6. THE BOREHOLE ENVIRONMENT

6.1 Introduction

Wireline logging has a single clearly defined purpose: to give accurate and representative data on the physical properties of the rock formations and fluids encountered in a borehole.

The tools used to take these readings have to cope with extremely tough conditions downhole, particularly, high temperatures and pressures, inhospitable chemical conditions and the physical constraints imposed by the physics of the measurements and the borehole geometry. It should also be remembered that we are interested in the properties of the rocks in undisturbed conditions, and the act of drilling the borehole is the single most disturbing thing that we can do to a formation.

6.2 Overburden Pressures

The formations in the sub-surface are at raised pressure, and are occupied by fluids which are also at high pressure.

The pressure that a rock is subjected to at a given depth is determined by the weight of the rock above it, and hence the density of that rock. This is called the *overburden pressure* or sometimes the *lithostatic pressure* (note that, to a first approximation, the overburden pressure is the same in all directions (*isotropic*)). We can write an equation to describe the overburden pressure

$$P_{over} = r_{rock}\ g\ h \qquad \textbf{(6.1)}$$

where, P_{over} = the overburden pressure at depth h
r_{rock} = the mean rock density above the depth in question
g = the acceleration due to gravity
h = the depth to the measurement point.

Clearly the rock above a given depth will have a varied lithology and porosity and hence a varying density. A more accurate determination of the overburden pressure can be obtained by summing the pressure contributions for each density by writing Eq. (6.1) for i different rock densities, each with thickness h_i.

$$P_{over} = \sum_i (r_i\ g\ h_i) \qquad \textbf{(6.2)}$$

The overburden pressure/depth curve is called the *geobar* or *lithostat*. An example is given in Fig. 6.1.

It should be noted that in actuality this pressure is not isotropic but operates vertically. The pressures horizontally depend upon the overburden pressure, but are modified by additional large scale sub-horizontal tectonic forces (in tension and compression), and are affected by local inhomogeneities in the crust, such as fractures. However, to a first approximation the pressure at depth can often be considered to be isotropic (hydrostatic).

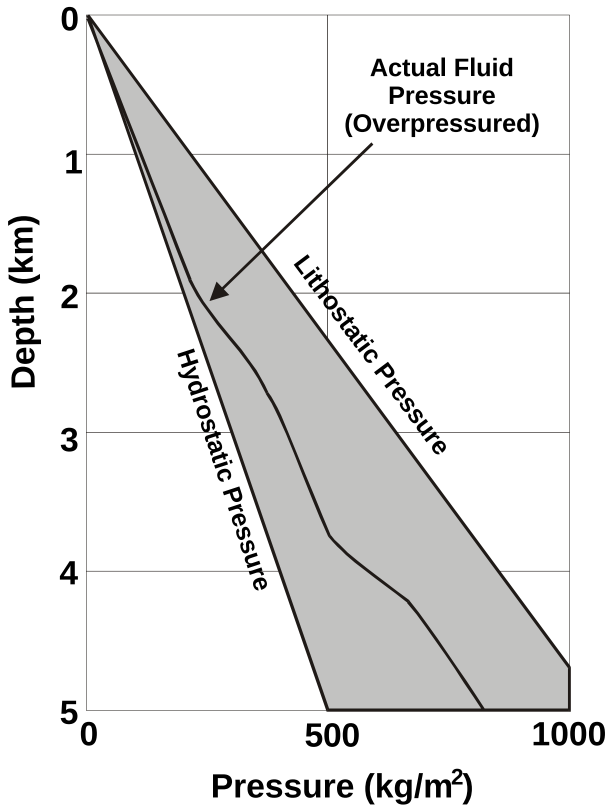

Figure 6.1 Lithostatic, hydrostatic and overpressures.

6.3 Fluid Pressures

The pressure in a fluid occupying a formation depends upon many forces. If there is a continuously connected pathway of fluid from the surface to the depth in question, the fluid pressure depends primarily upon the weight of the fluid above it, in a direct analogy to the situation for rocks. As the density of fluids is approximately one third of that for rocks, the fluid pressure will be approximately one third of the overburden pressure at any given depth.

$$P_{fluid} = r_{fluid}\ g\ h \tag{6.3}$$

where, P_{fluid} = the fluid pressure at depth h
r_{fluid} = the mean rock density above the depth in question
g = the acceleration due to gravity
h = the depth to the measurement point.

Clearly the fluid in the rock above a given depth may have a varying density, hence a summed equation may be better at describing the fluid pressure at depth. The connected fluid pressure is called the *hydrostatic pressure* and is shown in Fig. 6.1.

Clearly, the fluids will not always be in good connection with the surface, and indeed this will generally not be the case in reservoirs, where a seal is required to stop the hydrocarbons escaping. In these conditions the fluid pressure may be much higher than that predicted by Eq. (6.3). These fluids are called *overpressured* fluids (Fig. 6.1). Overpressurization is caused by a trap to stop fluids escaping, and a process that will raise the fluid pressure such as compaction of the rock.

However, the fluid pressure is also affected by other forces. These are capillary pressure, buoyancy forces (if the fluid is dynamically driven by a density gradient), and externally imposed fluid flow forces from aquifers.

6.4 Effective Pressure

The overburden pressure acts upon a rock to crush it. The fluids in the pore spaces would then be compressed. Hence, the fluid pressure acts on the rock to stop the rock crushing. The fact that the rock does not crush under the overburden pressure, is the combined result of the inherent strength of the rock grains and any cementation, and the strengthening effect of the fluid pressure. A total effective pressure may be defined, therefore, as the pressure that the rock effectively experiences. The *effective pressure* is the overburden pressure minus the fluid pressure. (Note there is increasing evidence that it is better to define effective pressure as the overburden pressure minus about 80% of the fluid pressure.)

The extraction of hydrocarbons in a reservoir ultimately lowers the fluid pressure, and hence raises the effective pressure experienced by the rock. Thus there may be occasions where, what was once stable reservoir rock, now is exposed to a greater effective pressure, and begins to crush and compact. This is currently occurring in several reservoirs in the North Sea, and causes huge problems for wellbore and platform stability.

6.5 Drilling Muds

Drilling muds are used for at least three reasons:

- To lubricate the drill bit.
- To remove drilled material away from the drill bit and transport them to the surface.
- To counteract the fluid pressure in the rock.
- Stabilize the wellbore.

If a well could be drilled without a drilling fluid, formation fluids, which are under their fluid pressure, would spurt out of the borehole (*blow-out*). The density of the drilling fluid used in a particular borehole is designed to generate a drilling mud pressure (due to the weight of the drilling mud in the borehole above a given depth) that counteracts the fluid pressure in the formation and prevent blow-outs. This is usually successful, but because sudden increases in overpressure can be encountered the drilling mud pressure is kept higher than necessary as a safety feature. When the mud pressure is greater than the formation fluid pressure, the well is said to be *over-balanced*.

Note that varying the drilling mud weight also helps to protect the wellbore from crushing by the high lithostatic forces, especially in deviated and horizontal wells.

The drilling mud is a suspension of mud particles (a slurry) in an aqueous or oil-based medium. Each of these will be discussed in more detail later in this section.

6.6 Invasion

6.6.1 Introduction

The drilling mud is at a pressure greater than the fluid pressure in the formation. When the drilling mud encounters a porous and permeable formation, the drilling mud will flow into the formation under the influence of this difference in fluid pressures. This is called *invasion*. However, the particulates in the mud will be left at the surface, with the rock acting as an efficient filter. Thus, there is a build-up of mud particles on the inner wall of the borehole, and this is called the *mud cake*. The remaining liquid part of the drilling mud enters the formation, pushing back the reservoir fluids. This part of the drilling mud is called the *mud filtrate*. The zone where the mud filtrate has replaced the reservoir fluids is called the *flushed zone* and there is a zone further into the rock where the replacement of reservoir fluids with mud filtrate is incomplete, which is called the *transition zone*. The Virgin reservoir fluids occupy the *uninvaded zone* further into the formation.

Figure 6.2 shows the general borehole environment with invasion.

Note that invasion only occurs for porous and permeable formations, and is a self limiting process because the mud cake is an efficient block to further filtration and flow. However, there is a qualitative relationship between low porosity and high permeability, and larger depth of invasion and thicker mud cake. High permeability formations admit the mud filtrate easily, so the invasion is deep and the mudcake builds up quickly to thick layers. High porosity formations allow the storage of more mud filtrate per invasion distance, therefore the depth of invasion is smaller than for low porosity formations of the same permeability.

The different fluid types in each of the zones, and hence the formations that they occupy, will have different physical properties. Only the deepest zone contains the circumstances of the undisturbed rock, while the wireline tools occupy the borehole. Thus, to get good readings of the true sub-surface properties of the rock, the tool has to either, (i) measure accurately through the borehole mud, mud cake flushed zone and transition zone, or (ii) make readings closer to the tool (i.e., in the flushed zone) that can be reliably corrected to represent the values in the uninvaded zone.

All wireline companies provide correction graphs for their various tools. However, the accuracy of the correction diminishes as the diameter of the borehole, the thickness of mud cake, and the depth of invasion increase. Effort is therefore made to ensure that these are minimized by (i) ensuring the mud is sufficiently saline to avoid wash-outs increasing the borehole diameter, (ii) ensuring that the mud is not so low salinity that it causes the swelling of formation clays, (iii) minimize mud filtrate, and (iv) set the mud weight such that the mud pressure is only slightly greater than the formation pressures (only slightly *over-balanced*).

One simple method of checking for invasion is by measuring the loss of drilling fluids. This is done regularly at the wellsite for water-based drilling muds by forcing samples of drilling mud through filter paper with a 100 psi pressure for 30 minutes and measuring the volume of the mud filtrate. For oil-based muds a high temperature apparatus is required as the filtration of oil-based muds is low at surface temperatures. While mudcake is a useful indicator of porous and permeable formations, it can cause the drill-bit, drill-pipe and wireline tools to stick in the hole, and the associated deep invasion causes problems for accurate wireline data acquisition.

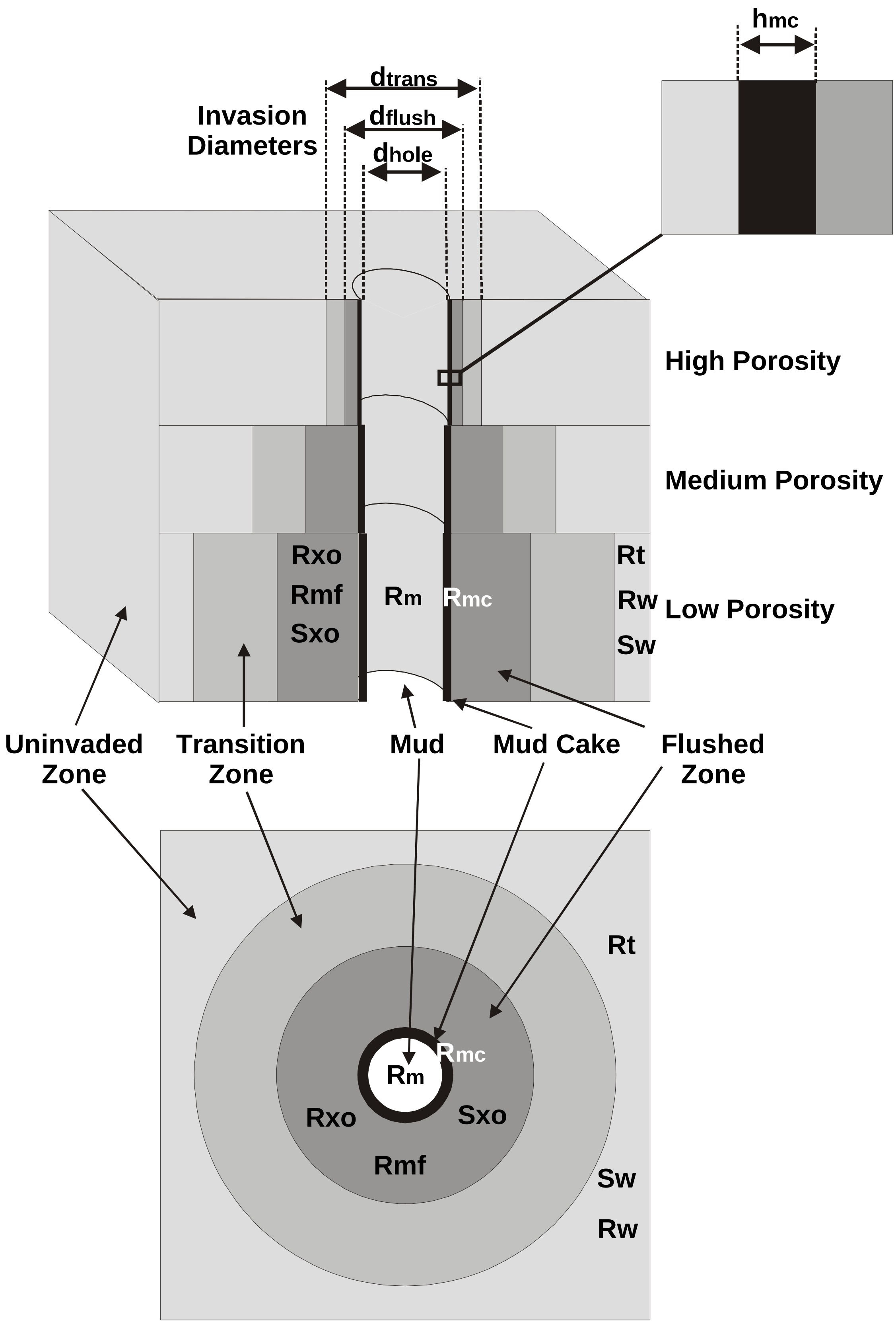

Figure 6.2 The borehole environment.

6.6.2 Invasion with Water-Based Drilling Muds

The depth of invasion is related to the permeability of the rock. The water-based mud filtrate diffuses into the formation water in the rock at a rate that depends upon the pore size distribution and hence the permeability of the rock. This diffusion can be faster than the rate of filtration at the borehole wall in highly permeable formations. Thus the invasion is limited by the rate of filtration, and the build-up of mudcake stops the process limiting the depth of invasion. For lower permeability formations, the diffusion is slower but reaches a greater depth (Fig. 6.3). The replacement of oil by the water-based mud filtrate is by pressure driven displacement.

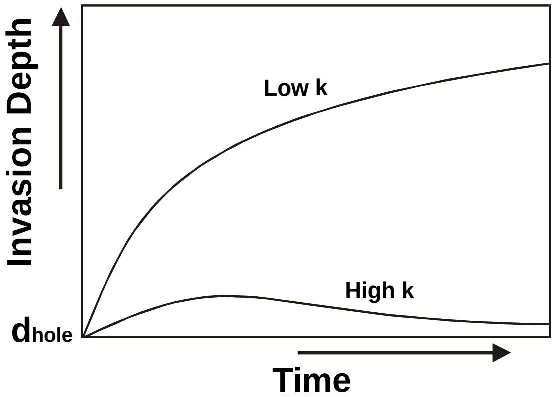

Figure 6.3 Effect of time and permeability on invasion depth for water-based muds.

In water-bearing formations the mud filtrate replaces all of the formation water close to the borehole (Fig. 6.4) and this decreases with depth of invasion. In oil-bearing formations the mud filtrate replaces all the formation water and most of the oil close to the borehole wall, again decreasing with distance into the formation (Fig 6.4).

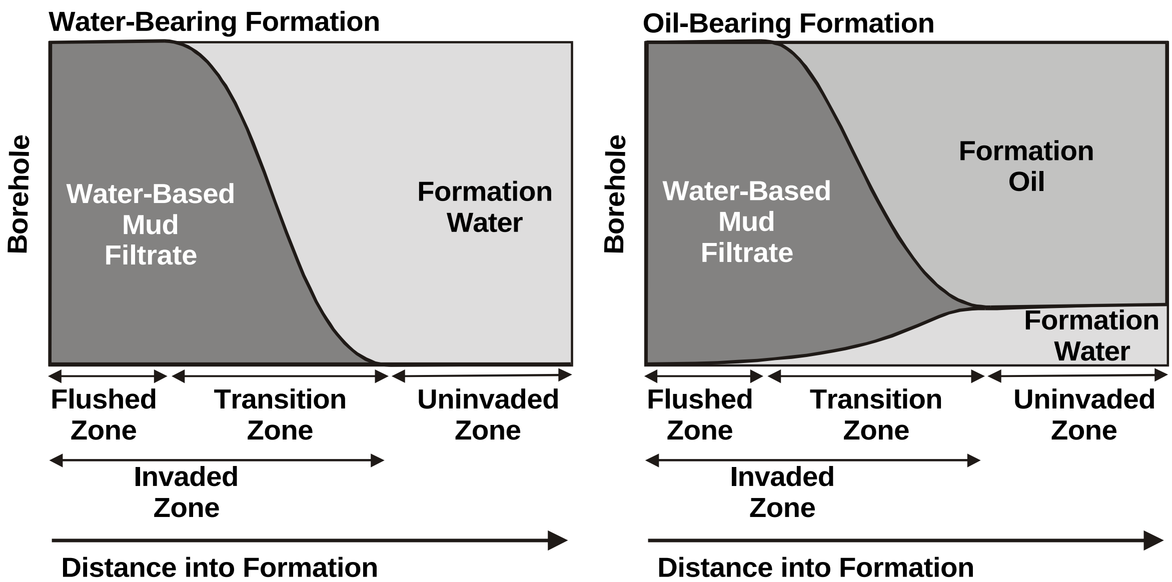

Figure 6.4 Invasion profiles for water-based muds in water and oil bearing formations.

6.6.3 Invasion with Oil-Based Drilling Muds

Oil-based mud filtrates replace the fluids in the invaded zone by pressure driven displacement alone. The resulting invasion profiles are shown in Fig. 6.5. Note that in water-bearing formations the oil-based mud filtrate does not replace all the formation water even close to the borehole wall, and that in oil-bearing formations the oil-based mud filtrate only replaces the oil in the formation, leaving the formation water in place.

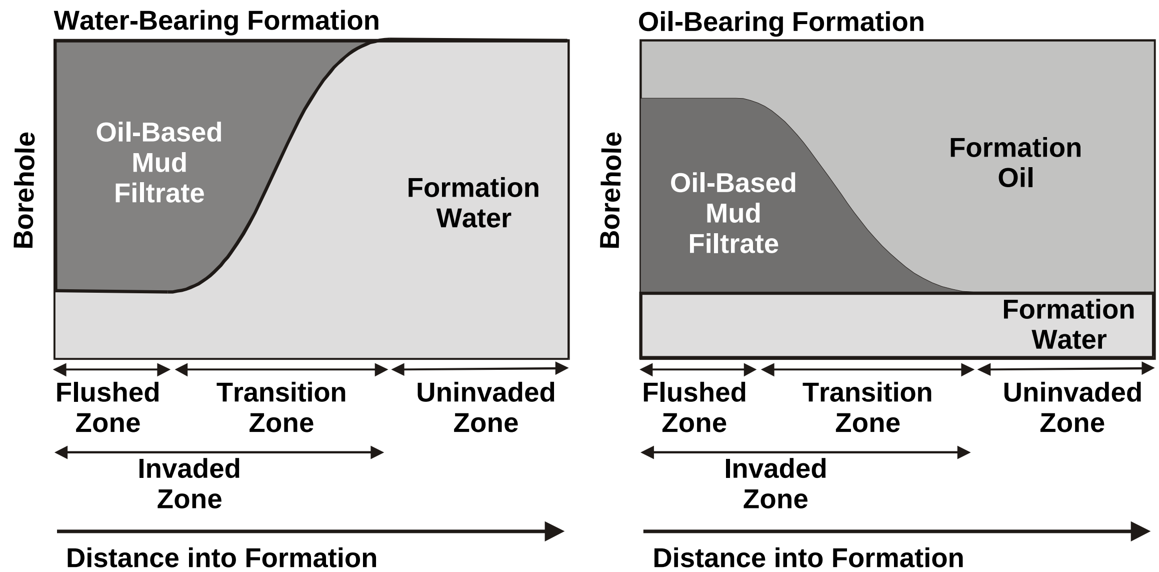

Figure 6.5 Invasion profiles for oil-based muds in water and oil bearing formations.

6.6.4 Fluid Segregation

In general, the fluids in the invaded zone are formation water, water or oil-based mud filtrate and oil in various saturations. These have different densities, and so may undergo gravity driven fluid segregation resulting from their relative buoyancies, if the vertical permeability of the formation is sufficiently high. While this may seem like a subtle effect, it is not uncommonly seen on wireline log data. The effect is well developed in the following two scenarios, which are shown in Fig. 6.6.

Drilling oil-bearing formations with salt saturated water-based muds. The high density salty mud filtrate accumulates at the bottom of the formation resulting in a resistivity profile that has lower resistivities at the base of the formation than at the top.

Drilling water-bearing formations with oil-based drilling muds. The low density oil-based mud filtrate accumulates at the top of the formation, again resulting in a resistivity profile that has lower resistivities at the base of the formation than at the top.

These effects usually disappear with time after the casing is set and cemented, remaining only if the permeability of the formation is very low.

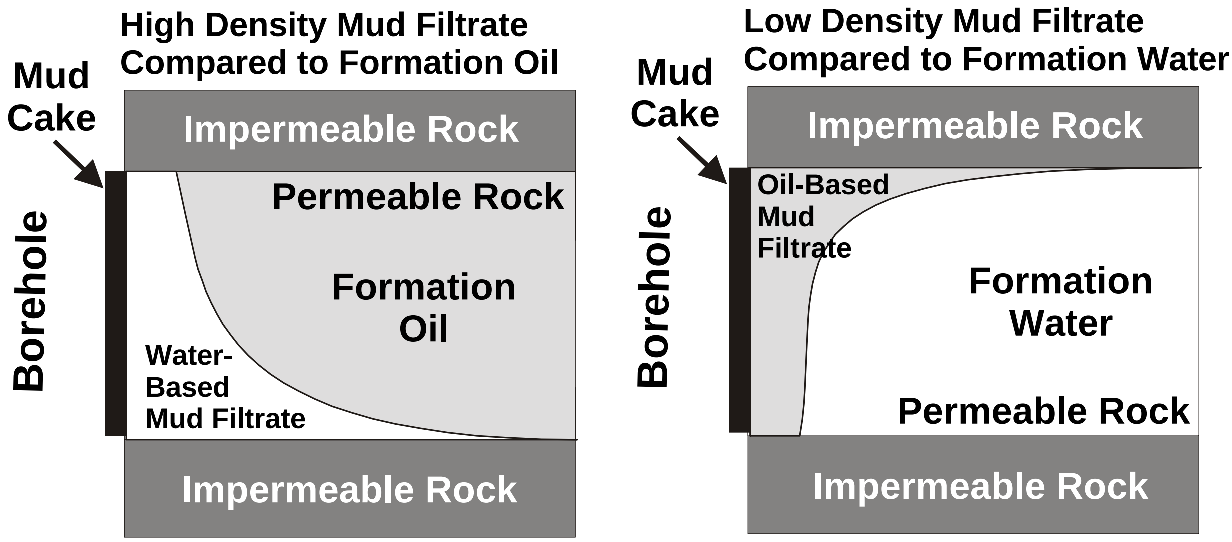

Figure 6.6 Gravity segregation during invasion.

6.7 Logging Tool Characteristics

Each of the logging tools has particular characteristics that depend upon the physics of the measurement of their particular parameters, and upon the borehole environment. These will be covered in the sections on the individual logging tools.

The main characteristics affecting log quality are:

Depth of Investigation. Most tools have a shallow depth of investigation, resulting in the measurement of the formation in the flushed or transition zones. Most radiation tools have an investigation depth of less than 0.5 m because they rely on measuring natural or induced radiations that are adsorbed by the rock or the fluids they contain. Electrical tools come in various versions with a wide range of investigation depths, from the micro-tool, which measure only the mud cake (a few centimetres), to the deep penetration tools (up to 5 m). The depth of investigation often depends upon the density/porosity of the formation.

Vertical (Bed) Resolution. This is closely related to the depth of investigation and to the logging speed. In general a tool with a large depth of investigation, has a low vertical resolution. The true parameters of the rock formation can only be measured if the bed is larger than at least the source-detector distance of the tool. An electrical log with a source-detector distance of 2.5 cm, has a bed resolution of about 7.5 cm, while a deeply penetrating induction log with a source-detector distance of 1 m can resolve usually only down to about 3 m. It is a reasonable rule of thumb to triple the source-detector distance on the tool to get the minimum bed resolution in ideal conditions. If the beds are thinner than the bed resolution for the tool, then the measured parameter is underestimated. This is the *thin-bed effect*.

Investigation Geometry. This depends upon the tool. Some tools have a pseudo-hemispherical zone of sensitivity (the radiation logs), some toroidal (the induction logs), some tubular (acoustic logs), and some focussed planar (the laterologs). The raw data that is measured depends very much upon the geometry of the measurement, but these effects are corrected for by the wireline logging company as standard.

Logging Speed. The speed at which the logs are run has an effect upon the quality of the data as a result of statistical fluctuations in the measured radiation in the case of radiation tools, and as a function of the measurement (sampling) interval in other tools. It can therefore be seen that logging speed, data quality and vertical resolution are linked.