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1. Learning outcomes

After studying this module, you shall be able to:

- What is secondary migration of petroleum?
- What are the different mechanisms of secondary migration of petroleum?
- How far petroleum can migrate from the source rocks?
- Which basins have the hydrocarbon potential?
- How the migrational history of the petroleum can be reconstructed in a sedimentary basin.

2. Introduction

It is now well established that the place of petroleum formation and the place of petroleum occurrence are different. This means that petroleum migrates from its place of formation to the place of its present occurrence. In the earlier lectures, we have learnt about the various parameters those control the migration of petroleum within a bed, and also from one bed to the other. We have learnt the mechanisms of primary migration too. While, primary migration is the movement of petroleum in the narrower pores of the fine grained sedimentary rocks, secondary migration takes place through the interconnected wider pores of the coarse grained sedimentary rocks and/or through the interconnected fractures in any rock. As migration path is an essential component of a petroleum system, this section would deal with the migration of petroleum in the coarse-grained rocks i.e., sandstones, which may be coarse grained to fine grained sandstones with good to poor sorting. Naturally, the sizes of the pore-throats vary with wide range, which results in differential permeability of the different sandstones, resulting in the variation in the rate of secondary migration of petroleum in the different sandstones.

When the petroleum passes through the narrower pores of the source rock, in the initial stage the oil particles are microscopic and submicroscopic in size, which are abundant and dispersed in aqueous pore fluid. These finely dispersed oil particles do not strictly follow the law of buoyancy and are more influenced by hydrodynamic condition existing in the sandstones, which are also known as carrier rocks as petroleum is efficiently carried from one place to the other.

There are models, which link the general movement of the pore fluid in the sedimentary basins to the different parameters viz., type and rate of sediment deposition, porosity, pore fluid pressure, temperature, etc. However, more significantly the secondary migration of petroleum and subsequent formation of oil/gas pools are controlled by:

- Buoyant rise of oil/gas in water-saturated porous rocks,
- Capillary pressure, and
- Hydrodynamic fluid flow.

Hence, it can clearly be seen that, the secondary migration takes place under two different conditions viz., (i) under hydrostatic conditions and (ii) under hydrodynamic conditions. While in the former case, the formation water/pore water remains stationary and the petroleum simply rises in the bed because of buoyancy, though the capillary pressure opposes the rise, in the latter case, the water moves through the formation/bed.

3. Secondary Migration of Petroleum under Hydrostatic Condition

The rise of petroleum under hydrostatic condition in a carrier bed is a function of the difference of densities of the water and the rising petroleum component, the acceleration due to gravity at that place. The buoyant force is given by

$$\text{Buoyant Force} = Z_o.g\ (\rho_w - \rho_p) \quad \text{......................................} \ (i)$$

Where, Z_o = height of the petroleum/oil column

ρ_w = density of the water, which is a function of the temperature and salinity, and of thermal expansion of the pore water.

ρ_p = density of the petroleum, which is a function of the composition, temperature, and the coefficient of thermal expansion of the petroleum in the carrier bed.

g = acceleration due to gravity at the place under consideration

As has been mentioned earlier, the rise of petroleum under hydrostatic condition in a carrier bed is opposed by the capillary pressure, which is a function of grain size of the carrier rock, the size of the oil globule and the interfacial tension between existing petroleum and the water in the pore. The following equation defines the amount of capillary pressure in the carrier rock.

$$\text{Capillary Pressure} = 2\gamma\ (1/r_t - 1/r_p) \quad \text{.............................. (ii)}$$

Where, γ = interfacial tension between oil & water,

r_t = radius of the pore-throat,

r_p = reservoir rock radii

When under hydrostatic condition an equilibrium state prevails between buoyant force and the capillary pressure i.e., equations (i) and (ii) are equal in magnitude but opposite in direction, hence the petroleum globule would not move; and the equation can be written as:

$$2\gamma\ (1/r_t - 1/r_p) = z_o.g\ (\rho_w - \rho_o) \quad \text{.. (iii)}$$

Hence, the maximum height of an oil column (= critical height, z_c) is expressed as:

$$Z_c = 2\gamma\ (1/r_t - 1/r_p)\ /\ g\ (\rho_w - \rho_o) \quad \text{...................................... (iv)}$$

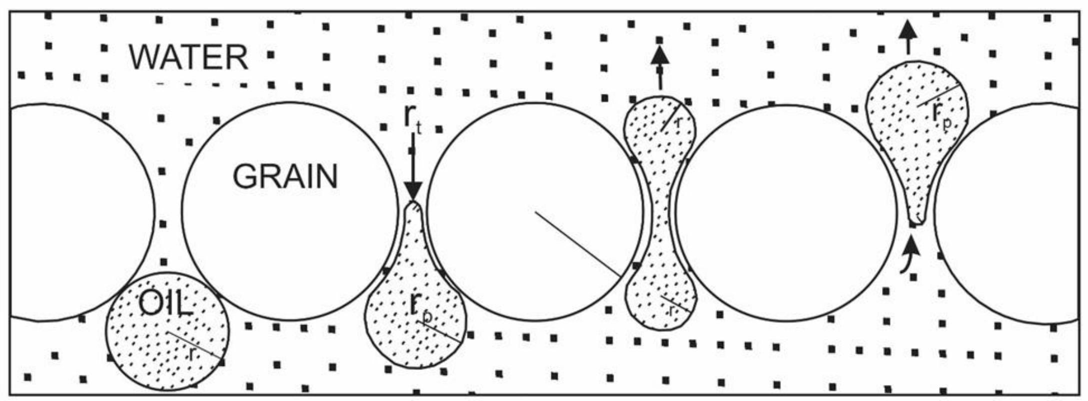
Moreover, the oil globule will rise when

$$Z_o.g\ (\rho_w - \rho_o) > 2\gamma\ (1/r_t - 1/r_p) \quad \text{..................................... (v)}$$

Which means, lighter the petroleum than the pore water in a particular rock, higher is the chance for petroleum to rise in the reservoir rock. Now, the inevitable question is, whether a petroleum globule in general and an oil globule in particular with a greater radius than that of the radius of the pore throat can overcome and rise through that pore throat? The answer lies in the equation given by Berg (1975) for the internal pressure (P) of an oil globule, which enables the oil globule to overcome the undersize pore throat. He mathematically demonstrated that the pressure inside a globule is dependent on the interfacial tension (γ) and is inversely proportional to the radius (r) of the globule and is given by:

$$P = 2\gamma/r \quad \text{...} \quad \text{(vi)}$$

Now, the oil globule in the water wet clastic reservoir rock will have pressure inside it equivalent to $2\gamma/r$ (Berg, 1975). Where r is the radius of the oil globule; and γ is the interfacial tension between water and oil. The size of the pore depends on the grain size of the rock, and the size of the oil globule is controlled by the pore size.



P = (**a**) $2\gamma/r$ (**b**) $2\gamma/r_t > 2\gamma/r_p$ (**c**) $2\gamma/r = 2\gamma/r$ (**d**) $2\gamma/r_t < 2\gamma/r_p$

Fig. 1 Buoyant rise of a larger oil globule than the pore-throat under hydrostatic condition, here P is the pressure inside the oil globule.

As the tiny droplets of petroleum are expelled out from the source rock, to reduce the surface tension, these droplets unite to form a larger spherical globule, and hence become more buoyant. By virtue of the buoyancy, the petroleum globule rises and comes in contact with the grains with smaller pore throat than its diameter (Fig. 1a). At this stage, the pressure inside the globule is $2\gamma/r$. The rising globule gets distorted when it comes in contact with the grains, thereby giving rise to a smaller sphere at the upper part with radius r_t, and bigger sphere at the lower part with radius r_p. According to the equation (vi), the pressure in the upper part would be greater than the pressure in the lower part (Fig. 1b). This would result in pushing the upper part of the oil globule through the smaller pore throat. This process would continue till both the upper and lower ends of the globule turns equal in size, which would result in a dumble shaped globule having equal pressures at both the ends (Fig. 1c). At this stage, the globule would rise further by virtue of the buoyancy and overcome the smaller pore throat than its size (Fig. 1d).

4. Secondary Migration under hydrodynamic condition

As has been discussed in the earlier lecture, because of various reasons, the water (connate or meteoric) flows through the coarse-grained rocks. This would result in the elongation of the oil globule thereby it would be converted to an oil stringer (Fig. 2). Hobson and Tirastoo, (1975), have discussed displacement and separation of oil and gas in an anticlinal reservoir under the increasing action of flowing water.

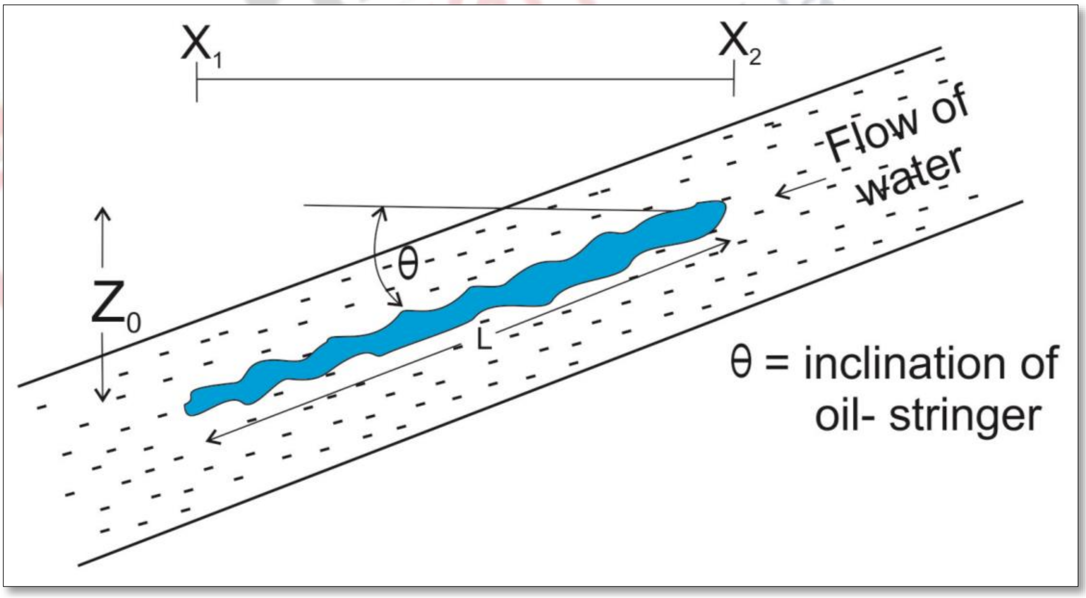


Fig. 2 Influence of hydrodynamic condition on the transport of oil globule.

X_1 and X_2 are the hydrostatic heads at the two ends of the oil stringer, the difference of which determines the strength of the flow. Less the strength of the flow of water, lesser would be the displacement of the petroleum phases, and vice versa. The Z_0 is the height of the oil column. When flow of the water in the inclined bed is up-dip, the column would be shorter and in case of a down-dip flow, the column would be longer, because of the influence of the acceleration due to gravity.

Under hydrostatic condition in an anticlinal bed, oil and gas would rise to the top by buoyancy. The further upward migration of the petroleum accumulation would cease, if, there is an overlying impermeable layer. Under this condition, both water-oil and oil-gas contacts would be horizontal. If water begins to flow through the reservoir that would exert pressure on the accumulation and would try to drag the accumulation in the direction of the water flow (Fig. 3).

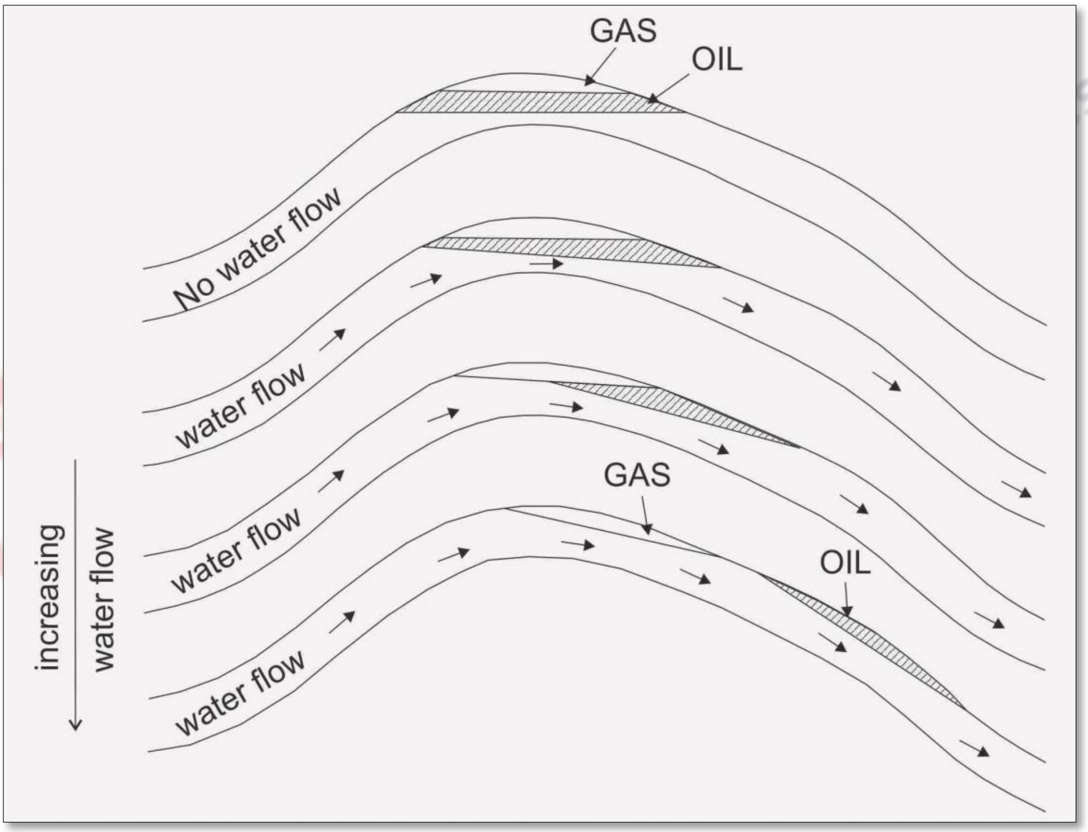


Fig. 3 Displacement and separation of oil and gas in an anticlinal reservoir under the increasing action of flowing water (after Hobson and Tirastoo, 1975).

With increasing velocity of the water flow, first the water-oil contact would become inclined, while the oil-gas contact would remain horizontal. There would not be any contact between water and gas under this condition. With further increase in the water flow velocity, the oil accomulation would be dragged further, causing considerable displacement of the oil from the position of its earlier accumulation. Under this condition, both oil and gas would have contacts with the water.With further increase in the water flow, the oil accumulation would be separated from the gas and the water-gas contact would also be inclined. If the water flow increases further, both oil and gas would be flushed from their earlier position of accumulation (Fig. 3). The accumulation would be totally flushed out from the reservoir/antiformal trap, if, the water flow continues for a prolonged period, and/or the dip of the limb of the antiform decreases or even remains same throughout. The displaced oil and gas could be located at the flank of the antiform, if, the dip in the lower part of the limb is more than in its upper part (Fig. 3).

The mechanism of displacement of the petroleum accumulation from the crestal part of the antiformal reservoir and its emplacement in the lower part or complete flushing out from the antiformal structure has been explained by the isopotential surfaces. Isopotential surface is the surface, in which the potential energy is equal; and hence this is also known as equipotential surface.

An oil accumulation in a reservoir, can be considered as a combination of numerous surfaces parallel to the water-oil contact. When water flows through such reservoir, the energy decreases in the oil, upward from the water-oil contact. The isopotential surfaces (U_0) in relation to buoyant (P_b), hyrdrdynamic (P_h), and confining (P_y) forces in an antiformal reservoir under hydrodynamic conditions has been demonstrated in figure 5. More the energy of the isopotential surface of the oil/gas, more the drag force it would suffer. Hence, the isopotential surface closest to the water-oil contact would be dragged more than the overlying isopotential surface. Hence, if the velocity is enough to drag the petroleum, petroleum would be displaced from its initial position of accumulation towards the direction of water flow.

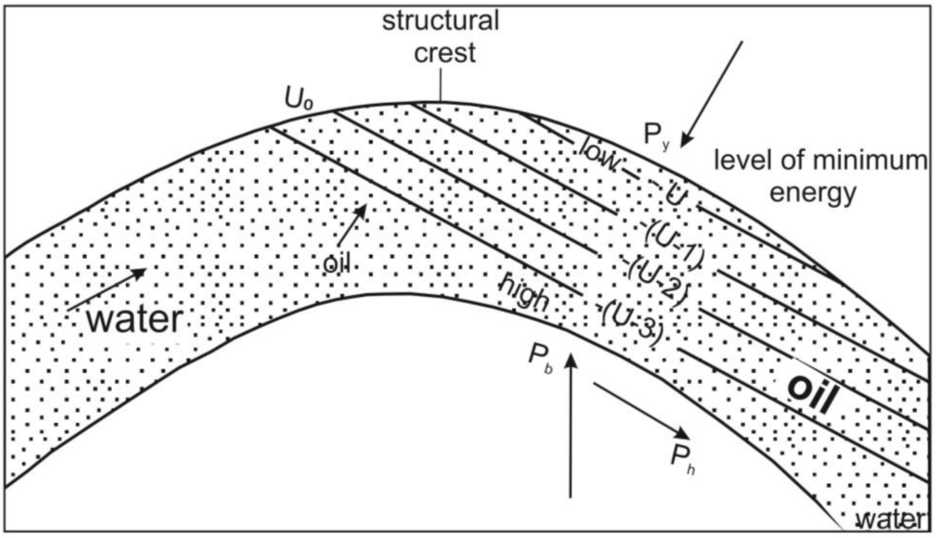


Fig. 5 Oil isopotential surfaces in an antiformal reservoir (after North, 1983).

If we consider a system consisting of a convex trap with both oil and gas accumulations in it, along with the hydrodynamic condition existing in the trap; the equipotential surfaces for the gas, oil and water would occur as shown in the figures 6, 7, and 8. This is clear from the respective figures that the inclinations of the isopotential surfaces of the gas and oil are different (Fig. 9); and the inclinations depend on the density of the petroleum components. The inclination of the isopotential surfaces are very important, as it determines that different petroleum components would be displaced from its initial position by the flowing water. The petroleum components would even be flushed out of the convex traps if the dip of the isopotential surfaces of the different petroleum components were more than the dip of the limb of the convex trap.

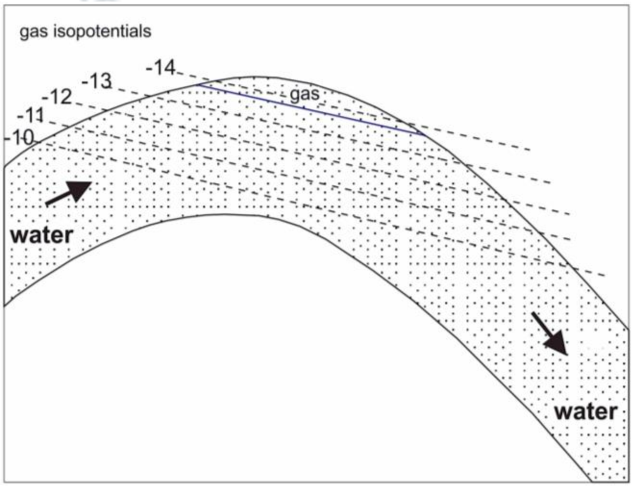


Fig. 6 Isopotential surfaces of the gas accumulation because of water flow

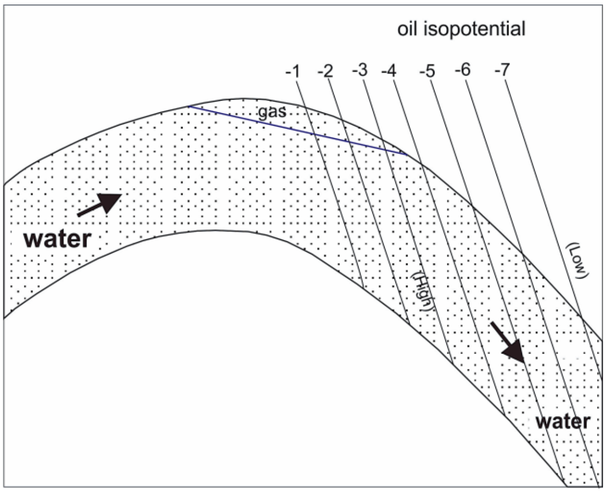


Fig. 7 Isopotential surfaces of the oil accumulation because of water flow

The relocation of the displaced petroleum accumulation in the Fig. 3 can be explained by the attitudes of the isopotential surfaces. In this figure, it can be noted that the inclination of the water-oil contact, and hence the inclination of the oil isopotentials are more than the dip of the limb of the fold at its upper part than at the lower part. Because of this, while the oil has been flushed out of the upper part, it has been emplaced at the lower part, where the dip of the confining surface of the folded antiformal structure is more than the inclination of the oil isopotentials.

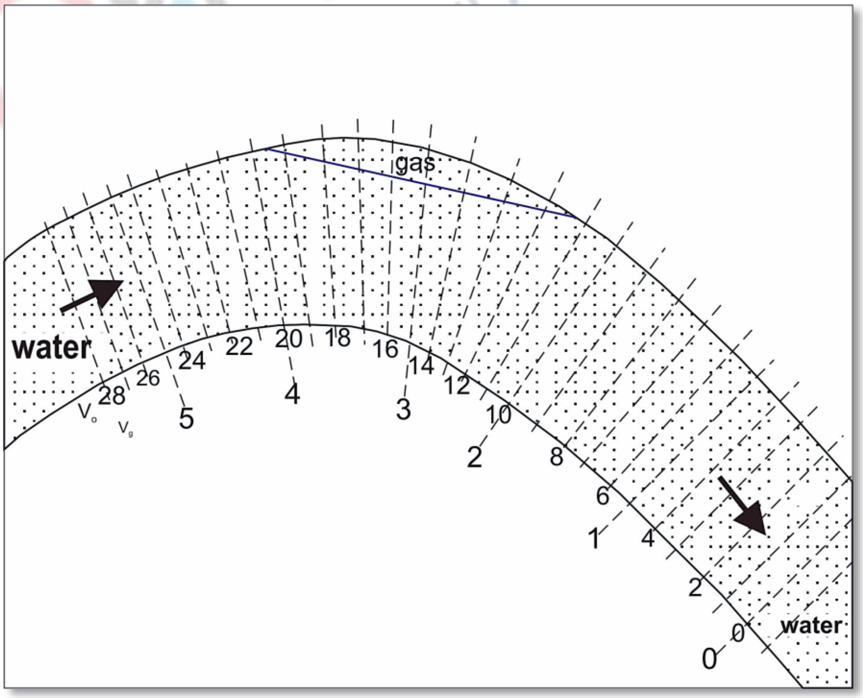


Fig. 8 Isopotential surfaces of the flowing water.

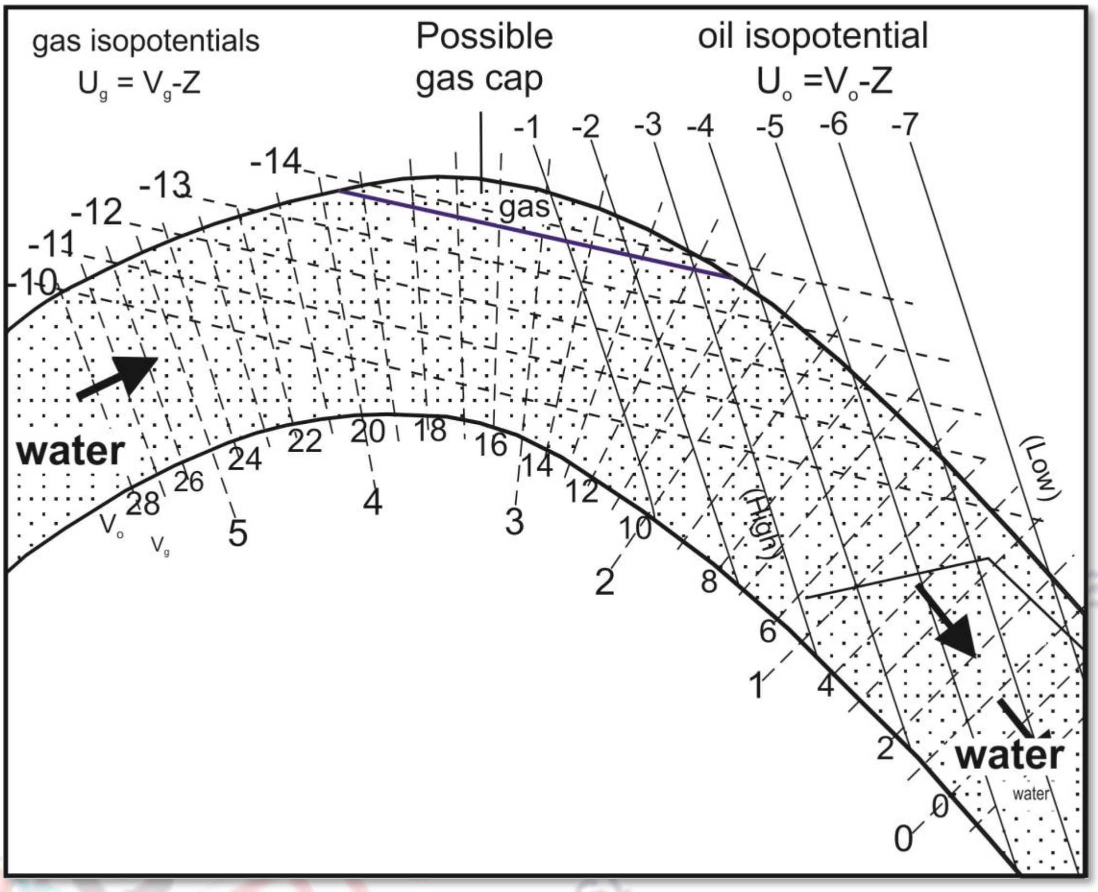


Fig. 9 Isopotentials of gas, oil and water (North, 1985).

5. Classification of Sedimentary basins based on Hydrodynamic Condition prevailing in the basin vis-à-vis their Petroleum Prospects

Coustau et al., (1975) classified sedimentary basins based on the hydrodynamic conditions existing in the sedimentary basins and commented on the petroleum potential. Based on the time of invasion of meteoric/fresh water i.e., (a) before, (b) during, & (c) after the invasion of meteoric water in the basin they classified three main types of basins: which are as follows

a) **Juvenile Basin:** these are not necessarily young. They are characterized by the compaction-induced centrifugal, lateral water movement in the basin (e.g., Nigeria, Gulf of Mexico, Douola Basin, North Sea, North-East Sahara – between salt deposits). These basins have very strong petroleum prospect as meteoric water has not yet entered into the basin and hence flushing of petroleum from the basin has not yet taken place.

b) **Intermediate Basin:** They are characterized by centripetal water movement from the central part of the basin to its flanks. Meteoric water invades the layers because of differential erosion of rocks at some parts. Artesian conditions may occur. (e.g., Persian Gulf, east Sahara, Paris Basin, Central Tunisia, Sahara – below the salt, etc.). Petroleum interests in such basins vary from very strong to moderate.

c) **Senile Basin:** Hydrodynamic conditions with the invasion of meteoric water occur all over the basin, leading to the flushing of petroleum from the basin; and hence, there is very little or no petroleum prospect is left in these basins (e.g., Northwest Aquitaine Basin, part of North Spanish Basin).

Strong and long-lasting hydrodynamic flow retards the formation of pools or even destroys the existing accumulations by the flushing.

6. Distance of Secondary Migration

The presence of overlying impermeable beds stops the vertical secondary migration of petroleum and helps in trapping the petroleum in the underlying permeable rock. However, the fracture systems viz. permeable joints, faults, dykes, mud volcanoes may facilitate the vertical migration of the petroleum more than the thickness of the clastic reservoirs. It has been well noted that the growth faults in the deltas open multiple avenues for the vertical secondary migration of petroleum far more than the thickness of the reservoirs.

When it comes to the determination of horizontal distance of secondary migration of petroleum, remoteness between the source rock and it's adjacent and/or nearest reservoir rocks in a sedimentary basin gives the distance of secondary migration for a pair of source and reservoir rock. Bruce & Schmidt (1994) attempted the application of chemical fingerprint in the source rock and oil in the reservoir rock by using gas chromatographic techniques. In order to understand the distance of secondary migration, Larter et al. (1996) used the regional variation of traces of non-alkylated benzocarbazoles, which is apparently effective and independent of the maturity of the oils. Some notable examples of distance of secondary migration have been given in the following table.

Basin/Location	Distance of Migration
Athabasca tar Sands, Canada	100 km
Magellan Basin, Argentina	100 km
Pennsylvanian Oklahoma, USA	120 km
Gulf Coast, Pleistocene	160 km
Illinois Basin, USA	200 km
Paris Basin	200 km
Phosphoria Formation	400 km
Alberta Basin, Canada	1000 km

7. Summary

Petroleum prospect of a sedimentary basin to a great extent depends on the migrational history of the petroleum in the basin. For the Reconstruction of the migrational history of oil/gas, various existing conditions in the basin have to be analyzed logically and critically. These conditions are: (i) Geological conditions viz., disposition of strata, areas of homoclinal dip versus areas of folded strata; availability of carrier systems; presence/absence of restraining structures or strata near source-rock areas; history of earth movement; variations in geothermal gradient; etc. (ii) Physical & chemical character of fluids viz., gravity & viscosity of oil; state of association of oil, solution gas, free gas, & water; state of dissemination of fluids within sediments; availability of meteoric water recharge; etc. and (iii) Lithological characters of reservoir rocks viz., porosity & permeability; proportion of induced openings (fissures, joints, solution pipes, etc.); entry pressures and permeabilities of roof rocks; degree of saturation with water; effectiveness of cementation.

Hence, from the above discussion, it is very clear that reconstruction of migrational history in a basin is one of the key components for the success of petroleum exploration.

Frequently Asked Questions-

Q1. What do you understand by the secondary migration of petroleum?

Q2. Enumerate and explain the various parameters, which influence the secondary migration of petroleum?

Q3. How does the density of the crude oil influence the secondary migration of petroleum under hydrostatic condition?

Q4. Under the hydrostatic condition, can a larger oil globule overcome a smaller pore throat during secondary migration?

Q5. How does the hydrodynamic condition affect an oil accumulation in a convex trap?

Q6. What is an equipotential surface? With the help of equipotential surface, show under which condition petroleum would be flushed out from convex trap?

Q7. How the geometry of the folded reservoirs and the direction of water flow through it influence the amount of petroleum accumulations in them?

Q8. Based on the time of invasion of meteoric water in a sedimentary basin, with reason(s), comment on the petroleum prospect of that sedimentary basin?

Multiple Choice Questions-

1. Secondary migration of petroleum is not influenced by

(a) density of the petroleum
(b) interfacial tension
(c) chemical composition of the grains of the clastic reservoirs
(d) dip of the folded clastic reservoir under hydrodynamic condition

Ans: c

2. Under hydrostatic condition, the buoyant force in the petroleum migration is given by

(a) $Z_0.g\ (\rho_o - \rho_w)$
(b) $Z_0.g\ (\rho_w - \rho_o)$
(c) $Z_0\ (\rho_w - \rho_o)$
(d) $g\ (\rho_o - \rho_w)$

Ans: b

3. Under hydrostatic condition, the capillary pressure in the petroleum migration is given by

(a) $2\gamma\ (1/r_p - 1/r_t)$
(b) $\gamma\ (1/r_p - 1/r_t)$
(c) $2\gamma\ (1/r_t - 1/r_p)$
(d) $g.\gamma\ (1/r_p - 1/r_t)$

Ans: a

4. The equipotential surfaces in oil under hydrodynamic condition are

(a) essentially non-parallel
(b) having no relation with each other
(c) parallel to each other
(d) none of the above are true

Ans: c

5. Down-dip water flow through the oil-bearing clastic convex trap

(a) does not have any effect on the height of the oil column
(b) shortens the oil column
(c) may shorten or lengthen the oil column
(d) lengthens the oil column

Ans: d

6. Petroleum prospect in a sedimentary basin is the strongest

(a) before the invasion of meteoric water into the basin
(b) after the invasion of meteoric water into the basin
(c) there is no relation between the petroleum prospect and the time of invasion of meteoric water into the basin
(d) during the invasion of meteoric water into the basin

Ans: a

Suggested Readings:

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