Plate Tectonics

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Lecture – 32

Magmatism & Metamorphism at Different Plate Settings-II, Metamorphic at Subduction Zone

Ok friends, in the last class we are talking about this. Magmatism in the subduction zone and we found this magmatic composition varies from the trench axis and as it is derived from different level with different degree of partial melting, assimilation, water content and due to this composition of this mantle is vary from different level. So, this magmatic composition is also varying and in today's class we will talk about metamorphism at the subduction zone. So, now how the metamorphism taking place at the subduction zone and what is their product that we will talk here. Now you see there is two diagrams, one is here the oceanic lithosphere is going down and it is serpentinized. And another figure here these are showing some of this temperature contours and you see this trench axis and through this trench axis this plate is going down and this is the mantle wedge.

So, this is the upper mantle wedge and here this is the area where hydration takes place and not only this is the area if you remember when we were talking about this mid-ocean ridge system their faults are there and through this faults the water was circulating and it was just altering this basalt into serpentinized. Apart from that near to the trench here this is a zone that is called the bulge and in the bulge there are normal faulting and through the normal faults water is going inside and finally, this is the zone of hydration. So, now we are putting a hydrated slab into serpentinized slab into the mantle system and here this hydrated slab once it is reaching to this much depth due to temperature and pressure it dehydrating. So, this dehydration you see this blue globules these are the release of water.

So, where this water will go simply this is the mantle wedge and this water is released into this mantle wedge. So that its melting temperature is decreasing and once the melting temperature is decreasing it is coming close to this liquidus. So, here this partial melting is taking place and finally, this magma is generated and it is here. So, that means, it is a temperature and pressure environment. However, the temperature if you see this contours are moving and going like this.

So, that means, here this temperature contour is going downward and again releasing upward. So, that means, it is a varying temperature and pressure zone. Similarly in this zone you see there are two plates that is overriding plate and under thrusting plate they are in closely contact with each other. However, once you are going to the asthenosphere the asthenosphere is not that much rigid. So, that it will put pressure for thrusting if you remember our earlier class.

So, that means, once you are coming away from this zone that means to greater depth this pressure is gradually reducing. However, you are putting this slab into a high temperature environment. So, that means, this slab which is coming near to the surface to this end it is going through a varying temperature and pressure zone. That is why a series of changes taking place in its mineralogy, in its density, in its temperature, in its pressure. So, now, you see the thickness of the slab here is this much and gradually once you are going down the thickness of the slab is decreasing and the decrease of the thickness of the slab is nothing due to squeezing.

So, once you are squeezing the system that means we are increasing the density. So, that is why the basalt or the oceanic basalt which is subducting at the convergent margin that is undergoing the changes. What is the changes? First change is the release of water into this upper mantle wedge. So, that we have discussed. The second thing that it is the increase in density of the subducting slab because once water is released and we are going to a high temperature environment.

So, that means, high temperature and pressure minerals that are formed. So, phase changes taking place which are result for earthquake generation. So, once these two changes are occurring finally, at this stage this slab is more dense and finally, a dense slab is subducting underground. These reactions involve specific metamorphic transformation that reflect abnormally low geothermal gradient. So, why that is low geothermal gradient? Because you see this is the temperature contour is going down and it is coming back is going down and that means, this temperature 300 degree at surface that 300 degree Celsius is reaching here that means, this much depth.

So, that is why here this is the zone of low geothermal gradient. However, if you see this zone it is the direct junction of this overriding and under thrusting plate. So, that is why this is the zone of high pressure environment. So, that is why the reaction in specific metamorphic reaction will takes place in this zone and it is characterized by low geothermal gradient and it is high pressure associated with the subduction zone environment. This geothermal gradient in a normal crustal level it is 25 degree Celsius per kilometer.

However, as here you are reaching it is a high pressure environment and you see the geothermal gradient is much much less than the normal. So, this is represented a low geothermal gradient and high pressure environment. Now, prior to this subduction zone this oceanic slab it is undergone a series of metamorphic changes and the mineral characteristics that has been produced there. If you remember our earlier class when we were talking about this divergent margin system, the water or this hydrothermal fluid that are released at the east Pacific rise and the mid Atlantic ridge they are equilibrated to greenschist facies of metamorphism. That means, it says before subduction this plate which is generated from the mid-oceanic ridge due to faulting due to water reaction this is water percolation.

This basaltic system it is metamorphosed up to greenschist facies of metamorphism that means, zeolite, prehnite-pumpellyite and greenschist facies of metamorphism. That means, up to here we have metamorphosed this slab then we are putting it to inside into the mantle system. So, in zeolite facies mostly if you see we have low grade metamorphism in zeolite facies and zeolite facies mostly often experienced in pelitic sediments, rock rich in aluminum, silica and potassium sodium and generally low in iron content magnesium and calcium. So, if you see this zeolites mostly the product is the clay minerals and its high temperature polymorph is kaolinite and vermiculite. And sometimes in basalt in vesicular basalt particularly the void spaces they are filled with zeolite you see these are the zeolite if you go to Deccan basalt you will find beautiful created zeolites within that void spaces.

Any Deccan mines if you go to basalt mines you will find the zeolites there. Then come to prehnite-pumpellyite facies it is the metamorphic facies typically of subsea floor alteration of the oceanic crust and the mid-oceanic ridge. And it is the metamorphic grade transitional between this zeolite facies and greenschist facies and the temperature varies from 250 to 350 degree Celsius and approximately the pressure ranges up to 2 to 7 kilobars. So, what is this product? The mineral assemblage in this prehnite-pumpellyite facies it chloride, prehnite, albite, then pumpellyite and epidote these are the mineral product in this group. Then coming to greenschist facies here the greenschist facies the name itself said it is a green-colored rock and showing schistose characteristics that is why it is called greenschist facies.

So, the typical minerals include we have chlorite, epidote, actinolite and which imparts the green color into the rock. And this type of alteration of basalt results from the circulation of hot seawater into the hydrothermal system the fluid it is seen here this hydrothermal fluid with cold water is going inside and is coming as hot water and during its coming back it is reacting with the surrounding rock and it is converting it to greenschist facies. These are minerals are common minerals they are found here in the basalt. So, if you remember this basalt it is essentially composed of olivine, pyroxene, plagioclase like that, but now due to alteration that is converted to chlorite, epidote, actinolite like this minerals. So, here this epidote, actinolite, serpentinite and chlorite you see most of these minerals are green in color and what is the common in these minerals if you notice here that is that means, all these minerals they contain water in their crystal structure and these water they are playing very major role in partial melting of this mantle and generation of magma as well as these water is playing major role in metamorphism in the underground.

So, now, as the altered basalt descends into the subduction zone it passes through a pressure-temperature field and it is a blueschist facies of metamorphism which is characteristics of high pressure like high pressure minerals, glaucophane and jadeite are formed So, now, you see we have already metamorphosed this basaltic system or the basaltic lithosphere which is underground up to greenschist facies. So, here up to here we have greenschist facies of metamorphism. Now, once this place is descending down it is coming direct contact with the overriding plate. So, this is the zone where high pressure sensitive minerals are formed because tremendous pressure is here this under thrusting is not an easy process this overriding plate it will resist to go down and however, this will go down forcefully so, this is a high pressure environment. So, that is why with respect to this pressure sensitive minerals like glaucophane which is a amphibole and jadeite which is a pyroxene these minerals are commonly found here at this zone.

So, here these are the jadeite and this is glaucophane and glaucophane it is containing some water however, jadeite is not containing any water. So, anyway in this metamorphic facies field we are moving upward that means, to a high pressure environment we are going to a high pressure zone. So, these are the blueschist rocks in the field. So, here this is the presence of blue glaucophane and other sodium amphiboles this is blueschist the name itself says it is blue color and it is showing schistose characteristics that is why it is blue color. So, here this is a cartoon it is showing this blueschist facies of metamorphism if you see this blue color this is the blueschist facies and this green color that the greenschist facies so, the greenschist facies it is gradually converted to blueschist facies.

Then it is further with increasing temperature and pressure it is converting to eclogite facies. So, the blueschist mineral typically mineral assemblage that is the zoisite, garnet, chlorite, phengite, this this kyanite, jadeite something like that. So, this feldspar and biotite are absent in these facies and blueschist facies assemblage are formed at low temperature and relatively high pressure zone. This is the blueschist it is a low temperature you see this temperature field around 400 or 500 degree Celsius also and it is a high pressure. So, that is why this blueschist facies is forming here.

And most characteristics mineral assemblage in blueschist facies of rock includes glaucophane, epidote, phengite, paragonite and chlorite this assemblage is must. So, we have a glaucophane, we have epidote, we have phengite, then we have paragonite and we have chlorite. So, these 5 they are essential minerals along with that we have plus minus mg chloritoid, plus minus quartz, plus minus garnet. These may or may not present, but these 5 has to be present in the blueschist facies. Apart from that the typical characteristics biotite it is not present and feldspar is not present because these are not pressure sensitive mineral, rather they are temperature sensitive minerals.

So, that is why at high pressure environment their absence is expected. So, now, the meta basaltic rocks of blueschist facies are typically found in subduction around later exhumed complex. For example, if you see here this plate is going down and once it is the overriding plate is here it is further not able to go inside. So, there is a return back. So, this is process is called exhumation.

So, once it open a time it was in the surface, then it goes to subsurface and again it is coming back. So, once it is coming back that means, it is carrying this imprints of this temperature-pressure of that depth where it was living. So, that is why this process exhumation this is the blueschist of metamorphic rock they are found. Otherwise they are at high pressure environment they should remain at the subduction zone system. So, another transition is there in this transition there is a mineral which is typically called lawsonite.

So, if the pressure is not reached of that much high so, that the glaucophane and jadeite can be formed in that case lawsonite is formed. So, lawsonite along with a glaucophane and other amphibole minerals they are important host for water. So, now, you see this plate which going down having water and it is day is over. Similarly you have epidote it is carrying water, we have amphibole that is carrying water, serpentinite that is carrying water, glaucophane that is carrying water and lawsonite that carrying water. So, now, the day is over they have to go inside so, inside the mantle system.

So, finally, once they are going inside so, there are number of metamorphic reaction taking place dehydration taking place because they are carrying water so, we are putting water inside. So, once we are putting water inside to a high temperature and pressure environment water is not stable it has to release. So, that is why dehydration takes place. So, further increase in temperature the blueschist of rocks is transformed to eclogite and this transformation is important in terms of following point. What are these following points? This transformation of eclogite enhances negative buoyancy.

Negative buoyancy and positive buoyancy means it is pushing upward and negative buoyancy means it is pulling downward. So, once it is transformed to eclogite, eclogite is a heavy mineral it is a group of mineral which are high density. So, that means, we are concentrating the heavies or the heavy minerals at certain segment of this plate. That means, the plate is itself bending down due to this overloading. So, that is why it is increasing the negative buoyancy of the descending lithosphere and it contributes the slab pull force acting in the subducting plate.

So, that means, once we are loading it here so, that means, the plate is bending down. So, the slab is pulling itself into the downward side. Now the eclogite is a dense rock it is consist of more like garnet and omphacite that we have already discussed. We have pyrope garnet, we have almandine garnet and we have omphacite like that and plagioclase not present in eclogite faces again plagioclase is not appeared here. So, this is the photograph of eclogite rock.

Eclogites are high pressure rocks that formed over wide range of temperature and occur very different geodynamic setting. If you see here this eclogite field, eclogite field is ranging pressure from here to here. Similarly, it is ranging temperature from here to here. So, this is a wide range of mineral assemblage you will find in the eclogite but the characteristic feature is that most of this minerals they are in the dense form high densitym high specific gravity minerals are here. So, low temperature eclogites may result from subduction of oceanic lithosphere that is intermediate temperature eclogites may result from thickening caused by nappe-stacking the continental crust.

Such eclogites may still contain hydrous minerals and mainly zoisite plus phengite. At high temperature eclogite hydrous phases are absent and kyanite is often characteristics additional mineral associated with garnet plus omphacite So, that means, as it is ranging from low temperature and pressure to high temperature and pressure. So, there is a chance that probably water may remain at this end because we have a amphibolite just here. So, amphibolite that means, it is contain water. So, there is a chance that some of the low temperature eclogite may contain water.

However, once the temperature and pressure is increasing so, that is high temperature eclogites are formed there no water is there. So, once it is a dried system here kyanite may appear along with garnet plus omphacite. The exact depth at which eclogite facies reactions occur depends upon the pressure and temperature of the subducting oceanic lithosphere. And in the relatively cool subduction zone such as the northeast Japan the transformation may occur a depth greater than 100 kilometer. However, in relatively warm subduction zone such as in the southwest Japan the transformation may occur around 50 kilometer.

So, depending upon the subduction zone temperature, depending upon this temperature of this slab which is going down it is a new slab or it is a old slab. What is this age of the slab? What is the thickness of the slab? What is the rate of subduction of the slab? So, this transformation varies with depth and also in temperature. Then another it is called regional metamorphism. So, that means, we have reached up to the eclogite facies that means we have increased the density of the subducting slab. So, due to this own weight this slab is pulling itself downward.

So, now, coming to this side this is the regional metamorphism. Regional metamorphism itself it says it is affecting a large area that is why it is called a regional metamorphism. So, now, if you see this plate is going down and it is dehydrating at this mental system and it is creating this magma and here is the magma chamber. The 4 zone where this fractional melting starts this is the magma chamber magma is occurring here pockets of magma and it is erupting here at volcanoes. So, that means, now we are getting this magmatic system here that means, a high temperature environment in this side.

So, addition to this low temperature high pressure type of metamorphism some convergent margin exhibit a regional metamorphism characterized by high temperature greater than 500 degree Celsius and low to moderate pressure. Because once we have magmatic intrusion definitely this temperature is increasing and this type of metamorphism commonly associated with high geothermal gradient that are characteristics magmatic arc. This side we are encountering low geothermal gradient and this side we are characterizing high geothermal gradient because for example, here you see this 600 or 400 degree geotherm it is coming here, but once it is coming to the subducting slab it is going to higher depth. So, that is why itself it is indicating this low geothermal gradient is here and high geothermal gradient is here. So, index mineral such as andalusite and sillimanite occur in the metamorphosed sedimentary rock because sedimentary rock there contain aluminum.

So, this andalusite, kyanite, sillimanite their composition is same and aluminum is the essential part for that. So, occurs in the metamorphic sedimentary rock temperature gradient more than 25 degree Celsius per kilometer up to 56 years kilometer result from this ascent of magma. So, this is the normal geothermal gradient that is 25 degree Celsius per kilometer. However, as the magma is ascending, magmatic intrusion is there this temperature may rise up to this and this affect large area of crust convergent margin and thus reflect the large scale thermal and tectonic disturbances associated with the subduction orogeny that is called Andean type orogeny. Andean type orogeny if you remember when there is a oceanic plate is subducting under this continental system that is the South American western side of the South America at the Peru-chile trench where the Nazca plate is subducting we have this Andes mountain here.

So, this is Andean type of magmatism is there we have volcanoes they are associated with the Andes mountain. So, this Andean type of magmatism there which is typical to that. And the most common group of rocks associated with the regional metamorphism includes greenschist, amphibolite and granulite facies. So, we have greenschist facies, we have amphibolite facies and we have granulite facies. So, these are very common in this Andean type of metamorphism.

The transition from greenschist to amphibolite and then amphibolite facies it depends upon the initial composition of the crust as well as the ambient pressure-temperature of the fluid condition. So, how this transition is occurring because it is a temperature related that means, we gradually we are increasing the temperature. So, that is why the transition from greenschist to amphibolite at which depth it will form and what should be the condition that depends upon the initial composition of this crust. Either it is basaltic crust or it is a granitic crust and how much sediment is there, what is the sediment thickness inside. So, that all defining at which temperature and pressure this transformation will takes place.

And the metamorphosed basalt this transition may marked by the change from actinolite to hornblende as amphibole is able to accept increasing amounts of alumina with high temperature. So, if you see here we have actinolite which is representing the greenschist facies and we have hornblende which are representing the amphibolite facies. So, with increasing temperature this more and more alumina can be incorporated within the system. So, that is why this aluminum is here and some aluminum it will be here. So, or it is less amount and with increasing temperature this system is able to incorporate aluminum in this crystal structure.

So, that is why from greenschist facies to amphibolite facies it is the amount of aluminum is increasing and the temperature greater than 650 amphibolite transform to granulite. So, once we are here so, we are reaching to granulite facies. The granulite facies the name itself indicate is granules if you see this minerals we have very equant-type of mineral. So, the cross-sections if you see this is equant type of minerals are present near equant-type of mineral.

So, that is why it is called granulite. And granulites they are highly diverse and maybe of low medium or high-pressure varieties because you see the granulite facies in the pressure axis that varying from this range to this range. So, it is a high pressure varieties it is characterized the presence of anhydrous minerals assemblage such as orthopyroxene, clinopyroxene, plagioclase and garnet oxides and possible amphiboles are present at low temperature. So, once we are at low temperature we have the chance that amphiboles may present because amphiboles are hydrous phases, but once you are going to high temperature. So, this amphiboles are absent, but instead we have pyroxenes then plagioclase then garnets like these minerals that will be found here.

So, if further increase of temperature occurs. So, high temperature if further and it is suppose there is some hydrous mineral because once it is amphibole is there so that means, chances of having water is there. So, if this condition happens and further high temperature we are increasing and some of this water is inside without it is escaping. So, Migmatite may form and Migmatite it is a mixed rock or it is called hybrid rock which have both metamorphic as well as igneous material. So, these are the field photographs of migmatite. So, these are the ways how this progressive metamorphism taking place from a subducting slab from this greenschist facies to eclogite facies and in the regional metamorphism it is changing from greenschist to amphibolite to granulite facies and further increase in temperature we are converting the rock into this migmatite this is the hybrid rock system.

At high-pressure low temperature and high-temperature low pressure varieties of metamorphic rocks in the context of subduction zone has been proposed that is called paired metamorphic belt because this side we have high pressure low temperature minerals. So, the rocks which will suppose I am taking a cross-section from here I am taking a slice. So, that means, you will get here the high-pressure low-temperature minerals and here you will get high-temperature low-pressure minerals and they are occurring side by side. So, that is why it is called paired metamorphic belt by Miyashiro and this is typically it was found in Japan arc. So, thank you very much we will meet in the next class.