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

Week - 07
Lecture – 34
Orogeny and Epiorogeny- II
Continent-Continent Collision

Okay Friends, welcome to this plate tectonic class. And in last class, we were talking about orogeny and epiorogeny and its special reference to continent-ocean interaction. So, in the last class we concluded that the angle of subduction of this oceanic lithosphere and the pre-collisional history of this continental lithosphere, they are important in deciding which type of mountain will going to occur and what should be the relationship between this orogenesis, the crustal thickness, the metamorphism, the basins, like the topography all those. And in today's class, we will confine ourselves in continent-continent collision. So, once we say it is continent-continent collision, it first come to our mind that is the India and Eurasian system or the Indian and Asian collision. And we all know this Himalayan is the product of continent-continent collision.

So, here if you see this continent-continent collision, it is the Himalayas and Tibet orogenesis. The Appalachians, the Caledonians, the European Alps, the Urals, the Southern Alps in New Zealand and many of these Proterozoic orogens mostly they are representing the continent-continent collision. So, here in this figure if you see, we have in a oceanic lithosphere which was subducting down and once this oceanic system is totally consumed under thrusted, so this continental mass it is coming to this continental mass together. And due to their buoyancy, none of this continental system they will move far beyond this line and finally, it is the mantle which is pushing it back and finally, it is deforming and it is producing this mountain system that is called the collisional mountain.

And here it is better depicted in this video, there is this Indian subcontinent it is moving and this is the ocean that is Tethys ocean and gradually it is decreasing and this Indian-Asia that is collision took place and finally, we are finding the Himalayas here. So, this anatomy of this belt is highly diverse in part due to difference in the size, shape and the mechanical strength of these colliding plates and their effect on the different pre-collisional tectonic history. So, once we are saying that continent-continent is going to collide, so what is their size? Whether they are larger or smaller or one is large another is small and what is their thickness? What is their age? And what is their pre-collisional history? Whether both are intact or having some basins inside, having magmatic intrusions like volcanoes, the magmatic arcs inside. So that means, the pre-collisional history as well as the thickness, its rheology, its age, all these mechanical strength, so all these parameters that is defining what should be the nature of this collisional mountain here. And continental collision can be arranged from being highly oblique to orthogonal.

So if it is highly oblique for example, here if you see southern Pacific. So that means, maximum of this movement or maximum of this interaction it is going on the slips, so it is near about sliding past with each other. However, at the northern Pacific you see, here this collision is orthogonal. So that means, maximum stress it is building up here, so that is why the mountains nature which is produced here and which is produced here will be completely different. The degree of metamorphism, the degree of deformation, the crustal thickness will be different here and different here.

So as a result, this orogenesis related mineralization will be also different. So these differences greatly influence the mechanism of this collisional orogenesis. So these differences greatly influence the mechanism of this collisional orogenesis. Now what is their mechanism of this continental collision? If you see here this oceanic lithosphere earlier it was subducting down, so now it is consumed. So, this continental part which is going down due to metamorphism which is converted to eclogite and with more and more compression the eclogite which is coming up and it is exhumed here.

So this evolution of this collisional orogen is governed by the balance among the regional and local forces and the strength and rheology of this continental lithosphere and by the processes that change this parameters with time that is very important. Suppose we have a crust having some thickness t and here this is thickness of t1 and this is t2 and we are colliding. Probably this temperature which is going down here this is geothermal gradient is different, here geothermal gradient is different, here the rheology is different, here the rheology is different. Now once they are colliding with each other, so gradually this crust is getting thicker and thicker here and due to the increase of thick due to increase of this compressional force this rheology changes with time. The heat changes with time, the geothermal gradient changes with time, the thickness changes with time.

So, that means not only the earlier parameters of this plate, pre-collisional parameters of the plate are responsible for the mountain building activities, but these parameters changes during this collisional system. So, as a result the mountains characteristics, the rock types, the metamorphism, the magmatic, the mineralization that will change with time. So, pre-collisional history that includes the strength and rheology of this continental lithosphere at the start of this continental collision is governed by this pre-collisional history of these two colliding plates. In the last class when we were talking about this continent and ocean collision, we have discussed in brief what is the pre-collisional history, whether this continental lithosphere is intact or it is composed of many volcanoes having some sedimentary basins inside, it is stretched and later it is compressed. So, like that all this pre-collisional history that defines the mountain building activities here, which type of mountain will be there.

In the case of the Himalayan Tibet origin, millions of years of subduction here and the magmatism here and metamorphism here, this part of this Eurasian system becomes weak. However, at the same time the Indian plate becomes stronger and it was become more strong and rigid as compared to Eurasian system. Now, the Indian lithosphere it is colliding with the Eurasian lithosphere. As the southern boundary of this Eurasian lithosphere was weak due to frequent magmatism, metamorphism, deformation, sedimentation like that. So, this weak zone when it is colliding with a strong zone, it is deformed heavily.

As a result during India-Asia collision, many suture zones, thick flysch sequence and other weak zones that characterize the Eurasian allowed the deformation to extend deep interior of this continent. So, that is why if you see in this cartoon, this Eurasian continent, its deformation is moving towards north. So, into deep inside is the Eurasian continent, the deformation is there. However, the deformation at the Indian plate it is confined just at the northern edge rather going inside. So, the relatively cool and deeply rooted Precambrian shield of this Indian plate resulted in a relatively strong plate that resisted shortening during collision.

So, that is why if you see here, this deformation is going on and going on and going on and you see in deep inside this Asian subcontinent, the deformation is there. However, the Indian plate only the northern edge is getting deformed and the sedimentary sequence which was deposited on the passive continental margin of the northern Indian plate, that is the loose sediments, the weak sediments. They were scrapped off during this collision and they are deformed and forming the Himalayan system. So, the Himalayan thrust fold belt, it is the result of these sediments which were deposited at the northern edge of this Indian plate. For example, if you see here, we have this Asian continental system, we have the Indian plate and in between we had the Tethys and we deposited the sediment here.

If I zoom this continental slope or continental shelf here, now what you see this is the Tethys ocean basin earlier existing and the sediments they were depositing here and it is filled with sediment. Now this sedimentary filled basin when this crumpled from two sides by this India and Asia collision, this is folded and finally, it is formed the Himalayan system here. Now the continental under thrusting or subduction of this continental lithosphere beneath another continental plate is one of the most important mechanism that accommodates this convergence in the zone of continental collision. So, this Indian craton or Indian plate it is going down and this is the Eurasian system it is on the top. So, now this is the most important part how much distance this continental system can under thrust, where it will interact with the other continental system it is in the coupling manner in this coupled manner.

So, that means, this zone this interaction it is coupling and decoupling this temperature here this degree of interaction here that define the mountain building processes. The define the seismicity, metamorphism, magmatism as well as this mineralization and the rheology of the two plates and the degree of mechanical coupling between these two that control the shortening and evolution of the stresses within overriding plates. So, now, if you see we have this Indian system and we have this Eurasian system and now you see this continental system of these two they are colliding and finally these are the weak zones they are generated and that is why this part is decoupled like this decoupling of this mantle similarly there will be crustal decoupling towards the up side. So, this is the Tibetan plateau which is now least affected by this collisional system because due to temperature increase inside this part is decoupled and becomes near about independent system. So, whatever is going on this collisional system now they are going on here and this remains unaffected.

So, now, you see the slip rates different part of this Himalayan arc they are representing different slip rates. So, here wherever the slip rate is high that means, here this coupling is less and where their slip rate is less this coupling is high that means, this area they are waiting larger earthquakes or larger amount of strain release in future. So, the resultant shortening it generates thick crust which contributes to the uplift and growth of this mountain system. Now this see how they are deformed and they are forming this mountain system. So, if it is happening so, suppose we are shortening it we are thickening the mountain system.

So, gradually we are increasing the heat inside. So, if you remember when we were talking about the heat has certain limit. So, once it increasing to certain threshold limit so that means, the bearing capacity of this rock. So, the rock started to melting and the convection process start. So, once the convection process starts melting starts so that means, it becomes weaker section weaker zone.

So, that weaker zone that means, this becomes independent. So, it is decoupled from this top. So, here if you see this is the Indian system and this is the Eurasian system they are colliding and due to this increase of heat in this side. So, this Tibetan system is totally detached and it forms this Tibetan plateau here. So, whatever the deformation is going on now they are confined in this region and this becomes near about independent.

So, conversely the plateau is associated with the high crustal temperature, wide spaced intra-crustal melting that may weaken the crust sufficiently to allow it to flow that we have discussed that how this Tibetan system or Tibetan plateau is detached from this ongoing collisional systems. This process may decouple the crust from the underlying convergent motions and may alter the dynamics of this orogen like this Tibetan plateau that we have discussed. Now there are three terms one is indentation, lateral escape and gravitational collapse. What is their role in this plate tectonics and this continent-continental collisional system? So, to discuss that we should know what is indentation and what is this lateral escape? and what is this gravitational collapse, where they occur, what is the requirement for this? So, this shortening deficit that is 500 kilometer to 1200 kilometer derived from this total amount of convergence between India and Eurasia and the total amount of shortening accommodated by fold-thrust belt in the orogen since their collision lead to this idea of indentation. So, indentation simply nothing it is the intrusion of a stronger material into a weaker material.

For example, this Indian lithosphere which is strong and rigid it is pushing this weak Asian lithosphere or this Chinese lithosphere from this northern side and this part is going down and finally, deformation is here and it is thickness is gradually increasing if you see the thickness is gradually increasing and finally, this is the decoupling occur and there will be decoupling also at the top as a result this Tibetan plateau is occurring. So, indentation is nothing it is the process by which a rigid block presses into and deform the softer block during the convergence. So, here it is pushing this system there was an experiment which was carried out by gentleman we will discuss later. So, how this indentation experiment and the theory of indentation could address and this issues that is related to this convergent boundary or this is collisional boundary. So, this could address the following questions.

What are the questions? Where this shortening had compensated? That means, this shortening deficit about 500 kilometer to 1200 kilometer how they are compensated that can be addressed by the indentation process. Second question it is addressed why the eastward extension of the landmasses if you see this Himalayan system you see this there will be extension to the east you see the GPS movement so, here the GPS movement is NE-SW or north-south but if you see the GPS movement here all the GPS movement that is showing the eastward movement. So, that means, this is the eastward extension of this Himalayan system. So, this why this eastward extension of the landmasses is occurring. Then third question it could address why the dominance of a sinistral strike-slip faults in Asia? we have different fault systems.

So, why this sinistral strike-slip faults are there and why most of these faults are curved if you see here there are most of these faults or the most of the larger fault rather you can say they are curved rather straight. So, these questions could easily be addressed by the indentation experiment. So, this indentation experiment was carried out by Tapponnier 1982 that explored the effect of indentation as a rigid 50 millimeter wide block that is exemplified as India. It is penetrates into the softer rock like Asia made up of laminate plasticine. So, plasticine is a material generally used for modeling.

Now the slip lines that is dextral and sinistral strike-slip fault they are representing the different strike-slip fault. For example, here we have a thick rigid system. Now this is the soft system and we are pushing it northward and what we are getting here we are getting this curved faults they are cross-cutting each other. So, here similar experiment is explained we have a indenter which is pushed northward and finally, we could create the deformation line. And here we are creating a part of this soft material which is intact with the hard material here and in the triangulated shape that is called dead triangle.

So, that easily this part becomes a part of this one and it moves along with the northern edge of this indenter. So, that is called dead triangle. So, now what is its products? Now you see we have a rigid block that is India and we have a softer block that is Asia and we are pushing it northward. So, once we are pushing it upward or northward you see there are deformation lines they are formed and with subsequent formation of the deformation line the first line it is bed. Suppose for example, it is forming at an angle of 25 degree.

So, with subsequent development of further line this is again it is curving here southward. So, that means, new and new blocks once it is added by faulting the older blocks they are gradually rotating southward and becomes here becomes to this side of this indenter and same thing is happening here that once the Indian subcontinent is indenting into this Asian lithospheric system the faults are developing here and the old faults they are rotating and this part becomes the rotated part from the Himalayan system. So, this is analogous to this experiment that the how indentation experiment could address the Himalayan disposition and the fault system which are generated at the Asian plate at the northern edge of the Indian subcontinent. So, the two experiment was carried out where the plasticine is bilaterally confined and two edges parallel to the motion of the indenter. So, here you see this two confined edges there and this indenter is gradually it is moving inside.

So, what is happening you see there is a undeformed sequence that is called the dead triangle that we have discussed and after this dead triangle we are creating some faults like that, that means, some sinistral as well as some dextral curved fault. So, once this curved fault are developing here and the indenter is going down the deformation is mostly confined at this part because both sides it is confined both side this plasticine is confined. So, it produces a symmetric pattern of slip lines as you see here symmetric pattern of slip lines are there and ahead of a dead triangle. Dead triangle what is we have already discussed this is a triangulated region of dead material bounded by two conjugate slip lines and moves with the indenter without internal deformation that rapidly welds into the indenter. Now you see this is not getting deformed this is intact.

However, it is deforming the parts which is just ahead of it. So, the second experiment that is unilaterally confined that means, confined at one side and other side is free. So, what is happening? at only one of this edge that is Indian plate and it is the Asian features it case generates an asymmetric pattern of slip lines where the faults that allowed displacement towards the free edge predominant such as F1. For example, here this side is confined only and this side is free. So, once the indenter is going inside so, it could develop some slip lines for example, this first developed here and with the further and further move of this indenter it could generate the second one that is F2 earlier it was created F1.

So, here you see first phase it could generate F1 and with further intrusion it could generate F2 once the F2 is generated the F1 is rotating and this block which was separating by this F1 it is now rotated towards the south and now it is coming close to this indenter. So, the block which was translated sideways rotates about 25 degree clockwise and it is followed by this extrusion of a second block another sinistral fault that is called F2 which allows the continued rotation of this first block about 40 degree. So, that means, here it is not the symmetrical faults that is creating earlier when there was a confined system from both side symmetric development of faults was occurring, but however, once it is one side unconfined like analog to this Indian and Eurasian collision here only one side faults are developing. So, pull-apart basins develop along the sinistral fault because of their irregular geometry, we can revive our class when we were talking about this conservative plate boundary, when we were talking about this faults or this strike-slip fault if it is not straight the fault line is curved we could generate this pull-apart basin the positive flower structure the negative flower structure. So, similarly once we have this sinistral strike-slip faults and if this fault line is curved like this, so we could generate some pull-apart basins here.

So, here this analogies to this discussion is expressed in this image. So, these are this pull-apart basins which is formed due to this extension or this is the negative flower structure. So, this pull-apart basins are here and this is the structure may be analogous to the extensional regime of the Shansi, Mongolia and Baikal all are the pull-apart basins. Then the Altyn Tagh fault here this is the Altyn Tagh fault and this Red River fault here the Red River fault they are analogous to this sinistral fault which are rotated. So, this Red River fault that can represent to F1 which was generated first and this Altyn Tagh fault we can be represented by F2 which is generated second.

Once this Altyn Tagh fault it is generated, so this earlier formed Red River fault it is now rotated and due to this rotation this part of this segment continental segment is rotated completely about 40 degree and becomes close to this indenter. So, this is analog to this indentation experiment which was carried out by Tapponier. The comparison also suggests that the indentation causes a curvature of fault lines or fault system located at the tibet. Now you see how this fault system at the Tibet they are rotating here then further rotating then further rotating like this. So, although this experiment explains the general pattern of distribution of the strike-slip faulting in the eastern Tibet and the southern Asia it has been less successful in explaining other aspects of deformation.

So, what is this other aspects of deformation? What this experiment could not explain? This problem 1 is it predicts the lateral displacement of 100 to 1000 kilometer on the large strike-slip fault within the Tibet, but actual measurement of the displacement is very small around 50 to 300 kilometer. For example, this Altyn Tagh fault around 200 kilometer displacement then this fault having 50 kilometer around displacement. So, these observations suggest that while a lateral escape is occurring it may occur on a smaller scale that the original predicted from the experiment. Second problem lies it does not take into account the effect of variation in crustal thickness during deformation because during deformation the thickness is increasing, but here in this experiment this increase of this thickness is just not taken into account. So, in addition to that the east west extension of normal faulting in Tibet has no analogue in this model, but one possible explanation for this east-west extension is due to this gravitational buoyancy force.

So, once we are increasing the height, we are increasing the thickness the gravity will work automatically. So, there will be a deformation and there will be that means, extensional deformation due to gravity so that normal faults can be explained. So, that is why this gravitational buoyancy forces associated with the great thickness of the high elevation of this plateau compared to the adjacent lowland area. So, once we have high elevation plateau is there we have thick sediment. So, due to gravitational collapse some normal faulting may be developed.

So, lower crustal flow and the ductile extrusion. So, here you can see a vertical stratification of the lithosphere into strong and weak layer influence the degree of strain localization during convergence. Where the lower crust is relatively strong and resist to flow, the crust tends to couple with the underlying mantle during shortening and results a relatively narrow zone of localized strain and at the surface. So, eastern and southern alps New Zealand it is one of this example. However, with contrast where there is a lower crust is relatively weak and it is easily flowing the crust decouples from this mantle and results to diffuse the strain that is the Tibet So, that means, when this temperature is rising once the temperature is large enough so that part of the crust or the crustal segment it decouples from this mantle. So, that means, whatever is going inside below it, it hardly affects or less effect is there on this detached part.

So, this happens in case of Tibet So, here you can say this Indian plate which is going down and this is the Eurasian plate. So, this is the Tibetan system it is decoupled due to this heat generated in this region. So, now, this part becomes independent and whatever the collisional activity is going on here whatever the changes are occurring here. And the another example is the eastern alps here the subduction was going on. So, it is further subduction now you see how the system is generating.

So, this part becomes separated and here it is colliding and it is folding occur and due to increase of heat. So, some part is detached and that is why this decoupling is occurring. So, this eastern alps and Tibetan plateau they are this example of this continent-continent collision. So, thank you very much. We will meet in the next class.