Plate Tectonics

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Week - 07
Lecture – 31
Magmatism and Metamorphism at Different Plate Settings-I,
Magmatism at Subduction Zone

Ok Friends, good morning and welcome to this class of plate tectonics. So, in the today's class we are going to discuss about magmatism and metamorphism at different plate settings. And in today specially we will talk about the subduction setting. If you remember our earlier class when we were talking about divergent plate margin setting, at the divergent plate margin, magmatism or partial melting was taking place due to decompression. So, that means two tectonic blocks they are separated and due to separation there will be release of pressure from this mantle. So, mantle is decompressed and due to decompression this melting was taking place and that was called decompressional melting.

However, in the subduction zone the melting mechanism is different. So, here we are putting a hydrated oceanic lithosphere into this mantle below another oceanic lithosphere or continental lithosphere. And finally, when it is coming to a considerable depth the water either it is from the sediment or from this hydrated metamorphosed mineral that is released. And as this water is released into this mantle the melting temperature of this mantle is reduced that is why the melting takes place.

And due to this melting magmatism occurs and once the plate is subducting into from the surface into the asthenosphere at different depth the magmatic composition are different so, in today's class we will talk about this mechanism of melting, the magma composition and its evolution from different depth to the surface level and what is the magmatic structure that means what is the igneous structure and what are the igneous rocks that form due to this magmatism. So, here if you see this is a hydrated oceanic lithosphere it is going down and once it is reaching around 65 to 130 kilometer depth its dehydration occurs. So, this volcanic and plutonic activity occurs giving rise to island arc or this Andean type or the volcanic arc system. If it is occurring or the volcanic system or the volcanic activities occurring at the continental lithosphere we say it is Andean type of volcanism or it is called volcanic arc and if it is occurring in the oceanic lithosphere we say it is the island arc so, here you see this is the hydrated oceanic lithosphere which is going down and once it is reaching into this asthenospheric system

here this blue lines they indicating the dehydration that means releasing of water. So, this distance that means depth it is varying from 65 to 130 kilometer depending upon the rate of subduction.

So, that is why this type of volcanism it is occurring either in the form of island arc or in the form of continental arc and the distance from the trench axis around 150 to 200 kilometers. So, if this is the trench position so now you see the volcanism occurring here. Similarly at the initial time when the subduction started. So, volcanoes are here then it is here then it is here and gradually this it was here and finally, when there is maturity of this subduction system when the subduction zone matured. So, due to when due to its own weight the lithosphere or this down going lithosphere it is bending towards the trench and finally, there is a permanent zone of magmatism So, now you see if you remember our earlier class when we were talking about the island arc system.

So, these are the older volcanoes this side and finally, the volcanic system it is retreating back. So, anyway this is the volcanic system and it is formed due to this dehydration mantle melting. So, the thickness of this crust that reflect both the age of the system and the type of crust on which the volcanism occurs. So, here if you see this is the thickness of this crust of the lithosphere here the continental lithosphere if it is then the thickness of this arc will be more and if it is an oceanic lithosphere because oceanic lithosphere is very thin around 6 to 7 kilometer so, that is why depending upon that this volcanic arcs thickness also depends so, the types of volcanic rocks that occur in the subduction zone environment generally it is of three types. What are the three types? The first one is the low potassium tholeiitic series magma, then second is the calc-alkaline series of magma, then the third is the alkaline series of magma.

This is the series of magma that means there is a range there is a variation it is not the exactly that this should be the exact composition of this magma. So, this is a series of magma that means there is a range of magmatism range of chemical composition varies in the magma. So, the low potassium tholeiitic series of magma it is dominated by basaltic lavas associated with lesser volume of iron-rich basaltic andesite and andesite. Then the second category which the calc-alkaline series it is dominated by andesites and that are moderately enriched in potassium and other incompatible element and the light rare earth and it is LREE what is LREE we will talk in the next slide. And the third category it is the alkaline series that alkaline series includes the subgroups of the alkaline basalt and are rare.

So, this magma series the alkaline series that are rare and very high potassium-bearing

that is the shoshonitic lavas. So, after all this three magmatic series they are found at the subduction zone system and this LREE that we have a rare earth element there are divided into two that is called heavy rare earth element HREE and light rare earth element LREE. So, they lie at the bottom of the periodic table and its use is very huge it to make flint and hydrogen storage, mobile phones, TVs, missiles that all these things where europium is used to produce the white light compound fluorescent bulbs then bank note securities. So, that means there is very heavy use of this REEE and mostly they are found in the pegmatite series or granitic series of rocks. So anyway, so these are this magmatic series and every magmatic series had its unique component unique constituents and they are useful in terms of mineral exploration.

So, that is why to knowing this mineral exploration in which way we have to go what mineral we should target at the subduction zone and if this magma is deriving from shallow depth then what should be this mineral constituents which type of minerals would be targeted. So, that will be taught in detail while we were talking about this tectonics and mineralization and use of tectonics in mineralization and other purpose that we will talk in detail. So, now you see there are three diagrams in the first one a oceanic lithosphere is subducting down and the partial melting is taking place at this level that means at our shallow level here the lithosphere and this asthenospheric system is there. So, this lithosphere is here and it is partial melting taking place. So, that means if you compare to the depth at a shallow level this partial melting is taking place.

So, at the shallow level when the partial melting taking place this magma which is generating it is the tholeiitic series. And once you are going down further so that means you see this magma is going this lithospheric system is going down and this partial melting is taking place at a relatively higher depth here. Here you see this partial melting it was occurring around 65 kilometers or so. So, here this partial melting is taking place around 150 or more than 150 kilometer or so. So, now you see this magmatic composition it is called Calc-Alkali series.

So, at the shallow depth we are getting the tholeiitic series of magma at relatively higher depth we are getting Calc-Alkali series of magma. Now if the subduction continues further that means to further greater depth what we are getting that means this partial melting again takes place at greater depth and finally, we are getting this Calc-Alkali series and further alkaline series. And you know when this plate is subducting down and there is melting which is taking place in the form of magma and there will be this forearc basin and back-arc basins and there are sedimentary basins are formed and the sedimentary basins once they are formed so that means there is a rifting environment.

And in this rifting environment we are getting the alkaline magma series. Similarly, here these are the hotspots the mantle plume.

So, mantle plume they are coming again further greater depth. So, this is the intra-cratotonic magmatic magma. So, it is forming here so that is the alkaline magmatic series. So, that means I want to say at a shallow depth we are getting tholeiitic magma at further greater depth we are getting Calc-Alkali series magma and at further greater depth and in the mantle plume that means further greater depth we are getting alkaline series of magma. So, that means with increasing depth the magmatic composition also changing and once the magmatic composition is changing we know this Earth it is in a composition of stratigraphy.

So, that means some heavier elements are here lighter elements are here. So, magma which is generating from this level obviously it will have enriched of this element and this magma which is generating at this level obviously it is enriched in this type of element. That is why the magmatic composition varies with depth and once we are going from this trench axis this way the distance from the trench axis increases and here the depth is increases. So, distance away from the trench axis and with greater depth the magmatic composition is varying. So, that is why we are getting a series of magma in the subduction zone.

In continental arc that is subordinate to andesite, dacite and rhyolite are also are abundant. In general the tholeiitic magma series derived by fractional crystallization of the olivine from primary magma originate a relatively shallow depth. And we have discussed about this shallow depth this is the tholeiitic magma series that is occurring due to fractional crystallization from this olivine and it is around 65 to 100 kilometer depth and it is well represented young subduction zone. Because when this subduction zone is young this much that means subduction is taking place. So that means at a shallow level we are getting this partial melting of the mantle.

So that means we are getting this tholeiitic series. So once this subduction zone will be matured and will grow to further depth so this magmatic series or the magmatic composition will change. For example here if you see these are two magmatic series one is by the partial melting of the crust. So what we are getting it is the felsic magma because crust that is of lighter elements. So now if you are coming to this Moho that means at the shallow part of this mantle this primary mafic magma is there that is mafic magma that is olivine fractionation that means this one is the tholeiitic magma.

So tholeiitic magma that is occurring at this level it is still in the shallower mantle depth because this is the Moho this side is the mantle. So at the shallower mantle depth we are getting this tholeiitic series and in the crustal partial melting we are getting the felsic magmatic series. So the calc-alkaline and alkaline series are encountered in more matured subduction zone generated at a depth greater than those resulted from the tholeiitic series that we have already discussed this tholeiitic series they are occurring at the shallow depth and calc-alkaline and alkaline series they are occurring at a relatively greater depth. So here you see alkaline magma it exhibits lowest abundant in the island arc system and are more common in the continental rift and intraplate environment. Here we have a continental rift system we have forearc basins we have back-arc basins like this continental rift system is there.

So we have this intra-continental environment like this mantle plume we are coming so that is why the alkaline magmas are more important there more abundance there and if you see here we have different magmatic plume or mantle plume is coming from the mantle plume different magma chambers they are generated. So we have intraplate volcanism here and here we have intraplate volcanism. So this intraplate volcanism that will give rise to alkaline magma series. Some island arcs like Japan arc exhibit spatial pattern of distribution of the volcanic series that is the tholeiitic, calc-alkaline, alkaline, volcanic rock it is apparent with the increasing distance from the trench. For example, if you see this block diagram here we have this trench here we have the Mariana trench here.

So we are going away from the trench system. So now you see we have the tholeiitic magma series here then we have a calc-alkaline magma series then we have alkaline magma series. Why the tholeiitic magma series is occurring this depth level this calc-alkaline magma series is occurring this depth level and the alkaline magma series that occurring this depth level that means once we are going greater to greater depth. So we are getting the change of this magmatic composition and we know here this is the Pacific plate which is subducting down. So these are the volcanoes, some volcanoes here we have this island arc system and once we are going to this area so that means extension is taking place.

So due to this extension taking place so we have this continental that is the rift system and due to the rift system we are getting this alkaline magma series and here we have calc-alkaline magma series and here we have tholeiitic magma series. And these trend may reflect magmas derived from increasing greater depth and of different sense in the degree of partial melting. That means once you are coming to a shallow depth your

degree of partial melting is different. Similarly a lithosphere which is going to a greater depth and it is degree of partial melting will be different. So that is why the magmatic composition is changed.

And some of this arc system like this Izu-Bonin-Mariana Arc that also show compositional trend along this axis not only across the axis in this Japan arc what we are getting this is the trench axis and across the axis there is a change. And however if you going to this Izu-Bonin-Mariana Arc system here along this axis we are getting this change. Why this change if you see here these are the cross-section where the line through which the cross-section of this lithospheric system in the subduction zone has been drawn. So now see how this plate is behaving and how this plate is behaving at this level. So that means I want to say at different segments different segment of this Izu-Bonin-Mariana Arc system this subduction characteristics of this down-going slab is different.

So here this can be better explained one a plate is going down it is segmented. So here there are different segments of this subduction zone and each segment that behave differently with respect to this mantle compression and the rate of subduction. So that is why the angle of subduction varies even if the angle of subduction remains same, but with respect to or in response to this mantle system that is the competency of this mantle. Here suppose for example one plate is going down and two plates they are divided one plate is divided into two blocks due to this fault that is a tear fault inside. So you see one plate is moving at a steeper slope and another plate it is going like this that means it is swallowing upward So that means a magma which will generated from here that will have greater depth and this magma which is generating here that will be shallow depth.

Similarly one plate is going down and it is tearing up one side is twisted and another side remain flat. Similarly once this plate is subsiding there may be a tearing along this system. So that means this plate is going down and magma which is generating from this level will be different at this level will be different. And once there is a tearing up so this mantle material it is coming up in this gaps. So that means this configuration of this subduction zone it is changing.

So that is why if you see along this trench if you are going one segment is going into steep dipping another is shallow dipping another may be further shallow dipping. So that means along this trench axis if you are moving this segment will give rise your alkaline series of magma or calc-alkaline series of magma. Here this side will give you the tholeiitic series of magma. So that means along this axis once you are moving due to the change of the nature of the subducting plate due to the tearing of the subducting plate

due to the angle of subduction of different segments this magmatic magma generation is from different levels and degree of partial melting will be also different. That is why this magmatic composition is different along this trench axis.

So vertical slab tearing has been widely reported in modern convergent setting profoundly influencing the subduction and the mantle dynamics and the slab tears under the Mariana arc affect magmatic series of distribution. So that means we are tearing the system so once we are tearing this mantle material is coming out. Similarly once we are tearing this mantle material is coming out here and mantle is under tremendous pressure once we are tearing this fault the tearing this lithosphere so that means it depressurizes here and that is why part of this mantle it is coming up as bulge. So that is why this configuration of this total subduction zone is changing. So due to this change in this configuration this magma occurring at different depth of different composition.

A low degree of partial melting tend to concentrate alkalis and other incompatible elements into the small melt fraction. This could lead to an increase of alkalinity away from the trench due to greater depth of melting and a decreasing availability of water. So once you are going down the availability of water is decreasing and once the water availability decreasing that means the mantle temperature is reducing at a lower rate so that is why the degree of partial melting also reducing. However there is many exceptions to this pattern of other arcs for indicating difference in the local condition strongly influencing the magma composition. The local condition that we have discussed few minutes back this is tearing then bulging of this mantle like that.

So not only this water is playing the major role there are other factors except water they are also playing some roles in creating magma from different levels. In Benioff zones there is a very strong correlation between the depth and the systematic variation of volcanic rock composition and elemental abundance. For example here there are number of Benioff zones that have been compared one is the Izu-Bonin system, one is the Shoshonitic province and another is the Merianas. So now you see mostly this Shoshonitic province here this Rhombus-type they are totally of different and these two that is the Izu-Bonin and the Merianas they are probably showing similar characteristics. And this great spectrum of rock composition reflect the diversity of the processes involved in this arc magmatism.

So what are these diverse processes? First is the variation is depth that we have already discussed how the depth-variation it is changing this partial melting. And this availability of the elemental composition of this mantle there which from which the

magma is generating that also affecting the magmatic composition. Then degree of partial melting the more water is there the more partial melting is taking place because it is reducing the melting temperature. Then magma mixing whatever the magma is produced there that magma is coming up. So during coming up how much distance it is travelling each if it is generating from the shallower level and it is emplacing here so there is less degree of contamination.

But if it is occurring at a greater depth and it has to travel long distance to erupt at the surface so that means this much distance it has to that means mix with this contrary rocks. So that is why the magma mixing that is also that means affecting the system. And magmas they are deriving at different levels they are also mixing with each other and finally this magmatic composition is changing. Then fractionation what is the degree of a fractionation this magma which is generated and it is emplaced how much fractionated is it. So how this different temperature regions different fractionation is taking place different minerals are crystallizing and this remaining constituents which are the remaining fraction of this magma which is erupting at the system.

So that means it is fractionation is also another important Assimilation. So how it is assimilating with the contrary rock the contrary rock sides when it is contaminating the system. So that means these are the different points they are influencing the final product of this magma which is occurring at the surface. Mature arc systems and especially continental arcs typically include large, linear belts of plutonic rock called batholiths. Batholiths they are nothing but the granitic body of granitic composition and they are huge in size.

For example, we have the Ladakh batholiths in the northern part of this Indian subcontinent. So there is the huge in size these belts are widely used as indicator of ancient now extinct convergent margins. And the majority of the batholiths they are composed of hundreds of thousands of individual intrusions that range in composition gabbro, tonalite, diorite, granodiorite and granite. So that means a compositional range is different because the magma is generating from different level. And second thing that this magma it is generating from different level and they are assimilating with each other they are combining with each other and forming a huge body of igneous mass; it is not a one-day process it is taking millions of years.

So that is why this batholith which is occurring at the subduction zone if you get it, it will not get a perfect age or particularar age because it is a range of time so that means this range of time and the range of composition it is giving a batholithic mass at the

continental-continental collision side within the subduction zone and water act as a primary agent that drives the partial melting. So apart from water there are some local conditions like this configuration of the slab inside the mantle that also influence the partial melting of the system. And the greater amount of water present the more the melting temperature of the mantle is reduced and most of the water carried to the great depth confined by hydrous minerals in the altered metamorphose crust including serpentinite that we have already discussed because the lithosphere which is the oceanic origin when it is coming from this mid-oceanic ridge system and it is going down at the subduction zone it has certain fractures and this faults through which this seawater is ingressing and it is altering this basalt into serpentinite. So that's why it is hydrous basalt or hydrous metamorphosed basaltic system is going down. Along with that we have a sedimentary layer and the top which is carrying water and clay minerals they are carrying water in their crystal structure.

So all total we are putting a hydrous metamorphosed basaltic lithosphere, oceanic lithosphere into the mantle system that means we are putting water inside along with the minerals. So with the increasing pressure this hydrous basalt and gabbros are metamorphosed progressively to blue cyst faces, then amphibolite faces, then eclogite, then water is released for each transformation. Yesterday when we were talking about this system of how this water is released at different level. And the fast-spreading oceanic crust is thought to contain little or no serpentinite however slow spreading ridges or slow spreading crust that is contain some perhaps about 10 to 20 percent. So, once it is fast spreading ridge that means it is less time it is interacting with the water and in the slow spreading ridge it is more time interacting with water so, it is more water is there more alteration is there.

so that is why a plate which is subducting at a higher rate it has a less chance that this that will partial melt takes at place at a shallow depth. And if a plate is subducting at a slower rate there is much chance that the partial melting takes place at just few kilometers below from this top. So, this is due to the availability of water and release of water. So, water is playing a major role in the partial melting in the mantle and creating this magma.

So, thank you very much we will meet in the next class. Thank you.