Plate Tectonics

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

Week - 06
Lecture – 29
Destructive Plate Margins-V, Seismicity in the Subduction Zone

Ok friends. So, in the last class we were talking about this accretionary prism and backarc basin, so that means, different elements in the subduction zone we have discussed and today we will talk about the seismicity in the subduction zone. So, if you believe me, seismicity is an integral part of the subduction system because here two plates they are interacting with a tremendous pressure with tremendous stress and one is going down to a high temperature and pressure environment from a near surface environment. So, that is why the pressure is changing, the temperature is changing, the stress regime is changing. So, that is why seismicity it is occurring in this subduction zone frequently because many thrusts, many normal faults and strike slip faults they are active in the subduction zone. And as a result of that you will get a wide zone where the seismic activities are distributed.

So, either they may be distributed widely or they may be confined in a particular plane. So, different levels starting from the surface to the subsurface the nature of the seismicity is also varying. So, that is why in this class we will talk in detail what is the region of seismicity in the subduction zone, what is their origin and what is their nature in the different levels. So, if you see this seismic map of the globe and particularly this is subduction zone map you see number of earthquakes and they are occurring at the plate boundary which are the subduction or the collision zones.

You see this is the circum pacific ring of fire where all sides the plates are subducting and this is the alpine Himalayan belt where there will be subduction zone as well as the collision zone. So, that is why if you see most of these earthquakes they are occurring at the subduction zone. And if you compare the earthquake nature from this spreading ridge to the subduction zone you will find in the spreading ridge mostly it is characterized by shallow focus earthquake. In contrast to that here these subduction zones they are characterized by deep focus earthquakes. So, subduction zone exhibits intense seismic activity that intense seismic activity is due to this subduction or due to collision as well as frequent faulting and frequent thrusting and strike slip movement.

So, that is why you will find number of earthquakes of high magnitude they are occurring from the surface to the subsurface level. A large number of events occur on a plane that average dipping around 45 degree. So, if you remember our earlier class when we are talking about the subduction angle the subduction angle of different plates they vary from 90 degree to very shallow level around 20 degree or so. So, that is why depending upon this angle of subduction the seismic zones distribution also varies. So, though it is an average angle of 45 degree dipping or subducting angle is there, but still it varies from 90 degree to around 10 to 20 degree.

And this plane of seismic concentration or seismic zones if this plane where these seismic events are concentrated that is called the Benioff zone or it is the Wadati-Benioff zone the named after its discoverer. So, that means, here this is Wadati Benioff zone or the Benioff zone whether it is existing or not existing to know it we have to think about the distribution of the hypocenters or the focus of this earthquake along this system. So, this earthquakes if it is occurring in the subduction zone it occurring from near to the surface and a maximum depth recorded so far is around 670 kilometer. So, that means, if you are going down to this subduction zone to the depth. So, finally, if you see here near to the surface we have seismic events and gradually with depth the seismic events are there and the maximum depth so far recorded it is 670 kilometer.

That means, it says up to 670 kilometer the subducting plate retains its rigidity. So, up to now this is the maximum depth we have recorded and the focus can be seen to occur at progressively greater depth at increasing distance from the trench. So, if you see here we have the trench its position is here and you are going away from the trench. So, once you are going down is going away from the trench gradually the depth of the seismic event is increasing. So, that means, near to the surface up to 670 kilometer.

So, this seismic events that distributed and information about this Benioff zone that is coming from the body wave of this earthquakes that are occurring at the subduction zone. So, we know during the earthquakes there are different types of seismic waves they are regenerated one is the body wave which is passing through the body of this earth and another is the surface wave they are passing on the surface or near surface of this earth and the surface or near surface waves they are more dangerous for devastating of this infrastructure rather this body waves. So, that is why once this body wave is coming suppose for example, here this is the focus and this is the hypocentral focus here this earthquake is occurring and this waves they are originating from here and are travelling at a different distance on different directions. So, these are the body waves and this body wave amplitude that says many things about this nature of this Benioff zone whether the

Benioff zone exist or not what is the angle of subduction what is the depth to which the Benioff zone is extending all those information that can be retrieved from the amplitude of the body waves. And earthquake hypocenters are arranged in a plane or in a zone representing the Benioff Zone. So, for example, here if you see if you plot this hypocenter with depth and distance what you are getting all these earthquakes they can be confined in a plane and within that plane.

So, this zone is called the Benioff Zone. So, if the earthquakes are distributed for example, here they are and like this that means, there is no preferred arrangement no arrangement in a plane or a zone. So, that means, we can say here the Benioff zone is not existing. So, the many of zone existing or not existing that depending upon the distribution or the preferred distribution of these earthquake hypocenters. If they are preferredly that is distributed along this zone along a plane and then we can say this Benioff zone existing whatever be the angle may be 45 degree may be 30 degree may be 60 or 90 degree irrespective of that, but if it is not there.

So, the earthquake hypocenters they are just distributed like here and there no preferred orientation is there. So, that means, we can say benioff zone is not existing. So, now, why it happens? Why the earthquake is happening near surface to the subsurface? So, to understand that we have to go for this understanding this figure. So, what does it says? It says that once we have a plate which is down going it is a slab which is of oceanic origin it is basaltic origin and this obducting plate may be oceanic or may be continental. So, once it is going down gradually the strength of this medium is increasing.

So, here it is a low strength and then it is strength is increasing and then it is a high strength. So, that means, from the surface to the subsurface once we are moving gradually the strength of the medium is increasing and we are putting a part of this plate it is going inside. So, now, if it is the low strength zone. So, once it is a low strength zone so, that means, once the plate is going down so, the gravity is playing important role to take it down. So, here this plate it is that means, it seems that it is as if it is hanging from the top.

So, once it is the hanging from the top so, that means, here mostly the extension type of earthquakes are occurring. So, here there are two types of circles one circle is closed circle another type of circle which is open circles. So, here if you see this closed circle that is represent the extensional one and this open circle that represent the compressional one. So, now, you see at this level when this plate is around the low strength zone so, mostly the extensional related earthquakes are occurring. So, gradually it is going down and down and finally, the strength of the medium it is increasing.

Once it is coming from low strength to relatively high strength zone so, that means, this high strength material of the mantle it will not allow this low strength metal to insert inside. So, it will push it back that is the buoyancy force it is pushing it back. So, now, imagine gravity is pulling it down and this buoyancy of this mantle it is pushing it back so, that means, there is a tussle between these two. So, that means, there is a very chance that plate will bend inside not remain at the straight that may be bending. So, here if you see this zone it is a zone of extension because of this gravity-related pulling down and here this is the zone of compression because the force is opposite the gravity that means, it is pushing back so, that is why it is a compression.

So, now, if further it moves down so, that means, it is coming directly to this high strength zone so, that means, here all along this plate the stress is upward that means, it is the pushing strength that means, the mantle which is pushing very tremendous force to this that means, opposite to gravity. So, that is why this whole plate is experiencing stress experiencing pressure from the inside of this mantle. So, that is why a result is that so, this plate is breaking into pieces. So, one plate is separated by breaking from the whole plate so, one segment is separated once this segment is separated now again the first condition is coming out that means, here again that means, there is no link between these two. So, again this extensional regime or extensional tectonics is here.

So, that means, I want to say with time when this plate is going inside and further inside the nature of earthquake is changing from extensional force to compressional force. So, that is why at a different level the earthquake generation mechanism is different. So, that is why here the model is showing the field circle represents the down-dip extension and the unfilled circle represent the down-dip compression and the size of the circle qualitatively indicates the relative amount of seismic activities. So, how much energy will be released at a different level that indicates by the size of the circle. So, here it is illustrated as we have discussed the slab sinks into the astrosphere and the load of this excess mass is mainly supported by the force applied to the slab above the sinking portion.

So, why there is a excess mass because we are putting one mass inside forcefully due to this ridge push system and due to the slab pull system. Anyway we are putting excess mass here which was earlier not here. So, this excess mass is supported by the force applied to the slab above the sinking portions. Then in b, this slab penetrates into stronger material and part of the load is supported from below because once it is going down so that means, here it is a high strength material is in the surrounding so that means, it is holding a support. That means, as if this plate is lying here with support is provided from below and the stress changes from extension to compression and in c this entire load is supported from below and the slab is under compression throughout and in the d it is break into pieces.

So, now if this is so, now you see we have some earthquake here, we have some earthquake here for example, here we have some earthquake points here and we have some earthquake point here and here these two are not connected to each other. And similarly if a earthquake which is earthquake points or this hypocenters which are arranged here and continued to that another zone of hypocenters there arranged here and you can draw a clear fault that means, you can predict what is the nature of this plate which is going down whether it is faulted or it is remain intact. So, by distribution of from this figure you can say it is a faulted block and one part is separated from this main segment. So, that is why from the near-surface to the subsurface the earthquake origin and the nature has been divided into four distinct zones like A, B, C, D. So, in A particularly here this earthquake is generated in response to bending of the lithosphere as it begins to descend and normal faulting mechanism is dominant here and it is up to depth of 25 kilometer.

Why it is happening? Because if you remember our earlier class when we are talking about this subduction system there is a bulge that is the flexural bulge in front of the trench. So, here this zone it is representing the bulge and bulge means it is the folding system. So, once we are folding we are stretching the system and once stretching we are creating normal faults here. So, if I zoom it here see this plate or the lithospheric plate which is going down and it is bending here in front of the strains there are normal faults developed here due to stretching. So, due to stretching there will be extension and the extensional cracks they are developed these are the normal faults.

So, this normal fault is the main mechanism of occurring earthquakes in the zone A. Now, if we are moving from zone A to zone B here if you see these two plates they are directly interacting with each other. This is the downgoing plate and this is the overriding plate they are in direct contact with each other. Once they are in direct contact with each other that means, they are under tremendous stress one is trying to go down another is here it is opposing. So, that means, tremendous stress is here and due to this tremendous stress.

So, we know in a stress that means, it is a compressional regime in the compressional there will be thrusting. So, that is why in the region B is characterized by earthquake related to thrust fault along this contact between the overriding and the underthrusting plate. And this angle between these two that means, the angle of subduction that defines how much stress is accumulated here. If the angle is low so that means, imagine this down-going slab was like this. So, that means, here low angle subduction is that that means, more interaction between the overriding and the underthrusting plates and more interaction that means, more stress accumulation.

So, devastating earthquake related to thrusting would be here. So, that means, this angle of subduction that also define how much stress can be accumulated here. So, in this zone B as there is a direct interaction between these two plate and this is highly stressed regime. So, thrust faulting is the mechanism of creating earthquakes in zone B. And the group of earthquakes lying under the island chains are indicative of thrust faulting.

You know that we have one plate is subducting down and we have this island arc system we are volcanic arc or island arc. So, earthquakes occurring just below it so, due to thrusting. So, here there will be thrust faults and due to thrusting this earthquakes are generated here. Now, going further deep so, we are going away from the direct interaction of the plate and we are entering into a region which is surrounded by asthenosphere. And the asthenospheric material it cannot provide so much stress as compared to this rigid plate which is here.

So, that is why this earthquake mechanism in zone C is completely different from zone A and B. So, here the Benioff zone in zone C at a depth greater than the thickness of the lithosphere at the surface not generated by thrusting at the top of this descending slab because the asthenosphere in contact with the plate too weak to support the necessary stress for thrusting. So, here we have necessary stress it is provided by the overriding and under-thrusting plate. However, as the asthenosphere is weak so, it is not able to provide that much stress which is related or which is essential for thrust faulting. So, that is why the zone C is characterized by earthquakes which are created due to internal deformation.

What is internal deformation? This term itself it is self-explanatory. So, internal deformation that means, deformation is going on inside the plate. So, now, the question arises what is the mechanism how this plate is deformed internally. If you see here this zone C too many of zones occurring. So, too many of zone if you see this image group of earthquakes hypocenters they are representing on the top of the slab and a group of earthquakes they are occurring from at the bottom of the slab to certain extent.

So, what does it mean? Now if you remember our earlier class when we were talking about this spreading system that this lithosphere particularly the oceanic lithosphere it is composed of mostly basalt which is layer 2 and above that we had layer 1 which is mostly of sediments. And layer 3 which is gabbro that is isotopic gabbro and that is a layer gabbro and zone 4 is with the peridotite. So, now, you see we have different phases they are coming out at a different level that is the first one that the first zone which is at the top that is representing the crustal part and here this is called the lithospheric mantle. This zone of earthquake they are occurring from the lithospheric mantle. So, the first one it is the crustal origin they are the first sequence of this earthquakes they are occurring here at the top of this plate they are of crustal origin and the second zone that is from lithospheric mantle origin.

So, how it is happening? So, this is indicating the upper of this zone corresponding to the crustal part of the slab and the lower one is the lithospheric mantle. So, that means, the crustal part is also occurring earthquakes and in the mantle part also it is occurring earthquake. However, the mechanism is different what is the difference between the two let us discuss. So, this is called double seismic zone and double seismic zone it is occurring between 70 kilometer to 200 kilometer depth. So, that means, if you see here these two zones gradually going down and then merging together.

So, here two distinct zone can be identified, but once you are moving down these two zones are merging. So, that means, starting from 70 kilometer to 200 kilometer this zone is existing. So, within that zone we are getting two benioff zones or the double benioff zone. So, here that is around 70 to 200 kilometers have been documented in numerous well studied subduction zone and that is why it is believed it is common in the subduction zones specifically and particularly that means, in the zone C we get two bany of zones. So, now, the question is what is the mechanism? How this zone C is showing two bany of zones? Most of these earthquakes in this zone are triggered by metamorphic reactions involving dehydration and those in the upper zone associate the formation of eclogite and those in the lower zone that is dehydration of serpentinite to fosterite and enstatite plus water.

Now, it has to be understood here. Now, we had the oceanic lithosphere which is going down and this is the overriding plate. The oceanic lithosphere earlier if you remember we had the layer 1 which was sediment and the layer 2 which was this pillow basalt and then gabbro then we have peridotite. And if you remember when we are talking about the mid-oceanic ridge system here the mid-oceanic ridge is here and once the plate was forming here this plate was moving away from the mid-oceanic ridge and there was number of normal faults there were fractures. And through this normal faults the water was flowing inside and was coming out as hydrothermal fluids. So, during this interaction with water and this particularly the hot water the basalt it is metamorphosed to serpentine.

So, if you remember we are talking about the greenschist facies of metamorphism that is occurring while this plate is coming away from this mid-oceanic ridge system. So, that means, along this fracture zone and around this fracture zone the basaltic rock or the basaltic lithosphere has been converted to serpentinite. And the upper part we have sediment and the sediment having pore space inside and they are containing water. And this serpentinite it is also occurring water in its crystal lattice in the crystal structure. So, now, anyway we have water either it is pore water or it is crystal bound water in the clay minerals as well as in serpentinite.

So, both water we are now putting it into a high temperature and pressure environment. So, once we are putting the water mixed with minerals or water containing minerals inside. So, in the high temperature and pressure this water is not stable in the crystal structure as well as in the pore space. So, that is why the water is released. So, once this water is released dehydration takes place.

So, here dehydration once takes place at the surface level when there is sediment which is aluminum rich. So, this aluminum rich sediment due to dehydration their density increases and the minerals which was present here that is converted to eclogite. So, eclogite is a group of rock and mostly this heavy high density minerals are present here. And the lower part when we have serpentite, so serpentite also dehydrate. So, serpentite dehydrates serpentite it was formed from olivine pyroxene is not it?

So, now, it will dehydrate again convert to olivine which is forsterite and enstatite which is pyroxene plus water. So, water is released. So, in the upper surface water is released from sedimentary part and the lower surface water is released from dehydration of this serpentinite part. So, anyway water is released. And once this water is released and dehydration taking place, so that means, we have generate we are generating the vapour pressure we are increasing the pressure inside.

So, finally, we are allowing faults to activate. So, here for your information the eclogite which is a fresh rock striking appearance it is pink garnet, then kyanite, rutile, quartz, lawsonite, coesite something like that. So, if you see here we have this rock which is eclogite and we have serpentinite here the serpentinite is there. So, that means, the mineral which is serpentinite it is there and due to dehydration of metamorphic transformation mineral alteration is particularly important in sea floor tectonics and boundary. So, either it is eclogite at the top or at the serpentinite at below. So, here we are dehydrating the serpentinite and we are dehydrating the minerals which are at the surface we are creating eclogite.

So, this is suggested that dehydration reaction generate high pore pressure along the pre existing fault plants in the subducting oceanic lithosphere producing earthquakes vibratory failure. Now, here once we are dehydrating this is this dehydration that means, release of water it is creating high pore pressure there and we have already faults that means, we are generating these faults at this level as well as we are generating fault at the mid-oceanic ridge level. So, those faults due to this high pore pressure they reactivate and due to this brittle failure during this dehydration and during this high pore pressure regime. So, the fault failure takes place and earthquakes are occurring. So, that means, here this internal deformation so that means, both top surface is deforming and this bottom surface is also deforming.

So, due to this internal deformation these earthquakes are occurring. So, this suggests that the oceanic mantle is serpentinized to a depth of several tens of kilometer whereas, hydrothermal circulation and alteration of mid-oceanic reaches is thought to be restricted to the crust. Normal faulting on the outer rise and the bending of the oceanic lithosphere oceanward of the strains permit ingress of seawater and hydration of this lithosphere to the depth of 10 of kilometer. So, that means, whatever the hydration is taking place here and hydration was taking place around this mid-oceanic ridge all these hydrated system they are dehydrating at the sub-surface level.

So, now, come to zone D. This zone D it is also again important and this mechanism of earthquake occurring here that is also completely different from this other three. Zone D The earthquake mechanism is believed to be result of the sudden phase change from olivine to spinel structure. We have olivine whatever left here due to dehydration we are creating olivine and pyroxene. Now, this olivine and pyroxene at zone C which was formed by dehydration they are again going down to a high temperature and pressure environment. Once they are reaching at a high-temperature and pressure environment their phase changes because those phases are not stable at that particular temperature and pressure.

So, particularly those phase changes they are converting to spinels and spinels if you see here spinal it is common it is in peridotite in the uppermost earth mantle between approximately 20 kilometer or 120 kilometer a possibility lower depth of depending upon this chromium content at significant shallow depth above the Moho calcic is the more stable aluminous mineral in peridotite where the garnet is stable phase in the deeper mantle below the spinel subunit region. Its harness is 8 and specific gravity is 3.5 to 4.1

that means, the high specific gravity mineral so that means, the minerals which are present here that is olivine and pyroxene. So, olivine is converting to spinel and the spinel it is a crystal which is very highly dense mineral.

So, that is why due to this phase change so, it takes place rapid shearing in the crystal lattice along the planes on which minute spinal crystalline is grown and due to this shearing effect this faulting takes place and that is why this olivine to spinel change that means, phase change it is creating earthquake in the zone D. So, generally in the normal mantle temperature this phase changes that is occurring around 400 kilometer. However, once a plate is going down that means, it is retaining its cold core to more distance. So, that is why once the cold core is returning to a higher distance so that means, this phase change is occurring around 700 degree Celsius and that is around 670 kilometer depth. So, that depending upon the rate of subduction if the rate of subduction is less so that means, at a lower depth this olivine to spinel transformation can occur.

If it is rate of subduction is high that means, a slab can retain its rigidity without phase change to a great depth. So, that is why at a deeper level this phase change can occur. So, this olivine to spinel phase change that depends upon the rate of subduction. So, in old rapidly subducting slab this may exceptionally be at higher depth that is maximum depth that is recorded around 670 kilometer. And similar transformation from enstatite to ilmenite contributes the subduction zone seismicity.

in this depth range. So, that means, either enstatite to ilmenite and this olivine to spinel both are contributing earthquake generation at the zone D. And this phase changes occurring at a slab depth approximately around 700 kilometer and produce fine grained minerals that behave as a super plastic manner and thus cannot generate earthquake further downward. So, that means, up to 700 kilometer or 670 kilometer we have recorded the earthquakes and that means, we believe the subducting slab retains its rigidity up to that, up to that this phase transformation occurring. And below that whatever the phase transformation is occurring, but the material is behaving in super plastic manner. So, though there is a phase change, but we cannot generate the earthquake. So, thank you very much. We will meet in the next class.