# **Migration from Source to Reservoir**



### **General Considerations**

Oil and gas migration are the least understood processes in the formation of hydrocarbon reservoirs. Much of the current thinking of how it happens is hypothetical and difficult to prove with either experiment or theory.

When potential source and reservoir rocks are buried, they contain water in their pore space. The oil or gas, therefore, has to replace this water in the migration process when it reaches the reservoir rock.

We have first a look at the composition of formation water.



# **Formation Waters**

Water in hydrocarbon reservoirs is usually connate water originating from the water that surrounded it during or shortly after the depositional process. It is, therefore, fossil water. Meteoric water, on the other hand, is fresh water that originates from the surface; it may significantly alter its aqueous chemistry during burial.

Water is special because of all hydrides that the life-forming elements (N, C, H, S, O) form it is the only one that is liquid at standard temperature and pressure, with the other ones being gaseous. It has other special properties that are generally caused by its dipole molecular structure (surface tension, dielectric constant, latent heat of evaporation). Its tendency to arrange molecules in tetrahedra and to exclude electrolytes (e.g. in freezing) causes it to assume special properties in the presence of minerals such as clays.



# **Formation Water Composition**

Most formation waters are saline, with sodium and chlorine being the dominant ions, constituting over 90% of the total ionic concentration. Calcium and magnesium are also typical present with a ratio of 5:1, while sulfates are notably absent.

There is a generally observed increase in the salinity of formation waters with depth, from a typical concentration of 35,000 ppm (seawater) at shallow depths to highly concentrated "brines" of up to 350,000 ppm at several kilometers depths. This phenomenon is related to reverse osmosis, a process wherein the water molecules are able to migrate upwards through shales, while the ions and the oil stay behind in the aquifer. Shales contain in general water that is less saline.



# Water Salinity vs. Depth



Source: North, F.K. (1985) Petroleum Geology, Allen & Unwin

An example of the salinity increase in oilfield waters with depth from the US Gulf Coast.



### **Pressure and Temperature During Burial**

During burial, temperature and pressure increase, leading to compaction of the sedimentary rocks. The pore space, therefore, decreases and with it the volume available for the fluids, principally formation water but also hydrocarbons. They have to support an increasing load of the overburden stress unless they escape. In shales, which are poorly permeable but which can be richer in hydrocarbon source material, the fluids take a much longer time to escape (and thus to equilibrate hydrodynamic pressures) than in porous and permeable rocks. This can lead to overpressure in the shales, a so-called compaction disequilibrium.

Compaction is the primary motor that leads to the expulsion of hydrocarbons from shaly source rocks.



# **Evidence for Migration**

Why do we need to invoke the scenario of migration in the first place?

The most compelling reason comes from the way oil and gas accumulate: They are typically found in porous and permeable rocks that are arched upwards and that are topped by an impermeable layer (the "seal"). The second reason is the relationship between source and reservoir rock: The latter is usually younger and/or structurally higher than the source rock. Visual evidence of migration is provided by oil and gas seepages found in many parts of the world.

But not all reservoirs need migration. There are known cases where the oil is internally sourced. Example: The Athel field in Oman



### **Migration Evidence: Structure**



In the Hassi Messaoud Field, Algeria, the Silurian source rock drilled by the well on the left is laterally and stratigraphically separated from the Cambrian reservoir rock where oil is found in the well in the middle.

Migration is an obvious mechanism to explain this situation.

Source: North, F.K. (1985) Petroleum Geology, Allen & Unwin





#### **Migration Evidence: Seepages**





Oil seepages can be seen from satellite images with SAR. Left: Santa Monica Bay, California. Above: Caspian Sea, Azerbaijan.





## **Migration Evidence: Oil Seepages**





The La Brea Tar Pits in Los Angeles are probably the most spectacular oil seepage. They are puddles of asphalt that seeped to the surface from young (Miocene) source rocks through faults. In the Pleistocene and Holocene many animals perished in them and became fossilized, giving us an extraordinary glimpse of the fauna at that time. Visit the George C. Page Museum.

![](_page_9_Picture_4.jpeg)

# **Primary Migration**

Mature hydrocarbons first have to migrate out of the source rock. This is in general a fine-grained rock that has a low permeability, for reasons outlined earlier in this course. During burial, this rock gets compacted and its interstitial fluid become overpressured with respect to surrounding rocks that have higher permeabilities and from which fluids can migrate with greater ease upwards.

Therefore, a fluid pressure gradient develops between the source rock and the surrounding, more permeable rocks. This causes the fluids - the water and the hydrocarbons - to migrate along the pressure gradient, usually upwards, although a downward migration is possible. This process is called primary migration, and it generally takes place across the stratification. Why?

![](_page_10_Picture_3.jpeg)

### Porosity Decrease with Compaction

Shown are shale porosities from various regions. The Dickinson curve is from undercompacted shales in the Gulf Coast. The Athy curve from Paleozoic shales in compaction equilibrium.

Smectite curves are from the Gulf Coast and indicate progressive, stepwise transformation to mixedlayer clays and illite. This releases more water into the rock, therefore the slower compaction of smectiterich rocks.

![](_page_11_Figure_3.jpeg)

### **Porosity Decrease with Compaction**

Source: North, F.K. (1985) Petroleum Geology, Allen & Unwin

![](_page_12_Figure_2.jpeg)

![](_page_12_Picture_3.jpeg)

# **Shale Pore Size with Depth**

Concurrent with the decrease of porosity with depth, the pore size decreases in an almost linear relationship. The diameter of many molecules may be too large to form globules and migrate through the shale pores, particularly since structured water on the clay surfaces further restricts the pathways. This is why a number of migration mechanisms are postulated.

#### Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_13_Figure_3.jpeg)

# **Primary Migration Controversy**

If we put the principal requirements for oil generation and migration together, we end up in a substantial dilemma:

1. Oil is generated at temperatures of 60° to 120 °C, which are typically found at depths of 2 to 4 km.

2. Source rocks at these depths are so compacted that their permeability is too low for efficient primary migration.

This dilemma is not solved yet, but many ideas have been proposed to circumvent it. At the core of the problem is the question of how hydrocarbons migrate.

![](_page_14_Picture_5.jpeg)

# **Primary Migration Mechanisms**

1. Migration by diffusion. Because of differing concentrations of the fluids in the source rock and the surrounding rock there is a tendency to diffuse. *A widely accepted theory*.

2. Migration by molecular solution in water. While aromatics are most soluble in aqueous solutions, they are rare in oil accumulations, therefore discrediting the general importance of this mechanism, although *it may be locally important*.

3. Migration along microfractures in the source rock. During compaction the fluid pressures in the source rock may become so large that spontaneous "hydrofracing" occurs. *A useful if underestimated hypothesis.* 

4. Oil-phase migration. OM in the source rock provides a continuous oil-wet migration path along which the hydrocarbons diffuse along pressure and concentration gradient. This is a *reasonable but unproved hypothesis*, good for high TOCs.

![](_page_15_Picture_5.jpeg)

# **Further Comments on Primary Migration**

There is geological and geochemical evidence for primary migration, but no single hypothesis explains all scenarios. In California, very young oil is found (Bakersfield etc.), suggesting that early expulsion is possible, perhaps in the form of immature hydrocarbons. But the dominant fluid is water, and it is questionable why oil should be expulsed first. Many oil fields have very large time gaps between the age of the source and reservoir rocks, and the formation of the trap (before which migration cannot occur). Most traps are, in fact, relatively young. This suggests that migration and accumulation may proceed in two or more different stages: An early migration in which permeabilities are relatively high and gas may be available to dissolve hydrocarbons, but where the hydrocarbon generation is inefficient, and a later stage at which oil generation is efficient but permeabilities are low.

![](_page_16_Picture_2.jpeg)

# Further Comments on Primary Migration /2

It may well be that undercompaction is crucial for primary migration. It may help preserve the source rock's permeability to a greater depth than in equilibrium condition, all the while reaching temperatures sufficient for significant hydrocarbon generation. Shown here are pressures and probable migration directions in a Gulf Coast setting.

Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_17_Figure_3.jpeg)

# **Secondary Migration**

The process in which hydrocarbons move along a porous and permeable layer to its final accumulation is called secondary migration. It is much less controversial than primary migration, and it is almost entirely governed by buoyancy forces.

These forces are proportional to the density difference between hydrocarbon and water. For continuous (but physically separate) hydrocarbon and water columns, the hydraulic potential, or the difference between the products of density times height of the two phases governs the flow of fluids.

The principal conduits for secondary migration are permeable sandstone beds and unconformities.

![](_page_18_Picture_4.jpeg)

#### **Migration Pathways**

Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_19_Figure_2.jpeg)

In the following, migration pathways - both primary and secondary - are shown for some typical geological scenarios.

The example here illustrates how excess hydrostatic pressure may control directions of fluid flow in the Paria formation, Orinoco delta, Venezuela.

![](_page_19_Picture_5.jpeg)

# **Migration Pathways /2**

Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_20_Figure_2.jpeg)

Direction of fluid migration on the flank of an anticline into the highest possible place of the reservoir layer

![](_page_20_Picture_4.jpeg)

# **Migration Pathways /3**

Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_21_Figure_2.jpeg)

#### Direction of fluid migration into stratigraphic - or better: combined - traps

![](_page_21_Picture_4.jpeg)

![](_page_22_Figure_0.jpeg)

Direction of fluid migration in an interbedded sand/shale sequence

![](_page_22_Picture_2.jpeg)

# **Migration Pathways /5**

Source: Hunt, J.M. (1995) *Petroleum Geochemistry and Geology*, 2nd edition. W.H. Freeman & Co

![](_page_23_Figure_2.jpeg)

#### Direction of fluid migration into a pinnacle reef

Notice: Migration through the shales above the reef is greatly exaggerated

![](_page_23_Picture_5.jpeg)

# **Differential Entrapment**

This phenomenon has been theoretically postulated and subsequently found realistic in many cases. It results in the heaviest fluid (water) being trapped in the highest anticline, and the lightest (gas) in the lowest! Quite the opposite of what is generally encountered.

Notice that for this effect to take place, free gas must be able to form.

Source: North, F.K. (1985) Petroleum Geology, Allen & Unwin

water

#### Petroleum Geology AES/TA 3820

![](_page_24_Figure_5.jpeg)

updip into Trap II; Traps III and IV are full of salt water and contain no oil or gas.

b) WATER

Trap I is completely filled with gas, all its oil has been flushed updip into Trap II; oil is now by-passing Trap I; Trap II is filled with oil and is spilling oil updip into III, it still has no gas cap; Trap III has a little oil, while IV is still filled with salt water.

![](_page_24_Picture_9.jpeg)

Trap I is unchanged with gas spilling updip into Trap II; oil is by-passing Trap I; Trap II now has a gas cap and is spilling oil updip into Trap III; Trap III is now filled with oil but still has no gas cap; Trap IV is dry.

# **Differential Entrapment /2**

The same scenario as before, but with different structural relationships

![](_page_25_Picture_2.jpeg)

Migration same as for C, but under different structural relationships; note that height of culmination has no effect on selective trapping, elevation of spill point is the controlling feature; height of culmination above spill point determines the maximum pay section; (a solution-gas cap has formed in Trap III).

![](_page_25_Picture_4.jpeg)

Source: North, F.K. (1985) Petroleum Geology, Allen & Unwin

![](_page_25_Picture_6.jpeg)

#### Seals

Secondary migration proceeds until an impermeable barrier is encountered that prevents further flow. The most common seal is a shale layer. The most effective seals are evaporites, notably salt and anhydrite, partly because of their inherently low intrinsic permeability, and partly because their capacity for viscous flow enables them to heal fractures and faults.

![](_page_26_Figure_2.jpeg)

A dual saltanhydrite seal in the Hassi R' Mel gas field, Algeria

![](_page_26_Picture_4.jpeg)

# **Conclusions on Migration**

We distinguish primary and secondary migration.

While primary migration is slow and proceeds over short distances, secondary migration is faster and can proceed over very long distances (more than one-hundred kilometers).

There are several theories for primary migration, among which diffusion, oil-phase migration, micro-fracturing and migration in solution.

Secondary migration is better understood and leads to the accumulation of hydrocarbon in traps where a seal prevents them from further migration.

![](_page_27_Picture_5.jpeg)

# **Study Task**

Calculate how much water is expelled from a shale layer 1 km thick and  $10 \times 10$  km in area, as it is buried from 1 km to 3 km depth, assuming its compaction is in equilibrium.

Assume now that this is a source rock with 600 ppm weight percent mature hydrocarbon, of which 15% get expulsed in primary migration.

How much oil is generated?

What is the average concentration of oil, in ppm, in the water that escapes from the shale?

![](_page_28_Picture_5.jpeg)