Plate Tectonics

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Lecture - 17
Magma Chamber Properties at Mid-Oceanic Ridge

Okay friends, good morning and welcome to this class of plate tectonics. If you remember the last class, we are talking about there are three types of spreading ridges depending upon the rate of spreading. We have fast-spreading ridge, slow-spreading ridge and ultra-slow spreading ridge. In between there are intermediate depending upon its velocity and the rate of spreading. So, we need a magma chamber to supply magma to this mid-oceanic ridge rift system. And as we discussed earlier, the magma chamber is permanent at the fast-spreading ridge and at the slow-spreading ridge there is no permanent magma chamber exist and there will be supply of magma from this crustal or the lower crustal boundary or this upper mantle boundary and this magma is distributed among this dikes and few of these dikes they become the conduit for this magmatic supply to this ocean ridge basaltic system.

So that's why the magma chamber properties that to be understood where this magma chamber lies permanently and how the magma is collected there and that collected magma how it is supplied to this upper surface that has to be understood Apart from that whether all these oceanic boundaries that is the mid-oceanic ridge system are magma dominated or there is something else which is depending upon the rate of spreading we will discuss in today's class. So, if you see these mid-oceanic ridges they are the planet's largest magmatic system. We have different magmatic system like volcanoes in terms of the subduction zone and we have volcanoes at the hotspots and apart from that their contribution is negligible as compared to this magmatic supply or magmatic eruption along the mid-oceanic ridge. Particularly, the fast spreading ridges they contribute larger magmatic system to this planet earth as compared to this other magmatic supply system like this volcanoes at the subduction zone and at the hotspots and at the convergent boundaries.

So, the divergent plate boundaries magma is generated by decompression melting. So, what is decompression melting? If you see this diagram here we have this temperature increasing in this way and we have pressure increasing in this way that is the depth increasing and here if you see this black line this is indicating the dry mantle rock that is begins to melt that is solidus that means in this way all these rocks are solid and this is the line which is denoting this is the liquidus or it is said the melting is complete. So, beyond this line all these rocks they are in the molten format. So, we have solidus and we have liquidus and in between this the region that is called partial melting. Partial melting means partly the rocks are in the melt form and partly in the solid form.

Why it is partial melting? Because we know from the Bowen's reaction series that these different rocks they form at different temperature. So, similarly once we are providing temperature that's why different minerals they will come to melt form at different temperature. So, a rock composition of "x" they may composed of minerals "x1", "x2", "x3" like that. So, that means different minerals they melt at different temperatures that's why the melting starts from here that means those minerals which melt at low-temperature and pressure they will start melting here and finally here if you are moving at this point those minerals which will melt that is melting temperature at high-pressure and temperature and gradually the melting continues the solid proportion gradually decreases and once it is reaching here. So, that means the complete rock is converted to molten format and that is the liquidus.

So, now decompressional melting it says decompression means we are reducing pressure. So, suppose a rock mass which is here now we are reducing pressure that means in the pressure axis we are moving up. So, we are reaching here and once we are reaching here we are cross-cutting the solidus here so, that means with cross-cutting the solidus the rock starts melting, but mind it here the temperature remain constant. So, keeping the temperature constant we are reducing the pressure and finally we are reaching the solidus and we are coming to this partial melting field. So, that's say the rocks started melting at this point.

So, at the mid-oceanic ridge system this decompression melting is the dominant process or the primary process of melting. Apart from that there are other two melting phenomena one is the heat induced melting that is caused by increasing of temperature. For example, suppose we are remaining the pressure constant and once we are increasing the temperature here we are remaining the pressure constant and we are increasing the temperature. So, still rocks are melting. So, pressure decreasing or temperature increasing.

So, that's why the rock can melt and it is solidus format to come to the partial melting format and finally it is the liquidus format. And the third type of melting that is called flux melting caused by adding volatile. So, here neither the pressure nor the temperature act major role rather the flux melting that is adding of volatile. Mostly this type of melting it is confined at the convergent boundary where this one plate is subducting down and it is reaching at the asthenosphere. So, due to high heat the volatiles which are trapped within the sediment, within the rock, within this minerals they are released and due to release of this volatile it reduces the melting point.

So, that means here it is changing the goalpost that means either the pressure is not a capable and the temperature is not capable. So, that's why this volatile we are adding so that the goalpost it changes that means is reducing the melting point. So, that's why the shifting of this solidus and liquidus to this way. So, that's why these type of volatile addition melting it is dominant at the convergent plate margin at the asthenospheric system. Now, once the melt is generated either it is the upper mantle or it is the lower crustal level the melt once is generated it is a low density as compared to the surrounding rock mass.

So, that's why the melt try to push itself up. So, that's why it ascends through this upper mantle and the lower crust and collected beneath the ridge axis and it is the elongate melt lenses is formed So, if you see this cross-section of this mid-oceanic ridge system we are getting a melt length here, but it is a cross-section, but if you see if you imagine the whole lithospheric system below this mid-oceanic ridge so that means it is an elongated system. So, just it is a cross-section you are looking here. So, that's why this mid-oceanic ridge system this magma which is generating at the lower crustal and the upper mantle level it is coming and aligning itself along this mid-oceanic ridge system magma chamber. So, at fast-spreading ridge suppose the east Pacific rise this decompression is faster than cooling because we have frequent magmatic supply we have continuous or near continuous magmatic supply.

Once phase of magmatic supply there then another phase of magmatic supply is there. So, they are just overlapping. So, that's why it is getting less time to cool. So, that's why here the decompression melting is faster than the cooling system. However, if you are moving to this slow-spreading ridges like the mid-Atlantic ridge, Indian ocean ridge system here cooling dominates over decompression because this magmatic supply the frequency is very less.

So, one set of magmatic supply or one pulse of magmatic supply is there then the magma cool down it is system is solidified then the another phase of magma supply is there. So, here the temperature or the cooling is dominating over decompression. However, at the fast-spreading ridge where this decompression is faster than the cooling because due to frequent magmatic supply it is getting less time to cool down. Now, this plate spreading is accommodated by episodic faulting and this magma injection into dike and some of the dikes they behave as a conduit to supply this magma from subsurface to surface and it form finally, the pillow basalt. So, if you see here this figure we have a melt lens and this magma chamber is here and we have this dikes and this dikes are aligned parallel to this ridge axis this is the ridge axis and few of the dikes they are moving to the top of the surface and finally, they are pouring magma here and creating this pillow basalt.

And this geometry of this magmatic system, dynamics of the seafloor eruption, lava geochemistry and the ridge morphology are among the host ridges that is properties controlled by the rate of magma supply which in turn it is controlled by this spreading rate. So, that means if you remember our earlier class when we are talking about this mid-oceanic ridge system, its geomorphology, its geology and its geophysics and its gravity, all those things they were controlled by this spreading rate. That's why this morphology of this mid-oceanic ridge then the geochemistry of this magma and this ridge properties it is totally controlled by the rate of magmatic supply and the rate of magmatic supply it is proportional to this rate of spreading. So, high rate of spreading like the east Pacific rise it is magmatic supply is high and low spreading is like the mid-Atlantic ridge and this Indian ocean ridge here the magmatic supply is raised. So, that's why its geochemistry is different, its geomorphology is different, its mineralogical component is different and its geophysics is different.

So, that's why all total it is governed by the spreading rate. Now, there are different models of a formation of magma chamber. Somewhere there are fossilized magma chamber mostly you can find along this ophiolite sequence and some of these pre-cambrian terranes where this mid-oceanic ridge they are lying idle. So, in that area you can study this magma chamber and mostly this magma chamber properties they are studied by laboratory experiment by artificial creation of magma chamber and artificial reducing temperature and pressure then mineral composition that different minerals are formed at different levels. So, that means different models have been proposed.

So, this models all these models they show the formation of oceanic lithosphere normally requires a magma chamber beneath the ridge axis. So, either this is a fast-spreading ridge or it is slow-spreading ridge but we need a magma chamber somewhere it is a permanent somewhere it is a temporary and from this magma chamber magma erupts and intrudes at the lava flow which is if you remember it is representing by layer 2 after the layer 1 which is the sediment layer layer 2 it is the pillow basalt and layer 3 it is the seated dike complex. So, this layer 2 and layer 3 they are representing this magmatic supply from this magma chamber in form of dikes, seals and in forms of pillow basalt lava. So, this is the oceanic ridge plumbing system that means the oceanic ridge magma is plumbed above. So, this plumbing system that is the piping system this magma supply system is means that the fast-spreading ridge magma is the dominant material added to make new crust and then typically it is the ophiolite sequence.

However, if you go to the slow-spreading ridge here the magmatic supply is less. So, that's why asthenosphere may rise to the surface without any magmatic crust forming that is serpentinite crust. So, if you remember in the earlier class we have discussed about this slow-spreading ridge which are generally characterized by low-angle normal fault, high stretching so, once it is a low-angle normal fault we are creating and we are stretching this lithospheric system. So, that's why the mantle moves up and once the mantle moves up it interacts with the water which is percolating through the fractures and many of this region or much of this region and this mid-oceanic ridge system at the slow spreading ridge they are serpentinized due to alteration. So, that's why this magmatic supply is dominant or the magmatic crust is dominant at the fast-spreading ridge whereas, the slow-spreading ridge is dominated by metamorphic or the altered lithospheric system.

If you see here this figure we have the slow-spreading ridge system now you see how the crust is thin and it is close to this asthenospheric system or close to the mantle system that's why there is a rise of the mantle system and due to this water percolation here we are getting this alteration zone and this alteration product of basalt it is converted to serpentinite. So, that's why this zone is serpentinite rich zone. However, if you see here this magma is supplied at a faster rate we have different dykes and different sills are there. So, this is magma dominated mid-ocenic ridge. Here it is metamorphic dominated mid-ocenic ridge and the oceanic crust at the slow-spreading ridge is thus it is called the exhumed mantle because once upon a time this was lying at a higher depth and due to depressurization due to releasing of the overburden due to thinning of this crustal system this pressure due to this mantle pressure it is coming upward and that's why it is called exhumed mantle and the exhumed mantle it is characterized by high degree of metamorphism and alteration that is the serpentinite formation.

So, one consequence of this that is the fast-spreading ridge the crustal structure is dominated by the magma and volcanics whereas, slow spreading and very slow spreading ridge where faulting and stretching is dominated allowing exhumation of this asthenosphere. If you see this figures there are different models proposed by different author from year 1998 to 2014 and all of these models that says there is a creeping lower crust below the upper crust and everywhere if you see this upper crust is getting thinned from away from this mid-oceanic system towards the mid-oceanic system. So, if you see here we have a crustal thickness of this much here and we have a crustal thickness of this much here. Similarly here it is this much and here it is this much. So, that means, every model it is takes into account about the crustal thickness around this mid-oceanic ridge particularly slow-spreading ridges and all of them shows that this mantle material it is coming up near to the surface and finally, with the interaction of this oceanic water they are serpentinized and that's why it is exhumed system and the metamorphic system.

Now, any departure from this general observation or the experimental procedures so, that means, any departure from that pattern happens where there is other influence such as the mantle plumes. For example, we know that is the mid-Atlantic ridge it is a slow-spreading ridge. So, that means, we believe the slow-spreading ridge we should find here this exhumed mantle that is the serpentinized and it is a thin crust it is there and serpentinized system is there metamorphic system is there but if you see here suppose we are adding some mantle plume. So, that means, the crustal thickness is increased. So, now, you see at this the mid-Atlantic ridge passing through Iceland and here this is the crustal thickness.

The crustal thickness says in this region the crust is much thicker and here the crust is much thinner. So, this crust is much thinner it is expected here crust is much thinner it is expected because it is a slow-spreading ridge this crustal thickness is very less and it is stretched and this exhumed mantle is expected but in between if you see here we are getting the thickest crust. So, why such deviation is there? So, this departure from this general assumption or general observation is due to the addition of mantle plume. So, now, we are stretching and the mantle plume it is supporting this magmatic supply So, that means, due to this magmatic supply here we are getting thicker crust and we know the rate of spreading is low. So, that means, we are supplying magma below and we are not able to spread it.

So, that's why thicker crust is expected. So, in Iceland the magmatic production is high compared to the spreading rate leading to the unusually thick crust. So, this unusually thick crust is due to the addition of this mantle plume. Now, the magma plumbing system at a mid-oceanic ridge starts with an area of partial melting and generation of migration, generation and migration within this rising asthenosphere. So, it starts partial melting at a point because this depressurization is there.

So, due to depressurization somewhere it has to start. So, there are different points this partial melting starts and due to this starting of the partial melting the magma started generating and with time this magma they are coalesced to each other they are added with each other and finally, a magmatic plume is generated and this magmatic plume it comes up to the surface through the dykes and sometimes it may reach to the surface and sometimes it is remain in the dyke form or in the sill form. So, when enough magma is collected it can move upward as a body magmatic body. So, through buoyancy force and may erupt at or cool at the surface or it may continue rise as a dyke and it may feed into the magmatic chamber So, that's why this partial melting points are here and here they are distributed and these magmas are generated and these magma finally, they meet each other and forming a magmatic body and this magmatic body it rises up either it is remained as a magma chamber just below or it may fed by dykes and some of the dykes they remain below this crustal system and some of the dykes are exposed and they are producing magmas here. So, if you see this diagrammatic representation of here this magmatic supply is there and this magma they are flowing as if like this alluvial fans at the mountain fronts.

So, here you will get this pillow basalt and this pillow basalt of different forms different size they are generated and representing the crustal system. And the thickness and the extent of the oceanic crust relate to the melt flux and the spreading rate such that at slow-spreading ridges some crust will be composed of a serpentinized mantle whereas, the fast-spreading ridge the crust would be extremely built on the plumbing system or this magmatic system that we have already discussed here. This fast-spreading ridge they are dominated by magmatic lithosphere or magmatic crust whereas, the slow-spreading ridge they are dominated by serpentinized or exhumed crust. And along a mid-oceanic ridge magma collects into discrete centers each of which concentrates magma at distribute it towards or outwards by a plumbing system that is called dykes and sills. So, that means, so far we are talking about the dykes or the seated dyke complex but it is not necessarily always it will be in the dyke format there may be any format so, that may be sills and that may be dykes and this orientation of dyke may be like this it is radiating from the system.

So, that's why there are different shape and size rocks or this intrusive rocks they are formed at the mid-oceanic ridge system. Therefore, the intrusive complex can be considered to extend from the axial magma chamber throughout the entire plate making of the largest intrusive system on the earth. So, there are different intrusive systems we have different regions where intrusions or magmatic intrusions are there, but this mid-oceanic ridge system they representing the largest intruding system on the world. So, two types of plumbing system occur at the mid-oceanic ridge system. The first type, so the central intrusive system with cone-sheet intrusions and dyke swarms where more dykes remain below 2 kilometer depth and very less are exposed to the surface A majority of dykes do not reach to the surface that is the old Iceland system.

If you see here majority of dykes they are remaining at the depth but the other type of system that the complex plutonic sequence of coarse gabbros that translations up to sill and dykes and finally, into lavas representing typical fast-spreading mid-ocean.ic ridge system so, where the fast-spreading mid-oceanic ridge system the magma much of this magma that is extruded that is poured on the surface. However, at the slow-spreading ridges mostly this magma the dykes they remain below the surface and few of these dykes they become this conduit and become this plumbing system and they expose the magma or that is the extrusion of magma they are to the surface. And if you see this magma chamber and here this is the mid-oceanic ridge system and we have a lensoidal magma chamber is there and within that this magmas are separated.

And here suppose we have a transform fault. So, at this transform fault region this magmatic supply is less whereas, once you move away from this ridge system that is the transform fault region this magmatic supply again increases. So, along one segment of mid-oceanic ridge there may be one or more axial magma chambers and this axial magma chamber may be separated by this rock mass itself or may be separated by the fault system where the magma is stored before it is intruded vertically and laterally along the ridge axis. So, magma chamber is a lens-shaped body and mostly molten rock it rest within that and extend below the fast-spreading ridge systems. The chambers sits at top of the reservoir typically the melted rock that we have already discussed so, this is a melt lens is there. So, lens-shaped magmatic chamber is there and the chamber and the reservoir are small and poorly supplied with molten rock near a discontinuity that is the transform fault that we have already discussed once we have a transform fault that means here the magmatic supply will be less and here the transform fault the magmatic supply will be less but the number of magma chamber is related to this plate motion rate, lens of the ridge segment and this magma supply to the ridge.

So, how much a magma chamber lens would be, what should be its extension should be. So, that depends upon this the relative plate motion rate and the lens of this ridge segment and the magma supply that is the rate of magma supply to the ridge all these three parameters that define what should be the magma chamber properties at the mid-oceanic system. So, magma chambers are viewed as a composite structure comprising of a outer transition zone made up of a hot mostly solidified crust with small amounts of interstitial melt and an inner zone of crystal mush with sufficient melts for it to behave as a very viscous fluid system. Now, if you see here we have a transition zone that is the outer transition zone and we have inner system that is called crystal mush. So, this is the magmatic lens is here and from this lens due to magmatic differentiation we have crystal system and the crystal system they are just floating within that magma and are settling down to this magma chamber.

A melt lens only develops at the fast-spreading ridges where there is in sufficiently high rate of magma supply for it to persist at the top of this mush zone. So, this melt lens whatever it is shown in this figure that is only and only present at the fast-spreading ridge and the slow-spreading ridge there is no permanent melt lens is there. So, there will be magmatic supply and there will be distribution. So, there will be no permanent melt lengths exist here. And these magmatic systems have been well imaged geophysically and geologically mapped on the ophiolites and this is the tertiary lava piles of Iceland.

The gabbroic lower crust accounting for this 5 kilometer crust thickness and layer 3 from this lateral flow and cooling at the edge of these magmatic bodies. So, the upper mantle is composed of this ultramafic rock peridotite and this boundary between the layer 3 and 4 that is the Moho defined both petrological and seismically. So, this petrological Moho is there and seismically Moho is there. So, that means it is depending upon the density of system. So, with time the rock alters and their density changes.

So, that's why this petrological Moho and this seismic Moho they changes themselves. So, that's why this magma chambers they are a complex thing. So, within that there are magmatic supply at different rates at different places and this length of this magmatic system that is magma chamber that depends upon the rate of this magma supply and the spreading rate and the length of this segment of this mid-oceanic ridge system. Now seismic refraction over the east Pacific rise shows a slightly thinner crust than the main-ocean basins and it is anomalously low upper mantle velocity layer beneath the crust and that low-velocity layer extends up to a depth of about 100 kilometer. So, now if you see this velocity layer here this velocity scale is there and this east Pacific rise it is showing a low-velocity zone at the mid-oceanic system and this low-velocity zone at depth wise it is varying about 100 kilometer depth.

Then why this low-velocity zone is present below this ridge axis? So, this can be explained in these three formats. One is the thermal expansion. So, thermal expansion that means, we have a high-temperature zone we have molten rock. So, this due to this high temperature the surrounding rocks are expanded thermally. So, the upper mantle material beneath this ridge crest that is followed by this contraction at sea-floor that is spreading that carries it laterally away from the source of the heat and the presence of molten material within the anomalous mantle.

We have molten material obviously, this p-wave velocity will be decreased. Then there is a phase transition. This phase transition that is mineralogy transition once we have a high-temperature and surrounding is a low temperature. So, obviously, there is a phase transition. So, these three possible reasons one is the thermal expansion, second is the molten material presence and third is the mineralogy transition or the phase transition.

They may be these three best possible explanation for this low-velocity zone along this mid-oceanic ridge system. So, thank you very much. We will meet in the next class.