Mineral Resources: Geology, Exploration, Economics and Environment
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Lecture – 08
Magmatic Processes (Contd.)

Welcome to today’s lecture, we will continue discussing on the magmatic deposits starting with deposits of chromium and the nickel copper and platinum group of metals associated with magmatism of ultramafic affiliation. And in the last class we where, we just started to discuss the bushveld complex, which is one of the major and an important resource almost constituting 80 percent of the total chromium resources of the world and also in addition to that, the major resource of platinum group of metals and also titanium and vanadium.

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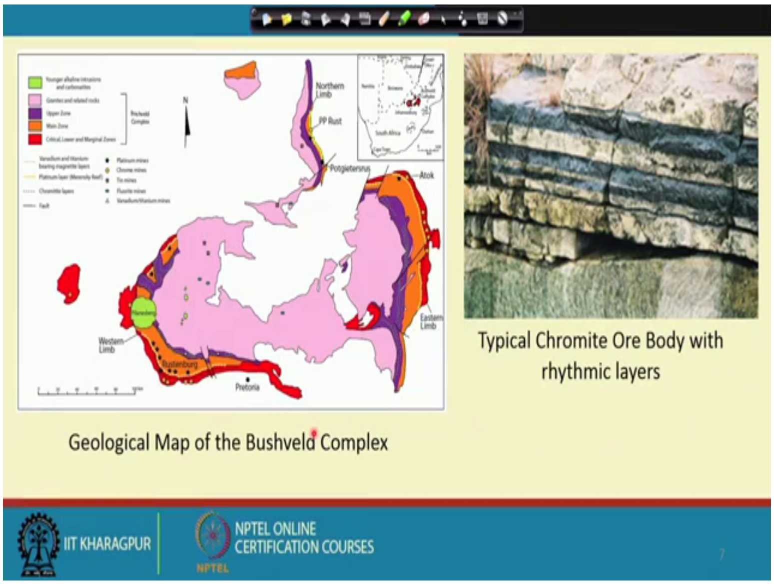

So, let us get back and discuss the bushveld geology in at little greater details, what is interesting is that this kind of these are which is named as reefs, which runs for and even sometimes even 100-85 kilometers. So, these 2 fragments are even correlateable the eastern limb and the western limb, and they northern limb it would be go to just see kind of a cross section of this bushveld complex. This is a section which is almost about 9000 meters as you could see here, starting from the so these are divided into zones the lower zone, the critical zone, the main zone and the upper zone.

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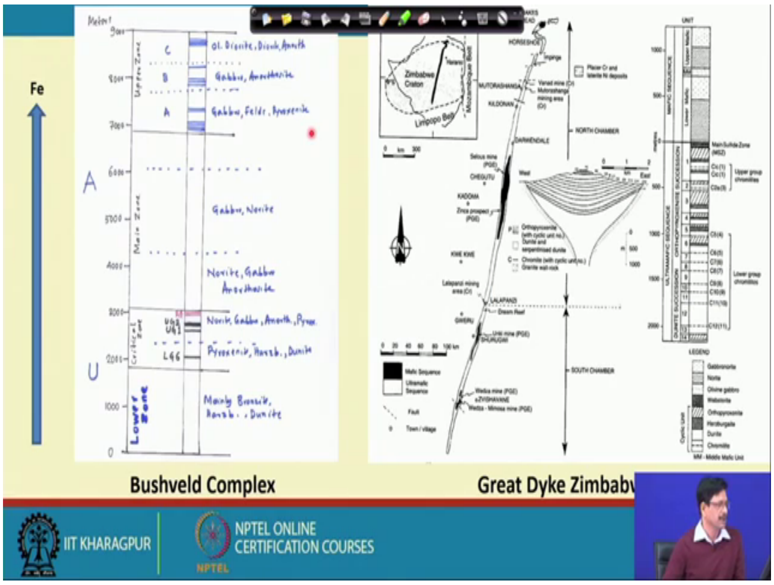

The lower zone is divide of any chromite reefs, their mainly the most ultramafic part of the differentiated complex mainly bronsite harzburgite and dunite and the critical zone, which follows the lower zone is the one which hosts some of the important chromite bearing origins where, in their the LG the being denoting the lower group, there are about 7 such repetition of these chromite layers and they range in thickness from some of few centimeters 2 meter more than a meter or 2 meters or so and followed by the upper group where, there are 2 important chromite bearing origins the UG1 and the UG 2 and here, we see that the composition of the rock is changing from 2 a little less mafic composition with norite gabbro annerth pytic and paragenetic and which if it look at the entire sequence it is a iron increasing iron content the sequence of the rocks, that we see here.

The more important point or the more important part to be observed here, is the lines in red, which are the 2 different 2 reefs one is known as the bastard reef the other one is equal to Miriinsky reef these 2 reefs are very, very important because, they are the platinum rich reefs in this sequence essentially the sulfidic component of the ultramafic complex and then, the main zone this is giving rise to Lowretic Gabbro and this is the upper zone which is mainly annerthsitic and olivine diorite gabbro annerthsitic and this is about multiple, such layers which are essentially the iron the titanium vanadium varying oxide phases of the complex.

So, as I said that, such reefs or in or the diagram here, they traceable for great strike lengths and very substantial down depth extension and a very rich chromite bodies. This is the section of the great dyke of Zimbabwe where, you could see that this is running for about more than 3100 kilometers this is a great dyke of Zimbabwe.

In the great dyke of Zimbabwe also like the bushveld complex, it could be it is also has many multiple number of such, chromite horizon which are shown here, from C1 to even C12 if this is the lower group chromites and the upper group chromite. And so, this is how the ultramafic complexes are they disposition of the ore bodies and they general geology, which is pretty interesting and it gives us, firsthand information that is, they look to be products of crystallization differentiation of what we know about a parent basaltic magma, but then when we look at them very carefully and minutely sometimes it becomes difficult to accept such a very simple model of a normal crystallization sequence of differentiation it of this complex in 2 different members in the layered complex.

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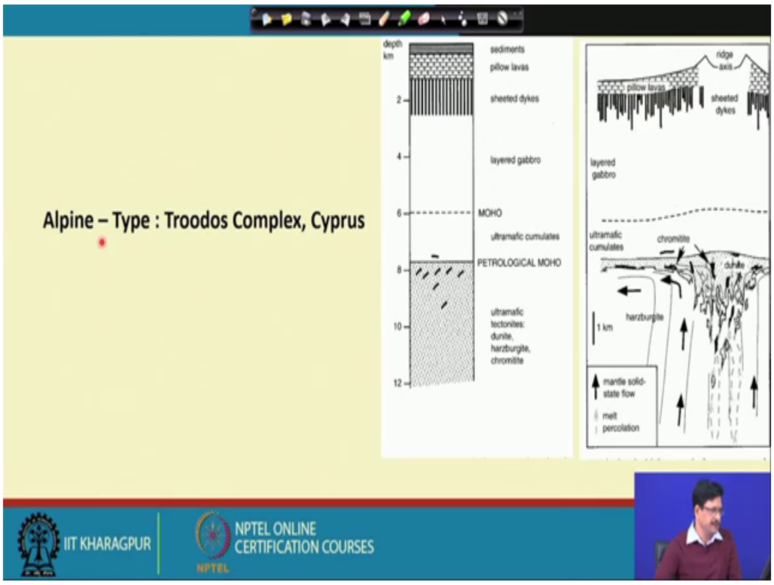

Why did so? We will just possibly a look through a little bit here. So, before we go to the I go to understanding the process in a very simple term here, is another type of the chromite deposits which we showed there the is present in the Troodos ophiolites, they are the alpine type chloride deposits, which occur in Terrence which are presently which basically represent the continental collision and the fuelite sequence and it is a generalized sketch of such, kind of a sequence where, it starts with the ultramafic tetronites, the dunite harzburgite and there are these are the chromite bodies.

So, they derive their name as the podiform chromites as against the chromite, which occurs in the ultramafic complexes which are known as the stratiform. So, these are the podiform because, there present in dismembered and fragmented lens shaped or what we call as a pod shaped bodies of chromite within the ultramafic sequence and as we know there is such kind of situations very well correspond to because, they are supposed to be formed in the in conditions a very, very much I came to the mid oceanic ridge system.

Where there is, mental upwelling and generation of basaltic crust presence of sheeted dykes and the ridge axis, which is and the deeper part we have the asthenosphere melting and giving rise to this ultramafic rocks, from which we also do get the chromite formed and these possibly these are ones, which we get them as your fuelites in the collagen zones in the a fuelite sequence like, the one we see in Cyprus.

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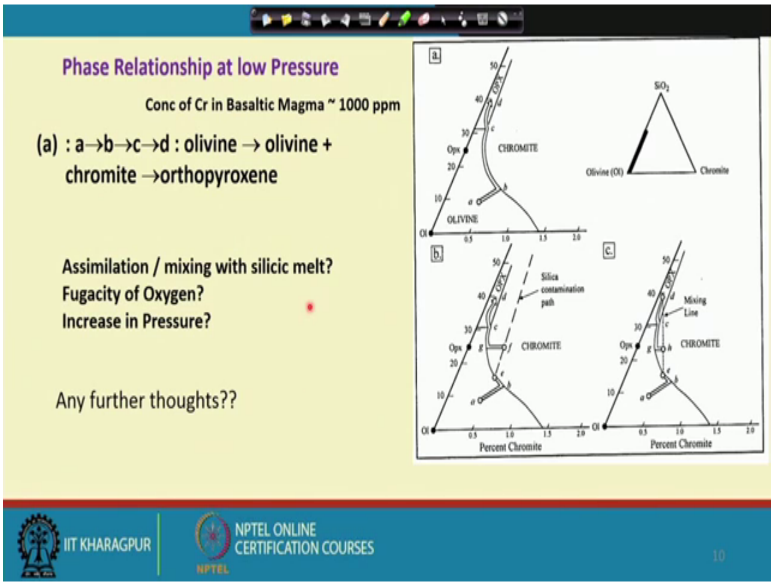

Now, if we want to try to understand where, the process is how we got how we can get such, chromite rich layers. If we just have to recollect, these are essentially the layers which are chromite reefs and that is why they called the chromatids, they are not much mixed with the other silicate minerals here, and as you know in any normal crystallization sequence we should be getting the graphic minerals this olivine, pyroxene and so on, which would be crystallizing along with the chromite, but then something special must have happened to give us the chromatids, so the chromite rich layers.

We all know that the, concentration the normal concentration of chromite and a basalt chromium in a basaltic magma is about 1000ppm and then, how is it that we get this chromite rich layer the chromium concentration being much higher in terms of several tens of weight percent. To explain that, we take help of this diagram phase diagram, where the it is a ternary diagram, where the components are the (Refer Time: 8:46) are silica oliven and chromite and we take only the SiO2 oliven side with very little concentration of chromite, and look at the phase diagram as to what how we could explain the formation of this chromite by taking help of this diagram.

Here we see, if we start from a composition like this, which is given by point a then the normal crystallization sequence would make the liquid move from a to b where, it riches the core tactic this is the chromite stability field and they riches the core tactic b where, after it riches the core tactic b, it follows a path up to c and all along this path of b to c chromite and oliviner supposed to co precipitate or crystallize together from the melt, which would otherwise give us a olivine rich rock only with some interest to sell chromite.

And from c it moves to d and get it gets into the field of orthopyroxene and then, this if we look at this normal crystallization sequence, which is presented in the figure a here, then we will not be able to get the chromitite layers.

Let us, think of a situation where it could be possible once we rich the point b either just about point rich or just about the crystallization co precipitation of both chromite and oliven has going on, this melt is contaminated by more silica rich fraction or is more siliceous melt, which is contaminated which contaminates the original melt from which, these crystal these are crystallizing.

So, then it will enter into the field of chromite and from e to f we will only have chromite crystallizing from the melt. So, that would possibly give us, the explanation is to why we get this chromitite rich layer and after that, again it will follow from f to g and normal crystallization sequence by which, it will give rise to the other members of the complex. It can also happen, if the melt is mixing with more differentiated well; that means, if kind of an inter mixing here, mixing line that also will again from b to e and if we think that, there is a composition melt composition something like d is mixing with e the point e, then it will follow a line which is shown dotted line from e to c and all along this line up to up to the point h the chromite will crystalize and again it will follow the normal crystallization sequence.

Now, then it is fine. So, it will we will from a little bit of a perturbation in terms of mixing with the cilice more silicate more felsic melt or even the mixing of the melt within the magma chamber by less fractionated to a more fractionated one, we will be able to explain the formation of the chromate chromite rich layers, but the problem remains in terms of the total volume of the melt magnetic melt, that we must have to give rise to such rich layers of chromite as we seen in either a take it take for example, the Bushweld complex or the Stillwater complex or the great dyke of Zimbabwe.

So, then how we can explain and such repetitive sequences of layers, that we have seen in the UG player in the in the LG layer on the UG layer and different reefs, which turns for and such layers themselves have got so many reputed layers of chromite ranging from the dimension in few centimeters to even meter scale thickness. So, that eventually led to the hypothesis that possibly it was a case where, there were subsequent batches of magma coming and mixing within the same magma chamber and giving rise to this.

The other thoughts other ideas, that came to explain such kind of rich chromitite layer was that, pressure could be one of these variables because, pressure the solubility of chromite is a pressure dependent phenomena, that might have some situation where, pressure possibly would have fluctuated to give rise to this chromite layer intermittently, but then, in a huge magma chamber like the one which we see in case of bushveld complex it is not very easy to reconcile, that pressure could actually have fluctuated in that range to give rise to such change in the solubility of having alternate episodes of crystallization of this chromite it is layers.

Even fugacity of oxygen was also proposed is one of the possible mechanism for explaining such chromitite layer. So, all these have their in shortcomings finally, this definitely gives us a working model for the origin of these chromite deposits and all these layered complexes, and when we talk about these situation that the volume of the magma that is, if we take the mass balance into account then still such kind of model will remain inadequate, there were later ideas for the situation that, actually the magma were actually convicted basically were in terms of layers and each layer was convicting independently and the model such as a double diffusive kind of layer concept came up.

But, details of which is not very well understood about how it works, but only in the context what is more important here is that, if we look at the situation here, it is actually the chromitite layers are not very uniformly distributed in any particular column or any particular height within these different members of the magmatic body, but rather they are more like as if they are somehow being controlled by some kind of contract zone that, gave rise to the idea that possibly it is some kind of different layers of the magma chamber are actually are circuit at actually convicting and there is a transfer of the material between the 2 layers and that is how, the it the chromite rich layers or even when will be going to see the other phases also the similar kind of explanations could be given to x 2 of 2 reconciler to actually a visualize the formation of such kind of chromite rich layers.

So, this kind of situation would give rise to a simulation or mixing with silicate melt because, the oxygen increase in pressure which we have discussed.

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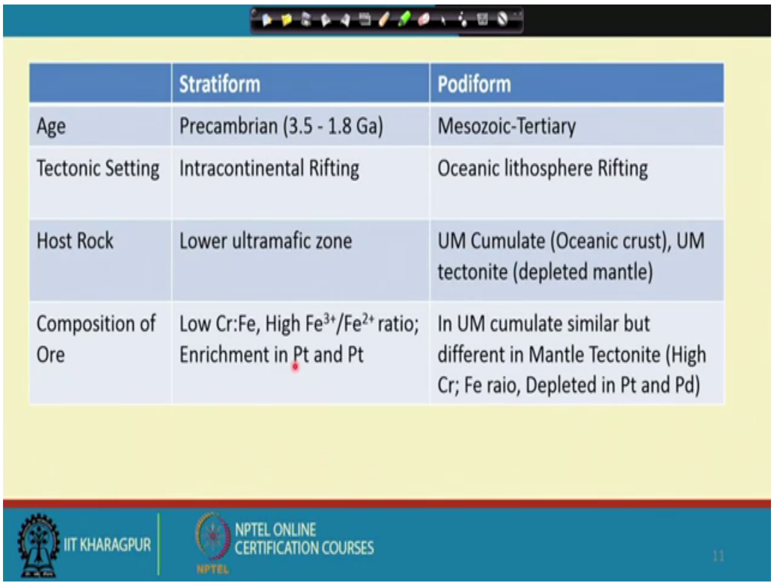

	Stratiform	Podiform
Age	Precambrian (3.5 - 1.8 Ga)	Mesozoic-Tertiary
Tectonic Setting	Intracontinental Rifting	Oceanic lithosphere Rifting
Host Rock	Lower ultramafic zone	UM Cumulate (Oceanic crust), UM tectonite (depleted mantle)
Composition of Ore	Low Cr:Fe, High Fe^{3+}/Fe^{2+} ratio; Enrichment in Pt and Pt	In UM cumulate similar but different in Mantle Tectonite (High Cr; Fe raio, Depleted in Pt and Pd)

So, the dominate 2 types the stratiform type actually which constitute the bulk of the chromite resource of the world, as it against the podiform type which are constituting less some insignificant in terms of the resource of chromium, the is for the stratiform is dominantly Precambrian between 3.5-1.8 Gigayan and the podiform are mostly

Mesozoic to tertiary because, they are supposedly the c floor the objected oceanic lithosphere where, we get this chromite bodies within the ultramafic, which were essentially generated during the or at the mid oceanic ridges.

Tectonic settings more or less there is always a problem, wherever we bring in contamination of silicic magma or more differentiated magma or mixing in any kind of a stratified magma or density stratification so on. Then we find that the, rifting kind of setting becomes inadequate and it always eventually leads us to situations where that, would possibly be some kind of subduction component somewhere, which the rifting of which will be beyond the scope of this lecture to discuss.

So, these give us a gross are comparison between the 2 and the host rock in this case is a lower ultramafic zone, in this case it also ultramafic cumulate there are some subtle compositional characteristics or compositional differences between the 2 types, the strata from typer a little low in their chromium is to iron ratio and the ones they associated with the podiform variety in the mental tectonite are essentially, having a very high chromium to iron ratio and they are depleted in platinum and palladium whereas, the bushveld complex is pretty much enriched with this platinum group of metals, which will be the topic of discussion in the next slide here.

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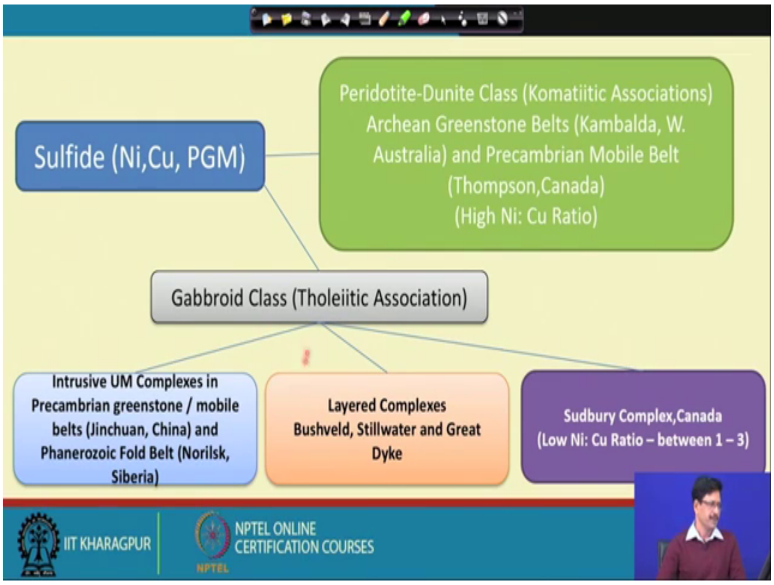

So, from the oxide phases now, we switch over to move on to the sulfide phases, this usage of the term is phasis absolutely mine, because it can be used that way. The

Sulphide component of the ultramafic complexes or the in general the occurrence or the mineralization of the nickel copper and the platinum group of metals in rocks of graphical traffic composition, they could also be divided into 2 broad types.

The one type is the peridotite dunite class where, there mostly associated with Komatiltic rocks and they are generally, the members of the Archaean greenstone belts are present in the Kambalda in western Australia and the Precambrian mobile belts like, in the Thompson Canada in Manitoba and Canada and here, the nickel is to copper ratio is high and the other class is known as gabbroid class, they are associated with Tholeiitic association dominantly.

And the gabbroid class can be further subdivided into 3 the intrusive ultramafic complexes, in Precambrian green stones or the mobile belts like, the example is the Jinchuan deposit in china and the phanerozoic fold belt fold belt the example is coming from Norilsk, Siberia and Russia and the layer complexes, which we already have seen quite in good amount of details about out what they are and the most in the unique among them is the Sudbury complex in Canada, which has a lower nickel by copper ratio between 1 and 3 and will give a brief overview on the characteristics of such deposits, which are the richest resources of nickel and the platinum group metals.

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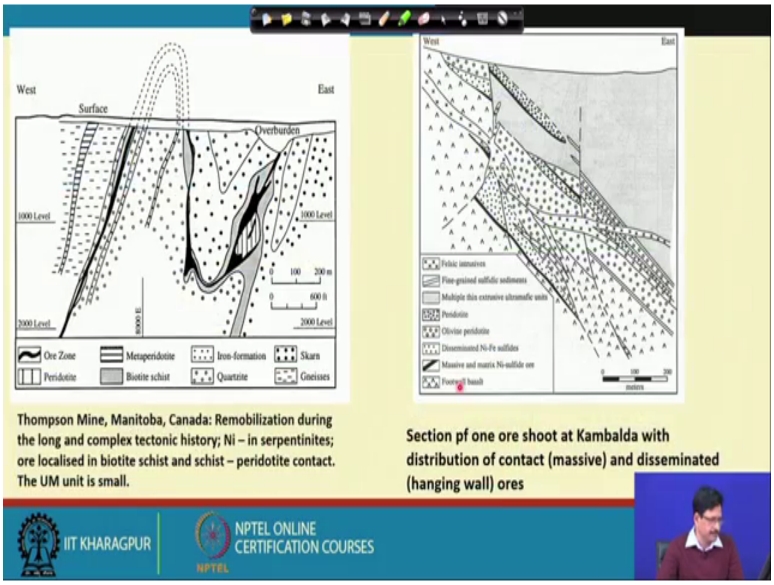

So, this is an example from coming from the Thompson mine, where it is associated with the green stones and here, the as we know that they are the older green stone Terrance, that they are structurally quite then been modified there metamorphosed altered submitnized the mafic rock, the Komotataic rock and there has been re mobilization during the long and the complex tectonic history and the nickel mineralization is mostly confined to the serpentinites and the localized in biotite schist and nicest within the contact with peridotite and the ultramafic unit, which is shown here is small. So, most of it would look like as if there and the sulfide nickel sulfide body, which is shown as black is this ore zone which almost looks very clearly, that it is a deformed sequence and still it is definition is quite clear with the green stone some iron formation and some amount of skarn also being there.

And this is the Kumbalda the occurrence in western Australia, where the ores could be seen has at the contact of the massive and the massive ore is in the contact between the different rock units here, then have disseminated ore and massive ore hanging wall ore and here, we could see that there in the ultra graphic complex the dissimilar nickel iron sulfide the oliven peridotite.

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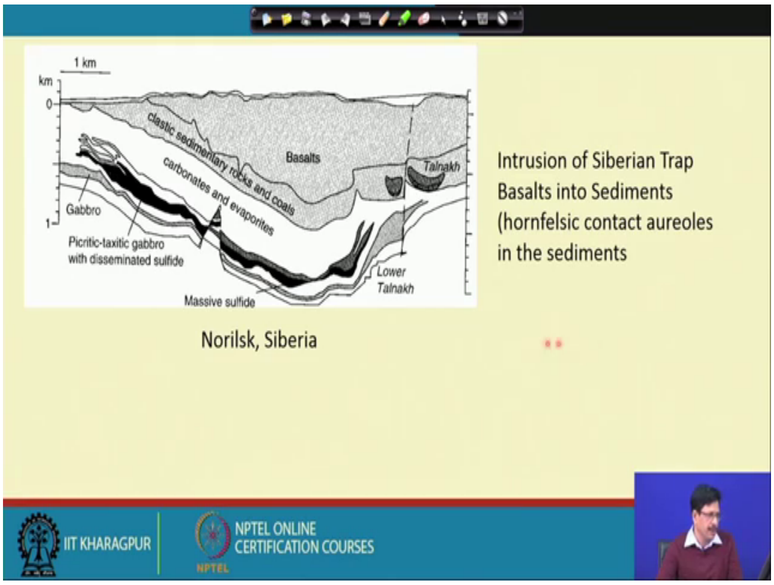

So, this is the this also another member another example of the green stone associated nickel sulfide deposit or mafical remarfic class and this is the Norilsk deposit from Siberia, Russia where, you could see the association of this sulfide deposit with the flood basalt the picritic and taxitic gabbro with disseminator sulfide, the sulfide form in the form of dissemination with a minor member of gabbro and this overland by younger sediments and this carbonate and evaporates and the plastic sedimentary rocks and basalts.

So, that primarily there with the continental flood basalt intrusion of the Siberian trap basalt, in the sediments giving rise to some holf hornfelsic contact.

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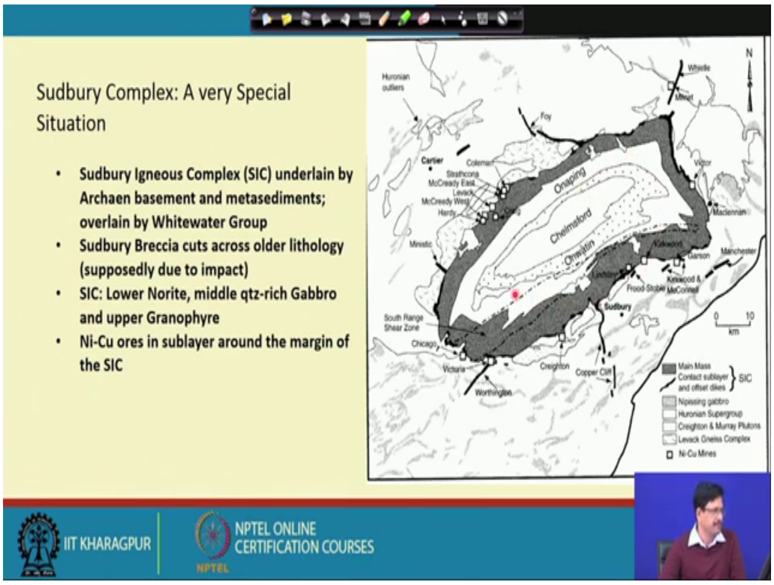

This is the Sudbury complex, which is basically known as the Sudbury igneous complex or the SIC, here it is interesting, because of this very shape and the amount of interest, that the deposits are generated is essentially belong to the gabbroid class and here, you could clearly see there is a younger group of rocks, which has basically the onaping and the Chelmsford and unwean this onwating groups, which are younger which are lower length which basically over lide a sudburying re igneous complex, where this is the main mass and this is separated by a contact layer within the country rock.

So, it is basically underlain by an Archean basement with the sediments and the overland by the whitewater group the whitewater group is consisting of these 3 formations, and interestingly there is a breccia complex, which cuts across the basement which is on the contact of the Sudbury igneous complex, which is essentially a Neritic Gabbron, right? Kind of composition consisting of a lower norite middle quarge this Gabbro and upper granophyre this constitutes the Sudbury igneous complex and the nickel copper ores or they occur in the sub layer and the around the margin of this sub Sudbury igneous complex.

And the local it is over here, are the different working mines likewise you could see there are many and this deposit gave rise to a lot of interest because, it belongs to a it is different than the other deposits which are associated with and this is essentially a gabbroid class. The one of the hypotheses for the formation of this Sudbury igneous complex is that, it is formed due to the impact of a huge meteorite that caused the melting of the rocks their mental of the underlying melting of the underlying mantle and the emplacement of this Sudbury igneous complex.

As already stated here the nickel is to copper ratio is low compared to the other nickel sulfide deposits, which are associated with the mafic ultramafic and then layered complex and please be reminded that, the bushveld complex itself which also has a very significant member arising out of the immiscibility of the sulfide liquid and there is an enriched layer, which also give rise to even though the grade of the total quantity of nickel I have the total the quality in terms of the grade is a little lower, but it is the huge resource of nickel, as well other than chromite for which it is the most well known.

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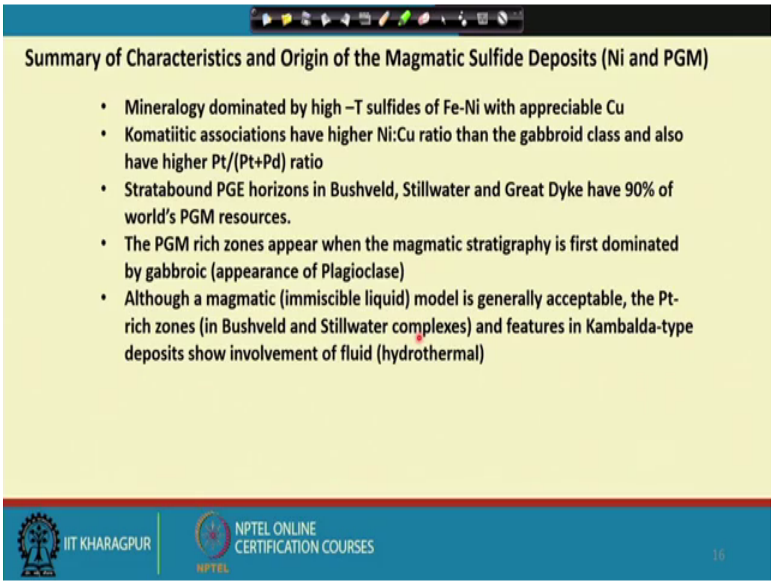

So, if you summarize, then the characteristics and the origin of the magnetic sulfide, then the mineralogy is dominated by high temperature sulfides well mineralogically, when we go to this deposits they are dominated by the high temperature sulfides iron, nickel, sub the pentlandide may milaride (Refer Time: 26:24) type of sulfide species of nickel along with nickolite and they are, they took on their essentially high temperature sulfates which substantial copper dissolved in them, which later form the chalcopyrites. So, and essentially a ultramafic the sulfide bodies the nickel sulfide ore bodies in almost all these will be essentially be constituting of the nickel sulfide minerals along with pyrite, perotite and chalcopyrite is also one of the minerals in them.

The komatiit associated have higher nickel is to copper ratio, than the gabbroid class and also have a higher platinum by platinum plus palladium ratio, and this platinum group of filament mineralization in case of bushveld is stratabound PG horizons and bushveld Stillwater and great dyke also have 90 percent of world the total taken together.

The bushveld complex deal water complex and great dyke have 90 percent of the worlds PGM resources, even one of the to go back here, this in the bushveld geology the has I has I showed here, the 2 reefs which are within the critical zone the mariinsky reef and the bastard reef is one these 2 reefs are the major platinum bearing by the sulfide phases reefs, which has the platinum enrichmenting them in addition to that, the northern part it also has a very well developed reef, which is known as the plat reef which also is very much platinum enriched and has a huge reserve or platinum there.

And the platinum group metal re zones appear, when the magmatic stratigraphy is first dominated by gabbroic appearance it is very interesting, that the like what is shown in case of the bushveld complex, the platinum group of metal where, the PGM rich zones only appear when the magnetic stratigraphy is dominated this or the first appearance of plagioclase of first it gets changed to a more like, a gabbro type of composition which is explained by the fact that, when plagioclase started to crystallize from the resulting melt the male becomes denser and so that, helps in the subsequent batch of melt which will be lighter to move through and enhance or facilitate the magma mixing process, which gives rise to the which makes the Sulphide phase exolve out of the parent melt and eventually to give rise to the to make them enrich through respect to the platinum group of metals.

So, this is one of the important aspects as far as the origin of the earth this ultra graphic complex is concerned it is very interesting to know that, the platinum group metal rich PGM zones only appear when the stratigraphy changes to form a dominantly mafic rate gabbroic composition. So, although a magmatic invisible liquid model is generally acceptable the platinum of rich zones in bushveld and Stillwater complexes and features in Kambalda the type deposits.

So, some involvement of fluid interestingly, the Millionsky reef or the plat reef and the occurring in the bushveld complex, they somehow have a pegmatroidal appearance of them which is very distinct and there are which led many of them, many people to propose a hydrothermal origin for the platinum group of metal mineralization in these complexes and from based on a lot of study on platinum mobility in hydrothermal fluid, they proposed this model, but then the fact the question remains in a dominantly mafic ultramafic complex, how do you explain or how do you generate this kind of hydrothermal fluid?

So, that essentially has given rise to mixed kind of tectonic environment and the many of the variations to the model of many local scale variations which have been suggested to explain for the pattern of enrichment in many of these synthetic members with this we conclude with the mineralization the magmatic deposits, which are dominantly associated with mafical dram of a complexes will continue discussing with some other mafical deposits.

Thank you.