Plate Tectonics
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Week - 01
Lecture - 05
Interior of Earth- V

Okay friends, welcome to this class Plate Tectonics. So, in the last class if you remember we are talking about this interior of this earth, what is their composition and how this composition helps us to determining this product that we get during the plate interaction. So, apart from that composition there are many factors which are important to know before going to actual plate interaction session. So, those parameters are heat, pressure, so like that. So, today in this class we are going to discuss about the heat production in different types of crust or the lithosphere and how this heat is behaving during plate interaction and what is its product and what is its influence on the plate interaction. So, continue with that heat production and flow.

If you see this surface heat or the surface heat flow in the crust, it is totally controlled by some factors and it is not uniform throughout this globe. If you see here many segments of this crust they are high heat region, similarly these regions they are representing the high heat regions. However these regions which are in blue part it is representing relatively cool region. So, now the question arises why such uneven distribution of heat and second thing that very carefully if you see here most of this heat generating regions or high heat regions they are coming under the mountain building environment.

So, here we have the Himalayan mountain systems, alpine Himalayan belt, here we have this Andes Rockies like that. So, that means here these tectonic belts they are producing more surface heat flow as compared to the other part of this system. Similarly if you see here this East African rift valleys that is the rift systems they are also creating more heat compared to the other part of this globe. So, that means the mountain building systems that means the convergent plate boundaries, the divergent plate boundary to certain extent they are demarcated at the high heat flow regions on the earth. And this heat flow and the heat production it decreases with the crustal age.

So, that means those crusts which are of Archean time so, mostly the continental crust because we know this oceanic crust they are recycling and mostly the oldest live oceanic crust is up to cretaceous that we found nowadays. So, here this age is inversely proportional to the heat production that means if its age increases the heat production is decreasing. Heat flow on the continent and islands varies as a function of age of the last magmatic event and the distribution of the heat producing element and the degree of erosion level so, now here if you see there are three factors discussed one is the age of last magmatic event. So, you know when there is magmatic event there is increase in heat system. So, if the last magmatic event it is near to the present time that means this region is experiencing high heat flow and the distribution of heat producing element how the heat producing element particularly the uranium, the thorium, the potassium how they are distributed are they uniformly distributed or depth wise they are distributed to certain layers or even in the surface they are concentrated in particular zones that depends upon how much heat can flow on the surface of the earth in a particular region.

If you see this graph it is the total heat production and here the uranium it is producing more heat and it is from the beginning of this earth 4.6 billion years up to now that is the zero time and if you see earlier time that means from the beginning of this earth uranium it was producing more heat and followed by we have potassium and thorium it is more or less constant though there is a decrease in the system, but still it is more or less constant compared to the potassium and uranium. So, that means it says these three principal elements their distribution and concentration that indicates how much heat we can feel on the surface of this earth as heat flow. Now potential scenario for this concentration of the heat producing element if you see here it is the depth and this is the concentration of this uranium thorium and potassium. Now you see near to the surface the potassium is much much more as compared to thorium and compared to uranium and similarly if you see here we have a altered zone or it is the weathered zone that is the upper crust mainly granite.

So, here we have magmatic and metamorphic water circulation. So, that's why if you see here the heat production as well as this the depth wise this alteration zone and the weathering zone and this rock composition that it says there is a relationship and here the radiogenic heat concentration it is it was shown in this map if you see here, here the red regions they are representing the radiogenic heat more. So, that means you can say this uranium, thorium, potassium the concentration of the heat-producing element they are mostly they are concentrated here as compared to the other part of this globe. Now, here this typical concentration of radioactive element and heat production of some rock types if you see here different rock types that is granite which is the most composition of the upper crust if you remember it is granitic to granodioritc composition the upper crust. Then we have tholeiitic basalt that is the ocean surface then we have alkali basalt then we have peridotite which is the layer 4 and there is average continental upper crust, average continental crust, average oceanic crust and undepleted mantle.

So, if you see this concentration of these elements uranium it is 4 here and here if you compare the other litho units it is less. Similarly thorium it is more here and other litho units and other types of environment it is less. Potassium it is more here and here it is generally less. So, that means, it says the granite rock it is the most mineral which are concentrated here that is the heat producing element. So, this granite is accommodating most of the heat-producing element.

Similarly heat generation if you compare here uranium, thorium, potassium and total It is the total heat generation this unit is given here the total heat generation in granite is here then other minerals or other rocks it is compared to that. That means, this mineral which are producing heat that is highly concentrated in the granitic body. Similarly the heat-generation in the granite is maximum and the density is less and this heat generation is this much. So, that means, we can say mostly where we will find the granitic body that are mostly the heat production is more. Now, come to this previous slide if you see here most this area it is representing a convergent plate boundary one plate is going down and these are the volcanoes this Andes and Rockies mountains are there.

Similarly, we have Himalayan mountain belt. So, it is a collisional zone. So, most of these granitic rocks they are emplaced here during subduction. So, that's why these regions are remarketed as high heat production environment. Similarly if you see the relative abundance of isotopes in the crustal heat generation in the past relative to the present.

So, in the present if this is one in the past that means, if it is given it is 3500 million 3500 million years, So, it is 1.75. So, that means, almost double. So, that means, in the geological past the heat production was very high or almost double than the present. So, that indicates that the with age with increase of geological age the heat production of the surface and heat circulation gradually decreases.

Although the heat generation of this crust is some two order of this magnitude greater than that of the mantle the rate at which the earth as a whole produces heat it is influenced by the mantle. Why? Because of its volume. Because the mantle is highly volumetric as compared to the crust. So, though its concentration is less, but once we have high volume of the mantle material that means, compared to this concentration it becomes more. That's why volume of this mantle is so greater than this total volume of the crust.

So, that's why the mantle is the forerunner of heat generation. However, the concentration wise if you compare with the crust it is less. Then thermal modeling indicates that a decrease in the radiogenic heat production with depth in the crust now concentrated with crust itself. So, in the crust we have upper crust, we have lower crust. So, once we are going down the heat production in the crust that is decreases with depth.

Uplifted block in the middle crust such as this province in Canada it have moderate level of radiogenic element. So, most of this drop in radiogenic heat production must be occur in the lower crust. Because if you remember our earlier class we are talking about the upper crust and lower crustal composition. The lower crust it is mixed. It mixed with felsic as well as mafic some of this granitic material and some of the mafic material.

So, once it is mixed with the mafic material that means obviously its heat production or the concentration of this heat producing element gradually decreases. So, that' s why in the middle crust wherever it is exposed it is compared to the upper crustal surface. So, then it is found that in the middle crust this concentration of this uranium, thorium, potassium is less as compared to the upper crust. So, that means it is believed that once you are going from upper crust through middle crust to the lower crust the heat generation substantially decreases. So, here we have some of this tectonic province that the Basin and the range province, then Australia, then here very interesting is the Indian shield.

Now you see how the heat generation with the age it is decreasing. So, this younger tectonic province they are producing high heat as compared to the older tectonic province. So, that means once we age wise we are going to this older system. So, we are going towards a lower heat generation rock type. Heat flow decreases with average age of the continental crust a relatively low heat flow is observed in all Archean craton compared to this post Archean cratons.

So, this means all Archean cratons all over the world it may be India, it may be Australia, it may be Africa where the heat generation is less as compared to the post-Archean cratons that we have. So, that may be caused either by a greater concentration of this heat-producing element in the post-Archean craton or a thick lithospheric root is there which is preventing the heat to come to this upper crust. So, but once you work in this field you will find this first option is the most appropriate. So, that means this greater concentration of uranium, thorium and potassium that is and the post-Archean and the Archean if you compare it is more in the post-Archean as compared to this Archean. Because if you see in the Archean time when we are talking about in the few class before that is how this earth evolved in the Archean time when this earth was beginning just at the initial time there was high heat flow and there was convection current.

So, that there was mixture of this mafic and felsic content, but once with more and more differentiation took place it becomes more granitic composition. So, the upper crust becomes more granitic. So, that' s why this upper crust which will become more granitic it is a storehouse of uranium, thorium and potassium as compared to this Archean time crustal composition. Now age dependent heat-flow, how age influencing the heat-flow of the system. Average surface heat-flow decreases with the average age of the crustal rock in both oceanic as well as its continental area.

So, so far we were discussing about the continental lithospheric system or the continental crustal system, but the oceanic system also this average heat-flow decreases with age. At the mid-oceanic age where this oceanic lithosphere is newly formed there you will find high heat flow because it is close to the magma chamber and the magma is continuously being supplied to that. But once you go away from this magmatic system or the mid-oceanic system the heat-flow gradually decreases and continental heat flow drops with an age of approximately constant value of 40 to 50 milliwatt per meter square about 1 gigaannum But in oceanic area similar constant heat flow-values are reached only in 50 to 100 million years. If you see here we have this average heat flow of this earth and we have oceanic crust and we have continental crust. Now you see the oceanic crust the graph is reducing at a faster rate and finally, it is merging with the average one.

So, where it is merging? It is merging here and it is about the 50 to 100 million years. However, if you the continental crust if you see here it is going down and it is merging here about 1 giga annum or so. So, that means, at the oceanic areas this type of heat drop it reaches very less time as compared to this continental crust. Now continental heat flow can be considered in terms of three components and all of which that decay with time. What are the three components? First is the radiogenic heat.

So, it contributes around 40 percent of this total heat system and this continental crust of all ages and decreases with time in response to the erosion of the upper crust. We know erosion of upper crust because the upper crust is the that means, the concentration of this heat producing element is more. So, once the upper crust is eroded so that means, we are losing the heat-producing elements. So, that's why this contribution though it is

40 percent of this total heat flow, but it decreases with the time response to erosion of the upper crust. And this second one is the residual heat.

Residual heat means the heat which was gained during the formation of this earth it retains the system. So, that means, here if the igneous activity associated with the orogeny, orogeny means mountain building activity. Once we have mountain building activity then there will be magmatic intrusions, there will be Batholith intrusion, there will be Batholith emplacement and there will be   heat-producing elements will be there and there will be high heat environment. So, it contributes about 30 percent of the system total heat flow. So, that means, you see the radiogenic heat it is contributing 40 percent and this magmatic activity during this last orogenic activity is contributing 30 percent of the system and rest 30 percent it is the convective heat flow with the mantle.

So, that means, there is mantle convection everywhere and this mantle convection it is the heat flow is there it is producing heat it is providing heat from the mantle, but it is of minor component. So, these upper two components that means, the radiogenic heat and the residual heat of this igneous activity these two components decay rapidly of a few hundred million years with age and with rock so like that. So, that means, these two they are the most contributors collectively to the heat flow of the system. In oceanic area surface heat flow it can fall off with square root of this crustal age (t) according to this equation given here.

$q_0 = 11.3\ t^{(-1/2)}$

So, it is approximately it is 120 million years.

So, if you see in the if you remember in the last graph that the continental and this oceanic system the oceanic system it is 50 to 100 million years it is begin cooled and it is coming to this normal level of the heat production. However, this continental system it is taking 1 giga year, thousands of million years coming to this normal heat flow level. So, the heat flow decreases distance away from the MOR if you see here at the mid-oceanic ridge basalt it is producing here and this mid-oceanic ridge basalt then we have a magma chamber here it is magma is continuously being supplied or there is a magma chamber through which felsitic magmatic supply is there. So, this area is the high heat environment. So, the rocks around this it is representing high heat flow as compared to this system which is away from this mid-oceanic ridge.

More mantle heat enters into the base of the oceanic lithosphere then the continental lithosphere while moving to this mantle affecting the surface heat flow. So, suppose this continental plate and the oceanic plate which are moving together and on this mantle system. The mantle will continuously supplying heat. However, the continental lithosphere it will absorb less heat compared to this oceanic system because if you know the continental lithosphere it is mostly composed of granitic to granodioritic composition it is quartzo-feldspathic minerals are there which are not good conductor of heat and electricity. However, compared to that the basaltic system which is the component of this oceanic system.

So, the basalt which is mainly composed of the ferromagnesian minerals they are good conductor of heat. So, that means on a same heat supply that means from the mantle heat supply this continent it absorbing less heat. However, at the same time the ocean is observing more heat. So, that's why if the ocean and the continent placed side by side the absortion of more heat by this ocean lithosphere and less is the continental lithosphere. Considering all the source of heat loss the total heat loss from this earth is about to 42 into 10 to the power 12 watt from this continents and 30 into 10 to the power 12 watt from the oceans.

And models indicate 88 percent of this earth heat flow lost from the mantle. And 66 percent lost at the ocean ridge by the subduction and 10 percent by conduction from the subcontinental lithosphere and 12 percent from the mantle plumes. So, these are the heat distribution. Why I am emphasizing it here because in the future classes when we will talk about this continental interaction. So, this heat how much heat budget is there that will play a significant role to decide which type of mineral will be there, which type of metamorphism will be there, which type of magmatism will be there all that depends upon the how this heat is influencing the converging or diverging system.

So, this leaves only 12 percent lost from the contributes by the radioactive decay and of the heat-producing elements. So, that means whatever the heat loss is there from this earth surface most heat it is lost from this mantle and only the heat 12 percent is lost by this system which is of radioactive decay. So, here if you see this image the total heat interior of the earth flow this crust it is 24 percent, the upper mantle it is contributing the 22 percent, the lower mantle it is contributing 32 percent and this outer core it is contributing to collective with inner core is 22 percent. So, that means here if you see most of this heat loss it is occurring from the lower mantle system as compared to this crust here and this upper crust and upper mantle here. In continent heat flow values are significantly affected by age and intensity of the last orogenic event.

The distribution of radioactive element of the crust and the amount of heat coming from the mantle. So, we know it is the amount of heat which is coming from the mantle to the continent is less as compared to the ocean and the last orogenic event The orogenic event they are the mountain building event they produce a huge amount of heat that's why if you remember earlier slides those areas which are demarcated by the subducting system, the mountain building system, the collisional system they are represented as high heat flow areas. So, that's why this orogenic event when it occur the last orogenic event if it is the older one that means there is heat production is nowadays is less. However, it will be the younger orogenic event was there then we will find high heat flow environment. And the distribution of radioactive element as I have already emphasized earlier whether it is uniformly distributed or it is concentrated in the particular location or particular fault zone or particular layer on the surface of the earth.

So, that depends that decides this continental heat flow. A continental surface heat flow is linearly related to average radiogenic heat-production of the near surface basement rocks by the equation which is given by this.

$$q_0 = q_r + A_0 D$$

So, this near-surface heat production or heat flow it is by the related to this average radiogenic heat production and near-surface basement rocks by the equation is given here. And if you see here there is average heat flow and the age of this system. So, here this subaqueous continental on differentiated lakes continental shelf and slope they are producing this much heat.

So, now you go to the Archean the heat production is decreasing. So, that means that depends upon the age that depends upon the concentration of the radiogenic elements. And the reduced heat flow decays with 200 to 300 million years to a value between 20 to 30 megawatt per meter square which is about 3 times faster than the surface heat flow decay. So, that means in 200 to 300 million years this value becomes this much and this value it is nothing it is the 3 times more than the average crustal heat loss or heat flow. So, heat flow and the crustal thickness if you compare this to for the continental crust less than 40 kilometer thick average heat flow is inversely correlated with the crustal thickness by this equation which is given here.

$$q_0 = -2.48\ (t - 3.48) + 61.2$$

Where q0 is given in milliwatt per meter square and t is in thickness. And now if you see some of this mountain building areas that means, tectonically disturbed area they are compared here the basin and range province this is the extensional tectonic regime. If you see this graph how this is the rate of that is the heat flow or surface heat flow and this is Appalachian Mountains this is Lake Superior province then Western Australian Shield.

So, there are different rate of heat loss or heat flow and that heat flow that depends upon the distribution of this element and that depends upon the age and that depends upon that which level or when the last magmatic activities they are occurring and what is the degree of erosion at what is the level of erosion if it is up to the upper crust if it is the lower crust or the middle crust. So, all those that decides what will be the heat production and heat flow of that region.

And finally, during this plate interaction that heat flow will play a significant role to decide what type of mineralization, what type of metamorphism, what type of magmatism that we will expect in particular tectonic environment. Now if you see this major crustal type one is shield and platform that means, this collectively that is called craton. So, this cratonic area if you see this heat flow in the shield area it is 40 and in the platform it is 49. So, now you see the shield is less heat production house than compared to a platform region. So, how it is happens? So, shield and platform collectively they create craton.

So, shield where the pre-cambrian rock is exposed, the basement rock is exposed and the platform it is the cover sediment around this shield. So, here you see the platform is producing more heat as compared to the shield. Why it happens? Let us wait for the next slide. So, shield area exhibit the lowest and the least variable continental heat flow and values generally in the range of 35 to 42 milliwatt per meter square average is about 40 milliwatt per meter square. Now platforms are more variable usually falling between 35 to 60 milliwatt per meter square and the average about 49 milliwatt.

So, the difference between the shield and platform heat flow reflects the greater thickness of the crust and hence more radiogenic element is there in the platform area. So, now you see here we have the shield area that is the exposed pre-cambrian basement and now we have platform cover we have the sediment which are covering the shield area. Now this covered regions they are producing more heat. Why? Because this cover region if you remember our earlier class these sediments are produced from the erosion and weathering of the upper crustal area. So, that means most of this upper crust rocks they are now representing at the sediment.

So, this upper crustal composition which is enriched in uranium, thorium and potassium that must be enriched here. So, that's why this concentration of uranium, thorium, potassium are here that is why it is producing more heat compared to the shield areas because here there are distribution of the uranium, thorium, potassium, but here it is concentration. So, that's why this due to this concentrated nature it is producing more heat as compared to the shield area. Young orogens, arcs, continental rift and oceanic island exhibit high and variable heat flow in the range of 50 to 8 milliwatt per meter square. So, here if you see this is the orogens and this the subduction zone and here this is a subduction zone which is low angle subduction here it is a high angle subduction.

Now if you see this heat flow, this heat flow graph it is varying like this and similarly here this heat flow graph it is varying like this. So, that means it is indicating the orogens the orogenic area where this continental-continental collision is there or the subduction is there these regions and island arcs then continental rifts these environment they produce more heat compared to the normal continental or oceanic crust region. The high heat-flow in some arcs and volcanic islands reflect recent volcanic activity in these areas. So, we know the volcanic island, the volcanic arcs they are represented by continuous magmatic supply and there are volcanoes where are frequently erupt.

So, that's why these regions represent high heat flow environment. Heat flow in ocean basin generally falls between 35 to 60 milliwatt per meter square average about 50 milliwatt per meter square. So, ocean ridges on the other hand are characterized by extremely variable heat flow ranging from less than 100 to more than 200 milliwatt per meter square this heat flow decreases with increase in distance from the ridge. So, now if you see here this is the heat flow which is theoretical curve from the heat flow where scientist is predicted. However, this is the measured one and this difference it is nothing this due to hydrothermal circulation because we are continuously at the mid-oceanic ridge there are fractures we are continuously supplying water where percolating water and this water is interacted with the system rock system here and it is coming up. So, that means, it is decreasing heat this water it is carrying out heat from this deeper level to the surface level.

So, that's why this gap is there. In the future classes we will talk about this divergent system we will talk in detail how this heat system is distributed in the mid-oceanic ridge and what is their role in mineralization particularly the volcanogenic massive sulphide deposit. Back-arc basins also characterized by high heat flow environment whereas, inland-sea basins exhibit variable heat flow that is reflecting in part variable cenozoic sediment rates in the basins. So, we have this is the back-arc basins, this is the back-arc basins they are also represented by high heat flow environment because it is a rift basin. One of the most important source of the heat loss from the earth is hydrothermal circulation associated with the ocean ridges as in the previous slides we are discussing this is the hydrothermal circulation. We are percolating water, the water is going inside it is interacting with the rock and it is coming out as a hot water that is brine so that it is responsible for the mineralization in this area.

So, this is one of the most significant method that is the heat-production and heat circulation at the mid-oceanic ridge system. And modern calculations suggest that the approximately 25 percent of this total global heat flow can be accounted by the hydrothermal transport. So, this oceanic ridge it is around 75000 kilometer length. So, now, only 75000 kilometer length around 50 to 100 kilometer wide. So, this fracture zones it is distributed throughout this mid-oceanic ridge system.

So, water is percolating down and coming as a hydrothermal solution. So, they are distributing heat in a huge area. So, that's why around this 25 percent of this total global heat flow it is concentrated at the mid-oceanic ridge system particularly through the hydrothermal system. Now this heat flow either it is continental system or it is in oceanic system. Once you are going down the heat increases. If you see here some of this graph is representing once you are going down the temperature it is increasing.

So, this is called geotherm or this is called geothermal gradient. And this geothermal gradient it is about 25 degree Celsius per kilometer. However, it is the average one, but at the mid-oceanic ridge it is different, at the subduction zone it is different, it is the island arcs it is different. That means, in specific different tectonic environment this geotherm shape or the geothermal the quantity of this 25 degree Celsius per kilometer does not hold good. So, this is average geotherm it is 25 degree Celsius throughout the surface. So, it is the temperature distribution with depth in the earth beneath the given surface location is dependent upon surface and the mantle heat flow and distribution of thermal conductivity and the radioactivity with depth.

Now here if you see this geotherm with depth we have basin range province, we have cenozoic orogen, then we have Sierra Nevada batholith, we have shield area. So, that means, if you see here this geotherm is varying depending upon the age, depending upon the tectonic environment. Even the shield area here if you see it is tectonically stable. So, that's why the heat flow is somehow different.

And the basin range province this is the extensional tectonics it is going on. So, it is a tectonically active environment. So, that this heat flow is different. And the geotherms in 4 continental crust type it is given here and the shaded area represent uncertainty range of each geotherm. Now if the geotherm is increasing and we have 2 graphs here, one is the red one it is representing the geotherm and the blue one it is representing the melting curve.

And here if you see the melting curve is higher than the geotherm. However at this point at the mantle-core boundary at the outer core and mantle boundary here the geotherm exceeds the melting point. That's why the rocks in this region that means the outer core it is in the liquid form as compared to the other part. So, again once it is reaching at the base of this outer core again the same happens that means the geotherm is lower as compared to the melting curve. So, that means it becomes again solid. It is thought that the actual temperature at the center of this earth is about 7000 degree Celsius on the basis of available evidence.

What are the available evidences? That the thermal and seismic data. We have seismic data as if you remember earlier class we are talking about there is no direct evidences to study to the center of the earth. So, it is the seismic which is the indirect and the most reliable method through which we are studying to the center of this earth, the rock properties, the layered properties like that. Then we have laboratory behavior for solid at high temperature and pressure. So, we are experimenting at different laboratories at different temperature and pressure interval in different rock types.

So, what would be the temperature inside depending on the rock types. And the laboratory melting of iron rich iron and nickel rich material. So, all these direct and indirect evidence as it says the center the temperature is around 7000 degree Celsius. So, thank you very much. We will meet in the next class. Thank you.