Plate Tectonics

Prof. Pitambar Pati
Department of Earth Sciences
Indian Institute of Technology, Roorkee

Week - 01
Lecture - 04
Interior of Earth- IV

So, ok friends. So, if you remember our earlier class, we were confining ourselves at the crustal composition and mostly we found that the crust particularly the continental crust, the upper crust it is of granitic to granodioritic composition and our discussion was there to determine the crustal composition at the lower level and we found that the lower crustal xenolith, they are the good indicator of the lower crustal composition. So, continuing this discussion further, the early crustal model to suggest that the lower crust to be of basaltic composition. Why it is basaltic composition? The argument behind is that the basaltic magma were derived from this level. So, now if you see we have a crustal depth is moving increasing inside and here the lower crustal composition we believe it is 40 kilometer and this is the level where this basaltic magma is deriving. So, that means it is obvious to think that if the basaltic magma is derived from this level, so probably the lower crustal composition would be of a basaltic in nature.

And to substantiate that experimentally derived P-wave velocity correspond to the basaltic composition. There are different experiments to determine the lower crustal composition. So, here the P-wave velocity that means it is the seismic wave P-wave, S-wave, L-wave, R-wave these are the seismic waves derived from earthquakes and the P-wave it is called the body wave as well as the S-wave. So, the P-wave velocity which is corresponding to basaltic composition.

So, that means it is obvious that the basaltic nature the lower crustal composition is at that level. However, had it been of basaltic nature, so basaltic mineralogy should support this evidences that means basaltic mineralogy it is mostly composed of plagioclase and pyroxene. So, that means this mineral component of the basalt that should support yes it is the basaltic magma which deriving from this crustal level. However, the investigation of mineral assemblage present under the physical condition in the lower crust reveals that basalt cannot be present at the lower crust. Why? Because this plagioclase and pyroxene which are the essential component for this basalt to form they are not stable at that temperature and pressure condition.

So, though this P-wave velocity suggest it is of basaltic composition and this basaltic magma is deriving from that level, but the mineral assemblage to the basalt it is unstable at that temperature and pressure regime. So, that means that is something different this lower crustal composition is. So, now let us talk about if it is in wet condition. Suppose the lower crust is wet, so that means the basalt if it is in wet condition would have converted to amphibolite that means that is water is intermixed. Now if you see this amphibolite chemical composition here we have water.

So, that means if the lower crust is wet, so basalt it would have converted to amphibolite, but the mixed with more silicic material this would have a seismic velocity of correct range. So, that means we are intermixing the amphibolite with some silicic material that what we are getting that this seismic velocity is correctly fitting here. So, that means we can say this lower crustal composition is of amphibolitic nature as well as with a mixture of amphibolite as well as some felsic material. Now wherever these exposures are there the lower crustal rocks wherever it is exposed it says the rock in the lower crust both are of dry and wet. So, that means we have already discussed about the wet condition that means that is of amphibolite composition.

Now, if it is dry that means no water is there that means this composition would be correspond to a high pressure form of granulite. Granulite! We know this is the granulite it is high temperature and pressure range varies from here to here. So, now if it is dry condition, so it would have high pressure form of granulite that mean this region. So, it is ranging in composition from granodiorite to diorite containing the abundant plagioclase and pyroxene minerals. So, if it is of granulite so that means it is of a of a plagioclase and pyroxene would have been abundant.

So, at that pressure temperature regime. Lower crustal composition can be estimated by the elastic deformation parameters that is Poisson's ratio. So, this Poisson's ratio it is coming from the ratio of a P- and S-wave velocity. Few minutes back we are talking about the P- and S-wave which is generating from the earthquake or from the shock waves these are the waves they are called body waves and during the earthquake this P- and S-wave and other surface waves are also generating and the P-wave it travels faster than the S-wave and this for your information you can remember the P-wave it travels throughout the globe. However the S-wave it cannot penetrate to the outer core due to liquid in nature.

So, this P-wave and S-wave travel time distance that is the ratio of this velocity of a P-wave and S-wave it gives the Poisson's ratio and the Poisson's ratio in the crustal region it varies from 0.2 to 0.5. So, if it is towards lower end it indicates it is felsic in nature. If it is towards higher end it indicates it is in mafic in nature.

So, lower values characteristics rock of a high silica content and higher values indicate it relative low silica content that means high mafic content. So, in this graph if you see here this is the velocity and this is the Young's modulus and this is the Poisson's ratio. The Poisson's ratio it is varying from 0.

2 to 0.5. So, had it been at lower crust origin so that means a earthquake which is occurring at the lower crustal level and coming to the surface and it is detected by our seismometer. From this P- and S-wave velocity ratio we can calculate the Poisson's ratio and depending upon its variation from this where it is falling we can say at that particular region or through which this P- and S-waves are coming out. So, what would be their composition either it is more felsic composition or it is mostly of a mafic composition. Example, its the best example is the East African rift valley. Here if you see if the East African rift valley this is a triple junction and in this triple junction this is a rift where this Poisson's ratio value was calculated and it was experimented here.

Beneath the East African rift valley main of Ethiopian rift the East African Poisson's ratio varies from 0.27 to 0.35 and by contrast the crust located outside of the rift is characterized by Poisson's ratio varies from 0.

23 to 0.28. So why this contrast? Now if you see it is varying from up to 0.35 that means high as compared to the outside of the rift. So, that means near to the rift or on the rift the Poisson's ratio is more as compared to the Poisson's ratio which is detected outside of the rift. So, the explanation is the higher ratio beneath the rift are attributed to intrusion and extensive modification of the lower crust by mafic magma. So, that means we have an extensional environment we are extending the system.

So, the lower crust it is stretching and that means the temperature-pressure regime is changed and due to this change of pressure-temperature regime the magma or the mafic magma it is coming out and is emplaced near to the surface. So, that's why the Poisson's ratio is varying at the crustal level at the East African rift valley. However, if you are moving away from this rift system that means the crust is relatively undisturbed. So, that means it is of granitic or granodioritic or whatever may be the composition. So, it is giving the Poisson's ratio is 0.

23 to 0.28 that means it is more felsic in nature and at the crustal position where this rift is occurring the higher mafic magma which is occupying the lower crust it is emplaced to the near surface regime. So, it is giving the higher Poisson's ratio value. So, to substantiate it to the lower crustal composition what could be the best possible fit for that there was an experiment carried out by Green and Ringwood in 1967 at temperature 1100 degree Celsius and pressure 2100 mega Pascal. So, this temperature and pressure that is typical for the lower crustal regime where the basalt in dry condition is converted to eclogite. Basalt in wet condition will converted to amphibolite and in dry condition it will converted to eclogite.

So, now the question arises the P-wave velocity in the eclogite is 8 kilometer per second which does not fit to the actual P-wave velocity in the lower crust. So, we know that lower crust the P-wave velocity varies from 6.5 to 7.6. However, the P-wave velocity which is experimentally derived from this basaltic magma with the this dry condition which is formed eclogite it is giving to 8 kilometer per second which is a misfitting to the actual lower crustal velocity.

So, that's why once there are experiments, there are mineralogical experiment, there are the P-wave that means seismic experiment. So, that means we are not in a position to define what exactly the lower crustal composition should be. So, that's why Green 1970 he suggested that the lower crust is a gabbroic and anorthositic composition which fit to the P-wave velocity trend. So, once it would be gabbroic and it is of an anorthositic composition. If it is anorthositic composition then how this anorthositic magma it is emplaced to the lower crust.

So, that's why he proposed a model. What is that model? Now you see we have a crustal thickness this pink colour and the mantle derived magma it is under plates the crust as it becomes densely equilibrated. So, now you see we have a magmatic supply from this mantle and this magma it is coming and it is getting under plated at the lower part of the crust. So, now if you see here this crystallization of mafic phase which sink and partial melting of the crust above the ponded magma the melt become enriched in aluminium and Fe/Mg so, here this crustal melt is here and it is somehow it is mixing with this magma and this mafic percentage it is gradually decreasing because the mafic minerals which are crystallized they are settling down. So, the magma is automatically enriching in felsic content in Si and Al content.

So, once the Si-Al content increases plagioclase forms when the melt is sufficiently enriched in Si and Al. So, plagioclase rises to the top of the chamber where is the mafic sinks. So, that means here there is a contrasting minerals they are forming one is the mafic which is settling down and this felsic mostly it is dominated by plagioclase which is coming up. So, there is a clear cut separation between these two layers. So, once plagioclase accumulation becomes less dense than the crust above and rise the crystal mush plutons.

So, here if you see once we have the plagioclase which are less dense and it is here trapped. So, it will try to move up. So, that's why it is deforming the lower crust and it is moving up as crystal mush. So, that means the mafic part which is settling down probably it is creating a lower crustal layer or it is going down into the mantle. So, it is remixing with the mantle and this upper part the plagioclase crystal mush it is moving up.

So, plagioclase plutons now coalesce to form a massif anorthosite whereas, granitoid crustal melt rise to shallow levels as well. Mafic cumulates remain at the depth or it sinks into the mantle. So, this is the model which was proposed by Ashwall, 1993 that this lower crustal level we have this anorthositic system or the anorthositic massive anorthosite and beyond that whatever the mafic were there they are settling down into the mantle So, that's why it probably the lower crust it is of anorthositic composition. So, now if it is anorthosite which is forming at the lower crustal composition it is mostly anorthosite it is emplaced at the continent-continent collision zone where the crust is thickened and due to increase in heat flow granite melt moves upward leaving the anorthosite composition at the lower part it is very important to understand. We have a continental-continental collisional system like the Himalayas where we have anorthositic system which was earlier occupying the lower crust.

Now due to collisional system due to high heat flow this granitic melt which is formed due to melting due to high heat flow it is moving upward and the anorthosite being dense compared to the granite it remained at the bottom. So, now we are creating a crustal system where the upper part which is of granitic melt and the lower part it is of anorthositic melt. So, that means in a cross-section in the upper part we are getting more granite and this lower part it is mostly anorthosite. So, that means the Conrad discontinuity is present just above these two layers. So, here it is the Conrad discontinuity if you see here this is the granitic rich and this is the anorthositic rich.

So, anorthosite it is mostly forming the labradorite, the labradorite mineral which mostly we use for gemstone. So, it is comes from this anorthosite. So, it can be speculated that the Conrad discontinuity may only be present at the certain terrain which is undergone continental collision, but which is not true always. So, that means by and large we can say the lower crustal composition which is mostly of anorthositic composition and the upper crustal composition mostly of a granitic to granodioritic composition. Source of the deep crustal xenolith and the crustal contaminated magma that indicate there is a significant regional variation of the lower crustal composition, age and thermal history.

So, that called the crustal evolution. So, that means I want to say the crust it is not formed and evolved and it is not formed at a single temperature regime. The temperature varies from place to place, the composition varies from place to place and the age also vary from place to place. So, that means the crustal evolution or history it says the lower crust it is evolved stage and it is evolving now a days also. The lower crustal composition is more complex than it is suggested. So, that means till now wherever the experiment based on the mineral experiment, based on this P-wave velocity, based on the laboratory experiment all says there is variation because none of them are matching with each other.

So, that's why there is no definite crustal composition, there is no definite crustal temperature, there is no definite crustal pressure so, it varies from place to place. In the normal crust condition it will be different, in the orogenic belt it is different within that normal crust also from place to place the crustal composition will be different. So, this compositional complexity is matched by heterogeneous structure. So, that means the lower continental crust it is of not of uniform structure like if you go to the oceanic system, the oceanic crust it is homogeneous, it is basalt, it is homogeneous except where this volcanic islands are there. However, the continental crust, the upper continental crust it is of granitic to granodioritic composition that we agreed, but the lower crustal composition till now we have not reached to a particular composition, particular temperature, particular pressure, yes we can say this is the crustal composition here lower crustal composition here.

So, that means it is varying from place to place. This heterogeneity reflects a wide range of processes that create and modify the lower crust. So, that means it is not formed by a single process like magmatic differentiation, like metamorphism, like something. So, that means it is in inter-mixture, there will be magmatic emplacement, there will be metamorphism, there will be folding, there will be shearing.

So, everything is there. So, that means it is a continuous mixture, it is a modified, it is a complex process. So, these complex process through which this lower crustal is evolving and finally, we are not getting a definite crustal composition or not definite crustal temperature and pressure regime. So, what are these processes which include the lower continental crust process? This the emplacement and crystallization of magma derived from the mantle. So, the mantle derived magma which is somewhere it is more, which is somewhere it less. So, suppose a magmatic emplacement is here is there.

So, that means at this region, the lower crustal region, it is changing the temperature-pressure, the metamorphism is different. So, that means here we are getting a different mineral assemblage, a different temperature-pressure regime and similarly, this is different types of folding and faulting. Similarly, once there is no magmatic emplacement is there. So, this magmatic emplacement once it is not there, so that means definitely this area would be temperature and pressure wise and metamorphic wise different from here. So, that means there are number of places in the lower crust where the mantle magma is coming out as a tongue and apophysis as bulge like that and those areas they are getting changed mineralogically and compositionally and temperature and pressure wise and structure wise.

So, that's why at the lower crustal system, it is very difficult to say what are the exact temperature and pressure regime and what is exact the composition regime particularly. The generation and extraction of crustal melt. So, here suppose a magmatic system is emplaced, it is that means this due to this pounding of this magma, it is melting the part of the lower crust and that melt it may be circulating to the surrounding and may be it is possible the melt is coming up. So, during it is coming up some compositionally it is depleting to certain minerals, it is enriching to certain elements. So, that means I want to say this lower crustal regime it is completely different and it is unpredictable as compared to the other part.

Similarly metamorphism, different areas at the lower crustal level they are undergone different degree of metamorphism because we know this temperature and pressure regime varies with metamorphism or the reverse is true. So, that means at different temperature and pressure at the orogenic belt, so it will give rise different type of metamorphism. At rift it will give rise different type of metamorphism. At hotspots different types of metamorphism. So, that means I want to say that different areas in the lower continental crust it will give rise different type of metamorphism.

Similarly erosion, erosion means not the surficial erosion, I am talking about the erosion at the shear level at the lower crustal and upper crustal movement level. So, here we are getting the shear zones at the lower crustal and upper crustal material one is plastically deformed, one is elastically deformed. So, once we are moving so that means we are getting a shear zone that means there will be erosion, there will be fragmentation that means stretching and shearing. So, this type of erosion is there. Then tectonic burial , different places of the crust it is undergone tectonic burial for different time duration and different levels.

So, if it is higher level that means low temperature and pressure so its mineralogy will be different. If it is undergone for a long time for low temperature and pressure regime there mineralogy will be different. And if it is undergone different the temperature and pressure for a higher temperature regime for example and it is for a long time it will give rise to different mineralogy. So that means different degree of burial, tectonic burial, different level of tectonic burial different duration of tectonic burial that will yield different type of mineralogy. And many other types of tectonic reworking, what are the other types of tectonic reworking in the future classes we will deal with it. So, thank you very much we will meet in the next class.