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Table of Content

1. Learning outcomes

After studying this module, you shall be able to:

- Know about primary migration of petroleum.
- Learn about various proposed mechanisms of primary migration.
- Know about the validity of all these mechanisms by knowing the merits and demerits of each mechanism.
- 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

Organic matter turned kerogen are found dispersed in the fine-grained sediments/rocks. With the increasing burial depth, which results in increased temperature and pressure, the kerogen is converted to various petroleum components, which occurs, dispersed in the rock in different forms. These can be precursor of petroleum viz., ketones, acids, easters, colloids, tiny droplets of petroleum oil and/or gas. Whatever may be the form of the petroleum; this needs to be migrated from the source rock to give rise to an accumulation. In the preceding section, we have seen that primary migration of petroleum includes the movement of petroleum within the fine grain rock viz., shale and expulsion of the petroleum from the fine-grained rock to the coarse-grained rock as well. Since there is not much real data available from the subsurface conditions, it is difficult to propose a full proof mechanism to explain the migration of petroleum through the tiny pores in the shale, at times having much lesser size of the pore throat than the molecular size of the various components of petroleum. In order to search for the answers to the questions viz., what is the form and state of crude oil (crudes) occurring in the fine grained rock? At what stage migration of crude begins, and how it takes place? What is the driving force for migration of petroleum? What is the preferred direction of migration from the source rocks? various mechanisms and theories have been proposed. In order to understand the least understood and complex process in the petroleum geology, following proposed mechanisms would be discussed.

3. Mechanism of primary migration of petroleum

3.1 Expulsion of proto-petroleum: When we think of petroleum being moved out of the ‘source rock’ with water, a major problem arises because of the very low-to-low solubility of the oil in water. So the question was raised about petroleum getting dissolved in water. To suggest a solution on the problem of solubility of petroleum in water, it was proposed that petroleum actually moves out of the source rock not in the form of petroleum but as proto-petroleum viz., ketones, acids, and easters. Since these are soluble in water, it was proposed that, these are the earlier form of petroleum, which are soluble in water and hence can migrate along with water. However, the demerit of this mechanism of primary migration of petroleum is that, the mechanism fails to explain that how these proto-petroleum gets separated from the water after they are expelled out of the source rock.

3.2 Influence of geological conditions on the migration of petroleum: This mechanism proposes the expulsion of petroleum not in the form of proto-petroleum but in the form of petroleum, itself dissolved in the water. It was thought that though the solubility of petroleum in water at the STP is low, at the reservoir temperature and pressures the solubility of petroleum increases considerably. However, contrary to this, it was found by McAuliffe (1966, Table 1) and Price (1973, 1976) that at 25°C, the aqueous solubilities of various petroleum compounds remain very low. McAuliffe (1980) showed that while normal alkane with carbon number twelve or more are very less soluble (Figure 1) in water at 25°C, the solubility of n-alkane increases with decreasing carbon number below twelve at the same temperature. However, the solubilities of aromatics with low carbon number are to some extent higher at the 25°C and the solubilities of n-alkane with low carbon number at 150°C though increases, still is considerably low. Effect of temperature on the solubility of whole oil had been studied by Price (1973, 1976), which depicts that the solubility of whole oil though increases with increase in temperature, it remains below 150 ppm even at 150°C (Figure 2). It is argued, given the considerably low solubility of hydrocarbon in water, for the migration of commercially exploitable amount of petroleum, huge amount of water is required, presence of which in the source rock is questionable.

Table 1: Aqueous solubilities of some petroleum compounds at 25°C in ppm (after Tissot and Welt, 1984).

Compound	Solubility*
Methane	22.4 ± 1
Ethane	60.4 ± 1.3
Propane	62.4 ± 2.1
n-Butane	61.4 ± 2.1
n- Pentane	38.5 ± 2.0
Isobutane	48.9 ± 2.1
Isopentane	47.8 ± 1.6
Cyclopentane	156.0 ± 9.0
Cyclohexane	55.0 ± 2.3
Benzene	1780 ± 45
Toluene	515 ± 17

* McAuliffe (1966)

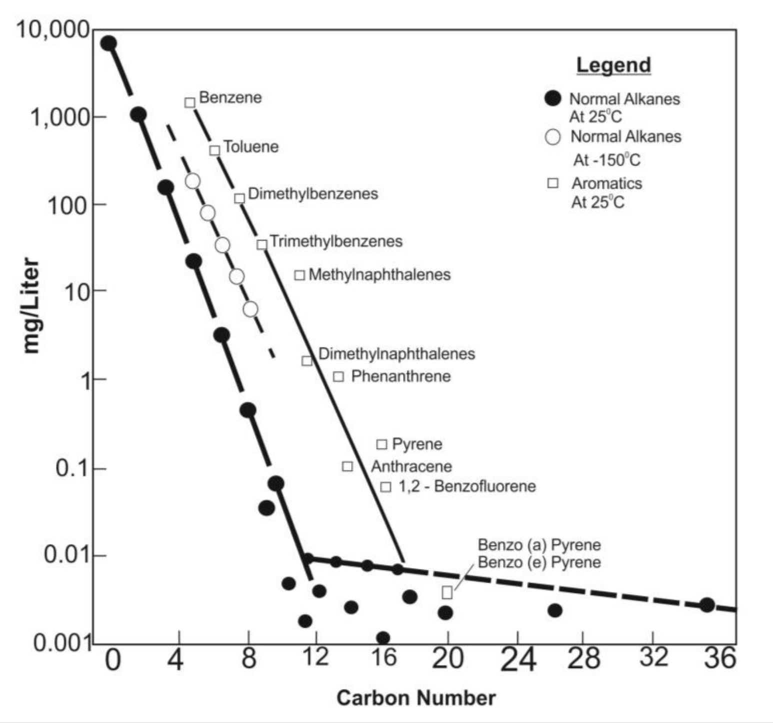

Fig. 1 Solubilities of normal alkanes and aromatics in water (After McAuliffe, 1980).

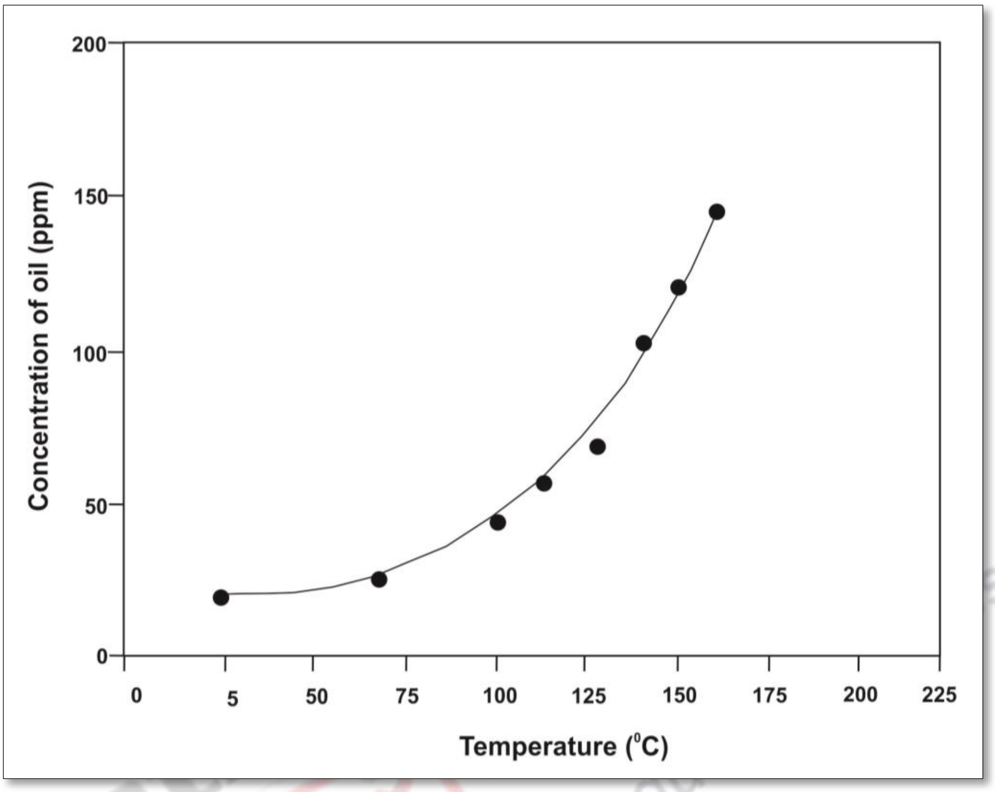

Fig. 2 Solubilities of whole crude oil as a function of increasing water temperature (After Price 1973, 1976).

Moreover, when the conditions of petroleum generation are superimposed on the depth versus porosity diagram in a sedimentary sequence with a geothermal gradient of 25°C/km (Figure 3), the optimum oil generation conditions occur at a depth of around 4 km. The porosity at this level would reach to near constant as shale compaction because of overburden is completed much before this level. As a result, there is minimal water loss from shale through compaction over the depth range of the oil window. Hence, a low volume of water is available to carry the hydrocarbon in solution.

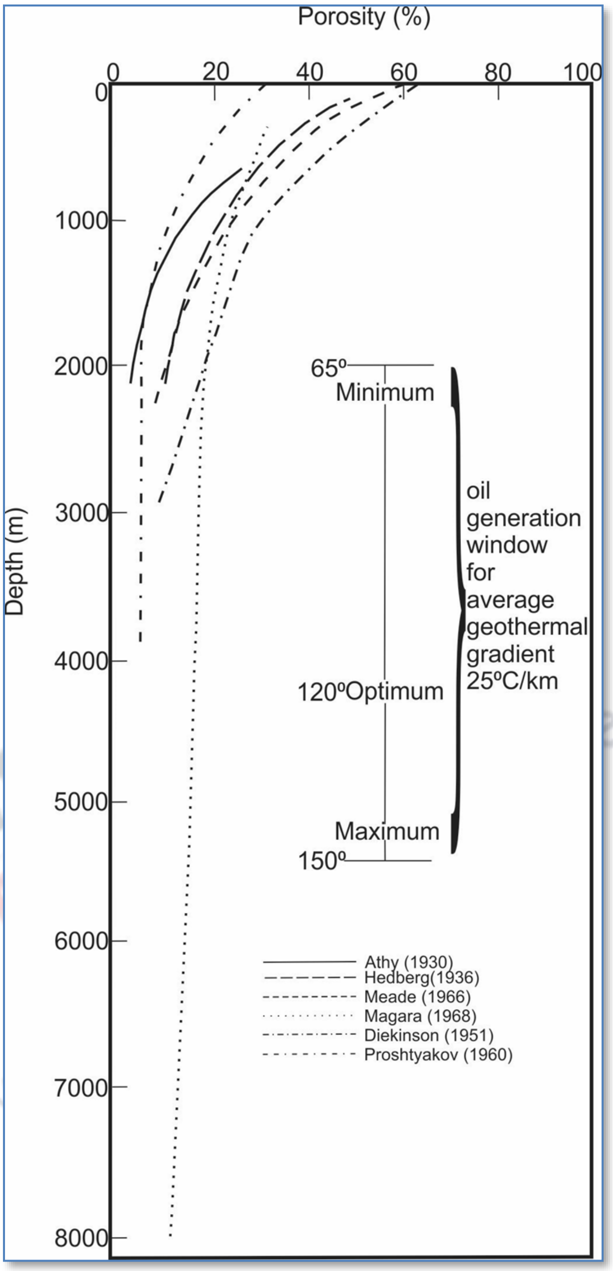

Fig. 3 Change in shale porosity with depth as proposed by various workers (after Tissot and Welt, 1984).

3.3 Expulsion of petroleum as micellar solutions: This is another mechanism, which has been invoked to solve the low solubility of petroleum in water. In this mechanism, it is proposed by Baker (1962, 1967) that solubility of petroleum hydrocarbon in water at low temperature is enhanced by micelles. Micelles are ordered aggregate of polar organic molecules, known as natural soaps. They possess hydrophobic parts on the inside and the hydrophilic parts on the outside. While water molecules gets attached to the hydrophilic ends of the micelles, petroleum hydrocarbon molecules attaches at the hydrophobic end. Under the increased compaction of shale as the pore-water is squeezed out, the water molecule linked with micelle and the petroleum hydrocarbon pulls out the petroleum molecule out of the shale. Though this mechanism of primary migration of petroleum hydrocarbon looks fine, it raises few questions. First, the abundance of micelles in the shale is found to be not enough to solubilize the entire petroleum hydrocarbon formed in the shale. Second, the size of the micelles is much more than the size of the pore throats, and hence it remains a question that how the micelles and the petroleum hydrocarbon molecules bigger than the pore throat overcomes the pore throat (Fig. 4)?

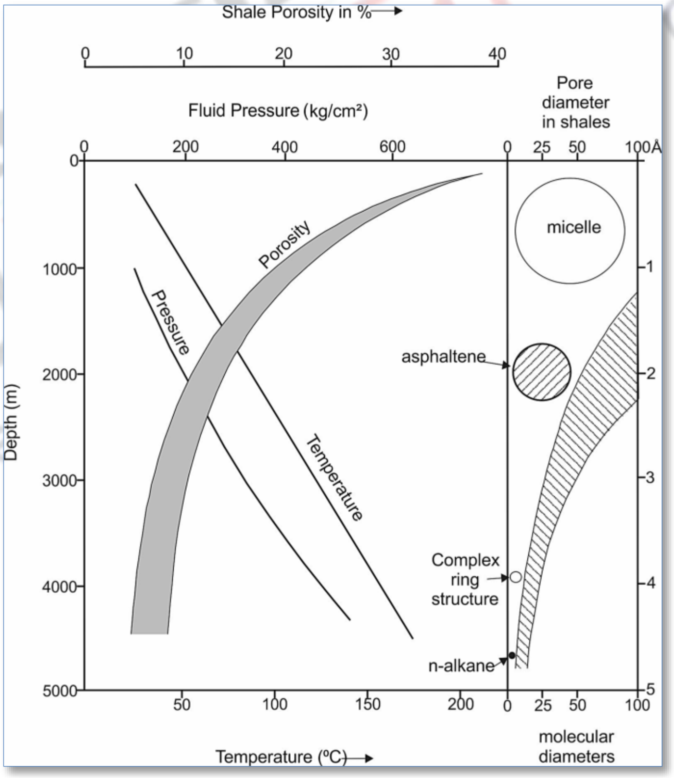

Fig. 4 Interrelationship of various parameters viz., temperature, fluid pressure, shale porosity with depth of burial in the left panel; and in the right panel comparison between the sizes of the molecules of various hydrocarbon components occurring in petroleum and the change in pore size with increasing depth has been shown (after Tissot and Welt, 1984).

Third, even if the linkages of water-micelle-petroleum hydrocarbon molecule are squeezed out from the shale, how petroleum gets detached from the micelles after the migration? Fourth, Most of the pore water is squeezed out from the shale before it reaches 2000 m and with a geothermal gradient of 25°C/km (Figures 3) petroleum forms at around a depth of 4000 m; hence the availability of the water for primary migration of petroleum looks to be insufficient. The approximate molecular diameters of water and some selected petroleum compounds (Table 2) have been given for comparison with the dimension of the pore throat in shale.

Table 2: Approximate molecular diameters of water and some selected petroleum compounds (after Tissot and Welt, 1984).

Molecule	Size in Å (= 10^{-10}m)
H_2O	3.2
CH_4	3.8
n-Alkanes	4.8
cyclohexene	5.4
Benzene	4.7
Asphaltene	50 - 100

However, the availability of water at a deeper level can be explained by the water escape curve and plot of water content of shale with the depth of burial. The plots show that, second stage of dehydration takes place at an elevated temperature, when the clay minerals in general and montmorillonite in particular lose water, which is contributed to the source rock (Fig. 5).

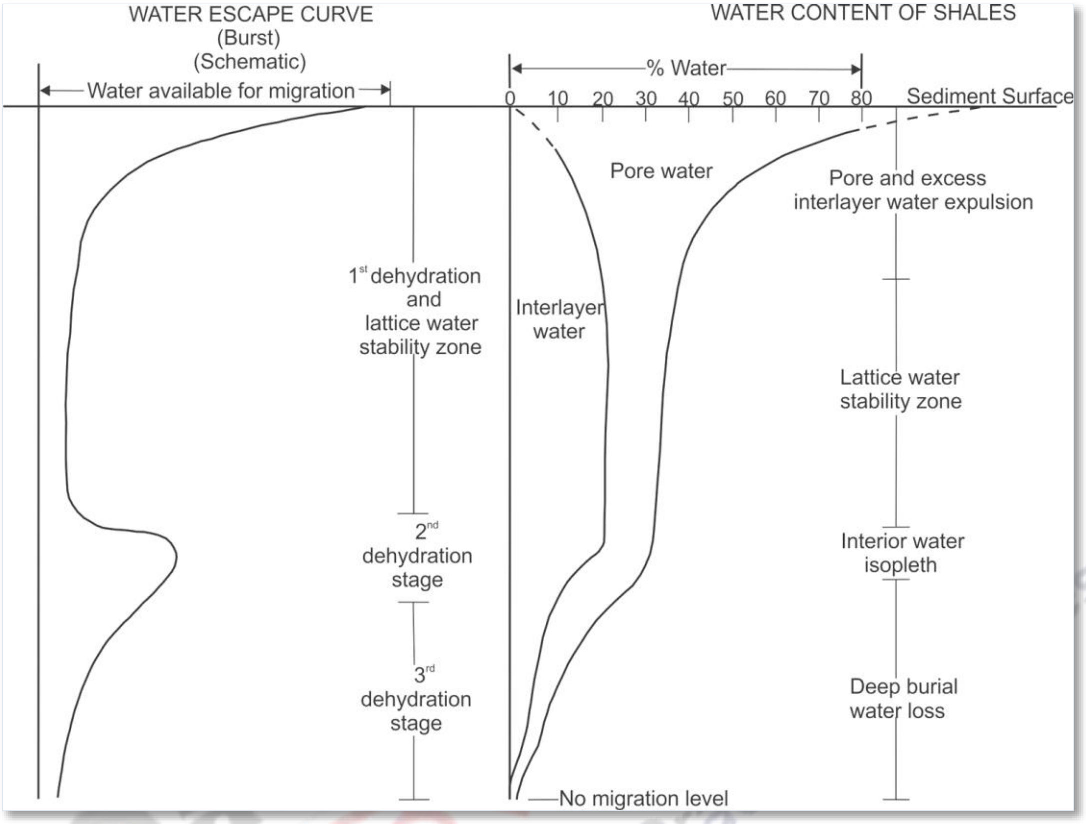

Fig. 5 Dewatering curves for clay burial (after Burst, 1969).

3.4 Solution of oil in gas: Carbon dioxide and hydrogen are generated along with the hydrocarbon in the shale. These gases dissolve in the pore water, which in turn mobilize the liquid hydrocarbons along with the water expelled during the shale compaction (Bray and Foster, 1980). The process is similar to the enhanced oil recovery, in which carbon dioxide is injected to the depleted reservoir. In this case, the hydrocarbon production enhances because of solubilisation of the carbon dioxide in oil resulting in swelling of the hydrocarbon phase resulting in decrease in viscosity and interfacial tension. Similarly, in source rock, the hydrocarbon phase charged with carbon dioxide and/or hydrogen would result in the decreased viscosity and interfacial tension, which in turn would induce increase in relative permeability of the oil and hence cause enhanced migration of the oil in the source rock.

3.5 Migration of petroleum hydrocarbon in continuous phase: This mechanism of primary migration of petroleum hydrocarbon through narrow pores of clastic source rock is also popularly known as grease-wick theory. This mechanism resembles with the rising of melted wax through the narrow pores equivalent to the capillaries of the cotton wick. This theory does not require the presence of water in the source rock, and is free of the solubility of petroleum in water. The theory is nearly independent of the size of the pore throat. Here, interfacial tension and capillary pressure in the oil-rock system are considered the deterministic conditions for the migration of petroleum. According to this theory, nearly separate and continuous oil phase, irrespective of its composition rises through the narrow pores of the shale because of interfacial tension (Dickey, 1975). Examples of primary migration as a separate oil phase have been cited by Meissner (1978), McAuliffe (1980), and others. The demerit of this mechanism is that, not most of the rock-grain surfaces are oil wet but are water wet. It remains to be explained, how this mechanism is effective in a water-wet system.

3.6 Diffusion as a primary migration mechanism: In this mechanism, hydrocarbon phase moves from higher concentration site to lower concentration site without the movement of the aqueous phase. While diffusion of gas is an effective process, is not effective for oil (Leythaeuser et al., 1980. 1982).

4. Concluding Remark

None of the mechanisms of primary migration of petroleum hydrocarbon proposed so far fully explains the phenomenon as all the proposed mechanisms. All the mechanisms have both merits and demerits as well. Hence, it is believed that all the proposed mechanisms contribute towards primary migration of petroleum hydrocarbon through fine-grained clastic rock (source rock).

5. Summary

Petroleum cannot form where it is found, hence migration must be a mechanism associated with the expulsion of petroleum from the source rock. This is the least understood topic in petroleum geology. Workers during the last half a century proposed various mechanisms to explain the various mechanisms of expulsion of petroleum hydrocarbon. Petroleum generally forms at a subsurface depth over 3000 m. At this depth in the shale there is (i) compaction induced very tiny size of the pores with very narrow pore throats; (ii) a lack/paucity of the carrier system (water); (iii) very little solubility of the various petroleum hydrocarbon components in the water; (i) very low permeability of the system which may be termed practically impermeable. In order to overcome these shortcomings for transport of petroleum hydrocarbon components in the low/no permeability medium, mechanisms have been proposed to explain the solubility of hydrocarbon in water. Other than these mechanisms, transport of hydrocarbon as separate and continuous oil phase has been proposed. Finally, to facilitate the transport of hydrocarbons through shale, mechanism has been proposed for the development of micro fracture in it. Unfortunately, none of the mechanisms can explain the transport of petroleum hydrocarbon in/through shale without ant fault. Hence, it is believed that all of the mechanisms proposed and explained so far facilitate the primary migration of petroleum hydrocarbon components within/through the shale.

Frequently Asked Questions-

A. Long Questions

Q1. Enumerate the different proposed mechanisms of primary migration of petroleum hydrocarbon. Discuss the importance of aqueous solubility of various petroleum components in water?

Q2. Discuss the solubility of various petroleum hydrocarbon components at the surface and subsurface temperature. Explain the merits and demerits of the hot oil theory?

Q3. What are micelles? Explain the expulsion mechanism of petroleum hydrocarbon from the source rocks with the help of micelles. What is your opinion about the validity of this mode of primary migration?

Q4. Explain the primary migration mechanisms of petroleum hydrocarbon in continuous phase, and by rock fracturing. Add a note on the validity of these mechanisms?

Q5. Enumerate the primary migration mechanisms of petroleum hydrocarbon. Which one according to you explains the primary migration of petroleum hydrocarbon best and why?

B. Match the Following

1. Size of water molecule	A. Pore pressure
2. Microfractures	B. ≈100 Å
3. Size of a micelle	C. Capillary pressure
4. Grease-wick theory of primary migration	D. <15 Å
5. Size of shale pore at ~4km depth	E. 3.2 Å

Key: 1-E, 2-A, 3-B, 4-C, 5-D

C. Fill in the Blanks

1. While solubility of methane in water at 25°C is ___________, that of ethane is _____________.

2. While solubility of methane in water at 25°C is ___________, that of benzene is _____________.

3. The molecular size of water and methane are ___________ and ____________ respectively.

4. Size of micelle is ________________ than the shale pore size at 4000 m depth.

5. Micelles are ____.

6. Primary migration is accomplished in ________________________________.

7. In order to produce micro fracture in shale the pore pressure should be ______________ than the mechanical strength of the rock.

8. Conversion of kerogen to petroleum hydrocarbon results in _______________ pore pressure.

9. Conversion of montmorillonite to illite results in the __________________ of water.

Key:

1. *22.4 ± 1 and 60.4 ± 1.3 ppm*; **2.** *22.4 ± 1 and 1780 ± 45 ppm*; **3.** *3.2 and 3.8 Å*; **4.** *Greater / larger*; **5.** *ordered aggregate of polar organic molecules, known as natural soaps*; **6.** *Fine-grained rock*; **7.** *Greater*; **8.** *Increase*; **9.** *Production / release*.

Multiple Choice Questions-

1. At higher temperature solubility of gas in liquid

(a) Increases
(b) Decreases
(c) Remains same
(d) May increase or decrease

Ans: b

2. Grease-wick theory of primary migration holds good

(a) In both water and oil wet systems
(b) In water wet system
(c) In oil wet system
(d) None of the above

Ans: c

3. Drawback of the micellar theory of primary migration is

(a) Larger micellar size than the pore throat
(b) Insufficient abundance of water in the source rock
(c) Insufficient abundance of micelles in the source rock
(d) All of the above

Ans: d

4. Micro fractures in shale are produced when

(a) Pore pressure in shale is more than the capillary pressure
(b) Capillary pressure in shale is more than the pore pressure
(c) Both pore pressure and capillary pressures in the shale are same
(d) None of the above

Ans: a

5. Micelles are

(a) A form of pollutant
(b) A form of polar organic molecules
(c) A hydrocarbon compound
(d) A non-hydrocarbon, N-S-O compound

Ans:

6. Micellar theory has been invoked to explain the

(a) Increased solubility of the petroleum in water
(b) Decreased solubility of the petroleum in water
(c) Both of the above
(d) None of the above

Ans: a

7. At 25°C n-Alkanes are soluble in water

(a) If carbon number is 12 or more
(b) If carbon number is less than 12
(c) Irrespective of carbon number
(d) Always in very small amount

Ans:

8. Solubility of whole crude oil in water increases above

(a) 45°C
(b) 100°C
(c) 150°C
(d) 25°C

Ans:

9. For a shale, maximum porosity reduction takes place

(a) between 4-5 km depth
(b) between 2-3 km depth
(c) below 5 km depth
(d) within 2 km depth from surface

Ans:

10. Second stage of dehydration of sediment in course of burial takes place because of

(a) Reduction in porosity
(b) Dehydration of clay minerals e.g. montmorillonite
(c) Decomposition of organic matter
(d) Solution of carbonate cement

Ans:

Suggested Readings:

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