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

Week - 02
Lecture - 06
Interior of Earth- VI

Okay friends, welcome to the next section of this class plate tectonics. So, if you remember the last class, we are emphasizing on the heat distribution on the earth surface and that different levels on the earth's crust and lithosphere. Similarly, in the lateral scale whether this continental lithosphere or the oceanic lithosphere, how heat production and heat flow is distributed and how it will play a role in this plate techniques that we discussed. And today we are going to discuss about pressure and gravity. Because the pressure if you imagine once it is an extensional environment or it is a compressional environment or it is a slight past environment, there is a play of role in the pressure, similarly if a subduction zone is there so one oceanic lithosphere is subducting down under this continental lithosphere or under another oceanic lithosphere, it is going under tremendous pressure. Now how pressure at which level it changes with the what value that we will discuss.

Similarly, the gravity value that is the density whether these two continental systems they are colliding or two oceanic system they are interacting. So, that will play the role the density of the plate. For example, if the two oceanic lithosphere they are interacting, the more denser lithosphere that will go down. So, that's why it is important to know what is the pressure distribution through depth and what is the pressure distribution in the lateral scale and in the gravity distribution throughout this globe and at the different continental plates or oceanic plate and in the plate boundary.

So, if you see this graph the right hand side, here the depth in kilometer it is written that is the surface of this earth to the core and the pressure in gigapascal. So, pressure in the gigapascal if you see at the surface and it is moving to the core. So, it is varying from 0 to approximately 400 gigapascal. So, in this atmospheric level the pressure we generally measure in millibar, bar like that. However, this earth pressure is a tremendous it is very difficult to express in terms of bar it may be some million bars.

So, that's why for this safer side or for the convenience of expression we use this the gigapascals in order to express the pressure of this earth or the continental or the oceanic lithospheric system. Now the pressure is continuously increasing hydrostatically with the increasing of the depth, but that is the condition is after the depth of compensation. Now, the question arises what is the depth of compensation? Probably you know this term isostasy. So, isostasy is nothing it is the balance of density. So, different density material on this earth lithospheric system they are placed side by side and at certain depth all this either it is a high density material or the low density block or high density block they are compensated with a certain depth.

So, that vary from place to place. So, it is not just a smooth surface this balance is or this compensation depth it is an uneven surface that depends upon the block, it depends upon the density or so. So, that means, I want to say after that depth of compensation this pressure inside the earth or up to this core of this earth it is varying hydrostatically, isnt it? So, the rate of increase at the depth of this major seismic discontinuities are there So, here if you see this is the pressure variation and wherever there is a major discontinuities is coming either it is crust-mantle boundary or mantle-core boundary or upper crust- lower crust boundary the slope of the graph is changing. Because the rate of change of pressure it is changing from one discontinuity to another discontinuity. And the high pressure in the earth are commonly quoted as gigapascals that we have already discussed because it is very difficult to express it in bar or millibar or so something.

So, it is tremendous that's why we use this term gigapascal to study the earth's pressure. And here if you see this image the density and the pressure increases with depth increase. So, that means, from the surface of this earth we are going to this core through density is increasing the pressure is increasing. And that means, at the core we are experiencing high pressure that is about 400 or 380 gigapascal or so. But our main concern is not up to this core our main concern is up to few kilometers that is around 40 kilometer depth in the continental crust and around 6 to 7 kilometer depth in the oceanic crust.

So, whatever the pressure distribution there that we will discuss in detail. The pressure reaches to a value around 380 gigapascal that is 3.8 million bar at the center of this earth which is about 4 million times of the atmospheric pressure at the sea level. So, if this earth suppose it is in hydrostatic pressure we are going to measure for a particular depth from the surface of this earth up to that depth. Suppose that depth is R we believe.

So, this pressure at depth, depth R is the due to this weight of this overlying earth's layer between R and the earth surface. So, that means, if this is the globe and we this is the center of this earth. So, we want to measure the pressure up to this depth. So, that means, what we are doing this is the distance R. So, up to this distance we can calculate the hydrostatic pressure and that hydrostatic pressure it is the function of density and the gravity.

So, this formula is already given here

$$p(r) = \int_{r}^{R} \rho(r) g(r) dr$$

based on the formula at any point of this earth we can calculate the pressure value. Now the pressure at the core-mantle boundary about 136 gigapascal and at the core around it is 380 gigapascal. So, now, if you see this figure it is given here this is the pressure how it is increasing with depth it is given and here it is the crust and this is the mantle. So, you see at the crust and the upper mantle this pressure is this much and in the transition zone this is around 14 gigapascal. Now if it is coming to the upper mantle- lower mantle it is around 24 gigapascal Similarly once we are going to this mantle-core boundary it is coming around 136 gigapascal.

Similarly at the outer core- inner core boundary around it is 325 gigapascal at the center of this earth it is around 380 gigapascal. So, that means, tremendous pressure you will experience at the center and our main concern it is about at this upper mantle up to this upper mantle because in the plate tectonics we will confine our self around this depth. So, now the question arises if this much pressure is increasing to depth that means, at the high pressure zone this rocks must be in the solid form then why there is an asthenosphere which is just below the lithosphere it is semi-solid or it is semi-liquid form. So, now this answer is here the high-temperature and pressure which exist at the depth of the asthenosphere it causes its viscosity to be low enough to allow viscous flow to take place on a geological time scale this viscous flow is going on. So, that is the temperature which is playing major role there than the pressure.

So, that means, at that asthenospheric level if we calculate the pressure from this formula that means, we are getting the pressure of something-something. Suppose it is x. However, if you are talking about the temperature the temperature it is playing dominant role rather pressure. So, that's why this material which is below at the depth of asthenosphere it is temperature wise more influenced than the pressure wise that's why it is becomes low viscous material and it is flowing or it is deforming like this convection current and it is deforming in the plastic deformation type. Now it comes to gravity because we know once we are going down the pressure increases the density also increases density of the medium increases.

So, that's why a continental crust having different density than the oceanic crust. Similarly within that continental crust there will be variation in gravity, variation in density. So, this areas where the concentration of high dense material is there for example, if you go to this greenstone belt the greenstone belt there high dense areas or high density areas. So, if you go to the granitic terrain it is low density areas. So, that means, that's why there is a variation in also gravity.

Similarly, compared to the oceanic crust and the continental crust the oceanic crust is heavy and composed of ferromagnesian minerals that's why they show high gravity value and this gravity value it is playing major role or the density it is playing major role while there will be a plate interaction. Suppose we are stretching a continental crust so that means, we are stretching it stretching to certain extent and finally, we are creating a rift basin through rift basin we are allowing this magma to come and forming a mid-oceanic ridge. So, imagine earlier it was a low density material it is a continental crust now with time more and more dense material we are intruding with that and before this drifting state before the emplacement of full-fledged mid-oceanic ridge there will be normal faults and through this normal fault there will be magmatic intrusion and once the magmatic intrusion is there again it increases its density. So, that means, I want to say with a low density material we may include we may include high density material similarly within a high density material we may intrude low density material and overall it affects the plate behavior. So, during the plate interaction this gravity value or this density value it plays a major role to decide whether this plate will go and that means subduct or it plate will be abduct.

If it is abducting what will be the subduction angle and if it is abducting at what extent it will abduct and whether this will bend or that will fold or which type of fold will form that depends upon all these things. So, now if we assume this earth to be perfectly sphere the gravitational acceleration "a" towards the earth is then given by this formula

$$-a = \frac{GM_E}{r^2}$$

where this "ME" is the mass of this earth and g is the gravitational or the Newtonian constant and R is the radius of the earth. So, at any point like we are able to calculate the pressure similarly at any point we are also able to calculate the gravity value and the fact that the earth is spinning on its axis it means that the value of gravitational acceleration on its surface is reduced. So, that means we have a gravity value which is the lateral density change that can detect but in the surface as it is spinning this gravity value is reduced. So, if you see this figure it is very interesting in terms of defining the geoid and spheroid.

So, imagine the earth is neither a perfect sphere nor it is a oblique spheroid because suppose for example, we think it is about a globe and we are taking a cross section and where as a earth scientist we are or a common man we are moving on the surface. So, we have to go high to reach the mountains. Similarly we have to go low much deeper into the ocean basin to reach up to the trench. So, overall if you are drawing a cross section of this earth. So, here this cross section will be like this at the mountains region and similarly, you are going to this lower level that is the trench at the ocean basins like this.

So, that means the earth is not a sphere, earth is not an ellipse. it is of different shape that is called the spheroid shape. So, now the question is how to calculate the gravity value at a particular portion. So, the mountains and the deep oceanic trenches are the deviations of the several kilometers. If you talk about the mountain this averaged it is about some thousands of meters, some thousands kilometer.

Similarly, you are talking about the Mariana trench it is the kilometers depth. So, that means it is not a smooth surface, earth's surface is not a smooth surface it is a rugged surface with some mountains and some valleys some trenches like that some ocean basins is like that. So, these geodesists who people are working in the gravity they use the surface of the ocean as a reference surface which is sensible since it is a liquid and it is necessarily it will take equipotential surface. So, that's why this equipotential surface that is called a geoid surface that is called a geoid surface. So, now this geoid surface and if you are measuring the gravity value and this gravity value with respect to this, but this gravity we have an equipotential gravity surface that is called the geoid surface.

Over the ocean the geoid is the mean sea level and over the continent it can be visualized at the level at which water would lie if you are digging a canal. That means if we allow the surface of this ocean to penetrate into this continental system what would be its level. So, this is the surface it is the equipotential surface. So, all these navigations, all the surveying are referenced to the geoid. So, here there are two terminologies can be introduced that is called free air anomaly and bouguer anomaly.

So, generally those people who are working in a gravity survey they are very familiar with this free air anomaly and the gravity anomaly. It is nothing this the we are measuring a gravity values at a particular point and if it is above the sea level or what extent it is what above the sea level how much it is above the sea level if we want to calculate the free air anomaly we just remove the material. So, we believe that is only free space it is an empty space and we measure the gravity value there with respect to the geoid. Similarly, Bouguer anomaly that means we are inserting a slab of the equal density of the similar density to that level and we are calculating the value here and we are comparing with the geoid value. So, this measured versus the calculated that is the anomaly.

So, if the free air anomaly and Bouguer anomaly there are number of anomalies these people who are working in gravity survey these people are using. So, just for your information this is the difference between free air and the Bouguer anomaly. So, Bouguer is the density element that means we are inserting a slab of equal density of this much so that it will give some value so in the calculation. So, this is the difference between the free air and Bouguer anomaly. Now, we have shield area, we have platforms, we have mobile belt.

If you see this shield area and platform areas they are characterized by broad Bouguer gravity anomalies it is varying from minus 10 to minus 50 milligram and occasional sharp anomalies which are local importance. This is very important for exploration point of view. For example, we are doing the gravity survey and in this gravity survey we are getting a local anomaly that is high depth and high density material is inside. So, that means we may interpret there is a dike intrusion or a high density material is emplaced there. Similarly, suppose there is a low density material is there and we are carrying out the gravity survey.

So, there will be the gravity value will fall down like this. So, that may be we may interpret there is a granitic intrusion that means low density material is there. So, that means if it is a local that means it is useful for exploration point of view, but however if it is broad. So, that is related to the crustal composition either it is a platform, it is a shield area or this is continental crust, oceanic crust that means it is a broad region. So, it is important for this plate tectonics point of view, but the local anomalies it is very important for this exploration point of view.

So, anomalies with width of hundreds of kilometer reflect inhomogeneities in the lower crust and upper mantle and those of a smaller size reflect the surface rock types of a fault zone. Yes, as we few minutes back we are talking about this mineral exploration this is structurally advanced feature identification like fault. So, fault zone that is enriched in low density material it is a local anomaly. However if it is a broad anomaly like width of hundreds of kilometer that is reflecting the inhomogeneity in the crustal composition in the crustal structure. That's why local anomalies they are very useful for us for exploration point of view and this broad anomalies they are useful for plate techniques point of view.

If you see here this geophysical feature of this crust and their Bouguer gravity anomaly here the shield it is minus 20 to minus 30, platform minus 10 to minus 50, then orogens it is coming you see it is around hundreds of times. So, that means more broad the matter is more the value is. So, that's why local values they are important for exploration and broader values, higher values they are important for plate tectonics. Now you see this some of these images representing different types of basins this importance for local and regional importance. If you see this is a sedimentary basin and this is the gravity anomaly.

So, you see how broad is that. So, this is the sedimentary rock and sedimentary rock it is low density material. So, this low density material it is lying on the high density material. So, that's why it is giving a broad negative anomaly in terms of kilometers. So, here the Bouguer gravity anomaly profile across a granite body. In the last to last class when we are talking about or defining the upper crustal composition probably you can remember we are talking about when there is a granitic intrusion and we are doing this gravity anomaly.

So, this gravity anomaly is giving lower than the average continental anomalies. So, here if you see it is a granite intrusion and this is basic igneous and contrary rock. So, this gravity anomaly it is falling down it is less as compared to this surroundings. So, that means, the granite it is a low density rock. Similarly, sedimentary basins the sediments they are the low density material.

So, that's why these can be detected by gravity profiling, but here suppose there is a ore body either it is platinum or any ore body. So, these are the high density material. So, the high density material if you see this gravity value it is going and finally, it is going up at this section and this is giving the high density that means, surrounding to compared to the surrounding we are concentrating high density material here. So, that's why we are getting a positive gravity anomaly here. Similarly, if you see this continental crust and the oceanic crust placed side by side.

So, this is a transitional crust that means, neither it is continental fully nor it is oceanic fully. So, now, this is the gravity value that you see this continental crust it is giving low gravity anomaly and this oceanic crust it is giving high gravity anomaly. The purpose is to show it here this continental crust it is composed of low density material like quartz feldspar like that. However, this is composed of high density mineral like olivine pyroxene like that. So, that's why this gravity value it is in a broader value that means, it is easy to distinguish the low density material or the low density crustal composition from the high density crustal composition.

However, if it is a local importance then means it is useful for distinguishing the exploration material whether there is a low density material like granite or it is a high density material like any ore body or so. Now, not only it is useful for this mineral exploration or this distinction of the crustal density from place to place. There are gravity value which is successfully been used to identify the faults and particularly if you see this a gravity map of Indian context. The gravity anomalies can be used to trace the structural trend of this rock units like the precambrian shields beneath the sedimentary cover in the platform areas. Now, you see here this is the high gravity values mostly the Precambrian rocks, the Aravallis, the Eastern ghats, all these Vindhyans like that.

So, Delhi supergroup so, all these sedimentary that means, all these Archean terrains or this Precambrian terrains they are represented by this high gravity data or high that is in high density material is there. And similarly if you trace these gravity value across the Himalayas you will find some of these trends, these trends are nothing they are the basement structures. Similarly here these are the basement structures they are cross cutting the Himalayas. So, based on this gravity value some of this very high crustal scale faults have been identified and had been traced across the Himalayas from the peninsular system to across the Himalayas in between this is the Ganga plane which is covering of or covered by low density material like the sediments. So, that's why its signature the gravity signature in this Ganga plane is negligible as compared to the Himalayan system as well as in the peninsular system.

So, that's why tectonic contact between the crustal province in the shield and platform areas are also often expressed by the gravity anomalies and tectonically adverse features like the faults that can be traced based on the gravity anomalies. So, that means, this crustal density change which is detected by the gravity that plays an important role in the plate tectonics. Now, Phanerozoic orogens have large negative Bouguer anomaly that is minus 200 to minus 300 milligal reflecting their thickened root. So, a mountain having thickened root that have negative gravity anomalies. So, if a young orogens belt near the continental broad land and island arcs that exhibit is smaller anomalies.

So, that means, based on this gravity anomaly we can detect which type of material is lying beneath. So, that will help us to understand the plate tectonic setting that what this plate interaction on has created either what is lying inside either it is high-density material is lying or low-density material is lying. So, plate can be identified which were in the subducted already subducted and there is no surface indication whether this subducted plate residual or not it is lying there or not that can also be detected by this gravity anomalies. Large negative anomalies in the basin and range province and in the most continental rift reflect thinning of the lower crust and the presence of the shallow and low-density upper mantle. So, here if you see the basin and range province here it is large negative anomalies why? because the system is stretching the continental system is stretched.

So, due to stretching the crust becomes thin. So, it is the sedimentary basin most of these horst and grabens hundreds of horst and grabens are there filled with sediment. So, this is due to stretching the crustal thinning we are getting negative gravity anomalies. Small positive gravity anomaly superimposed on regional negative anomaly occurred in the center of the some of the rifts appear to be caused by near surface intrusion of mafic magma that is mafic magma had it been a felsic magma. So, that is of negative gravity because it is already tested by this granitic intrusion. So, if it is crust is stretching and is intruded by mafic magma and we are carrying out this gravity survey.

So, that means, we will get a positive gravity anomaly. This positive gravity anomaly is nothing it indicates that this due to stretching there is magmatic intrusion and the magmatic composition it is of mafic magma it is not felsic one. So, these are the use of this gravity value or the gravity survey and how it is used in the plate tectonics. Bouguer anomalies in the ocean, volcanic islands, range large and positive that is plus 250 milligal to small as minus 32 plus 45 milligal. Negative anomalies observed over trenches reflect the descent of the less dense lithosphere into the upper mantle. And some gravity profile suggest thinning of the crust on the oceanward side of the trenches.

Bouguer anomalies range from plus 250 to plus 350 in ocean basin and from 200 to 250 on a ridges and 0 to plus 200 over marginal and inland sea basins. So, based on this gravity value we can say which type of tectonic environment we are dealing with. And in the North Atlantic the bouguer anomaly increases away from the mid-oceanic ridge and due to cooling of this lithosphere as a function of age. If you remember we are talking about the age once we are moving away from the mid-oceanic ridge system, it the system cools down and becomes rigid and once becomes rigid it is density increases. So, that's why this Bouguer anomaly increases away from the mid-oceanic ridge due to increase is due to the increasing of density.

And the minimum in the Bouguer anomaly over ocean ridge suggests that they are isostatically compensated by the hot low density upper mantle material beneath it. So, that is ocean basin is isostatically compensated. However, the continental system it is isostatically not compensated that's why you will find number of variation of the gravity value in the continental system. However, in the oceanic system except the island arcs and this in volcanic system that is the volcanoes that hotspots otherwise you will find a uniform gravity value in the oceanic system. Smaller Bouguer anomalies in the marginal and inland sea results from thicker sedimentary layer in the basin.

So, that means, by this looking this gravity data or gravity value we can say what type of sedimentary basin is there, how much thickness of sediment is there, what is the nature of the sediments are there either it is high density material sedimentation is there or it is low density material sedimentation is there. And this is the gravity value it is starting from this 0 that means from surface to the center of this earth. So, thank you very much we will meet in the next class. Thank you very much.