Plate Tectonics

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Week - 02
Lecture - 10
Continental Crust- II

Okay friends, welcome back to this class plate tectonics. So, in the last class we are talking about this crustal behavior, crustal nature particularly the continental crust. And to an add to this discussion here we will talk about the rheology of the lithosphere, how the rheological properties of the lithosphere varies laterally and vertically and what conditions there will be a lateral variations. Either there is a fault zone, there is a collisional system, there is a rift system or there is a boundary of this transition zone between this continental crust and the oceanic crust so, we will discuss in this class. So, the behavior of this continental crust under this stress it depends upon the temperature and the duration of the stress. For example, if you talk about this collision of India and Eurasian system, we have this stress from both sides that means the Indian plate is moving northeast and the Eurasian plate is moving towards southwest and how it will behave this collisional zone, this crustal system how it will behave there that depends upon the temperature there.

So, the temperature is playing a major role there to define what should be the crustal behavior and the duration of the stress whether the stress is long lasting or the stress is for a shorter geological time. So, that defines what should be the behavior of this continental crust under that stress regime. For example, if you see here this is the dry lower crust and mantle lithosphere and it is wet lower crust and mantle lithosphere. In dry conditions if you see we are having a granulite around 30 to 40 kilometer depth and this is strong enough.

Similarly, olivine it is occurring below this moho and it is also strong and dry at the upper mantle it existing. However, the same condition if it is the presence of water this is wet condition is there. Now you see it is the strength increasing in this axis. So, if you see here this is restricted up to this so that means the strength is up to this. So, that means the upper crust it is behaving simultaneously or similarly as in case of the first image.

However, once you are coming to this lower part of this crust it is weak and wet lower crust we are creating. However, contrasting to that here we are creating a strong and elastic lower crust and if you see the strength is increasing in this axis here the upper crust is less strong or it is weaker than the lower crust. You see the strength is up to this level. However, here the upper crust is more strong as compared to the lower crust. If you are going beyond the moho if you see here this is strong, dry, upper mantle and it is high strength is there.

However, here the strength is again decreasing. So, that means in the wet regime the crustal behavior it is gradually the strength decreasing from the upper to lower crust. However, in the wet region this crustal behavior it is like that that the strength is decreasing from this upper crust to lower crust. However, in the dry region the crustal strength is increasing from this upper crust to lower crust regime. And the distribution of the strength with depth in the crust varies with tectonic setting.

Then it is strain rate, its thickness, this composition of this crust and the geothermal gradient. So, all these parameters that define how this strength distribution of the crust should be and it is clear from these two images depending upon its dry and wet condition and similarly the mineralogy also changes and the strength varies. Now, let us talk about the brittle-ductile transition zones. In the brittle-ductile transition zones it is corresponding to an average surface heat flow of about 50 milliwatt per meter square. It is about 30 kilometer depth which is also corresponding to the depth limit of the most shallower earthquakes.

So, this transition zone here you can see it out around to 50 milliwatt per meter square it is the heat flow is experiencing and it is lying around here around 30 kilometer depth. Even in the lower crust however, if stress is applied rapidly it may deform by fracture and likewise the pore fluid are present in the upper crust weakening it and the stresses are applied slowly the upper crust may deform plastically. So, that means, there is no universal role depending upon this stress condition depending upon the duration of the stress and how rapidly or how slowly we are experiencing stress there and the presence of pore fluid is there or absence is there. So, the lower crust may behave like a upper crust and the upper crust may behave like lower crust. So, that means, even though the lower crust if the stress is applied rapidly it deform by fracturing.

So, fracturing it is a characteristics feature of the upper crust regime. However, the lower crust is behaving like upper crust if the stress is rapidly applied to there. So, this lower crust and upper crust depending upon their conditions, pore fluid condition, rate of applied stress, duration of the applied stress may behave alternatively. For example, if the lower crust is stress is applied to the lower crust very rapidly and it can be deformed by fracturing. However, the upper crust which having the pore fluid pressure if it is slowly pressure is applied or stress applied it may behave plastically.

So, that means, the upper crust and the lower crust their nature of deformation that depends upon the stress regime, depend upon the pore fluid pressure, depending upon the how rapidly or how slowly this stress is applied to them. The reasons of low heat flow such as shields and platform brittle fracture may extend to the lower crust even into this mantle because mafic and the ultramafic rocks can very resistant to plastic failure at this depth and thus brittle faulting is very much common and the only way that can deform. So, that means, this shield and platform these are representing low heat flow regions, rift basins they are representing high heat flow regions. So, that's why if these regions this crustal deformation occurs the fractures are developed these fractures can penetrate up to this lower mantle region or this mantle part because the resistant rocks are there they are very resistant to plastic failure that's why brittle failure that can adapt very easily that's why that can extend the fracture to this mantle or even to the upper mantle up to this upper mantle. So, if you see here this is the temperature and this is the depth and how this is heat flow, this is the dry solidus and this is the pyroxene geothermal field and these are these regions how this geothermal system is varying.

So, this shield area if you see here this shield is representing the lowest one this is the region of low heat flow that means, low geothermal gradient is experienced here. So, the brittle-ductile transition occurs at relatively shallow depth in a warm and young crust it is around 20 kilometer depth, but if it is old crust that is the particularly the proterozoic shield area is here that is brittle-ductile transition that is occur around 30 kilometer depth. So, depending upon its age either it is a younger crust or it is a older crust the brittle-ductile transition as it is temperature dependent the phase change is temperature dependent that is placed either it is a shallow level or it is a deeper level that depends upon the age of this lithosphere. The rapid increase in strength beneath the Moho reflects chiefly the increase in olivine which is stronger than pyroxene and this feldspars. So, once we are reaching this beyond the Moho there is a strength rapidly increasing.

So, this is indicating the presence of olivine there rather than pyroxene and feldspar which are relatively less strong as compared to olivine. In both cases the strength of the ductile lower crust decreases with increasing depth reaching to a minimum at this Moho. So, that means, if the strength of the ductile lower crust is decreasing and it is at the increasing depth and reaching at the minimum at the Moho. So, once the Moho reaches the strength again increases and that increase meant is due to this presence of olivine. Now, another point regarding the crust that is called exhumation and cratonization.

What is exhumation? Exhumation means which was earlier at the deeper level now it is coming to a slower level this is called exhumation. And cratonization that means amalgamation of cratons crustal deformation and finally, amalgamation of one cratonic part to another cratonic part. So, forming a full-phase craton that is called cratonization. So, the exhumation it refers to the process by which an area or rock mass that was formed or formerly buried it is approached to this earth surface. So, this is the process of exhumation earlier the rock was at lower level now it is coming to this upper level if you see this figure here this is the points where the deep metamorphic crust was there either there is a faulting and due to the faulting this system is going further down and this is further down and here due to the stretching of the system this mantle is coming up and finally, this metamorphic rock or high grade metamorphic rock which was earlier at the lower regime they are coming near to the surface.

Similarly exhumation of the deep crust if you can say this crustal material which is coming close to the surface due to decompression due to releasing of the stress particularly along this rifting systems where this crust is stretched. So, this mantle material it try to move up try to expand. So, that's why it is coming up that is called exhumation. So, exhumation is nothing by crustal deformation by this exhumation of this mantle material the lower rocks types which are earlier existing at the lower crustal level they are coming close to this surface that is called exhumation. However, it differs from this rock uplift and the surface uplift that is explicitly measured relative to the surface of this earth rather to the reference to this geode.

However, the exhumation is measured with reference to the geode. So, there is a local upliftment or there is a local subsidence we cannot say it is an exhumation process. For example, suppose there is groundwater extra extradition and finally, overexploit of this groundwater this area is subsiding and the nearby area is uplifting relative to this cannot be called as exhumation. So, exhumation is a large scale process it affects the gravity and overall system of this earth. So, it is affecting the geode system the gravitational system of this earth that is exhumation and mostly this is the density difference between the surrounding area and the area which is exhumed because those rocks which are exhumed earlier which was residing at the lower crustal level they are more dense as compared to the surrounding if it is coming close to the surface.

The process by which cratons are formed that is called cratonization. If you remember our earlier class we are talking about this lateral accretion and vertical accretion. Imagine in the pre-cambrian time when this crustal thickness or the lithospheric thickness was very small and due to the early phase of differentiation we created some felsic crust of smaller size and they were randomly navigating from different directions and they are amalgam with each other and finally, the size increased this process is called cratonization process. Though there is much uncertainty remains about this process the first craton landforms that likely formed during the Archean eon and it is completed during the Proterozoic. Subsequent growth of continent was due to this accretion at this continental margin like this India and Eurasia they are colliding it is accretion process it is at the continental margin.

So, here one continent another continent and with time you see these two continents or three continents they are amalgam together and this is representing a suture zone. So, that's why at present day if you analyze this cratonic system you will find number of suture zones existing these are nothing these are these areas or these are the lines through which these different cratons they were amalgam together during this cratonization process and finally, it is forming a full-fledged continent or full-fledged craton. So, during this continental collision large segment of the continental crust they are highly deformed and thickened and later they are uplifted and eroded to form this craton and this process is called crustal evolution. This crustal evolution it is better understood you can see from this figure here this is the Hadean time and here this is the enriched Rb/Sr crust and this is the lithospheric mantle the red color is the lithospheric mantle and this is the Hadean mafic crust. So, with time we are reaching from Hadean to Eoarchean time what is happening is this thickness of this lithospheric mantle it is increasing.

Similarly, the thickness of this Hadean or Eoarchean mafic crust it is increasing and finally, what we are creating we are creating mafic volcanism which is reaching from here to here and with further increase of time we are reaching at the Meso- to Eoarchean and finally, what we are getting it is the TTG crust forming and this system that is the dense mafic crust is here and some part it is going down due to this gravitational collapse it is going into this mantle and finally, this is the full-fledged cratonic composition. So, that means, from the Hadean time through Eoarchean through meso-archean the crustal system evolved both compositionally both dimension wise. It becomes thin to thick and similarly in the two dimension that is in the areal extension from small to large and Similarly compositionally it evolved from different composition to a different composition. So, this process is called crustal evolution both size wise composition-wise how the crust changed with time this is called crustal evolution and these crustal evolutions they are imprint within the metamorphic rock within the structural signatures so, this structural signatures and the metamorphic signatures they are better indicator of this crustal evolution and followed by this magmatism. If it is there that different phases of the crustal evolution they are ended with or they are accompanied with certain magmatism.

So, that can indicate with the time sequence how, when, which time this crustal evolution that occurred. So, crustal evolution is imprinted in rock as a pressure-temperature time trajectories generally referred to as PTt path it is pressure then temperature this is time. So, that means, at what pressure it occurred at what is the temperature that time and when it occurred this is time. So, that's why this time temperature and pressure these three components they are studied for the studying or for the understanding the crustal evolution. Burial of rocks in the earth's crust result progressive metamorphism with loss of water and volatiles and producing almost anhydrous rock and the metamorphic rocks.

So, here with if you see we are going to a higher temperature regime from the low temperature regime and finally, we are creating metamorphic rock relatively high grade into the depth. So, here with the slate, then phyllite then schist, gneiss then migmatite. So, gradually once we are going to depth the degree of metamorphism increasing and the metamorphic mineral assemblage may record the highest PTt regime to which the rock have been subjected later exhumation makes it possible to study this information directly. So, once upon a time those rocks which are at depth for example, here this migmatite which was in the depth. So, this migmatite it has to come to the surface either due to thrusting or due to stretching once we are stretching the system is coming up.

So, either way once it is coming to the surface it is giving us this natural samples to study this PTt regime at this depth. So, these are the ways how this crustal evolution can be studied. However, minor changes that occurred during the retrograde metamorphism may be identified by studying the textural features. So, we know there are two types of metamorphism prograde and retrograde. So, retrograde is nothing when we are reducing the temperature-pressure.

So, it is coming to retrograde metamorphism and this retrograde metamorphism can be studied by the textural features. These textures are the key things that indicate how this retrograde metamorphism works on the rocks. So, using experimental petrology and oxygen isotopes data it is possible to estimate the temperature-pressure at which the metamorphic mineral assemblages that crystallize and the burial depth of metamorphic terrain exposed to this earth's surface can be estimated. For example, if you see here these are these experimental petrology laboratories how people are working this creating magma they are creating this new rocks from this old rock with increasing temperature and pressure. Similarly, we are reducing temperature and pressure from the older rock that means, from the high-grade rock they are creating the low-grade rock.

So, that means, everything is understood through laboratory process. So, this laboratory process that can substantiate the field process that we are looking at the field from this oxygen isotope data and from the experimental petrology these are substantiating to each other. So, minerals that form along different segments of the PTt path and become isotopically closed at a given temperature and they are dated isotopically or add time to this event. So, time is very important event like temperature and pressure time is very important event determine when it occurred at what geological time this crustal evolution occurred whether the crust has evolved at one phase or there are different phase of evolution finally, the resultant crust is in front of us. So, that's why time is very much important and different degree of this evolution or different phases of evolution they leave different imprints that indicate when it occurred and what was the temperature and pressure regime.

For example, if you see here there are two PT path or PTt path is showing here one is moving clockwise and another moving anticlockwise what does it mean? For example, here it is A it is represents the rapid burial and uplift path typical areas of continental convergence that means, it is a collisional system rapid burial is there less temperature is there that means, we are reaching at the highest pressure rapidly rather reaching at highest temperature. So, this is the characteristics feature of this burial system or this is a collisional mountain system. However, the other one the represents heating and burial in response to regional scale magma intrusion followed by prolonged cooling and slow uplift these are representing the rifting systems because magma is supplied below here temperature is more dominant than pressure. So, one is moving clockwise another moving is anticlockwise. So, two different PTt path that indicates two different geological condition different geological stress regime and this crustal evolution history.

Diffusion experiment have confirmed a few mineral closure temperature and those mineral closure temperature they are crucial to determine at what temperature this occurred. For example, this argon 40/39 that method can be used for the hornblende dating which close the argon diffusion at around 500 degree Celsius, muscovite that closes at 350 to 400 degree Celsius, K-felspar around 150 to 350 degree Celsius, fission track which is anneal in apatite around 150 degree Celsius. So, that means, these are the closing temperature if we have these minerals by this closing temperature we can determine when this crustal evolution occurred at what temperature it occurred. Thus, to unravel the PTt histories of the crust it is critically necessary to combine the results from the field, petrography, experimental dating and the isotropic studies. Because this laboratory experiment laboratory data must has to substantiate with the field evidence.

So, once they are converging and they are supporting each other that means we have interpreted the crustal evolution rightly. Though cratons have long been recognized in the important part of this continental crust their origin and evolution are still not well understood that's why we are doing so. Why we are going for this crustal evolution? Because we have not understood it clearly till yet though we have cratons starting from the pre-cambrian to recent, but still this process how the cratonization occurred how this PTt path is behaving we have not understood yet. That's why we are doing some laboratory experiment, some experimental petrology, we are going for field and we are doing field works, we are doing thin-section analysis all these things they are converging together to study this crustal to understand the crustal evolution. Most investigators agree that the cratons are the end product of collision orogenesis and thus they are the building blocks of the continent.

Just how orogens evolved into cratons and how long it takes however it is not known yet. So, that's why we are continuously engaging ourselves to unravel this crustal history, the evolutionary history how the system change from one to another. Using a variety of radiogenic isotope system and estimated closure temperature in various minerals it is possible to track the cooling histories of the crustal segment and when this coupled with the geothermal barometry this uplift and exhumation history can be established. So, even then the multiple deformation and metamorphism many possess difficulties and uncertainties about these complexities because it is not one event multiple events they are superimposed on one another. So, to understand that we have to gradually unravel one after another.

So, we have to reduce the degree of uncertainty. So, that's why mineral identification and experiment and this field observation all these things are very much necessary. So, that's why to unravel this crustal evolutionary history the laboratory as well as the field that has to be combined together. Now, the PTt path of the collisional orogen are typically clockwise as we have discussed few minutes back and the PTt space and are reasonably well understood from the classic studies different mountain systems like this Appalachians, Caledonides, like the Himalayas, Alps like that. So, here if you see we are reaching the maximum pressure and before we are reaching the maximum temperature. So, maximum temperature we are reaching for example, here the maximum temperature is here before reaching the maximum temperature we are reaching the maximum pressure.

So, how it is possible? That is possible due to this collisional system because in the collisional system pressure is a dominant factor. So, we are reaching maximum pressure before reaching the maximum temperature. This type of PTt path results from the rapid crustal thickening so that the maximum pressure is reached before the maximum temperature arrived. Hence, the metamorphic peak that is generally post-dates early deformation in this orogen. So, this type of PTt path it is very common in the collisional mountain system.

The evolutionary path commonly leads to dehydration melting of this lower crust producing granitic magma, which is very common in collisional mountains because we know this Ladakh batholith it is a result of collisional mountains. So, this granitic magma it is occurring due to dehydration melting of the lower crust and emplaced here. So, this dehydration melting which is a characteristics phase or characteristics properties of this collisional mountain system and which is the product is the granitic magma and that leads to the emplacement of large scale batholiths along the collisional mountain system. Another one it is the continental rift it is the crust is heated from below by mantle upwelling before crustal thickening occurs and thus the maximum temperature is reached before the maximum pressure is reached. And this produces a counter-clockwise PTt path the metamorphic peak usually predates or it is synchronous with the early deformation in this cases.

If you see here we have a rift system and we are supplying this magma from below here temperature is playing larger role compared to the pressure. That's why this PTt path is like this it is moving here it is this is the anti-clockwise system. So, that's why this counterclockwise system PTt path is observed in terms of rift basins and mostly this metamorphic peak usually predates or it is synchronous with the deformation of this cases because where temperature is reached at the peak much before than the pressure and this is the characteristics of the rift system. Heating of this lower crust can lead to dehydration melting as a consequence of metamorphism and produce felsic magma and any crust heating precedes thickening the crust results in the counterclockwise PTt path. In addition to rift that extended margin of the platforms then magmatically under plated crust such as beneath the continental flood basalt have counter-clockwise PTt path So, not only the rift basins so, this counter-clockwise PTt path we have these extended margins of the platforms then marginally or magmatically under plated crust they also showing similar counterclockwise PTt path as the rift basins.

In some instances, clockwise and counterclockwise PTt path they occur side by side. For example, if we think about this subduction system and the back-arc basin system. The subduction system we have the pressure is more dominant here and this stretching system here the temperature is more dominant here. We are getting a counterclockwise PTt path here.

However, we are getting a clockwise PTt path here. So, the counterclockwise and clockwise PTt path they are placed side by side and it happens and it is common in the subduction zone system where the back-arc basin is actively being developed. Now, if you see this two images here this is showing the cooling history of this two separate systems. In (a) if you see it the over printing of the post-tectonic granite intrusion. Now, you see this was the cooling history had it not been there this peak is not been there suppose there is a granite intrusion here at this granitic intrusion. So, it was cooling like this, but due to this intrusion of the granite this there is a deviation from this normal pathway of this graph.

Similarly, in (b) it is a complex multiple event of cooling history that is final exhumation it age S and it is suturing age in terrain A and B. So, we have this complex cooling history because multiple intrusions are there it is not very simple if you see here it was cooling like this and finally, it is super cold here then it is increased that means, there is an intrusion. Similarly, it was cooling very rapidly, but again there is an intrusion then there is a constant then it is moving like. So, that means, I can say the crustal evolution that we talk about it is not very simple thing. So, there are many phases of crustal evolution which was disturbed by magmatic intrusion disturbed by metamorphism, folding, thrusting like that.

So, due to that it is not a simple history the crustal evolution establishing the crustal evolution history is not very simple it is a complex thing but the beauty of this system is that we have to take the help of the field as well as the laboratory suits so, that this laboratory experiment, result and the field observations both should substantiate each other to unravel the crustal evolution history. So, the result suggests a wide variation in cooling history of different continents. For example, if you see here this is the orogen having cooling rate mostly that is 2 degree Celsius per million years. However, there are some exception like this southern Brittany. If you see it is this cooling history is showing greater than 10 degree Celsius per million years.

So, now, if you see here this is the southern Brittany this one you see this cooling history is very high it is cooling very rapidly. However, all others they are following a particular path. So, this why this exception is there, why the rate of cooling somewhere it is fast, why the rate of cooling is somewhere it is very that means normal so, that depends upon this magmatic system and away from this convection system that will be studied in detail in the next class or when we will talk about the subduction and this convection system of the mantle. Some terranes such as this Enderbyland in Antarctica have very long perhaps the exiting complex cooling history lasting over 2 giga years. So, this cooling history as we have discussed it is not same throughout all this continent.

Some of these continents some of these cratons they are cooling very rapidly and some are cooling very slowly. And that depends upon many factor that will be part of separate class. So, many orogens such as Grenville orogen in the eastern Canada have been exhumed as indicated by unconformably overlying sediments which is reheated during the subsequent burial and then re-exhumed. So, that means, it is not a single phase there are many phase of burial there are many phase of exhumation. So, a crust evolved through like this it is not a simply that it is subducted and simply it is come back due to exhumation.

Many phases of exhumation many phases of burial that is undergone and each phase of burial and exhumation it leaves certain imprints that this research can unravel this crustal history of that region. Still some important questions regarding the cratonization process it is remain unresolved. The first is how terrain that amalgam during continental-continental collision evolved to a craton? Because this is the terranes that evolved during this Precambrian time how it become a craton that is unanswered question. Does each terrane maintain its own identity and have its own cooling or uplifted history? or alternatively do the terranes anneal to each other at an early stage and entire origin cooled and elevated to a unit? And what is the effect of this widespread post-tectonic that is Plutonism Does it over print their eras the importance of segments of orogen cooling history? So, these are the few questions they remain unanswered and people are working at different segments on it to answer those questions. And finally, you can say on not only daily basis, but monthly basis new and new theories are coming out how the crust evolved and what should be the final outcome that will be studied once the new research there adds new data and new understanding to the existing one. So, thank you very much. We will meet in the next class.