Subject	Geology
Paper No and Title	**Sedimentology and Petroleum Geology**
Module No and Title	Migration of Petroleum
Module Tag	SED & PG XIc

Principal Investigator	Co-Principal Investigator	Co-Principal Investigator
Prof. Talat Ahmad ***Vice-Chancellor*** Jamia Millia Islamia Delhi	**Prof. Devesh K Sinha** Department of Geology University of Delhi Delhi	**Prof. P. P. Chakraborty** Department of Geology University of Delhi Delhi
Paper Coordinator	**Content Writer**	**Reviewer**
Prof. P. P. Chakraborty Department of Geology University of Delhi Delhi	**Dr. Ashish Sarkar** Pandit Deendayal Petroleum University Ahmedabad, Gujrat	**Prof. D. M. Banerjee** INSA Honorary Scientist Department of Geology University of Delhi Delhi

Table of Content

1. Learning outcomes

After studying this module, you shall be able to:

- Know about various types of migration of petroleum.
- Differentiate between primary, secondary, and tertiary migration.
- Learn about various physio-chemical parameters controlling migration of petroleum.
- Make the migration model in the basin.
- These would help one to understand the petroleum system existing in the petroliferous basin, as migration is an important component of the petroleum system.

2. Introduction

Petroleum, which also is known as hydrocarbon since the chief constituents of this is essentially hydrogen and carbon, is believed by majority of the contemporary researchers to be formed from organic matter. As far as the relationship of the petroleum and the clastic sedimentary rocks are concerned, since the organic matter is not effectively preserved in the coarse grained sediments (sands) because of macro-aerobic (oxygenated) environment prevailing within these sediments, it is believed that most of the petroleum has been formed in the fine grained sediments, where the organic matter is preserved effectively. Hence, the fine-grained rocks viz. shale is considered as the 'source rock'. Even though the fine-grained rocks are responsible for the generation of both petroleum crudes and gases, most of the petroleum accumulations in general and crudes in particular do not occur in the fine-grained rocks. In contrast, barring the non-clastic reservoirs, most of the commercial petroleum accumulations are necessarily associated with the coarse-grained rocks viz. sandstones, which are popularly referred to as the 'clastic reservoirs'.

Since the generation and accumulation of hydrocarbons take place in different rock types as has been discussed earlier, there must be some process existing by which the petroleum is transferred from the shale to the sandstones. The process by virtue of which the petroleum moves within a certain rock type, or moves from one rock type to another rock type is known as migration of petroleum. The migration of petroleum is one of the very important components of all the 'petroleum systems'.

The migration phenomenon would be discussed under the following heads:

i. Various parameters, which influence the migration of petroleum.
ii. Primary migration.
iii. Secondary migration, and additionally.
iv. Tertiary migration.

Let us begin our discussion with the understanding of the primary and secondary migrations. While the movements of petroleum within the source rock and the expulsion of petroleum from the source rock to the reservoir rock as well are termed as the primary migration, the movements of the petroleum within the reservoir rocks are known as secondary migration (Fig. 1). This essentially means that, the difference between the two migration processes lies in the fact that while the movement of petroleum in the 'fine grained' rock is termed as the primary migration, the movement of petroleum in 'coarse grained' rock is considered as the secondary migration. Because of the differences in the petro physical properties of the fine and coarse-grained rocks, the mechanisms of movement of petroleum through these rock types are visualized and are proposed to be different. Tertiary migration of petroleum accounts for the petroleum moving out of the stable trap because of tectonic deformation taking place after the secondary migration followed by accumulation of petroleum in a trap.

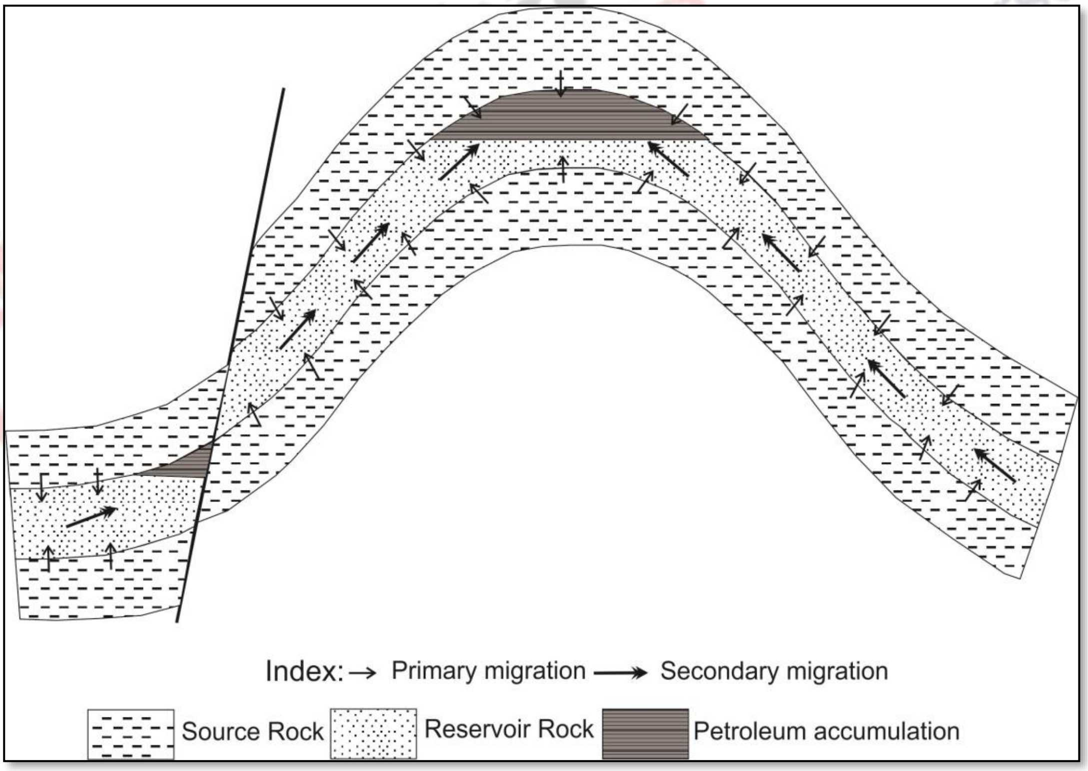

Fig. 1 Schematic representation of primary and secondary migration.

The quantum of migration of petroleum through the rocks is influenced by the various physico-chemical parameters and the geological conditions as well. Temperature and pressure has a direct effect on the fluid properties, which in turn influence the movement of fluids through the rocks. In addition to this the geological conditions viz., lithology of the strata, structural features, aquifer conditions, geological history of the area, etc. have a considerable control on the migration of petroleum.

3. Physico chemical aspects of migration of petroleum

3.1 Influence of temperature-pressure on the water and petroleum in the subsurface

3.1 Influence of temperature-pressure on the water and petroleum in the subsurface: Having discussed the difference between the primary migration and the secondary migration, let us first understand the parameters, which influence the migration of petroleum. The mobility of any fluid through the pore throats of the sedimentary rocks i.e., the ease or difficulty in the movement, chiefly depends on the density and viscosity of the fluid within a rock of certain permeability. Hence, let us first understand the conditions, which influence the density and viscosity of the petroleum. Of these conditions, heat has the direct influence on these parameters viz., density and viscosity of the petroleum. As, with increasing temperature the density of the fluid reduces, simultaneously the fluid becomes thinner i.e., the viscosity also decreases. Now, the question is under which geological set-up the subsurface temperature varies, which in turn influences the fluid property.

Tissot and Welt (1984) have quite logically discussed about the temperature and pressure conditions prevailing in the subsurface. According to them, the available data on the global oil occurrences depict that most of the source beds have not been exposed to 'much higher' than 100°C. However, they opine that light oils, condensates, and gases might have been generally generated at temperatures between 150°C and 180°C; and exceptionally reaching up to a temperature of 250°C. According to them, secondary migration through reservoir rocks also took place at the same temperature as that of the temperature of generation and primary migration of petroleum.

With the increase in overburden thickness i.e., with increasing burial depth the temperature in the subsurface increase as the heat moves from the interior of the earth towards the surface of the earth. The increase in temperature with burial depth follows certain conditions and at a place and at a particular geologic time the change in temperature has a certain gradient i.e., with change in unit distance there is change in certain temperature, which is expressed in either degree Celsius per km or per 100 m, or degree Fahrenheit per 100 ft. This is known as geothermal gradient. Earth processes taking place within the subsurface at a particular location determines the geothermal gradient at that location. While active places have higher geothermal gradients, the passive locations have lower values. Although the highest and lowest geothermal gradients in the earth has been reported to nearly 90°C per km and 5°C per km respectively, are aberrations. It has been found that the general variations in geothermal gradients in the sedimentary basins are generally between 15°C and 50°C per km respectively and the average global geothermal gradient is 25°C per km (Lee and Uyeda, 1965).

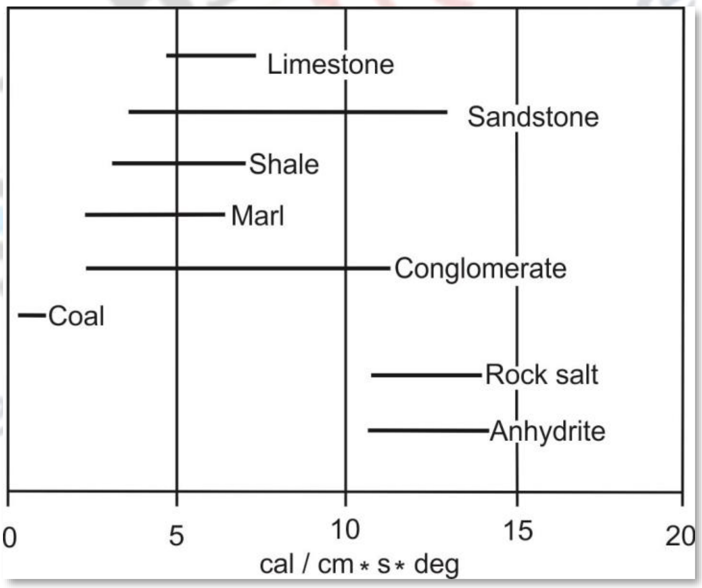

Fig. 2 Average thermal conductivities of common sedimentary rock types (after Kappelmeyer and Haenel, 1974).

Though we consider a certain geothermal gradient at a particular location, it is not linear throughout the depth and shows deviations at various depths at that location, primarily because of the variation in lithology along the depth. As the different rock types have different thermal conductivities owing to the different mineralogical and textural compositions, the heat flow through them may vary considerably (Fig. 2). The average thermal conductivities of different rock types have been worked out in some detail (Kappelmeyer and Haenel, 1974). While shale and marl have a thermal conductivity of nearly 5 (3-7) cal/cm s deg, rock salt and anhydrite have a thermal conductivity in between 11 and 14 cal/cm s deg. Because of the wide variation in the mineralogical and textural composition of sandstones, the thermal conductivity of them may be as low as nearly 3 cal/cm s deg and as high as 13 cal/cm s deg. The thermal conductivities in limestones are comparable to that of shale. Coal displays a near zero thermal conductivity.

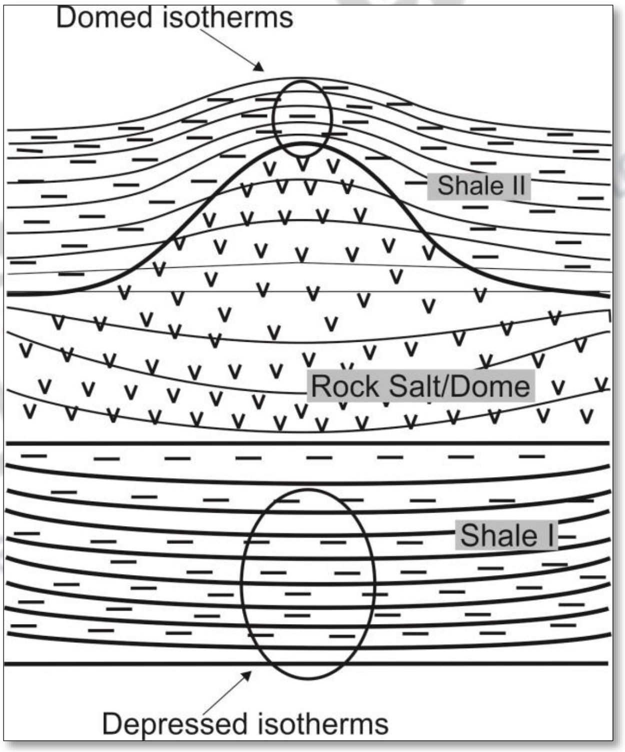

Fig. 3 Schematic representation of isotherms in the rocks of different thermal conductivities (λ), where, λ_1 (shale) ≈ λ_2 (shale) < λ_3 (salt dome).

As a result of this, the relative position of these rock types in a geological succession decides the amount of differential heating at a particular level/layer with same geothermal gradient e.g., If a shale overlies the rock salt/salt dome, because of the contrasting thermal conductivities of these two rock types, while the heat flow through the rock salt will be very fast, it would be very slow through the shale, resulting in accumulation of heat in the shale and hence the temperature in the shale would be significantly higher than the temperature in the rock salt. If the sequence is composed of shale – rock salt – shale (Fig. 3), heat content of the underlying shale would be lower than the heat content of the overlying shale. There may be various combinations of sequences of different rock types in a geological succession, in which depending on the sequence of different lithologies, accumulation or dissipation of heat would take place in a particular rock type. This in turn lead to differential temperatures at different depths resulting in deviation of the subsurface temperature from the normal temperature calculated at that level based on the average geothermal gradient at that location. Thus, the differential thermal conductivities of different rock types and hence differential heat flows at different levels in a sequence lead to the deviation from the linear geothermal gradient resulting in a nonlinear subsurface temperature profile.

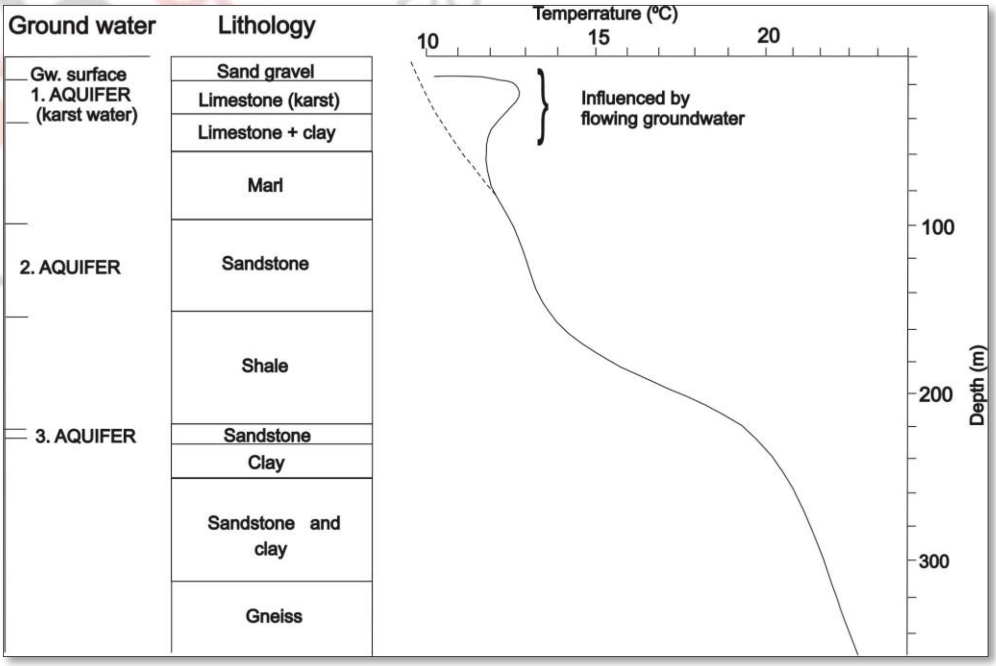

Fig. 4 Effect of ground water flow and rock types on the temperature profile along the depth (after Kappelmeyer, 1961).

Apart from the change in lithology, the presence of aquifer and the direction of the ground water flow is also a deciding factor of the accumulation or dissipation of heat at a particular location in the subsurface (Figure 4). If water flows from a region, where the heat content is higher than the surrounding, water would carry the heat from that location to the cooler location resulting in cooling of the locations with initially higher temperature. Similarly, heating of an initially cooler location also can take place by flowing in hotter formation water.

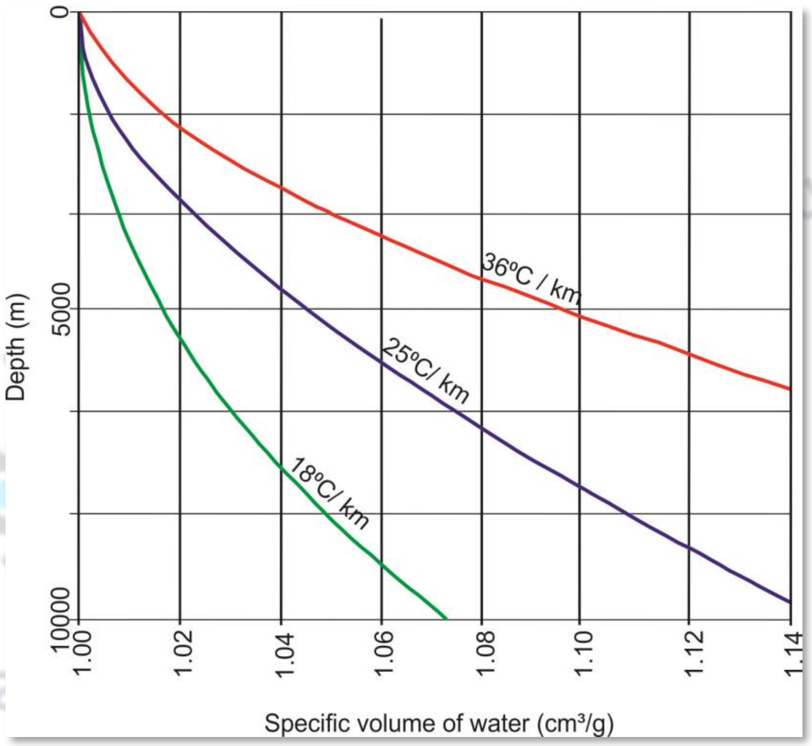

Fig. 5 Change in specific volume of water with increasing depth at different geothermal gradient (after Magara, 1974).

If effect of only temperature is considered on the volume of the petroleum and that of water, it is but natural that with increasing temperature, the volume of both would increase thereby decreasing the density of petroleum and water as well. As the coefficient of thermal expansions of crudes of various compositions and that of connate water of different salinities in the subsurface are different, an increase in temperature would result in the differential increase in the specific volumes of all these liquid components. This would in turn reduce the densities of the various liquid Components differentially. The interplay between the differential densities of water and the crudes would decide the buoyancy of a particular fluid component and hence the rate of the migration of that petroleum component.

Magara (1974) has given the relationship between specific volume of water as a function of changing temperature, and the increasing burial depth under the influence of different geothermal gradient (Figure 5). It is apparent from the figure that while under the influence of low geothermal gradient the specific volume of water is much lower even at a very great depth, it is quite high at much shallower depth with higher geothermal gradient. The increase in temperature would again lead to the decrease in the viscosity of the petroleum, thereby making it more mobile.

Pressure also plays a significant role in the migration of hydrocarbon. The pressure in the subsurface increases because of the increase in overburden thickness with depth. The pressure at a point in the subsurface is given by the combined weight of the mineral matter and the pore fluid lying on that point, which results in the lithostatic and the hydrostatic pressure. Hydrostatic pressure gradients generally vary from 10 to 10.9 bar per 100m and lithostatic pressure gradient is generally 23 bar per 100m. The mineralogy of the rocks and the salinity of the pore water also play a significant role in exerting the pressure at a point in the subsurface because of their differential specific gravities and hence their differential weights. It is interesting to note that as depth increases, the pore pressure also increases.

Under various geological conditions, the pressure at a particular depth in the subsurface would be different. While looking for the causes of over pressure in the subsurface, Fertl and Chilangarian (1975) enumerated as many as thirteen reasons, out of which four reasons were found to be most important. The major causes for the development of overpressure in a particular strata or zone are the prevalence of artesian conditions, structural deformation, compaction of the sediments in a stratum, and the diagenetic changes taking place in the sediments.

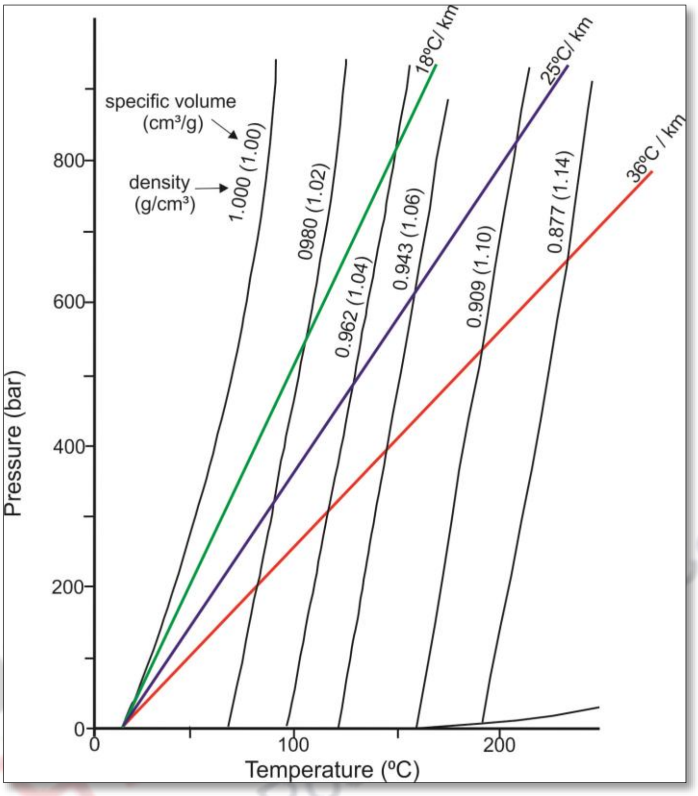

Fig. 6 Pressure-temperature-density diagram for water under geological conditions. Superimposed on this diagram are geothermal gradients of 18, 25, 36 °C per km for hydrostatically pressured water (After Barker, 1972; Magara, 1974).

The pressure in the subsurface often deviates from the hydrostatic. Bradley (1975) assigned temperature as the cause for this deviation. Barker (1972) and Magara (1974) have documented the effect of increasing temperature on the formation (pore) water volume and the pressure. It has been observed that as the temperature increases, the expansion induced increase in specific volume of water in the pores results in decrease in density non-linearly. This increase in volume of the water in the pore would enhance the pressure within the pores. As far as the migration of the fluid is concerned, because of the enhanced pore pressure, the fluid would try to escape from the pore thereby effecting the migration. They have also demonstrated the effect of geothermal gradient on the density of water by superimposing the different geothermal gradients on the figure (Figure 6). At the same pressure, the specific volume of water would be higher with higher geothermal gradient than with lower geothermal gradient. Another observation, which can be made here, is that the specific volume of water increases with the increasing depth at a particular geothermal gradient so as the specific volume of the various petroleum components increase with the increasing depth. Since the coefficient of thermal expansion of the pore-water and those of various petroleum components are different at a particular subsurface condition with respect to temperature and the pressure, the change in the specific volumes and hence the densities of all the fluid components would be different. These differential changes in the densities would result in the change in the relative buoyancy of each of the fluid components present in the rocks, thereby influencing the migration of the petroleum in the subsurface under a combination of pressure-temperature.

3.2 Influence of geological conditions on the migration of petroleum: Compaction of the sediments is another important factor, which influences the migration of petroleum because of reduction of porosity, pore size, pore-throat, and the surface area of the pores with increasing depth of burial. Tissot and Welt (1984) comments that, "It is surprising that for many years the effect and role of temperature has almost been neglected when considering compaction. The behavior of water, its specific volume, its viscosity, and capacity as a solvent, are all temperature-related. Bradley (1975) remarks that porosity loss in nature is caused by a group of inter related chemical processes dependent on reactivity, temperature, surface area, and pressure. He calls these processes 'lithification'. It refers to all processes whereby porosity is reduced in sandstones which become cemented, to shales, which are compacted, and to limestones which recrystallize". The carbonates being more reactive than the silicates, behave differently during the compaction. Porosity reduction in clastic sediments is more strongly influenced by the mechanical and physical rearrangements of mineral grains than generally encountered in the carbonates. Chemical processes dominate in the porosity and permeability reduction in carbonates with increasing depth. This leads to differential increase in pore pressure in clastic and non-clastic sediments.

If the area consisting of the petroleum system has undergone through upliftment before and/or after the petroleum accumulation in a particular stratum or structure (trap), the permeability of the system would be modified from its original permeability; and hence the geological history of the area/region is of utmost importance. When a geological sequence is uplifted followed by removal of the overburden by erosion, horizontal to sub horizontal joints are formed in the rocks because of the release of the vertical stress and subsequent extension in the vertical direction. Similarly, as the strata are uplifted, the arc length of the strata increase causing reduction in confining stress in horizontal direction and resultant extension in the horizontal and sub-horizontal direction, which would produce vertical to sub-vertical joints. All these joint sets in the rocks in turn would enhance the permeability of an uplifted sequence.

The stages of the basin evolution have a great effect on the migration of petroleum too. Coustau et al. (1975) Classified sedimentary basins based on the time of fresh water invasion in the basin, into three main types viz., juvenile, intermediate, and senile basins. The hydrodynamic conditions existing in the basins are different. While, juvenile basins have centrifugal lateral water movement because of higher compaction in the thicker part/depocentre, intermediate basins are the one with centripetal water movement in the basin because of the beginning of the invasion of the fresh/meteoric water in the peripheral parts of the basin. There exist complete hydrodynamic conditions in the senile basins. Hence the hydrodynamic conditions in a basin would determine, whether the hydrocarbon would migrate from the central part to the periphery of the basin; or from the peripheral part of the basin to the basin centre.

5. Summary

To summarize the above discussion on the physico-chemical and geological aspects of migration of petroleum, we can say that an effective petroleum system exists in the subsurface at depths between 1000 and 6000 meters where the range of the temperature and pressure are generally between 50°C and 250°C, and 100 and 1400 bar respectively. The fluid properties and the rock properties depend on various physicochemical and geological conditions viz., temperature, pressure, rock type, geological structure, geological processes, and the geological history. The fluids and the rocks in the subsurface respond to the changes in these parameters with the increase in depth in the subsurface leading to the quantum of the migration of the petroleum.

6. Anecdote

Exact understanding of the mechanism of the 'migration of petroleum' is probably the last frontier to be overcome in the petroleum geology. Laboratory experiments are difficult to be performed on this aspect considering all the variables in the subsurface. Hence, simulation of an effective model to explain a full proof mechanism for migration of petroleum in the subsurface is still lacking. People earlier used to believe in the inorganic origin of petroleum. Inability to explain the paucity and/or absence of petroleum in the rocks of all lithology and all ages throughout the geological time scale led researchers to look for an alternative model for origin of petroleum. Invention of various analytical instruments in the sixties and seventies of the last century, enabled researchers in petroleum systems to carry out different analytical procedures and to come up with certain ideas. This helped people to get inclined towards believing the organic origin of petroleum, which requires a robust migration mechanism in order to have a commercially viable petroleum accumulation. Using the research articles, mostly published until early eighties, Tissot and Welt (1984) came up with a document in the form of a textbook with absolutely a new insight in the petroleum geology.

The ambiguity in the understanding of the migration of petroleum can be very well understood from the words of Robert and Cordell (1980), which notes "We know there is little we can prove, and we do not excuse ourselves for the assumptions or conclusions which may later prove to be erroneous ... what little we do see is biased by what we look for with our mind ... we cannot actually prove when and whence a particular show of oil or gas came or how long it will remain where we see it. To be completely honest, we can only conjecture about oil and gas movements."

Frequently Asked Questions-

Short Answer Questions-

Q1. Critically discuss role of temperature and pressure in migration of oil?

Q2. Discuss the concept of 'hydrocarbon migration'. Enumerate role of geothermal gradient in hydrocarbon migration?

Q3. 'Depending on the sequence of different lithologies, accumulation or dissipation of heat would take place in a particular rock type' - Justify this statement with proper example and illustrative figure/s?

Q4. Discuss the significance of temperature and specific volume of water in migration of hydrocarbon?

Q5. With suitable sketch define 'Primary' and Secondary' migration?

Multiple Choice Questions-

1. The following sequence is correct in terms of increasing thermal conductivity

(a) coal- shale- anhydrite
(b) shale- coal- anhydrite
(c) conglomerate- anhydrite- coal
(d) shale-marl-coal

2. Amongst the following, fabric-selective porosity is

(a) Fenestral porosity
(b) Cavernous porosity
(c) Fracture porosity
(d) Mouldic porosity

3. In general, geothermal gradient noted in sedimentary basins is

(a) 50° -70°C
(b) 15° -50°C
(c) 0° -20°C
(d) It can assume any value

4. The value of lithostatic pressure gradient is

(a) 23 bars per 100m
(b) 10 bars per 100m
(c) 56 bars per 100m
(d) 23 bars per meter

Suggested Readings:

1. Tissot, Bernard P. and Welte, Dietrich H. (1984). Petroleum Formation and Occurance, 2nd Edn., Springer-Verlag Berlin Heidelberg. ISBN: 978-3-642-87813-8.
2. North F. K (1985). Petroleum Geology, Kluwer Academic Publishers. ISBN: 0045530041, 978-0045530045.
3. Levorsen, A. I (2004), Geology of Petroleum, 2nd Edn., CBS Publishers & Distributors Pvt. Ltd, New Delhi. ISBN: 8123909314, 9788123909318.

References:

1. Barker C (1972) Aquathermal pressuring- role of temperature in development of abnormal pressure zones. Am. Assoc. Pet. Geol. Bull. 56, 2068 – 2071.
2. Bradley JS (1975) Abnormal formation pressure. Am. Assoc. Pet. Geol. Bull. 59, 957 – 973.
3. Coustau H, Rumeau JL, Sourisse C, Chiarelli A, and Tison J (1975) Classification hydrodynamique des bassins sedimentaires, utilisation combinee avec d'autres methodes pour rationaliser, exploration dans des basins non-productif. Proc. 9th World Pet. Congr. Tokyo. London. Applied Science Publ., 2, pp. 105-119 (In: Tissot BP and Welt DH, Petroleum Formation and Occurrence, 1984).
4. Kappelmeyer O (1961) Geothermik In: Lehrbuch der Angewandten Geologie, Bd. I. Bentz, A. (Ed.) Stuttgart: E nke. pp. 863 – 888.
5. Kappelmeyer O and Haenel R (1974) Geothermics with special reference to Application. Berlin-Stuttgart: Borntraeger.
6. Lee. WHK and Uyeda S (1965) Review of heat flow data In: Terrestrial Heat. A.G.U. Geophvs Mon. 8. 87 – 190.
7. Magara K (1974) Aquathermal fluid migration. Am. Assoc. Pet. Geol. Bull. 58, 2513 – 2526.
8. Roberts WH & Cordell RJ (Eds). 1980. Problems of Petroleum Migration. AAPG Studies in Geology, no. 10. 273 pp. Tulsa
9. Tissot BP and Welt DH (1984) The migration and accumulation of oil and gas. In: Petroleum Formation and Occurrence. Springer-Verlag, Berlin. pp. 311 – 372.