of the source of fluid, source of metal, the dominant mechanism of the transport deposition processes operated by the fluid in different crustal domains. So, before we do that, let us try to recapitulate about the sources of fluid that, so essentially let us try to look at the fluid we broadly .

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**Attributes of Hydrothermal Fluids**

- Pressure
- Temperature
- Chemistry

| Ligand                         | Concentration range (moles/kg H <sub>2</sub> O) |
|--------------------------------|---|
| ΣCl <sup>-</sup>               | <0.03 to >7                                     |
| ΣSO <sub>4</sub> <sup>2-</sup> | 10 <sup>-10</sup> to 0.3                        |
| ΣS <sup>2-</sup>               | 10 <sup>-4</sup> to 0.1                         |
| ΣNH <sub>3</sub> <sup>2-</sup> | 10 <sup>-3.9</sup> to 10 <sup>-1.5</sup>        |
| ΣCO <sub>3</sub> <sup>2-</sup> | 10 <sup>-3.4</sup> to 1                         |
| Σacetate                       | 0 to 0.17                                       |
| Σpropionate                    | 0 to 0.059                                      |
| Σoxalate                       | 0 to 0.005                                      |
| Σmalonate                      | 0 to 0.025                                      |

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Temperature, Salinity, P

- 1) Meteoric fluid — low-temp, low-salinity oxidizing
- 2) Magmatic fluid — high-temp, variable
- 3) Metamorphic fluid — high-temp, low-salinity
- 4) Juvenile fluid — high-temp, low-salinity
- 5) Connate fluid — low-temp, high-salinity
- 6) Sea-water — low-temp.

Temperature

quartz, magnetite

$$1000 \ln \alpha = A \left( \frac{10^6}{T} \right) + B$$

T - Kelvin

A, B - parameters

$$\delta^{18}O = \left[ \frac{(18O/16O)_m - (18O/16O)_{std}}{(18O/16O)_{std}} \right] \times 1000$$

parts per thousand ‰

C, S

Mineral Thermometry

Arsenopyrite (FeAs<sub>2</sub>)

(FeAs<sub>1-x</sub>S<sub>x</sub>)

We have discussed about the possible sources of hydrothermal fluid, the meteoric fluid omit very water, is they essentially water rich fluid. So, we can use either the word fluid or water meaning the same.

Magmatic fluid, metamorphic fluid, connate fluid and we can also include sea water is, whether type of fluid is essentially a modified meteoric fluid, whose composition is different from the normal rain water that way or the water which falls as precipitation. So, these fluids need to be characterized in terms of their attributes.

So, meteoric fluid is a fluid which is; so, generally we will try to characterize this fluid into regard attributes, their temperature, their gross chemistry. We can put it broadly as a term is solidity for the time being, and also pressure which we will see the importance through the course of discussion.

So, if we try to broadly characterize these different fluid sources. Then the maturity fluid are the ones which are likely to be of low temperature, and also low salinity and this fluid invariably would be oxidizing in nature. Magnet fluid by default would be high temperature and a variable salinity; often this solidity could be very high in situations which we will be discussing and salinity will be variable broadly, from very low to intermediate salinities. Metamorphic fluid are also likely to be high temperature and generally low salinity, but on special circumstances they may also be, they may attain some substantial value of the salinity. This visualize fluid is like to be of high temperature and low salinity.

Although we have said that this is the fluid which very rarely sample in the O deposits. Connate fluid is low to moderate temperature, and generally of high salinity. Since this fluid have interacted with the sediments leading their residence in the sediment core spaces, and we all know sea waters chemistry, its identity lies in its chemistry and different concentrations of the species, and low temperature .

We see this involvement of these different types of fluids in many different situations. And when we mean, so magmatic fluid also, will be, they have the nature the chemical nature would also be varying something, sometimes would be quite oxidizing, sometimes quite reducing depending on the nature of the Felsic magma through which the fluid is evolving and so is metamorphic fluid. So, we will see them as and when we discuss the specific type of hydrothermal deposits; like magmatic hydrothermal (Refer Time: 14:52)

hydrothermal meteoric dominated hydrothermal systems like the geothermal systems and. Now, coming to the attributes of the hydrothermal fluid, when we talk about temperature generally while dealing with these deposits without getting much deeper into their genetic aspects, still we try to characterize these deposits.

So, we generally have to ask, what is the temperature range in which this deposit formed, and in the previous lecture we gave a bit of an introduction to this that what are the sources from which we could derive the information on the temperature of the over fluid, in which we discussed about the say oxygen isotope signature of the minerals in the ore. They could be, we discussed only the oxygen isotopes. So, they would only be applicable to the oxide minerals; like quartz, magnetite and; the fluid itself being water that also can be analyzed under certain favorable circumstances and the water stabilizer to pick composition could be found out, and that also can be used in reconstruction of the temperature condition of the fluid.

And we consider such kind of exchange reaction and derived expressions; such as the  $1000 \ln \alpha$  will be equal to something like  $A$  into  $10$  to the power  $6$  divided by  $T$  square plus  $B$ , where  $A$  and  $B$  are parameters that are worked out for different pairs of minerals or mineral water systems, this temperature is in Kelvin and the delta rotation we will show, we saw that delta  $^{18}\text{O}$  of any particular mineral is expressed as the  $^{18}\text{O}$  by  $^{16}\text{O}$  in the mineral minus  $^{18}\text{O}$  by  $^{16}\text{O}$  in the standard divided by  $^{18}\text{O}$  by  $^{16}\text{O}$  in the standard into  $1000$ , and this is expressed in the form of per mil or we say parts per  $1000$ .

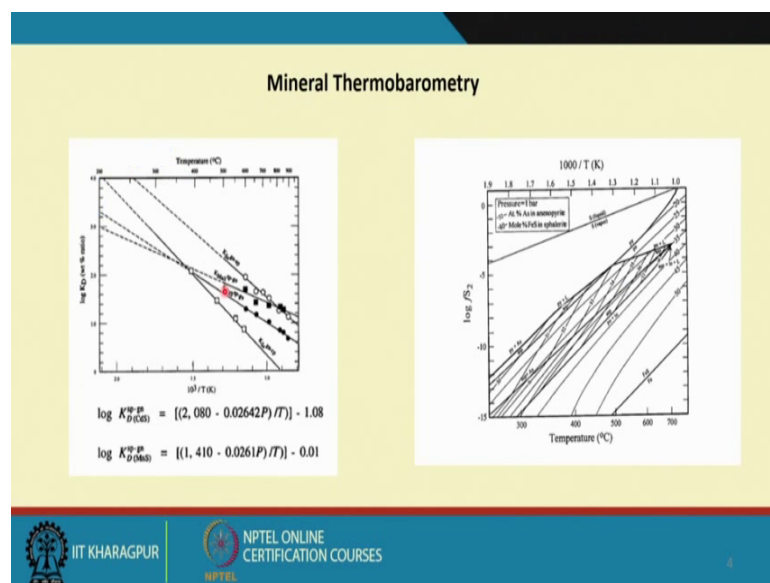
And this is not only restricted to oxygen, this also could be done for other lighter elements; like carbon and sulfur, and we can consider the carbonates and the sulfide or the sulfate minerals which occur in the ore and can constrain the temperature condition, or the range of variation of temperature which is more important to us in the context of hydrothermal fluid in any particular deposits.

And today, and there are other sources of determination of the thermal, state of the hydrothermal fluid, they could be done from the mineral themselves. The ore minerals; like the sulfide minerals are characterized by non stoichiometry, which essentially means that the composition of these sulfides, generally are not the original conditions of original signature of the compositional signature, it generally not preserved and the

composition generally get readjusted or changed from the condition of their formation to the later decrease in the temperature conditions of the changing environment.

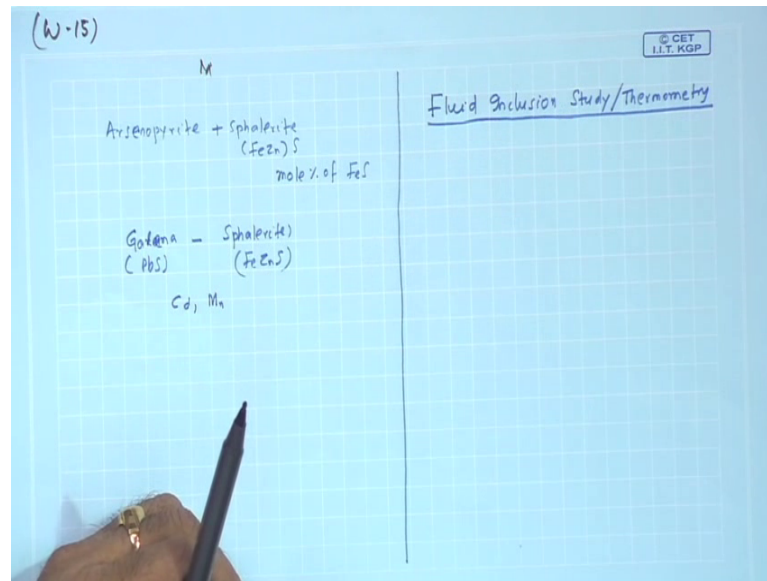
So, there are only a very few such ore minerals which indicate the conditions of, the temperature conditions of their formation. One such is a mineral which is arsenopyrite, and this mineral is essentially can be considered as a solid solution; 1 plus x plus and s 1 plus x, and this exact mole percent of the arsenic in this arsenopyrite mineral, under especially conditions can be used as a thermometer which is shown here.

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As can be seen here in this diagram which is a plot between the log of fugacity of sulfur versus temperature, and this is the perovskite stability field this is pyrite stability field, and in these perovskite stability field, the compositional isopleths of arsenopyrite in terms of atomic percent of arsenic in arsenopyrite, and the atomic percent of the mole percent of iron sulphide in sphalerite, because we all know. So, it should be, considering it should be corresponding to a situation where, it is not only that arsenopyrite would be occurring alone.

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But if this arsenopyrite is occurring along with sphalerite which is a  $\text{FeZnS}$  and the compositional variations in  $\text{FeZnS}$  can be expressed as mole percent of  $\text{FeS}$ . So, this mole percent of  $\text{FeS}$  in sphalerite, as well as this arsenic atom percent in arsenopyrite. They are indicating the temperature condition is very much subject to under mole or fixed values of the fugacity of sulphur, and with which only we can constrain the temperature; like as it is shown here.

So, here we see the intersecting isopleths of atom percent of arsenic in arsenopyrite, and the mole percent of  $\text{FeS}$  in sphalerite. So, once we determine the composition of the coexisting arsenopyrite and this sphalerite within the perovskite stability field here. Then we will be able to exactly pin point a temperature at which the arsenopyrite formed, and we presume that this arsenopyrite has formed from the fluid and essentially we are estimating the temperature of the fluid there. We do also have uncertain circumstances; they will be able to determine the temperature of the hydrothermal fluid from the mineral, mineralogy or the mineral assemblages that we see in the ore. Just for an for taking a small example here.

If we take a mineral like galena and another mineral sphalerite, which is a  $\text{FeZnS}$ , and these two minerals both they crystallize in the cubic system, and we can consider that these minerals, this co existing mineral pair or we can see whether these satisfy the condition of an equilibrium assemblage from the textural criteria, and we measure the



concentration of trace element such as cadmium or manganese, which are present in these major minerals as trace elements in their lattice.

And they follow the, we can formulate from fundamental thermodynamic considerations, we can formulate by taking into consideration their, the equal chemical potential of the components either cadmium or manganese in the two coexisting phases, and we could formulate. I am not getting into the details of this formulation, but we can still formulate some thermometric expressions like one which is shown here;  $\log K_d$  cadmium sulfide in sphalerite galena of pair can be formulated as a function of temperature, knowing the pressure.

So, there are ways and means to constrain, the temperature of the over fluid; like the two such cases that we have considered. One is use of the stable isotopes of oxygen carbon and sulfur, and sometimes the composition of the mineral themselves such as arsenopyrite, or using certain methods such as the trace element concentration in major phases and formulation of the thermometry to estimate the temperature .

Ah we will now go into the other method of temperature estimation which is a (Refer Time: 25:03) elaborate and evolved method and I will try to be brief, give a brief idea. So, this is essentially the fluid inclusion, we can broadly say the region study of the fluid inclusion or fluid inclusion thermometry. We use a word micro thermometry and I will be justifying that use of the word micro thermometry in the course of this discussion.

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**What are fluid inclusions**

- ▶ they are tiny fluid-filled cavities in minerals trapped during the growth of the host-mineral or any time after that
- ▶ they are aliquots of the *mother liquor*
- ▶ they display diverse shapes and have a wide range of sizes (<5 $\mu$  to cm scale; commonly between 10 to 100  $\mu$  in dia or max. dim.)
- ▶ They are distinct by virtue of the contrast in the optical properties of the fluid and solid host

“. . . and I argue that there is no necessary connection between the size of an object and the value of a fact, and that, though the objects I have described are minute, the conclusions to be derived from the facts are great." H.C. Sorby (1858)

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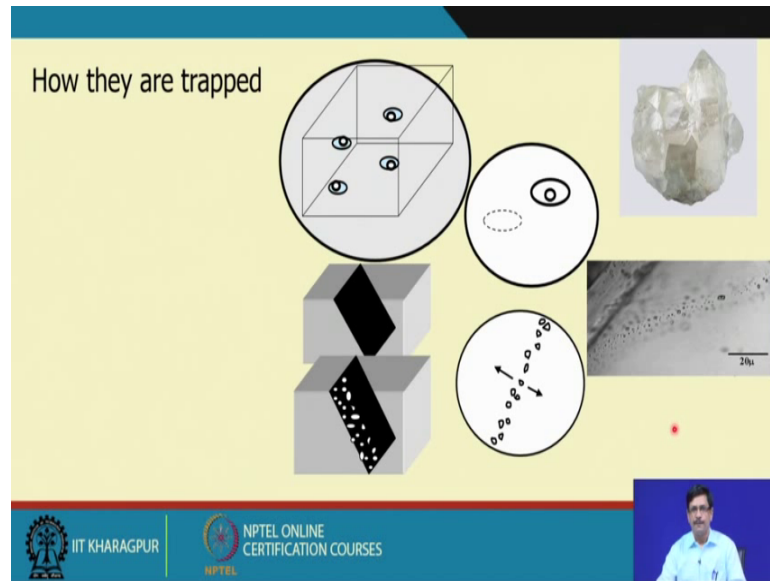
So, fluid inclusions are tiny fluid filled cavities inside the minerals which precipitate from the hydrothermal fluid. Anywhere there is the position, any surface condition or subsurface or any deeper pressure temperature condition in the crust, wherever there is mineralization from a fluid, they precipitating minerals invariably trap the parent fluid from which they are precipitating in the form of tiny fluid filled cavities, which we call them as the fluid inclusions.

So, if you look at the definition, so what fluid inclusions are. They are tiny fluid filled cavities in minerals trapped during the growth of the host mineral or any time after that. They are aliquots of the mother liquor, essentially meaning the fact that the fluid which deposit them, which the fluid from which they are precipitating, they invariably trap the same fluid in the solid lattices.

And which is a result of the process of their crystal growth from the fluid, when the crystal is depositing on any substrate. And they display diverse shapes and have a wide range of sizes, starting from 5 micrometer to even centimeter scale; generally commonly between 10 to 40 micron in diameter at maximum dimension. And they are distinct by virtue of the contrast in the optical properties of the fluid and the solid host. I will be elaborating them through a few of the photographs.

They are very tiny, measuring in micron scales, submicron, microns or at the most very tense of a few tens of millimeter scale, but they do give a lot of information in terms of the thermal regime, gross chemistry, and the other chemical properties of the hydrothermal fluid, which formed the mineral deposits. Even if the mineral deposits formed several millions years ago, we can still sample the minerals, the ore as well as the gangue minerals; gangue minerals like quartz, calcite, fluorite, appetite and so on and retrieve very useful information from them. So, the magnitude of information that we retrieve from them is to use compared to the very tiny size.

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So, here I would like to elaborate or to just to give some explanation about the mechanism of the entrapment of such kind of inclusions in the solid mineral lattices. If I represent the mineral in this term kind of a three dimensional diagram, then what is shown here, are the tiny cavities which are filled these tiny cavities, and they are the ones which got trapped during the process of the growth of this mineral, just for your appreciation, here there is a quartz crystal and that is how the crystals go in nature, and if you take a section of this crystal then you are going to see such kind of tiny cavities inside that mineral.

fluid ingredients do also form, anytime later after the mineral is formed, on fracture planes, because the fracture planes become the locals for later fluid to percolate through and also deposit the fracture field are sealed or healed, by the same deposition of the same material of the host mineral, and during the process a numeral number of small tiny inclusions are trapped on a regular, on a abiding by this plane with the healed cracks from the fractures inside the mineral.

If you take a section of this, then you do see these inclusions which are a part of the random three dimensional network, as well as some of the inclusions which are aligned on trails, and this is a sample of a fluid inclusion train with occurring in a host mineral quartz, you could see the of the dimension where it is only about 20 micron scale.

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**Growth of Hydrothermal Vein with multiple generations of fluid**

Type C inclusions  
Type B inclusions  
Type A inclusions

qz(I) qz(II) qz(III) qz(IV) qz(V)

co(I) spn gn

Wilkinson, 2001

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So, I will continue discussing on this topic

Thank you.