Plate Tectonics

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Week - 07
Lecture – 33
Orogeny and Epiorogeny- I
Ocean-Continent Collision

Okay friends, good morning and welcome to this class of plate tectonics. If you remember up to last class, we have completed the different types of plate boundaries, the convergent, divergent and the conservative plate margins. So today we will talk about the orogeny and epiorogeny. So what does it mean? If you say orogeny, so the oro- means mountain and -geny means genesis. So genesis of mountain that means mountain building activities. So now the question arises, taking the three types of plate boundaries, how these mountains are built up and which type of plate boundary is prone to develop which type of mountain and what are the processes responsible for this mountain building at different plate margins, we will discuss in this class.

So in this class, particularly we will confine ourselves in the ocean continent convergence. So ocean continent convergence, if you remember our earlier class, when an oceanic lithosphere is with contact with the continental lithosphere being heavy, it will move down and the continental plate it will remain at the top and the oceanic plate it will subduct down. So that means, by and large we are talking about a convergent plate margin or a subduction zone and in the subduction zone how this mountain building activities is going on, so that we will discuss in this class. So now if you see this four figures, we have a subduction type, another is accreted terranes type, the third is continental collision type and intracontinental type.

So this orogeny everywhere that it is related to these four types of tectonic activities. So that means, in this class we will talk about the different processes that are involved in this subduction type of plate boundaries, how this plate's interior geometry and its rheology, its strength, its pre-tectonic history that are responsible for the development of the mountain at this plate boundary. So whenever we are talking about a subduction zone, we have an abducted plate which is mainly the continental plate and the subducting plate which is an oceanic plate. So when these two are interacting, generally we know there is folding, thrusting, they are the main deformation events. Along this folding and thrusting, we have the magmatic activities, we have metamorphism.

So as a result what is happening that this plates characteristics changes with time. There are number of magmatic phases, there will be number of metamorphic phases and there will be number of thrusting events, there will be melting, temperature increase. So by and large with time the strength of these plates they are decreasing and due to the decrease of the strength of the plate, so their interaction characteristics that will also change with time. So if you see this global scenario, there are subduction type here, then we have accreted type here and we have this continental collision types here. All these type of plate boundaries or this orogenic mountain region, they are of arcuate shape and why it is arcuate shape? If you remember our earlier class when we were talking about the subduction system, this is convex towards the subducting system.

So this is arcuate shape geometry or the mountains and it is highly deformed. This highly deformed is due to folding, thrusting, faulting, magmatism like that. So that means we are creating a mountain front and this mountain range which are folded and thrusted metamorphosed and different sequence they are of trusted and over-thrusted above one another and their thrust slides they are generating from different depth. So that is the different degree of metamorphosed thrust events. So they are superimposed one another and finally giving us a mountain range.

Now the ocean-continent convergence, the Peru-Chile trench or this Andes mountain system or the Andean type, it is the best studies in the worldwide. So particularly the central Andes, if you see here this Andes mountain is extending from north to south. However, the central part it is more wide. So researchers have developed some mechanism, some understanding about this understanding of the central part of this Andes mountain compared to this northern and southern part. So that is why most of the examples in this class we will quote that is from this central Andes region.

So here this Andes exhibits the highest average elevation, the greatest width and the thickest crust and the great amount of shortening in this region. So here if you see this width of this Andes mountain is very high. So it is attending high elevations and its crustal thickness is more as we know when we are talking about this isostasy. So we have mountain system which is rising above of this much height. So it has a deepest root like that.

So that means we have a thickest crust, we have a highest mountain and highly deformed system here. So that is why it is worldwide mostly studied in terms of this continent-ocean convergent system. So the central segment of this Andes suggests that many of the characteristics features of the large orogens may form in the absence of the continent-continent collision because whatever we are discussing so far we are talking about this continent-continental collisional type like this Indian-Eurasian system. We have the thrust sheets, we have deep root, we have highest mountain. However in this case you see simply it is not this collisional system it is a convergent system.

That means it says not only the continent-continent collisional system can develop such type of mountain, it is the continent-ocean convergence can also create such type of mountain which is characteristics of the continent-continent collisional type. And the region shows the evidence of extensional back-arc basins in the past and later closed due to compression. So if you remember our earlier class where we were talking about the converging system one plate is subducting down and this is the obducting plate. So this is due to this overloading of this continental lithosphere and this angle of subduction is like this. So once it is reaching to certain depth this subducting plate it breaks down.

Once it breaks down so it becomes shallow deep. So now imagine when there were this plate was dipping at a higher angle so that means here the magmatic activities was going on and here we had this back-arc basin extensions and this back-arc basin extension so that means we are creating some horst and grabens like this and this extension was going on. But later on when this part is broken down and this plate which was subducting becomes shallow deep or about flat so that means the compression from this block it transferred to this block. So that is why instead of extension this region it expressed compression. So that means before this subduction this region of this central Andes it has undergone different phases of a back-arc extension.

So we have different sedimentary basins, horst and grabens earlier existing. But nowadays what is happening due to this convergence of this Nazca plate here and it is a shallow depth or it is a shallow deep plate which is going down. So it is experiencing a compressional tectonic regime so that the basins which were earlier formed due to back-arc extension they are now crumpled and squeezed and closed and finally there are thrustings, there are thrusts over thrusted above one another. So that is the peculiarity of the central Andes compared to the northern and southern part So studies around this Andes suggest subduction itself cannot account for the formation of the orogens. It happens only when the ocean-continent convergence leads to compression in the overriding plate that we were discussing few minutes back.

So earlier this was the extensional regime when this plate was dipping at a higher angle and due to this removal of this lower part of this plate due to breaking so plate becomes shallow, as a result this area becomes a site of compression. So that is why it is not only the subduction responsible for this mountain building it is the responsibility of this plate which is dipping at shallow angle so that this trace must transfer from the under thrusting plate to the overriding plate so that there will be deformation in the overriding plate due to compressional system. And once it happens then mountain building starts. Here at this convergent margins involve intraplate shortening, crustal thickening and topographic uplift. If you remember here we have the continental plate which is subducting down and once this part is total subducted here this is this shallow depth of dip so that this transferring of stress occur from this subducting slab to this obducting slab.

So as a result here there will be deformation and once there is deformation there will be crustal thickening, there will be topographic uplift, there will be intraplate shortening so all these characteristics they will be experienced at this part of this obducting slab. As a result what we are getting with the consumption of this intervening ocean basin the two continental systems they are colliding and finally, we are getting a collisional mountain system here. The process that control orogenesis very considerably depending upon the tectonic setting and the type of the lithosphere involved which type of lithosphere. Earlier we had a involvement of a continental lithosphere as well as a oceanic lithosphere. Now we have a continental lithosphere this side, we have a continental lithosphere this side So, the type of mountain building activity here that will depend upon which type of lithospheric plates are involved, what is the dip? what is their rheology? what is their pre-tectonic history all that is responsible for this mountain building activities.

Non-collisional or Andean type orogen results from ocean-continent convergence where plate motions and other factors controlling subduction that lead to compression and upliftment within the overriding plate. Now, what is this other factor that other factor is the dip, the pre-tectonic history, the rheology, the strength of this lithospheres that are very much important what should be the mountain type, what should be the height of this mountain, what should be the characteristics of the mountain in terms of metamorphism, in terms of igneous activity, in terms of thrusting, in terms of deformation like that. So, that is why those factors not only the plate motion which is responsible, the rate of subduction or rate of collision is responsible, but these pre-collisional history that is also very much important to define the mountain system. Collisional orogen developed when a continent or island arc collide with the continental margin as a result of the subduction and this is the reason how this continent started growing from the precambrian up to now.

Now, if you see this image here, we have the island arc, we have a subduction system.

Similarly, we have a subduction system, we have a island arc. What is happening with time, these two island arcs they are colliding with each other and forming one and similarly another new island arc is forming here and with time this island arc again it is colliding with this existing one and finally, forming a continental mass. So, these are the reasons how the continent started growing from the precambrian to now and that is called lateral accretion. If you remember our earlier class when we were talking about vertical accretion and lateral accretion, the vertical accretion mostly it is responsible for the thickening of this crust and reducing the thickness of this mantle. However, the lateral accretion it is the addition of different continental mass together and they are separated by suture zones.

So, in this case, the thickness and the positive buoyancy of the colliding plates inhibit their descent into this mantle and leads to the compression and orogeny. So, example is the Himalayan and Tibet We have this Indian plate which is colliding with the Eurasian plate and finally, we have one continent now you can say Eurasian continent. So, this existing Tethys is totally consumed. So, arc continent collision that includes belts of Taiwan and Timor-Banda Arc region in the southern Pacific. Here we have Timor and this is the Banda Sea and here there are collision between this Australian shield as well as this Timor arcs and Banda arcs.

So, this Australian shield it is the continental system and this Timor and the Banda arcs they are these arcs they are developed due to this subduction system and finally, with time this Timor arc it is colliding with this Australian shield and it is welded together and this growth of the Australian shield occurring. So, difference in the strength rheology of this continental lithosphere influence the internal variability of both collisional as well as non-collisional orogens. So, this is very much important. The strength of the rheology of this continental lithosphere and its pre-collisional history that defines how this mountain will behave, which type of mountain will form. Suppose we have a cool and strong lithosphere they are interacting.

So, this mountain range it will be of a narrow width around 100 to 400 kilometer because the stress is localized, centralized stress release. So, if you remember when we are talking about the divergent plate system or the rifting plate system, when there is a shield like Indian shield, African shield which are very cool and rigid and we are able to create this rift basin, rift basins are very narrow because the density of this plate are so much higher the rigidity of so much high that the deformation cannot transfer to a wide region. And similar thing happens here if the two continents which are strong and cool they are colliding with each other the deformation is localized and particularly around this edge of this plate. But in contrast we have a hot and weak lithosphere this delocalize the deformation and distribute the strain to a wide area and like this central Andes that is around 1000s of kilometer. So, in this lithosphere which is cool and rigid we have a narrow mountain system.

However if it is a lithosphere which is involved here is weak and hot then we will get a wide mountain system in this area. So, during orogenesis there will be magmatism, there will be metamorphism, there will be crustal melting, there will be crustal thickening, then sedimentation, erosion. So, all these that result the change in the strength and rheology of the lithosphere. So that means, at the initiation of this collision whatever these characteristics of this colliding systems will be that will change with time. As a result it will influence the orogenesis process.

So, as a result this orogenic mountain building activities the related magmatism, the related mineralization, the related metamorphism that will change with time. The gradual accretion of this continental fragment, island arcs, oceanic material onto the continental margin over millions of years is one of the reason how this continent started growing from the precambrian time that we have discussed that is called lateral accretion. Orogens that have grown sufficiently by these process over long period of time often without ocean closure generally that is called accretionary orogen. So, you can see here this accretionary orogen that how these continental systems or this island arc system they are colliding with each other without losing this oceanic system in between. So, this process is called accretionary orogen, accretion means addition.

So, it is addition of one continental system to another continental system. Mechanism of non-collisional orogenesis, it says that orogenesis at this ocean-continent convergent margin initiates where two conditions are met. What are these two conditions? The first is the upper continental plate is thrown into the compression. So, here if you see we have two systems, one is the oceanic lithosphere which is going down, another which is going down, but at a shallow dip. However, here it is going down at a higher dip that means, dip angle is around 45 degree or so, here it is 5 to 6 degree or 10 degree or so.

The first and foremost condition it says this upper continental crust is thrown into compression that means, there must be compression at the upper continental crust. But how this compression will be there in the upper continental crust? This is happening when and where there is the dip angle is less. If the dip angle is less so that means, there will be much interaction between these two plates. Once there is much interaction between these two plates so that means, stress is a transfer from these under thrusting plate to the overriding plate. As a result there will be compression in this region rather extension.

And these type of tectonic setting where it will promote extension that is called back-arc extension and the basin formation. However, here there will be back-arc compression. So, the second point is that the converging plates are sufficiently coupled. For example, if you compare to this first figure and the second figure here as the dip is very high there will be very less interaction here that means though these two plates are coupled here, but the degree of coupling is less. However, at the second figure here this angle is less so that the degree of coupling is more.

You can see the degree of coupling here. However, the degree of coupling here is very less and here the degree of coupling is very high. So, due to this high degree of coupling the stress can transfer from this under thrusting plate to the overriding plate. As a result deformation occurs in the overriding plate and the mountain building activities starts. Studies of the subduction zone in general suggest that the stress regime in the overriding plate is influenced by the rate and age of the subducting oceanic lithosphere.

Rate and age of the oceanic lithosphere. For example, if you see high convergence rate and the under thrusting of the young, thick and buoyant lithosphere tend to reduce the compression, decrease the slab dip. As a result it enhance transfer of compressional stress from the under thrusting plate to the overriding plate because if it is buoyant and hot lithosphere so that means, the buoyancy force is more it is uplifting it, it is pushing it up. As a result here it is degree of coupling is more. Similarly, if it is thick lithosphere and it is old lithosphere it is going down so that means, the degree of coupling is less here. So, that is why heat stress transfer from the under thrusting plate to the overriding plate is less pronounced as compared to the first figure.

Addition to this degree of coupling and this angle of subduction, the rate of subduction and the thickness and the age there are other factors that is the coupling of the trench and the inter-plate region and the strength of this plate and the strength of this coupling. So, not only coupling is important, the strength of coupling is important. For example, here this example was cited from this Sunda trench. Here you see this orange color dots they are the region they are indicating the degree of coupling or the strength of coupling between these two plates. However, the white regions here it is showing this strength of the coupling is very less.

So, once the strength of coupling is very high it will resist to go down or it resist to uplift. So, as a result it will accumulate this stress within that coupling zone or the within that coupled zone. So, in this region where this degree of coupling is less or the strength of this coupling is less, you will receive frequent stress energy or release of this frequent strain energy. So, that we will experience earthquake, but very less magnitude. However, here we will experience earthquake not very frequently but once it is released very high amount of energy is released.

So, the internal structure and the rheology of the continental plate, how this continental plates' internal structure is responsible for this mountain building activities. So, whether this continental lithosphere has undergone any subsequent deformation before it is taken part in this continental system or in the in the collisional system. Whether it is metamorphosed and if it is metamorphosed what is the degree of metamorphism. If it is magmatic intrusion or there what are the different magma that is intruded and when it is intruded, whether it is hot or cold. So, that means, the precondition which is experienced by this continental lithosphere before taking part in this collisional system that is responsible for this mountain building activities.

The interplate coupling at a trench, flat subduction control some areas and strong interplate coupling. The largest seismic energy released above the flat segment occurs up to several hundred kilometers inland of the trench. So, if you see here once the plate is going down at a higher angle another the plate is going down at a lower angle. So, here the degree of coupling is very high. So, that any energy which is released in this area it will affect to large distance or the overriding plate.

However, any energy which is released by the earthquake in this region, if the degree of coupling is very less it will affect up to certain distance like this. But in this case this energy which is released by this earthquake here it can affect to large areas So, the degree of coupling it also defining the region up to what or to which the seismic activity can be affected can be felt. The rheology of this continental plate is governed by the strength of this mantle lithosphere and the temperature at this Moho. So, this temperature of this Moho if it is high generally this lithosphere is weak and this lower crust and upper crust what is the temperature, what is the degree of coupling and what is the strength of this region which is separating this mantle and this crust that defining the strength of this continental lithosphere taken part in orogenesis Buoyancy forces associated with the continental crust dominate the force balance if the strength of this plate interface is low resulting in the upward movement of this forearc. Now, you see suppose we have a two plate here they are interacting and this interaction the degree of coupling is very less.

So, we have a continental lithosphere and we know it is buoyant. So, this mantle it will push it up. However, if it is degree of coupling is high so that for example, suppose one plate is subducting down here this is the oceanic system and this is the continental lithosphere and here the degree of coupling is less and once the degree of coupling is less. So, once this is going down and subducting here there will be partial melting the magma will rise and finally, as the strength of this coupling is very less here this plate it will move up. However, if this coupling is very high for example, in this case here this coupling is very high.

So, once this plate is going down so, gradually with time what will happen this type of situation will arise like this. So, that means, this plate will fold here and will go down along with the down going slab. As a result what is happening the system is going down. So, once the degree of coupling is less this system or this overriding plate is moving up. However, the degree of coupling is high the system is going down and this overriding plate which is also going down partly along with the subducting slab.

So, the tectonic forces associated with the sinking of the oceanic lithosphere it is dominant if the strength of this plate interface is high causing the downward movement of this forearc. So, either the forearc will move upward or the forearc move downward that depends upon the coupling of this two plate system here. So, now, up to which we are talking about the forearc region then what is happening at the back-arc region if this degree of coupling is different. So, in the backarc region this deformation is controlled by the absolute velocity of this continental plate. Its rheology the strength and inter-plate coupling of the trench and strong coupling result in large amount of compression in the back-arc which increase the crustal shortening and thickening and very weak coupling events that prevents the backarc shortening.

For example, that we are talking about once this coupling is very high the angle of subduction is less. So, stress is directly transferred here. So, that why we have back arc compression here. So, we will find the compressional basins here. However, if it is down and this angle of subduction is very high there will be back arc extension there will be extensional system here.

So, either there will be back arc region will be compressional deformed or extensional deformed that depends upon the coupling of this two plate systems here. The amount of surface erosion and deposition define the degree of coupling along this two plate. So, for example, surface erosion is occurring here and deposition is occurring here. So, that means, we have enough sediments. So, once we have enough sediment the sediment is going down and this uneven surface of the down going slab it is filled and once it is filled there will be very steady or smooth subduction here.

However, if this is sediment is very less. So, we have rough surface existing. So, there will be degree of coupling between these two plate will be more. So, that means, the deformation will be more and that is why once the degree of coupling is more that means, there will be compressional system and that's result we will have compressional deformation here on the overriding plates. So, a dry sediment-starved that means, we have little sediment. So, sediment starved from the surrounding region may result high degree of friction of this plate interface increasing the shear stress that leading to increase of compression.

That means, already we have discussed once there is a rough surface here that means, the shear strength between these two they are increasing and the shear strength is increasing that means, stress is transferred directly from here to here and there will be compressional deformation. And if it is sediment filled so that means, here it will experience a smooth subduction without much tectonic activity, without much seismic activity, without much deformation this plate will subduct down. So, by contrast the presence of large quantity of weak sediment, weak sediment it is here Why weak sediment? Because the sediment which are consolidated and welded with the down going basaltic lithosphere or basaltic crust of the ocean that is not affected. There is down going to this mantle or the asthospheric system there that will be dehydration and partial melting there is separate issue. But here if there is sediment is weak not consolidated or semi consolidated that can be easily scrapped up from this down going slab that will be accumulated here and forming this accretionary prism.

And once this accretionary prism is developed that means, this smooth system of subduction or the smooth subduction occurring here without much tectonic activity, without much deformation on this overriding plate. So, it may reduce the friction along this plate interface efficiently reducing the amount of shear stress and resulting the less topographic uplift and less intra-plate deformation. So, relatively smooth subduction takes place without much seismic activities and high magnitude of earthquake. But if the reverse is true that means, we do not have sediment here. So, high degree of friction is here that means, we have shear stress is more.

So, that means, we will find this high magnitude earthquakes otherwise low magnitude earthquakes are here smooth subduction is there. And the structures and rheology of the continental plate which is undergoing that depends upon many factors. So, this structure and the rheology of the continental plate which is taking part in this mountain building activities mostly the overriding plate the strength is depend upon few factors. The first is the pre-collisional history such as shortened before taking part in the orogenesis or not? If the pre-collisional history that means, whether this is an intact continental lithosphere or many times it is composed of the summation of many volcanoes. So, if there will be back arc extension before that so that means, the pre-collisional history the degree of metamorphism.

What is the degree of metamorphism here? And what is the temperature at this crust-mantle boundary? What are these upper crust and lower crust they are perfectly coupled. So, that temperature here at this upper crust and lower crust region. So, all that thickness so, all those things they are the result of this pre-collisional history which is responsible for this mountain building activities. Then the crust is intact or amalgam of different accretion segments so, that matters.

Then part of the sedimentary basins back arc basins or like that. So, if it is only this granitic to granodioritic composition or there are sedimentary basins having huge thickness of sediment here. So, uniform thickness of this upper and lower crust or there will be a variation in the thickness. Then temperature at the Moho and the strength of this mantle lithosphere. So, what is the temperature between the Moho and this crust? So, all that they are responsible for what type of mountain is going to happen, going to form. So, whether what is the degree of deformation of this mountain will be? What should be the width of this mountain range? What should be the height of this mountain range? What should be the rock type of this mountain range? That all depends upon the type of factors of this continental lithosphere which is taking part in the orogenesis.

And another factor is the delamination. Delamination we know when this plate is going down it is converted to eclogite facies and due to this eclogite facies as it is heavy this part of this lithosphere it is separated and this becomes called this process is called delamination. And due to delamination the strength of this lithosphere decreases. So, the delamination is driven by this transformation from gabbro to eclogite in the lower crust which increases its density and allows to peel off and sink into the mantle. Once it is peeled off once upon a time it was here.

So, now this part is peeled off because it is converted to eclogite facies. Eclogite it is being more dense and heavy so it will not able to survive here so it will settle down. So, once it is settled down that means the thickness of this lithosphere is decreasing and this high density material once it is removed from the system so the remaining amount or the remaining thickness of this lithosphere becomes more buoyant because mostly it is the lighter elements. So, that means the strength of this lithosphere is decreasing due to delamination. Another possible mechanism for reducing lithospheric thickness is the tectonic erosion developed by the convective flow of this mantle. We have the convective system of this mantle and once this convective system it is interacting with the lower part of the crust.

So, it is eroding the lower part of the crust. So, that means part of the crust it is removed from the lower side. So, this type of process that is decreasing the strength of this lithosphere. So, as a result this mountain building activity it is affected by this lowering of this crustal thickness. And these processes lead to an increase in temperature at this Moho which weakens the crust and allows the lower part of this crust to flow. So, now once this Moho is eroding here so gradually this part is removed and once it is removed so that means it is increasing the temperature at the lower part of the crust so, we know there is a particular limit of this temperature up to which the convection current can start.

So, once this temperature limit is exceeding so the lower part of the crust is started convective. So, once the convection current started at the lower part of this crust that means the crustal thickness is decreasing as well as the strength here at the lower part of the crust it is also decreasing. So, that means the crustal strength is gradually decreasing. So, if this type of crust it is taking part in the orogenesis that means it can easily be deformed so that the mountain will be of different characteristics. So, that means I want to say the pre-collisional history of this continental system that is much more important and the degree of coupling between these two plates that are much more important so to define what type of mountain is going to happen.

So, this is all about this class. Thank you very much we will meet in the next class.