Plate Tectonics
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Week - 09
Lecture – 45
Plate Tectonics and Hydrocarbon Exploration- I

Ok friends, good morning and welcome to this class of plate tectonics. So, if you remember in the last class, we were talking about the application of plate tectonics and particularly in the mineral exploration. So, this is the application part and today we are going to talk about this application of plate tectonics in hydrocarbon exploration. So, before going to talk about this hydrocarbon exploration, we must know where actually the hydrocarbon lies. So, to understand the system of hydrocarbon, we have to analyze this geological history or the geological time scale. So, if you see here, the geological time scale, if you remember our earlier plate tectonic classes, we were talking about hadean, then Archean, then this Proterozoic, like that.

And this tectonics, if we recollect, we are talking about that the Hadean it was and the Archean that these two systems or these two time that was responsible for this drastic change of this earth's crust or the crustal evolution and magmatism, mineralization like that. But if you see the geological time scale, this Precambrian, that means starting from the Hadean, the Archean, the Proterozoic, all those things, but they are contributing only 1% to this petroleum hydrocarbon. However, gradually if you are moving up in geological time, so here we are reaching to this Paleozoic, and this Paleozoic, it is contributing about 15% and then coming to Mesozoic, it is about 45%, then the Cenozoic, it is about 40%. So, that means, now you see, starting from this Cenozoic to Mesozoic, these two zones, or these two time scale, they are recording highest development of petroleum.

And among these two, these Mesozoic rocks, they are the forerunners and out of this Mesozoic, the Cretaceous, that is the forerunner of this petroleum hydrocarbon production. So, probably you would know that this Cretaceous, it was the sea level rise, it was worldwide sea level rise and for millions of years, this sea level was above the present-day position, and vast amount of carbon deposit, that occurred during the Cretaceous, and this carbonate, from this carbonate, the name Creta, the term Cretaceous was derived. So anyways, these Cretaceous rocks, they are the forerunners among the all these rock types, those are producing petroleum hydrocarbon. Now the question arises, why we are discussing so? Here, we have the Archeans, having less, that means, petroleum hydrocarbon less than 1% and then gradually, when we are talking about these Paleozoic, Mesozoic, Cenozoic, mostly we are coming towards the sedimentary basins, these sedimentary rocks because in the archaean, we have this igneous metamorphic rocks, gradually they eroded basins developed and those basins they received the sediment from this, that means, eroded sequences and due to this sedimentation, huge sedimentary basins were created and in this huge sedimentary basins, the petroleum hydrocarbon was placed and generated. So that means, so far though there are different theories, there are for petroleum hydrocarbon generation, but most of these people that think this petroleum is of biogenic origin.

So that means, we need organisms and in the Hadean and this Archean time, we have no organisms or less developed organisms like the cells only. So that is why there is getting chance in Archean and the Hadean time, petroleum hydrocarbon, it is really less. So that is why with the evolution of the sedimentary basins and the development of the sedimentary basins and deposited sedimentary rocks, so petroleum hydrocarbon becomes more and more available. So, that is why these rocks, they are the forerunners and particularly among the all the rock record, this Cretaceous is the forerunner of petroleum hydrocarbon generation, and we have different boundaries, there are drastic change in the geological environment, like this Permian-Triassic boundary, P-T boundary, similarly Cretaceous boundary, that means Cretaceous-Tertiary boundary that is called K-T boundary, and we have different other boundaries but these P-T boundary and K-T boundary, they are known for their biogenic evolution and biogenic extinction like these dinosaurs they extinct like that. So, that's why the sedimentary basins that were formed during this time, they received they received enormous amount of organic matter and with increasing temperature and pressure, they matured these organic matters to petroleum hydrocarbon.

So if you remember our earlier class when we were talking about the basins at this convergent and divergent margin, particularly when we were talking about mineralization, we were talking about the different source for this temperature and pressure like that. So that means now you imagine we have a basin full of sediments having organic matter within that and we are increasing the temperature, increasing the pressure. So that means gradually we are enhancing the enzyme reactions and finally we are creating this petroleum hydrocarbons which are stored in these rock records or which are stored in the rock pore spaces in the porosity and we are extracting it nowadays. So that means now the concept of sedimentary basins come in our picture. So the majority of these fossil fuels are found within the sedimentary basins and whose formation can be related directly or indirectly to the plate motion.

So if you see this figure here, it is given, based on the plate tectonic settings, there are different sedimentary basins have been shown here. First is the foreland basin, the example, Indian example is the Ganga basin, the foreland basin. Then we have rift basins, we have the Pranhita-Godavari rift, Mahanadi rift, we have Narmada-Son-Damodar rift. Then we have intra-cratonic basin, intra-continental basin, we have different basins which are interior of this crater, this is intracontinental basin. Then we have passive margin basin like this Bay of Bengal basin, it is the passive margin basin.

So that means I want to say you see the sedimentary basins everywhere because as a petroleum geologist or as an exploration geologist, we have to target these sedimentary basins and the sedimentary basins, they are close to the plate tectonic settings, different plate tectonic settings except this one which is the intracontinental basin. But still once it is a basin, it has sedimentary rocks, it has organic matter, that means there is very high chance that we are going to get this petroleum hydrocarbon. hydrocarbon. So that means here in the foreland basin, if you see the weight of this mountain belt pushes down the crust surface and the basin is formed like this Himalayas is loading on this Indian craton. So that Ganga basin, Ganga foreland basin is being developed.

The thrust sheets that are migrating from north to south, they are overloading, they are stacking with each other and they are overloading on this Indian craton and finally, this Indian craton is bending towards north. Then rift basin, that is downward slip of the fault that produces narrow troughs, we have Listric normal faults, they are going down or that is subsiding and finally, we are creating these rift basins like the Narmada. Then intracontinental basins, we know intracontinental basin when we are talking about the intracontinental mineralization when there is a plume and due to plume there will be subsidence and this intracontinental basins are formed that is the sag basins you can say sag basins. Similarly, passive basins that means, those basins where away from the Mid-Oceanic Ridge now become tectonically inactive or less active, that is passive margin basins. So that means, everywhere plate tectonic is associated in forming the basin and and those basins which are receiving sediments from the surrounding and far away from the surroundings by the rivers, so they are rich in organic matter with increasing temperature and pressure, they are creating petroleum hydrocarbon and storing them within that pore spaces.

So, generation of petroleum hydrocarbon is not also important, it is also important also whatever the hydrocarbon is generated should be preserved. We should have enough space and petroleum hydrocarbon, it easily, it evaporates as volatiles. So that means, it should be trapped, so there should be a cap rock. So that means, the sedimentary basins or the sedimentation mechanism should be in such a way, so that there should be pore spaces that means, porous and permeable rock below and it should shield and it should cover at blanketing effect by the impermeable rock.

So, whatever the petroleum hydrocarbon is generated within that it should be trapped inside for extraction. So now, some facts, sedimentary basins, they are the depression on the crust where the sediments accumulate. Now, we see, we have different types of sedimentary basins. So, here some foreland basins, then convergent margin basins, then Cratonic and passive margin basins, then subduction related basins and the trenches. So, now you see, the whole earth has been divided into different sedimentary basins based on the tectonic setting because here it is passive margin setting.

So, once upon a time it was near to the Mid-Oceanic Ridge. Foreland Basin - Foreland basins, this is the Ganga basin due to loading of this thrust sheets. Then convergent margin basins that we have well acquainted with this convergent margin basins like the foreland basin or this back-arc basin, forearc basin, this trench slope basins like that. Similarly, subduction related folded belt.

So, once there are folded belt different fold axis or within different folds we have small basins are there. So, that means this whole earth has been divided into number of sedimentary basins based on their closeness to their tectonic setting. And the basins are generated by plate tectonics, the process responsible for the continental drift. So, during drifting we created some basins. During rifting we created some basins and the rifting once it is reached to the drifting stage we created this ocean basins like Atlantic, like the Pacific, Indian oceans.

So, the larger oceanic basins nowadays once upon a time they were generated as a lake, as a pond. So, gradually they increase their size. So that means basins are generated due to plate tectonics, plate movement. Then origin, external geometry of basins help in understanding the hydrocarbon accumulation. So, what is this origin? Either it is rift related or it is sag related or it is a convergent related. So, that origin defines what kind of hydrocarbon should be there, what depth hydrocarbon should be there, what should be the temperature and pressure of that basin is.

Similarly, geometry either it is a linear basin or it is a circular basin or is any kind of basin. So, that means these factors that means influence in understanding the hydrocarbon accumulation, how much hydrocarbon would be there, which age of rock there are hydrocarbon bearing. Even if in a divergent setting where there is a high heat flow, even if the younger rocks they can get maturity in a less time. Because due to high temperature and pressure this whatever the organic matter it was inside that will be matured and finally, petroleum hydrocarbon generated. Wherever the basins which are characterized by this low geothermal gradient, even if there is organic matter, but due to less temperature generation of petroleum hydrocarbon need to take millions of years.

So, that is why origin of the basin is also important and the geometry of this basin is also important and all these are governed by this plate tectonics. So, now the question arises where this plate tectonics stands in the exploration chain? Because exploration chain starting from the upstream to downstream it is a long process. So, now where our this knowledge about this plate tectonics will help in understanding or helps in exploration. Where do geologists stand? What is the role of a geologist? Particularly the role of a geologist in terms of plate tectonics, which type of plate tectonics knowledge is required for exploration? So, in this exploration we have frontier exploration, we have exploration and production, then we have development of production and we have discovery and appraisal. So, now the question arises where this plate tectonics stands? So, this plate tectonics understanding of this basin development with respect to plate tectonics and understanding the types of basin and closeness to this plate margin setting, their temperature and pressure that will be helpful in understanding whether this given basin is responsible or it is suitable for generating petroleum hydrocarbon.

If it is suitable at what depth we are expecting petroleum hydrocarbon, which age of rock is now matured enough to generate petroleum hydrocarbon for use. So, sedimentary basins they are classified based on the type of lithospheric substratum. Either it is developed on the continental system or it is on the oceanic system or it is a transitional crust. So, oceanic crust basins are different, continental crust basins are different and transitional crust basins are different. Their position with respect to plate boundary that is either it is convergent plate boundary or it is intracratonic system or it is divergent plate margin, then type of plate motion near to the basins.

So, which type of plate tectonic settings are there in the basin? Oil industries are using the basin classification proposed by Kingston and this classification is nothing, it is for getting an instant idea of a hydrocarbon potential of the basin of concern. So, why we need a classification? Even if not the petroleum hydro or the basin classification, any classification, classification means just categorizing something and this categorizing means we are getting some instant idea about this system we are classifying. So, that's why this classification which was proposed by Kingston is still used in oil industry, and giving this instant idea about this hydrocarbon potential of a basin. So, if you see this figure here, we have this Indian subcontinent, we have different sedimentary basins, they are classified, and you see based on the colour codes, these sedimentary basins have been classified. And this classification put the basin under different categories based on their plate tectonic settings.

What is that? If you see here, we have continental or it is oceanic. Within this continental, if it is divergent system or trans-current system or it is convergent system. Similarly, same as in the continental system same in the oceanic system also, then in the interior of this basin or it is the margin of the basin. So, if the interior of the basin, it is cratonic sag, it is margin, it is failed rift. Similarly that means I want to say, these sedimentary basins, these oil industries are using for petroleum hydrocarbon exploration, it is based on the plate tectonic setting only.

But if you think about before plate tectonic setting, what was the basis of classification? Because plate tectonics, it is a new thing, new addition to Earth Sciences. So, in 1960s, around the plate tectonics was developed, and before 1960, there was no understanding about the plate tectonics, and the sedimentary basins they were classified, based on the Geosynclinal concept, 'Geo-synclinal' concept. So, this geosynclinal concept, that is called eugeosyncline, miogeosyncline there are different geosynclines there are different classifications, and based on the geo-synclinal classification, the sedimentary basins were classified. But now, it is no more existing because it is an old dated thing. So, with the onset of the plate tectonics, the geo-synclinal classification was totally abandoned.

So, now if you see, these basins are classified depending upon the types of plate margin, either it is a divergent plate margin or it is a intra-plate margin or it is a convergent plate margin. And the divergent plate margins, we have continental rift because it starts from here, if you see here, this was earlier an intact continent and now we created some rift, we are stretching it from both sides. So, this rift is generated, and once rift is generated the crust or the lithosphere becomes thin here. So, here we are creating a basin and the basin gradually it starts as a pond or a series of ponds like here and with time the coalescence with each other finally, a ocean basin is developed and gradually a Mid-Oceanic Ridge system is developed here and this two systems or two sides they go away from each other and finally, this becomes a passive margin. So, now it is away from the Mid-Oceanic Ridge system.

So, that means, we have a basin here that is passive margin basin, then we have rift basins, we have a syn-rift basin, post-rift basins. So, like that different types of sedimentary basins are there based on this rift or this time of rift. So here, in this continental rift, then description, it is rifted continental crust. Now, ocean basin, which is that means, with once upon a time it was generated as a rift, now it is converted to ocean.

Best example is the Atlantic. Then we have inter plate system. So, first we will talk about the divergent plate margin basins. So, it starts with rifts. So, that's why, we will talk about rift-basin first. So, here it is the continental rifting at the opening stage of the process that can lead to the full breakup of this continental mass and generation of the oceanic crust between the two fragment apart that here it is illustrated in this figure.

So, these two systems, they are separated from each other and finally, it's giving rise to a ocean basin here. And thermal disturbances controls the degree of uplift and the rate of rifting due to volcanism. So, we have already discussed this when we were talking about the rifting system or the development of the divergent plate margins. Then there is a model, which was proposed by McKenzie and McKenzie's pure shear model says, now you see, the rifting is here and this is the subsidence. So, here you see, this subsidence is increasing and the time is increasing.

So, now at a particular time, the subsidence is high this is the rifting stage. You see, how much subsidence is occurring and within a particular time. So, that means, to certain extent we are stretching the continents from both sides and at a particular threshold once it reaches, So, suddenly it creates a rift and here, that's why the subsidence is more at a particular time and gradually, with increasing time, the subsidence is increasing and increasing and finally, it becomes constant. So, this is the McKenzie's pure shear model. The subsidence curve of the McKenzie's model, its initial subsidence by brittle failure of this crust is modeled as instantaneous, time dependent slow subsidence occurring during cooling of this lithosphere.

So, now, this is the first, is the brittle failure because the crust is brittle once it is going down, the ductility increases. So, once we are stretching this, at certain time we are getting the cracks we are getting the faults, so, subsidence occurs, it is sudden. So, that's why this is a sudden instantaneous thing, and gradually when it is reaching to this ocean basin stage, ocean basin is created. Gradually the subsidence decreases and decreases finally, becomes constant. So, it happens, if the rift continues, if rift reaches to a drifting stage, but it may possible, at certain instance the rift failure occurs.

So, that means, it is called failed rift like the Pranhita-Godavari rift, we have Mahanadi rift, we have Narmada-Son-Damodar rift, all are the failed rift. So, that means, this rift is not reached up to the drifting stage that means, two blocks, or this lithospheric spectrum, total lithospheric thickness are not separated from each other. To certain extent, the rift are continuing, then it was failed. So, that is called failed rift and another terminology here, that is called Aulacogen. Aulacogen is nothing, it is a failed rift however, it is associated with a triple junction because if you see for example, Mahanadi rift, Godavari rift and in Indian context, we have Mahanadi rift here, we have Godavari rift here.

So, now, they are not related to a triple junction. So, simply they are failed rift. However, if you say this Aulacogen, Aulacogen that means, it is a failed rift associated with a triple junction. So, now, a triple junction that means, here one, another one and this is the third, and this is failed.

So, that is why it is called Aulacogen. So, these two, they are separated that reached up to the drifting stage similarly here, this rift is reached up to the drifting stage, but here, it could not. So, that is why this becomes a failed rift, and as it is associated with the triple junction, that is called Aulacogen. So, failed arm of a three-armed rift, that's why it is called triple, three-armed rift, two of whose arms continued to open to form ocean basin, like Gulf of Aden and Red Sea, and this is East African rift valley. So, this is a failed rift system. So, this here it becomes a sea, here it becomes a sea, however, this side it failed to operate.

So, that is why it is a failed rift system. So, initially, continental sedimentation will be there because once we are creating a rift so that means, we are decreasing this system that means, we are decreasing the thickness and we are creating a low-lying land here, that is the basin. So, in this basin, initially the continental sediment will be there from the surrounding, whatever the sediments are there that will be deposited by the river. Then character changes as sea floor spreading oceans. So, now once it is converted to a ocean basin. So, once upon a time, which was receiving the continental sediments, now they are receiving the ocean sediments.

So, that means, with time the sedimentation nature changes, the agents of sedimentation, this agent of a sediment accumulation that changes and later, phases of marine sedimentation. So, once it was continental sediment then it was occupied by marine sediment. So, if you take a stratigraphic cross-section at the lower side, you will get this continental sediments like the fans, and later it will be the deltas and finally, you will see the marine sediment. Then oceanic rift basins, it was the later stage of rifting mid-oceanic ridge is forming. So, you see here this is illustrated through the figure we have a mantle plume then we created a rifting system gradually we stretched the system we formed a ocean basin and gradually the width of the ocean basin increases and finally, we know this concept of plate tectonics the assumption says earth's total area remain constant. So, to make this total area remains constant whatever this area we have created newly by stretching that much area we have to consume.

So, that's why we created the oceanic trench in both sides and finally, we created a subduction zone here. So that means, this is the way how the rift basins are developing and this is the way how the rift basins are closing and sedimentation from the continental source at the initial time then alluvial fan, subkha developed, subkha, it is this evaporates generally sabkha, in this stage suppose for example, we have this ocean basin here and here the evaporation is more than its sedimentation then that means water supply. So, that means, we have evaporite. So, evaporite deposits will be there, initial stages isn't it? So, later on, it will be occupied by this marine sediment, but at this continental time when this continental sedimentation was there.

So, we have alluvial fan, then sabkha developed, then hydrothermal activity is high, why hydrothermal activity is high, because we have faults and through this fault there will be movement, and those movements, there will be hydrothermal activities because we have a magmatic plume here. So, this hydrothermal activity is there. so that this geothermal gradient is increasing. Then it is high heat flow because we are close to this asthenospheric mantle we are close to the asthenospheric magma here.

So, that is why we have high heat flow. So, now, imagine we have a sedimentary basin and we are cooking it putting a magma below. So, that means, we are increasing its heat, increasing its temperature very high. So, if it is containing organic matter, so this it will convert to petroleum hydrocarbon and even it may possible that the temperature is more and more than whatever is required for generation of a petroleum hydrocarbon. So, whatever the petroleum hydrocarbon generated it will be evaporated it will escape due to high temperature. Then, during this stage the Listric normal faults are developed.

Listric normal fault, we know that is the fault plane is curved when we are talking about this Mid-Oceanic system, we are talking about the listric normal fault. So, this listeric normal faults are developed, as the spreading continues, they develop. Large listric gravity driven fault in areas with high sedimentation rate such as delta program. So, sometimes that is called also growth fault. These growth faults are very much familiar in the oil industries that in deltas and environment this is found this is the listric normal fault due to gravity driven loading.

So, we are putting sediment on the surface and we are increasing its load. So, that there will be failure, and this failure, it is creating this listric normal faults. So, listeric normal fault then displacement of hanging wall without folding lead to the large open space here. Then hanging wall deforms by fault bed folding to produce rollover anticline here. So, finally, you see in the listric normal faults how it is accommodating sediments on the surface, how it is evolving with time.

Then another sedimentary basin that is called passive margin basins. So, they form because of the subsidence of this stress lithosphere continues long after long after the after it ceases. Now you see, earlier it was the Mid-Oceanic Ridge somewhere here, earlier it was here now due to that means, movement due to divergent movement, now it is here. So, this is the passive margin basin. Most of the marine transgression and regression sequences that can be recorded here at this coastal region.

So, extensional fault typical of rift phases become rare in the post-rift phases instead, gravity structures are common. Shelf-slope and abyssal plane are part of it. You may remember about the continental shelf, continental slope, continental rise, the abyssal planes. So, all these are related to this passive margin sequence. Then edge spreading occurs, continental margins moves away from the plate boundary and are not affected by tectonic activities.

So, it is away from this active tectonism. So, active tectonics that is occurring at the Mid-Oceanic Ridge system now we have separated it, we have migrated it from this Mid-Oceanic system to near to the continental system. So, that is why it is tectonically less active. In areas of low sediment input, distance from this major deltas carbonate factories can form on the top of the down rift blocks. So now, you see here, carbonate sedimentation, it is also that is carbonate sedimentation is a shallow water process because carbonate cannot be precipitated below CCD.

CCD means Carbonate Compensation Depth. So, whatever the carbonate sequence nowadays you see in this worldwide all these are deposited above the CCD regime. So, that means, those areas the specific margins once it is away from this mid-oceanic ridge system. So, away from the deltas because deltas mostly it is influenced by the river system, it is sediments they are coming from the continental system and depositing it here. So, once you are moving away from the deltaic system mostly the carbonate factories or the carbonate sedimentation becomes more dominant in the shallow water region. In such situation the intervening graben accumulate carbonate debris sets from the shallow platform areas.

And two conditions for their formation one is isolation from the clastic supply because clastic supply should not be there. So, that carbonate sedimentation because carbonate sedimentation or precipitation it is a non-clastic phenomena and deltaic sedimentation or whatever the sedimentation it is dividing from the river or the gravity from this basin side it is the clastic phenomena. So, that means, it should be isolated from this clastic supply. So, that carbonate sedimentation can occur. Then it is shallow marine water because deep marine water it is below the CCD where this dissolution is more than its precipitation.

So, that is why all this carbonate sedimentation that occur at the shallow water conditions and away from the clastics influence and above the CCD conditions. Then we have intracratonic basins. Intracratonic basins we know it is away from the cratonics system. So, here these intracratonic basins the formation mechanism is many one is thermal.

So, another is extensional one is erosional. Thermal that means, we are just cooking it by a mantle plume just below this continent we are putting a mantle plume. So, that we are extending it and finally, we are creating normal faults and the basin is gradually developing. So, you see here we have mantle plume is here and it is cooling down. So, it is subsiding and finally, we are creating a basin.

Then it is extensional, we are stretching the system. Now imagine we are stretching it this was the thickness of the block now we are stretching it. So, once we are stretching it, it is subsiding and finally, we are getting a sedimentary basin. Then erosional, it is cold lithosphere which is thick, now, it is hot lithosphere when it is moving up. So, now, here this part is eroded, why it is eroded, because it is lying at the upper region that means, it is height is more topographic effect is more so, that is why it is eroded.

So, once it is eroding so, finally, it is creating sedimentary basins. So, these are the intracratonic basins. So, heating, upliftment extension, cooling and subsidence they are the primary reasons for development of this intracratonic basin. And extension from the normal fault graben, rift value development then heat flow decreases and subsidence and basinal deposit starts and deposition thickens very high. So, these are the mechanisms how sedimentary basins they are filled with time.

Another type of basin that is called flexural basin. Flexural basin, flexural means bending for example, we are bending we are loading this one end of a plate with extra load so, that it will bend like this. For example, here we have a crustal thickness and we are putting some load here. So, gradually it is bending down once it is bending down so, that means, here we are creating a basin and this is the foreland basin system. At the northern edge of this Indian lithosphere, we are putting this Himalayan system we are just stacking this thrust sheets so, that means, this is a flexural basin.

So, new load causes the lithosphere to subside by isostatic adjustment. The lithosphere has flexural rigidity, adjacent lithosphere is bending down, high rigidity, broad and shallow basin. So, more the rigidity more the broad and shallow will be the basin. Then another type of basin that is intracontinental basin that is called sag basin. So, here you see this is the mantle convection current which is downgoing. So, it is downwelling current and at the place of downwelling there will be basin development.

So, that means, here once it is downwelling it is dragging this material this lower part of the crust below. Similarly, it is dragging the lower part of this crust below. So, that is why it is creating a depression here.

So, that is a sag basin. So, with time the sag basin size is increasing. So, it is receiving sediments from the surrounding and finally, we are getting sedimentary basin. So, sag basin created solely by impact of the mantle plume at the base of the lithosphere. Subsidence, downwelling of this descending plume coupled with lithosphere, then depression loaded by sediment 4 to 5 times. Thermal subsidence, response to temperature decrease at the base of the lithosphere by the plume and it takes 50 to 100 million to form. So, it is a slow process of formation and example is Michigan basin of USA.

So, thank you very much. This is the classification of the sedimentary basins. Mostly it is by this divergent margin setting and the intra-plate setting. In the next class we will talk about the sedimentary basins which are developed due to convergent margins. So, thank you very much. We will meet in next class.