Mineral Resources: Geology, Exploration, Economics and Environment

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Lecture - 10
Sedimentary Processes and Resultant Mineral Deposits

Welcome to today’s lecture. We have already started to discuss about mineral deposits which form primarily by sedimentary processes. Since we have sedimentary rocks arising out of detrital processes, thermogenic processes, and biogenic processes, so there are deposits which can be assigned as deposits from detrital sedimentary processes, thermogenic sedimentary processes and biogenic sedimentary processes. We will be restricting ourselves to discussing the first two types.

We will be begin and we already started to discuss about an important class of deposits, which are the iron formations, the banded iron formations. Essentially referring to the type of rock which primarily have a banded appearance, and they contribute the majority of the iron resources to the world and distributed in the cationic in older cationic blocks of almost all the continents.

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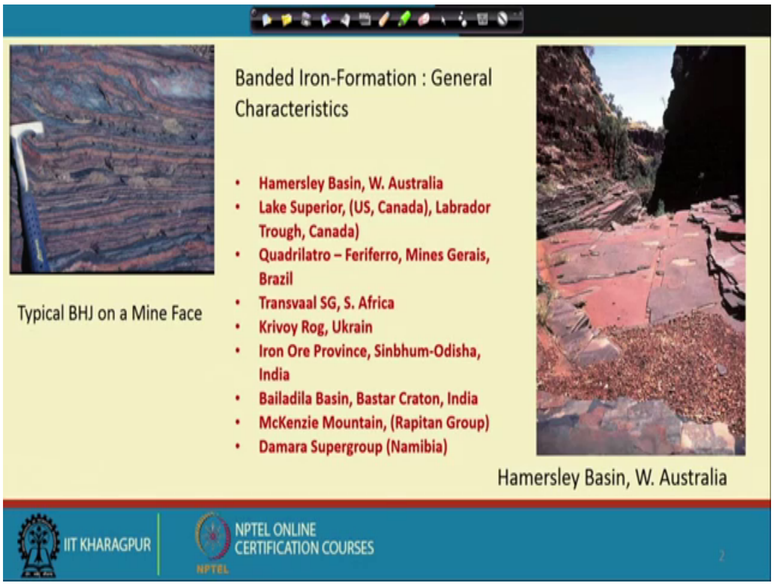

Banded Iron-Formation : General Characteristics

Typical BHJ on a Mine Face

- **Hamersley Basin, W. Australia**
- **Lake Superior, (US, Canada), Labrador Trough, Canada)**
- **Quadrilatro – Feriferro, Mines Gerais, Brazil**
- **Transvaal SG, S. Africa**
- **Krivoy Rog, Ukrain**
- **Iron Ore Province, Sinbhum-Odisha, India**
- **Bailadila Basin, Bastar Craton, India**
- **McKenzie Mountain, (Rapitan Group)**
- **Damara Supergroup (Namibia)**

Hamersley Basin, W. Australia

So, these are, this is the to on the right this is a photograph from the Hamersley Basin in Western Australia, where you could see an iron ore, iron mine, which is quite big almost like constituting series of hillocks there. And the left hand side is a exposure scale photograph of what typically known as the banded hematite jasper ore. There the way they occur and the banded nature is very clear from the photograph.

They distributed in the as I told in the most of the older cationic blocks, Precambrian cationic blocks like Western Australia the Hamersley basin, the superior province in Canada Labrador trough in Canada, the Quadrilatro - Feriferro in Mines Gerais in Brazil, the Transvaal Supergroup South Africa, Krivoy Rog in Ukrain, and the iron ore province in the Sinbhum Odisha region in India, Bailadila Basin, Baster Craton in India, McKenzie Mountain in Rapitan Group Canada, and the Damara Supergroup Namibia.

So, these banded iron formations which contribute to the majority of the world iron ore iron ore production. Primarily our old deposits Precambrian deposits spanning from mid to late Archaean to too late Proterozoic most of the age of 800 million years and the deposits which are in the McKenzie mountain belonging to the Rapitan Group and the Damara Supergroup belong to this the youngest of the iron formations of the world.

So, these deposits have generated huge interests amongst the ore geologists, extensive, they have been extensively studied and voluminous literature have been written and these deposits addressing the very issues of their origin.

And there are some very intriguing issues such as the very fact that such kind of extensive occurrences of iron ores in the form of the banded iron formations with lateral extent sometimes to going to hundreds of kilometers. They do not have much of the younger counterparts in the later part of the geologic history. So, it is a little intriguing and tricky at the same time, because we do not see the modern day processes analogue, there is analogs to the old deposits there are.

So, we just it will be difficult to give a very detailed review or detailed idea about these deposits, because they are older deposits they have been subjected to a lot of later processes in the respective cationic blocks, their characteristics, constitutions have been modified to great extents. And there is the primary reason why many different ideas on their origin, many different hypothesis have been proposed. We will be having a giving a brief overview of their characteristics and what we could infer from those characteristics and as far as their origin and the understanding the process is concerned.

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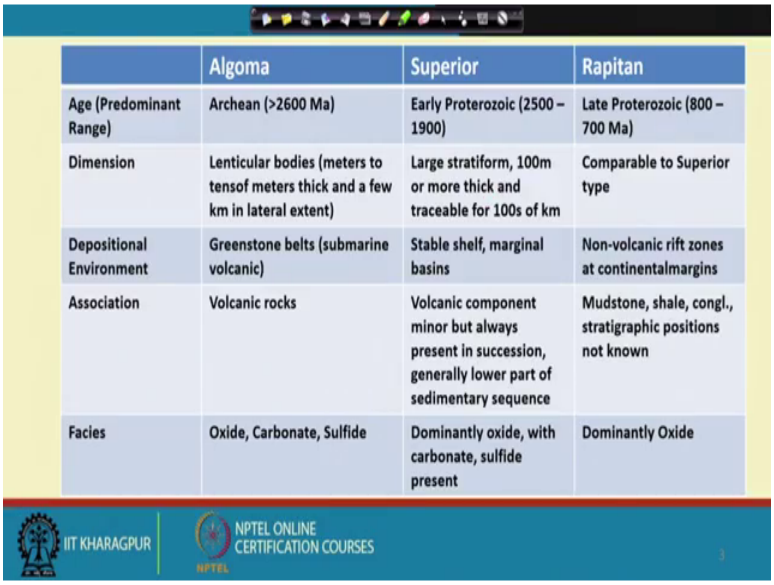

	Algoma	Superior	Rapitan
Age (Predominant Range)	Archean (>2600 Ma)	Early Proterozoic (2500 – 1900)	Late Proterozoic (800 – 700 Ma)
Dimension	Lenticular bodies (meters to tensof meters thick and a few km in lateral extent)	Large stratiform, 100m or more thick and traceable for 100s of km	Comparable to Superior type
Depositional Environment	Greenstone belts (submarine volcanic)	Stable shelf, marginal basins	Non-volcanic rift zones at continentalmargins
Association	Volcanic rocks	Volcanic component minor but always present in succession, generally lower part of sedimentary sequence	Mudstone, shale, congl., stratigraphic positions not known
Facies	Oxide, Carbonate, Sulfide	Dominantly oxide, with carbonate, sulfide present	Dominantly Oxide

Here have a brief idea about the three different types. The one which are the oldest amongst these among the members is the Algoma type which occurred in the Algoma mission in Canada. And the superior type and the Rapitan type as you could see the age ranges, this dominantly superior type is dominantly early to mid Proterozoic, and the Rapitan type is nearly going to the new Proterozoic time ending up at 700 million years.

So, as far as the dimension are concerned, the most extensive type of the superior type there is some there is there stratiform, and they are very they are thick almost of the extent of 100 meters or more in thick traceable for 100s of kilometer. As again the Algoma type which are mostly occurring in the green stones or green stone belts. They occur in lenticular bodies just about meters to tens of meter thick and a few kilometers in lateral extent and the Rapitan type more or less comparable to the superior type. But are very characteristic in their lithological assemblages with very little volcanic component in the succession in the and they occur at the base of the basin overlain in the overlay the basement rock and the superior type.

They generally are interpreted to be occurring in the stable shelf in the margin and basins and the Algoma type are in the greenstone belts which are extensively deformed metamorphose and we see them in the old greenstone belts in many parts as I have said. And the yes so, that is how the Algoma type have a very intimate association with volcanics with seafloor basasive rocks of basulting composition. Now, presentation fumaletic rocks and they are associated with the oldest of the units of the green stones and the superior type do have volcanic component minor.

But, always present in the succession and the sometimes they preserve the entire sedimentary succession from the basement to the youngest of the formations have been worked out in main deposits and the rapitans do have a glass use any glassugenic component with them and there the mudstone they associated with the mudstone shales and conglomerate. And the mineral logically this Algoma type dominant dominated by oxides mostly Magnetite, carbonate and sulfide. The superior type also, have similar mineralogical association. Mineralogical constitution where is the rapiton type mostly dominantly oxide.

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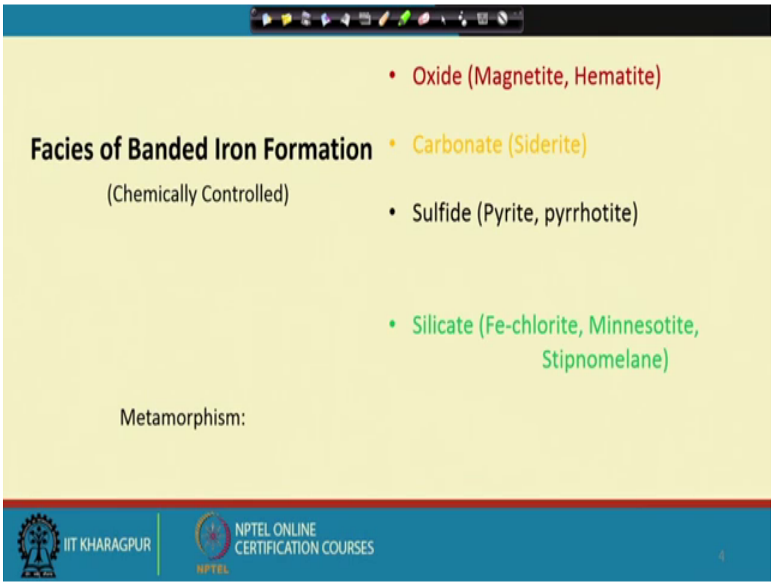

Facies of Banded Iron Formation

(Chemically Controlled)

- Oxide (Magnetite, Hematite)
- Carbonate (Siderite)
- Sulfide (Pyrite, pyrrhotite)
- Silicate (Fe-chlorite, Minnesotite, Stipnomelane)

Metamorphism:

There has been a proposed looking at the way these iron formations they occur in different parts is they can it is observed that they are from the constitution point of view, we can see that they are occurring in different compositional variations which we call them a facies of the banded iron formation. And these facies are generally they are chemically controlled, because we are essentially dealing with the sedimentary process which is chemogenic in nature. And this facies which we are dividing is oxide facies which is dominated by Magnetite, hematite, carbonate facies, sulfide facies and the silicate facies. The silicate facies is characterized by the different types of a fyrogenis clays, minosotite and greenalite kind of a clay minerals. And the sulfide facies is dominantly of pyrite almost like pyritic black shales.

And what is interesting is that this division into the facies and the occurrence of these banded iron formations in different mineralogical constitution can be explained chemically, and this is how we generally try to see or interpret them in terms of the variation of the oxidation state of the environment of the aqueous environment. And the pH that is the acidity or with as we say the activity of the hydrogen ion concentration these two parameters, because they are surface processes surface operating on the continental shelf region or someone in any intercontinental basin.

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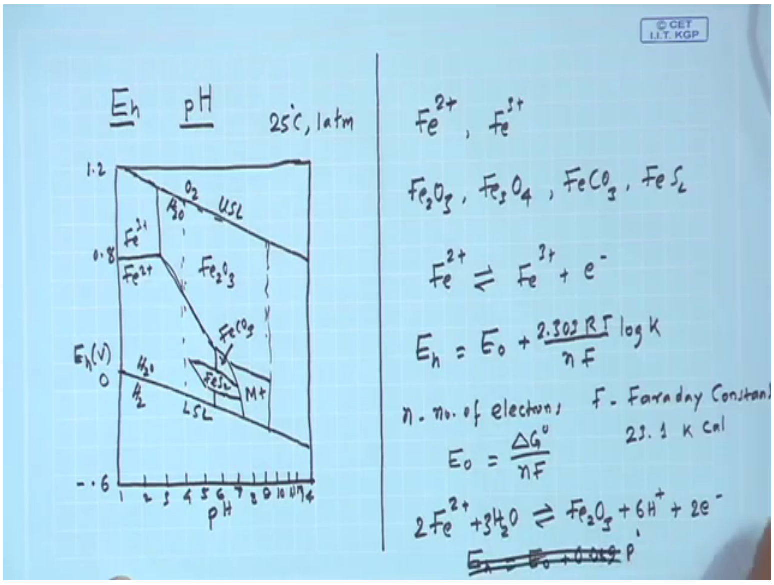

Fe^{2+}, Fe^{3+}

Fe_2O_3, Fe_3O_4, $FeCO_3$, FeS_2

$$Fe^{2+} \rightleftharpoons Fe^{3+} + e^-$$

$$E_h = E_0 + \frac{2.303 RT}{nF} \log K$$

n - no. of electrons; F - Faraday Constan

23.1 K cal

$$E_0 = \frac{\Delta G^0}{nF}$$

$$2Fe^{2+} + 3H_2O \rightleftharpoons Fe_2O_3 + 6H^+ + 2e^-$$

~~$E_h = E_0 + 0.059$~~ p

So, their conditions will be the near surface condition or 25 degree centigrade and we can see or characterize the environment chemically by using these parameters which is basically, the E h and p H. Even though you would be basically giving the details in supporting notes, I would just like to make a simple sketch on how this kind of E h, p H diagram can be constructed. So, the dominant species we can consider the iron to be in iron 2 plus that is the state in which the iron is soluble and the iron 3 plus that is the state in which it is insoluble. And we could consider the dominant mineralogy of the facies that we have just stated Fe 2 O 3 that is hematite, Fe 3 O 4 there is Magnetite, Fe CO 3 that is siderite, Fe S 2 that is pyrite.

So, we could relate them by some simple reactions. For example, these are all coming from very simple principles that we studied in our textbooks of chemistry high school textbooks in chemistry. If I put if I write a reaction simple reaction like Fe 2 plus giving rise to Fe 3 plus plus 1 electron. This becomes a reaction it redox reaction which can be calculate can be worked out. And based on the free energy change of this reaction and using the simple non strip equation which gives me E h is equal to E 0 plus 2.303 R T by n F into log of K.

So, in most of the cases, this n stands for the number of electrons involved. And F is the Faraday constant which is about 23.1 kilocalorie and this E 0 comes from the standard state free energy change of this reaction which is the del G 0 divided by n F and here the n and F are the same. So, we could by working out these kind of reactions like the one which I mentioned here or say.

For example, I will just first draw the rough boundary as it is. It is look like the E h would be somewhere around 0.8 which is expressed as volt and coming from say almost like minus 0.6 to 1.1 or 1.2. And these E h, p H, this is 0. They are basically bounded by the lower saturation, lower surface limit and the upper limit of the aqueous environment. This is defined by H 2 to H plus or we can say H 2 to H 2 0 and this would be H 2 O, 2 O 2, and pH of about 4 roughly 4 to 9.

So, this kind of boundary is defined for the natural limit of E h, p H. And if we see I am just making the very schematic, this is Fe 2 plus, this is Fe 3 plus. This is the stability field of hematite. This is the stability field of hematite; this is stability field of Magnetite. This area which is bound by here, here and here both these are small. This part are the stability field of siderite and this is the stability field of pyrite FeS 2.

So, generally this banded iron formation facies can be interpreted by using this kind of small this kind of diagrams which can be worked out at 25 degrees Celsius and 1 atmosphere pressure. And simple reactions like Fe 2 plus plus water Fe 2 O 3 plus 6 H plus plus 2 e when it is balanced. So, this makes a redox reaction which can be plotted as you can see that if we work out this reaction which will be the details calculation will be given. If this reaction is worked out and the Eh, pH relation series found out we can always have E h will be equal to E 0 plus 0.059 into p H.

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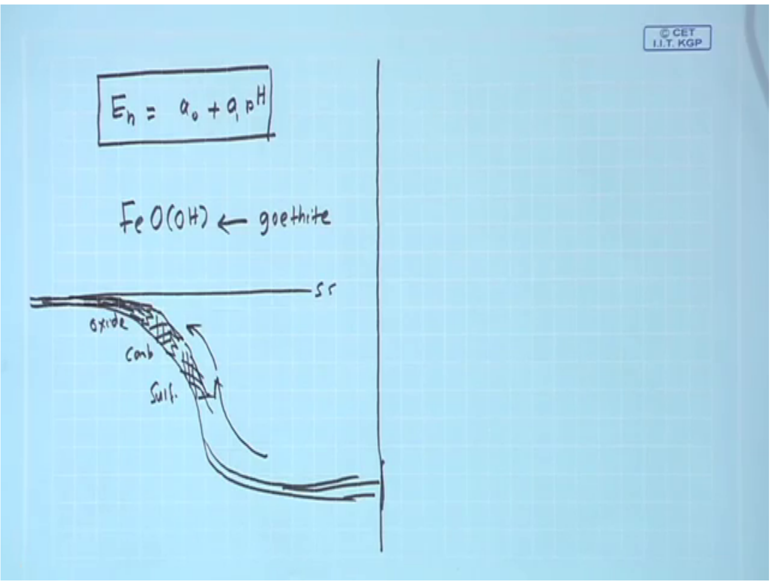

Or, we can just can almost like a straight line equation we can put E h is equal to a 0 plus a 1 p H, where these are the parameters which are coming from the E 0 which is where del G of the reaction by n F and a 1 is coming from the equilibrium constant other species which are considered. And when we consider such kind of diagram, the relative positions of these the boundaries very much at a sensitive to the concentration of the different species that we are considering the iron species in total iron content of the aqueous environment. Then concentration of the carbon dioxide total sigma carbon dioxide of the environment and the sulfurous species depending on that we can have this the stability fields of the species.

And we can interpret that if we are somewhere in a Fe 2 plus a stability field then if we increase this is a situation in which I can say that it is silica pore or silica deficient the moment the situation becomes silica enriched this will be replaced by some iron bearing silicate facies. And we see that with this help of this diagram, we are able to explain the different facies of and random information in what kind of E h p H condition will have from Fe 2 plus 2 Fe 2 O 3 which is hematite, and iron carbonate and sulfide to be stable in restricted environmental parameters which could be correlated to the conditions in which these rocks are likely to have this to a form in nature.

Interesting thing is that these deposits, which are older deposits Precambrian deposits, the age and this as do we have this we have stated. These deposits are subjected to definitely subjected to metamorphism and a different places the metamorphism grade could be variable. Sometimes very high grade conditions from 700-750 degree centigrade to 1011 kilo per pressure have been interpreted in some of the Algoma type deposits, and some of the superior type deposits have also been worked out, but some of them retain their unmetamorphose characters with the lithological characteristics like the shales and all percent within the different static horizon persisting.

And it is a belief that in a aqueous environment when this iron species here we showed here, when they are precipitating from aqueous environment it is very likely that instead of they being shown as oxide species, they would be actually be forming the hydrated oxide species such as something like goethite Fe O O H in different forms of this alpha, beta, gamma form of this hydrated oxides which generally named by is goethite or other hydrous minerals.

And what we see them in the form of the oxide species is presently mostly is Magnetite and hematite; some believe that they are product of metamorphism. But the way they are extensive occurrence and persistent lateral extension that we see them, they do not seem to be when measure it of the cases they do not seem to be product of metamorphism. At the most, we can think of a very low grade from the silicate associated silicates which we interpret in terms of going from very low grade to low grade diagenetic kind of environment where these hydrated iron minerals might get dehydrated and we get them in the form of hematite and Magnetite.

And then the diagrams the pictures that we have seen about this iron ore, it would look like that the iron content of them would not be that very high. Because going by the definition something which is more than about 17 percent 25 percent iron in this material which we see them in the form of banded hematite just banded hematite magnetite or banded hematite porazite.

But, we can only get them in the high grade means going the values going to 55 percent 56 percent or even sometimes a very high grade ore that we label them. So, we need to have this deposit somehow enriched in secondary processes. So, secondary enrichment processes are also visualized in case of these many of these deposits and they are definitely quite variable going from different terrain to terrain or different areas, different basin to different basin. So, it is a common attribute of them.

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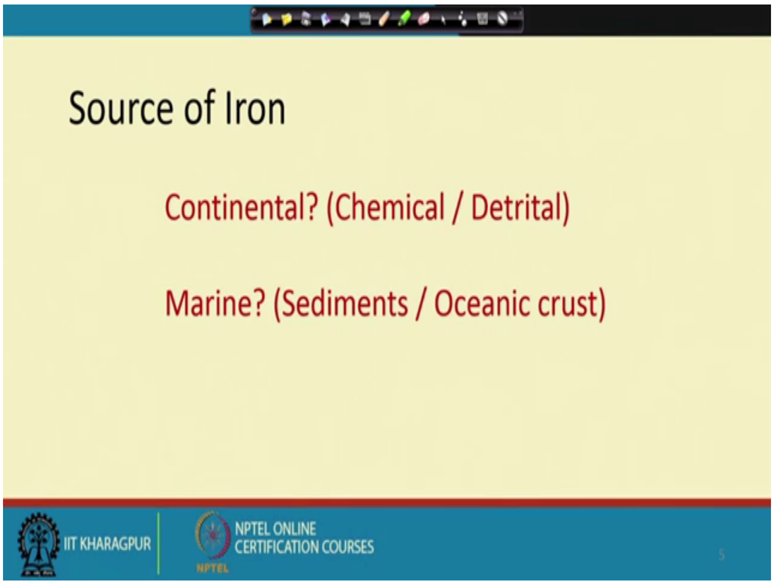

Source of Iron

Continental? (Chemical / Detrital)

Marine? (Sediments / Oceanic crust)

Now, while addressing the issues of the origin of this iron ore, the most interesting aspects are that there we see them they are pretty extensive, huge quantity of iron being mobilized. So, the very basic question arises that what could be the source of this iron. And, as we discussed earlier during the introductory sessions, while discussing the temporal distribution of the various types of mineral deposits, we recalled that the varied as per one of the hypothesis the origin this to begin with the atmosphere was much more rich in carbon dioxide, and the much more to the surface water is hotter and corrosive. And it different from what the systems prevailing conditions at the present time with the partial pressure of oxygen having the value of 4.2 it was not so in the Precambrian time.

So, they are two different sources for this iron, one could be the obvious choice could be deterrent to the continental; that means, this because of the continental erosion the iron is derived either by chemically by transporting them in the dissolved form or in the particulate form. Since, we see them in thermogenic sediments, so we can rule out more or less the detrital form of the transportation, chemical form of transportation look to be more reasonable. But then if we do some calculations say for example, take say simple example of a basin like Hamersley Basin where we know the how much of iron has been deposited there.

So, if we take if we think that they have been derived from the continental sources, if we calculate the total concentration or total amount of iron that is present there, and the time duration in which this Hamersley Basin as form let us say, it is about 6 million years or so, then the rate of iron input to the and considered in fact they are deposited in the in the ocean basin and the shallow continental shelf region where it is the environment is pretty oxygenated.

Then the amount of input of iron that will be required per year would far exceed the present day rate of input of the metal in dissolved form in the by considering any major river system of the world let us say, Mississippi river system. But that could possibly be accommodated that well it could be because of the atmosphere was more corrosive, more of iron was dissolved in the surface water, but still the mass balance constant will always be there as a concern.

The other possible sources marine there is the sediments that were deposited in the marine basins. It could be the marine deposits marine sediments were getting deposited or it could be the oceanic crust. Again, this we can also get down into being some kind of calculation on the possible sources from the seawater, because essentially they are marine deposits and they must have formed in some way.

If we consider that there and then one of the most obvious sources of this iron that we can have in the seafloor is the seafloor basalt itself, which will be able to contribute the iron by in the process of reaction with the seawater. And we already have stated that the seawater during that time was more carbon dioxide charged, more corrosive with more of acidity, and more of iron could be held in that in solution.

And the process could be visualized. And then when we calculate we find somehow its reasonable from the present day value of the seawater iron concentration, which is about 0.02 to 0.03 milligram per liter. And if that even going to some value as even a higher concentration that could have been there in the corrosive sea at that point of time. We generally, we kind of think of a picture like this. This is the sea surface; this is the sea.

So, what we see here the sediments, this is generally the domain in which the oxide facies is forming. Then this is the carbonate facies and this goes to the deeper part in which we are supposed to be getting the sulfide facies. And the model that we are thinking here that the ocean water is having substantial amount of iron dissolved in the lower part in the deeper part where the condition is very reducing.

So, then there must be some process of upwelling of this fluid which is of these of the seawater which is having a very high concentration of the iron. And then when it encounters, the more oxidative environment in the shales region, then the iron is precipitating which very much fits to the conditions of deposition in then shallow self conditions. So, the hypothesis that the iron metal is derived by the sea floor or the sea floor basalt, seafloor rocks with some input possibly coming from the seafloor sediments look like to be Feasible and this kind of model can be proposed for the origin of this banded iron formation. So, we will continue discussing the iron formations in the next class.

Thank you.