

6 RESISTIVITY AND CONDUCTIVITY LOGS

6.1 Generalities

The log

Of all the logging tools, those that measure resistivity are archetypal. It was with resistivity measurements that Conrad Schlumberger started his company in 1919.

The resistivity log is a measurement of a formation's *resistivity*, that is its resistance to the passage of an electric current. It is measured by *resistivity tools*. Conductivity tools measure a formation's *conductivity* or its ability to conduct an electric current. It is measured by the *induction tools*. Conductivity is generally converted directly and plotted as resistivity on log plots.

Most rock materials are essentially insulators, while their enclosed fluids are conductors. Hydrocarbons are the exception to fluid conductivity, and on the contrary, they are infinitely resistive. When a formation is porous and contains salty water the overall resistivity will be low. When this same formation contains hydrocarbons, its resistivity will be very high. It is this character that is exploited by the resistivity logs: high resistivity values may indicate a porous, hydrocarbon-bearing formation (Figure 6.1).

Principal uses

The resistivity logs were developed to find hydro-

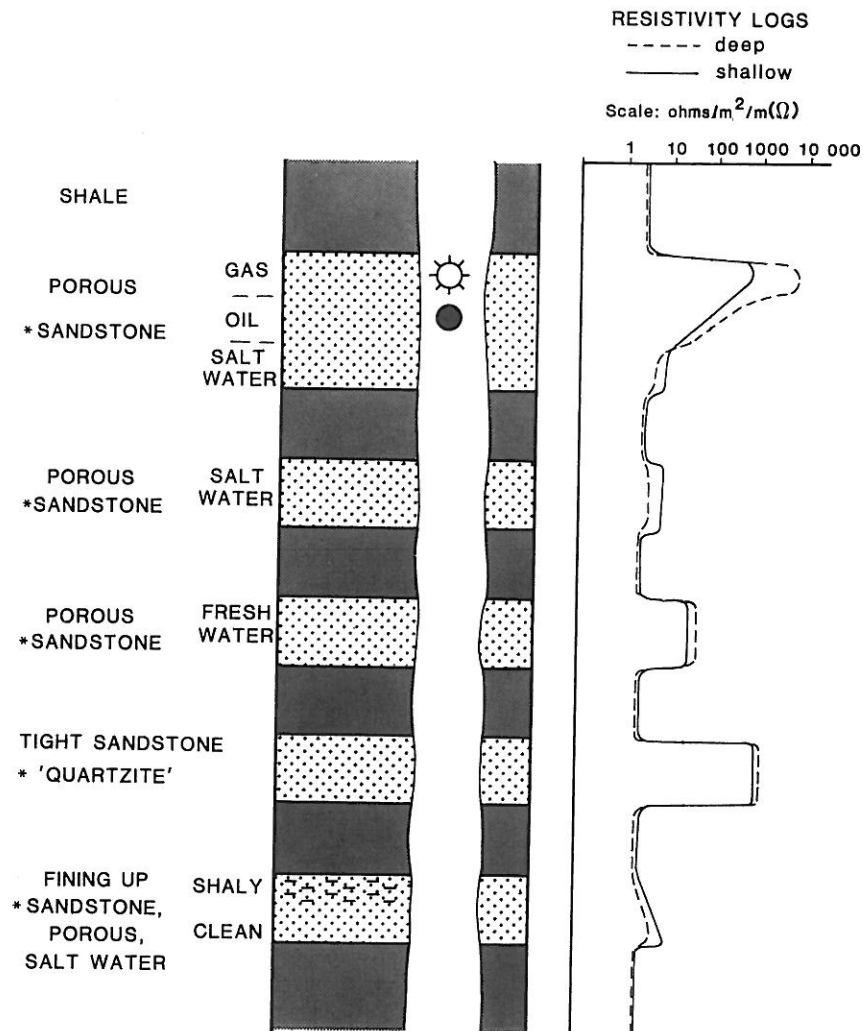


Figure 6.1 The resistivity log: some typical responses. The resistivity log shows the effect of the formation and its contained fluids on the passage of an electric current. *Limestone, dolomite, etc., equally applicable.

carbons. This is still their principal quantitative use: resistivity logs furnish the basic numbers for petrophysical calculations. However, a formation's resistivity is one of its typical geophysical characteristics and as such can contribute information on lithology, texture, facies, overpressure and source rock aspects.

The log is used frequently for correlation (Table 6.1).

Limitations

Resistivity tools (Section 6.4) can only function in boreholes containing conductive muds, that is muds mixed with salt water. They cannot be run in oil-based muds or freshwater based muds. Induction logs (Section 6.5), on the contrary, are most effective with non-conductive muds, oil-based or fresh water based. However, induction logs are also run in salt water based muds and are reasonably effective, although corrections to the raw readings may be necessary for quantitative use (Table 6.8).

6.2 Theoretical considerations

Earth resistivity and conductivity

The laws which govern electrical resistance in a wired circuit apply also to currents flowing in the earth. Resistance (in ohms) is the electrical term, while *resistivity* is the logger's term. *Resistivity* is in units of ohms m²/m, being the resistance with normalized dimensions.

Two tests can be applied under subsurface conditions to measure resistivity. The first test is a direct measurement. A current is passed between two electrodes on a logging tool and the potential drop between them provides the resistivity. The second test is indirect in that

it measures conductivity. A current is induced in the formation around the borehole and the capacity to carry the current is observed. This carrying capacity is the conductivity. The resistivity is simply the reciprocal of the conductivity. Thus in oilfield units:

$$\text{resistivity (ohms m}^2/\text{m)} = \frac{1 \times 1000}{\text{conductivity}} \text{ (millimhos/m)}$$

As previously stated, rock materials are essentially insulators (like all generalities this is a half-truth, and will be modified later). However, normal rocks consist not just of rock materials, but also voids or pores. The pore spaces are principally filled with water, in subsurface

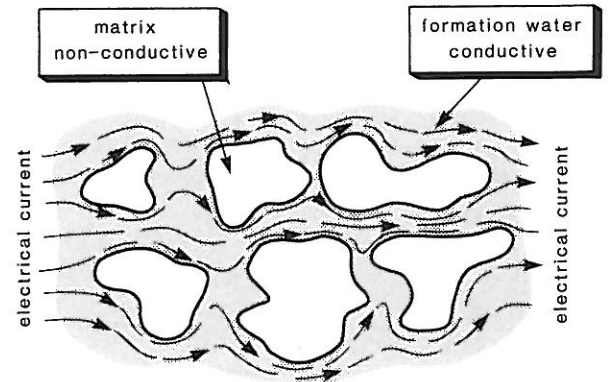


Figure 6.2 Formation conductivity - schematic. The electrical current is restricted to the formation fluids (formation water): the matrix is non-conductive.

Table 6.1 The principal uses of the resistivity and conductivity (induction) logs.

	Discipline	Used for	Knowing
Quantitative	Petrophysics	Fluid saturations: Formation (S_w) Invaded zone (S_{xo}) i.e. detect hydrocarbons	Formation water resistivity (R_w) Mud-filtrate resistivity (R_{mf}) Porosity (ϕ) (and F) Temperature (T_{fm})
Semi-quantitative and Qualitative	Geology	Textures	Calibration with laboratory samples
		Lithology	Mineral resistivities
		Correlation	
	Sedimentology	Facies, Bedding characteristics	Gross lithologies
	Reservoir geology	Compaction, overpressure and shale porosity	Normal pressure trends
	Geochemistry	Source rock identification Source rock maturation	Sonic and density log values Formation temperature

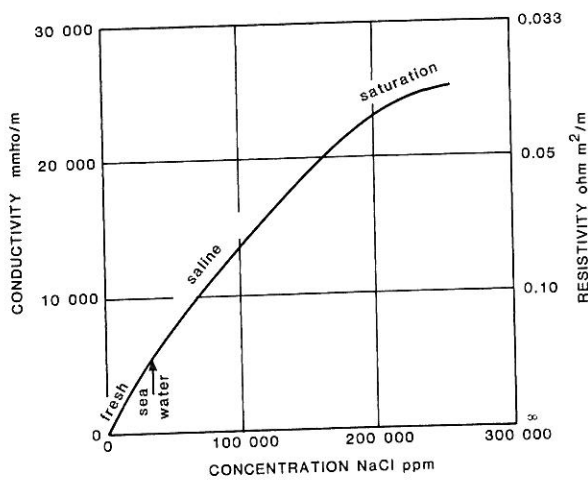


Figure 6.3 Relationship between conductivity (resistivity) and concentration in a salt (NaCl) solution, at 24°C (75°F), modified from Serra, 1979).

Table 6.2 Some typical formation-water salinities.

Origin	Total salinity (ppm)	Type	R_w^* ohm m ² /m
Sea water	35,000		0.19
Lagunillas, Venezuela	7548 [†]	Fresh	0.77
Woodbine, E. Texas	68,964 [†]	Saline	0.10
Burgan, Kuwait	154,388	Saline	0.053
Simpson sd., Oklahoma	298,497 [†]	Very Saline	(0.04)**

[†]From Levorsen (1967)

*Approximate R_w (formation-water resistivity) at 24°C (75°F).

**Near the saturation limit.

terms, formation water (pores, of course, may also be filled with oil and natural gas). Conductivity is essentially restricted to formation waters (Figure 6.2). They vary from fresh to very saline: usually they are saline, and the salinity increases with depth (e.g. Dickey, 1969). For oilfield purposes, salinity is usually quoted in NaCl equivalent salinity, although formation-water brines have a variety of dissolved solids. Sea water has an average salinity of 35,000 ppm (parts per million of dissolved solids) while a typical formation brine may have a salinity of 200,000 ppm (Table 6.2). Other factors remaining constant, the more saline a solution the greater the conductivity, the electric current being carried by dissociated ions, e.g., Na⁺, Cl⁻ in a salt solution. The same formation containing fresh water shows a far lower conductivity (higher resistivity) than if it contained salt water (Figure 6.3).

It is often necessary to consider the resistivity of a formation water *per se*, that is its resistivity as a solution. The symbol used is R_w (resistivity of water) (Table 6.2).

Rock resistivity – formation resistivity factor ‘F’

If, as suggested above, it is only the formation waters that are conductive, the conductivity of the rock in general should be that of the solution it contains. But it is not. Although the rock plays no active part, it plays an important passive one (Figure 6.2). This passive role is basically dependent on rock texture or more specifically on the geometry of the pores and pore connections (Figure 6.4). A good analogy is that of a comparison between conventional roads and motorways. Vehicles will travel far more quickly and in greater volume between two towns along a wide straight motorway than along a narrow twisting conventional road. Thus, in rocks, the easier the path through the pores the more current that passes. The expression of this passive behaviour of a rock is called the *Formation Resistivity Factor*, usually abbreviated to *F* (sometimes *FF*). When the passive role of the rock is small, *F* is small: when the rock has a large inhibiting effect, *F* is large (Figure 6.4).

To understand *F* better it is useful to examine the influence porosity has upon it. In any one rock formation, *F* and porosity can show a consistent relationship (Figure 6.5). However, as indicated, porosity is not the only influence on *F*, and the *F* to porosity relationship varies from one rock to another. Laboratory work with artificial mixtures shows that in any grain population with similarly shaped grains, the *F* – porosity changes are mathematically

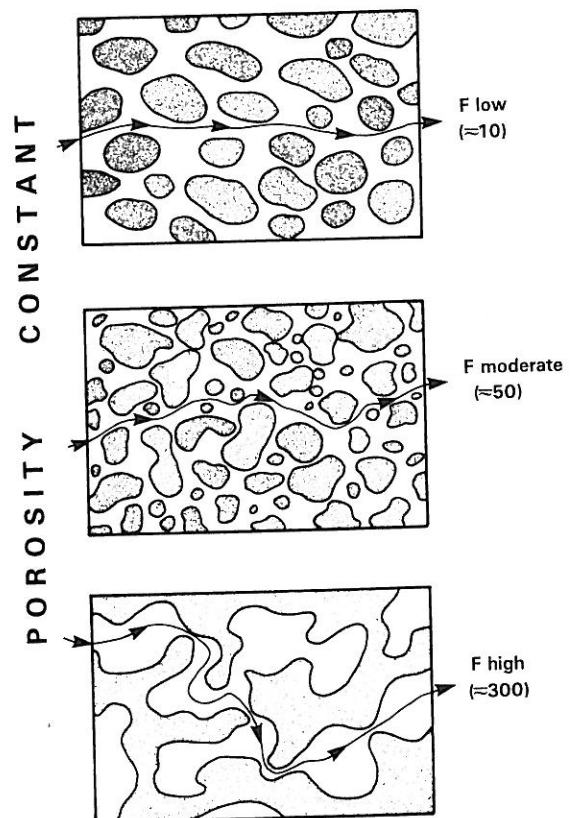


Figure 6.4 Schematic illustration of three formations which have the same porosity but different values of formation resistivity factor, *F*. The role of the matrix is evident: less at low values of *F* (top), greater at high values of *F* (bottom).

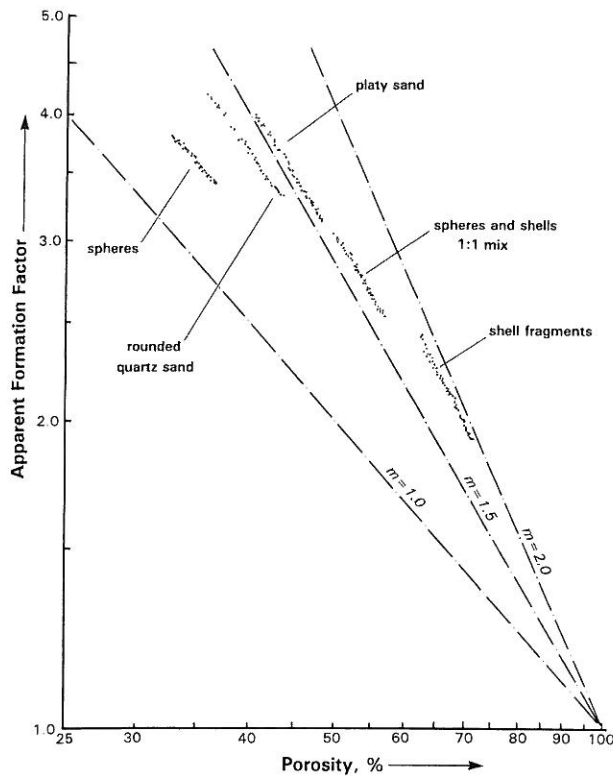


Figure 6.5 Graph of formation resistivity factor, F and porosity showing their relationship to grain shape (texture) illustrated by analyses of laboratory samples. A predictable relationship between F and porosity only exists for one type of grain population m = cementation factor (re-drawn from Jackson *et al.*, 1978).

predictable (follow Archie's law, Section 6.7) (Jackson *et al.*, 1978). But, when grain shape is changed, the relationship changes, although still in a predictable way (Figure 6.5). F is therefore strongly influenced by grain shape, (theoretically because of changes in pore throat geometry). However, in geological terms, grain shape is an element of texture, along with other factors such as size and arrangement (sorting). Geologically then, F becomes a texturally related term, an aspect which will be considered in more detail when the geological applications of resistivity logs are considered (Section 6.8).

For petrophysical purposes, it is necessary to quantify the relationship between F and porosity (porosity being measurable by other logs). Fundamental work by Gus Archie established an empirical relationship (Archie, 1942), which has been confirmed by subsequent work (e.g. Figure 6.5). However, as indicated above, the relationship varies with each population of grains and to establish a universally applicable relationship has proved elusive (e.g., Winsauer and McCardell, 1953; Maute, 1992). Presently available formulae give only a good estimate (see 'Basic equations of petrophysics' Section 6.7).

F is usually between 5 and 500, the higher numbers indicating a greater effect due to the formation. Good porous sandstones will have an F value around 10, while

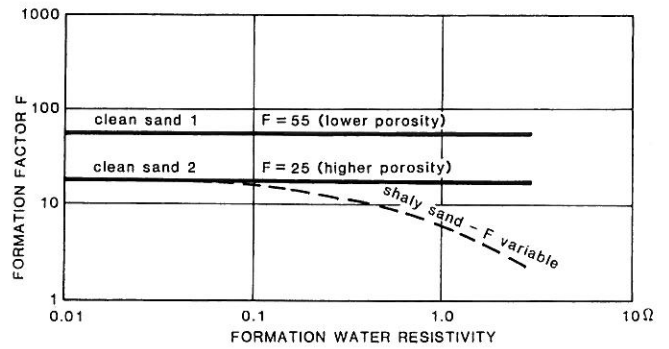


Figure 6.6 The effect of changes in formation-water resistivity on F (formation resistivity factor). F will not change with different water salinities in a clean formation. In a shaly formation F will constantly change (schematic).

a poorly permeable limestone may have a value around 300–400. F is dimensionless (Figure 6.4).

F is an independent element in the expression of rock resistivity. The F value of a particular rock reservoir will remain constant no matter what the resistivity of the fluid filling the pores. In other words, F will not vary with changes in formation-water salinity which entail overall rock resistivity changes (Figure 6.6). The F value is therefore constant between the reservoir containing oil and the same reservoir containing water. This behaviour can be expressed mathematically:

$$R_o = F \times R_w$$

That is, F is the ratio of the formation resistivity to the resistivity of the fluid which it contains. Hence when porosity is 100% (impossible) F is 1 (Figure 6.5). This is the basic relationship which is used in all calculations involving the resistivity measured by well logs (Section 6.7).

Resistivity (conductivity) of clays

Discussion thus far suggests that rock resistivity (or conductivity) is only a function of the active part played by a conductive formation water (resistivity R_w) and the apparently passive part played by the rock skeleton (F). However, the part played by the rock skeleton is not always passive. When shale is present it plays an active role in conductivity and F is no longer constant (Figure 6.6).

Clays conduct electricity in two ways, through pore water and through the clay itself. The porosity in clay, like that in other rocks, encloses conductive formation water. This may be up to 80% in newly-deposited clays but diminishes rapidly through compaction (see 'Compaction, over-pressure and shale porosity', Section 6.8). Conductivity in the clay mass itself is more complex.

Clay consists of stacked silicate layers which, in the presence of water, become negatively charged. Clay may in fact be considered to act like a salt, dissociating into an immobile, negatively-charged framework and positive,

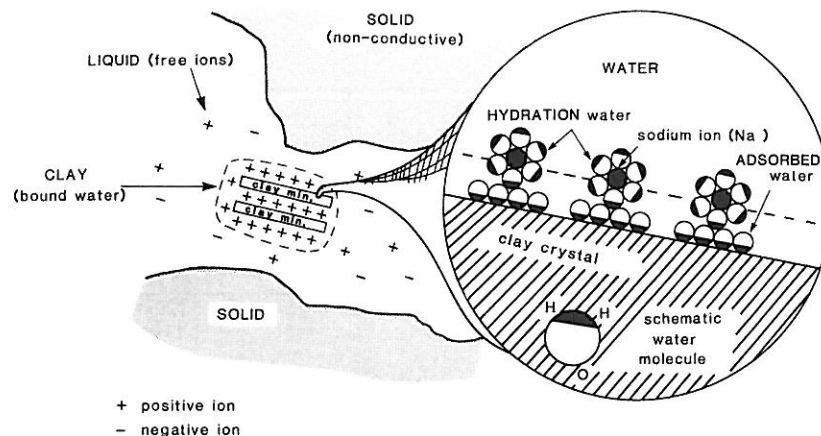


Figure 6.7 Models of the conductivity capacity of clay minerals. (Modified from Wyllie, 1963; detail Clavier *et al.*, 1977).

current-conducting ions (Wyllie, 1963). However, it is only at the surface of clay-mineral layers that the dissociation occurs and a current is able to be carried (Figure 6.7). Clay is like an inverted electric cable; the inside is non-conductive while the outside conducts electricity. The outside conducting layer is complex; adsorbed water clings to the immediate clay layer and the positive ions (Na^+ in a salt solution) surrounded by hydration water form a further, outer layer (Clavier *et al.*, 1977) (Figure 6.7). The external water, called 'bound water', is chemically free but physically bound.

The capacity of clays to conduct electricity varies between clay species and seems to depend on the surface area available in the clay. An independent expression, but one related to the surface area (which is difficult to measure), is the cation exchange capacity or CEC (Patchett, 1975). This is simply the ability of the clay to exchange cations, expressed per unit weight of clay and is measured chemically. The surface area-CEC relation suggests that the number of exchangeable ions per unit surface remains constant whatever the type of clay (Patchett, *op. cit.*). This means, as indicated, that differences between the conductivity of clay species should be related to surface area. Geologically this is of interest, since montmorillonite has a far greater specific surface area than the other clays and is therefore more conductive (Table 6.3).

The conductivity behaviour of clays in clay-sand mixtures (shaly-sands) is complex. Because of the bound water, the conductivity of clays is to some extent dependent on the surrounding formation fluid. As a general rule, the higher the resistivity of the formation fluids,

the greater the current carried by the shale: that is, the greater the shale effect on F (it diminishes, Figure 6.6). Importantly, in oil zones where the formation fluids have very high resistivities, the clays are conductive: resistivities in oil-saturated shaly-sands may be quite low. This is the reason for the petrophysicists' interest in shaly-sands.

Without entering into the details of the shaly-sand problem, it is worth concluding by quoting from a review article by an experienced petrophysicist from a major company; it sums up the industry view of the shaly-sand question at present and for the foreseeable future (Maute, 1992):

'More than 50 different shaly-sand equations, frequently empirical variations of Archie's equation, exist. No equation is definitive or universally accepted. Some equations work well in local regions. Shaly-sand interpretation is an important unsolved problem in petrophysics. One point that has emerged in recent years, is that knowing the shale volume and shale conductivity is not enough; the distribution of shale in the formation is also important.'

So that even for shaly-sands it comes back to a question of texture again. (For details on shaly-sands see SPWLA, 1982, or for a discussion, Dewan, 1983).

Conclusions: earth resistivity

The conductivity of a rock is due to interstitial pore waters (formation waters) which contain dissociated, current-carrying salts. The rock skeleton is a non-conductor but plays an inhibiting role expressed quantitatively by $R_o = F \times R_w$. In mixtures of clay and non-conducting materials, conductivity is afforded by the formation water but also by the clay itself.

Table 6.3 Clay mineral properties (from Dewan, 1983)

Clay mineral	CEC (meq/g)	Av. CEC
Smectite	0.8 -1.5	1.00
Illite	0.1 -0.4	0.25
Chlorite	0.0 -0.1	0.04
Kaolinite	0.03-0.06	0.04

6.3 Zones of invasion and resistivity

The notion of invasion has already been described (Chapter 2) and it is all-important to the understanding of borehole resistivity. The essential target of resistivity logging is that of the true resistivity of the formation (R_f) and, especially, its saturation in hydrocarbons. To this

Table 6.4 Resistivity notation.

Zone	Formation resistivity (tool measured)	Fluid resistivity (laboratory measured and/ or log calculated)	Fluid saturation
Hole	R_m (m = mud)	R_m	
Mud cake	R_{mc} (mc = mud cake)	R_{mc}	
Flushed zone	R_{xo}	R_{mf} (mf = mud filtrate)	S_{xo} (saturation in mud filtrate)
Invaded zone (transition)	R_i (i = invaded)	R_z ($R_{mf} + R_w$ mixed)	
Uninvaded zone	$*R_t$ (t = true)	R_w (w = formation water) R_o (o = original)	S_w (saturation in formation water)

* R_t = true, uninvaded formation resistivity of rock which may contain hydrocarbons – tool measured.

R_o = Original, uninvaded formation resistivity of rock with 100% formation water saturation. Cannot be tool measured.

It is an ideal figure for calculations. In clean 100% water-saturated zones $R_t = R_o$ (or is very close).

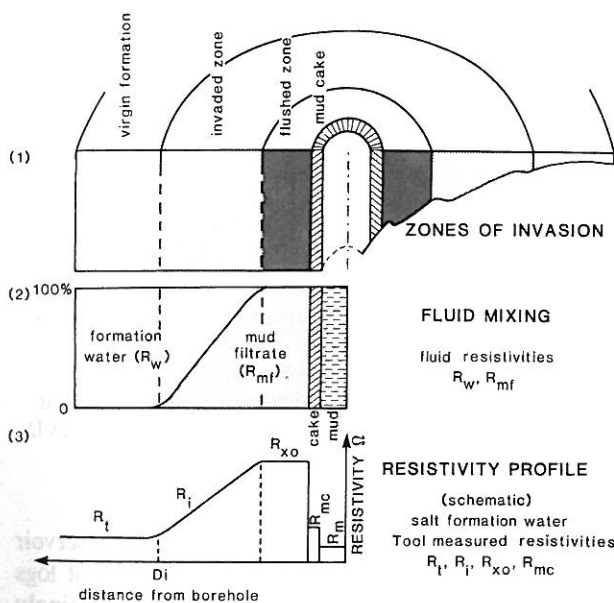


Figure 6.8 (1) Zones of invasion about a borehole; (2) equivalent schematic representations of fluid mixing; (3) resistivity profile.

effect, it is necessary to consider the invasion of mud filtrate (with a certain salinity and hence resistivity, R_{mf}) into a formation containing either formation water (resistivity R_w) or hydrocarbons.

For convenience, the invasion of a porous and permeable bed by mud filtrate is divided into zones (Figure 6.8, 1). In reality the zones grade one into the other. Closest to the borehole, behind the mud cake, is the flushed zone where the mud filtrate has replaced all but a small volume of the original, in-place fluids. Gradually, further and further away from the hole, the volume of invading mud filtrate becomes less and less until only original formation fluids are found (Figure 6.8, 2). This is the transition or invaded zone which gives way to the uninvaded, virgin formation.

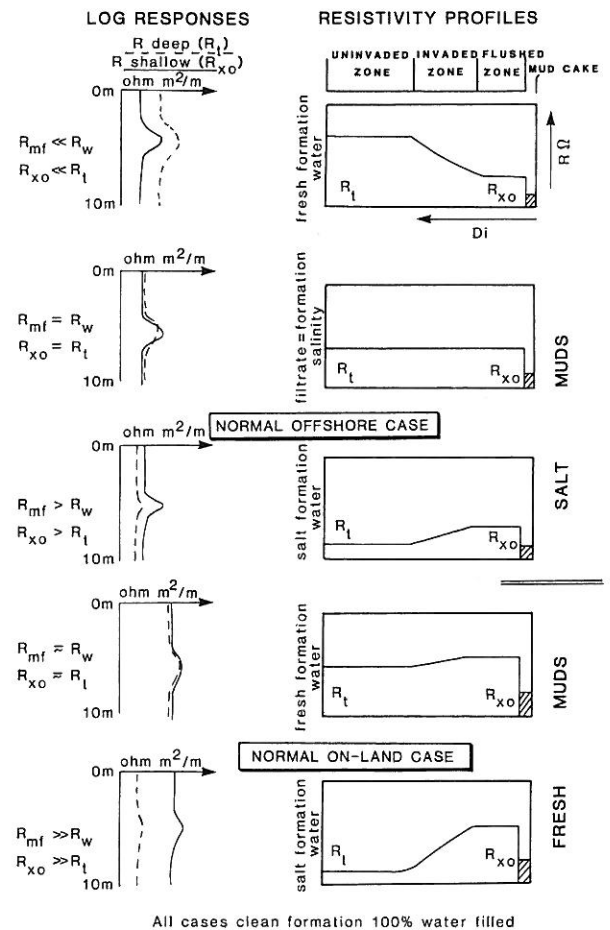


Figure 6.9 Schematic log response and resistivity profiles for water-bearing reservoir considering various cases of mud resistivity and formation-water resistivity. For symbols see Table 6.4 (see also Table 6.5).

The regular change in fluids away from the borehole gives rise to a parallel change in the resistivity of the formation as a function of the distance away from the borehole. The resistivity variations can be conveniently

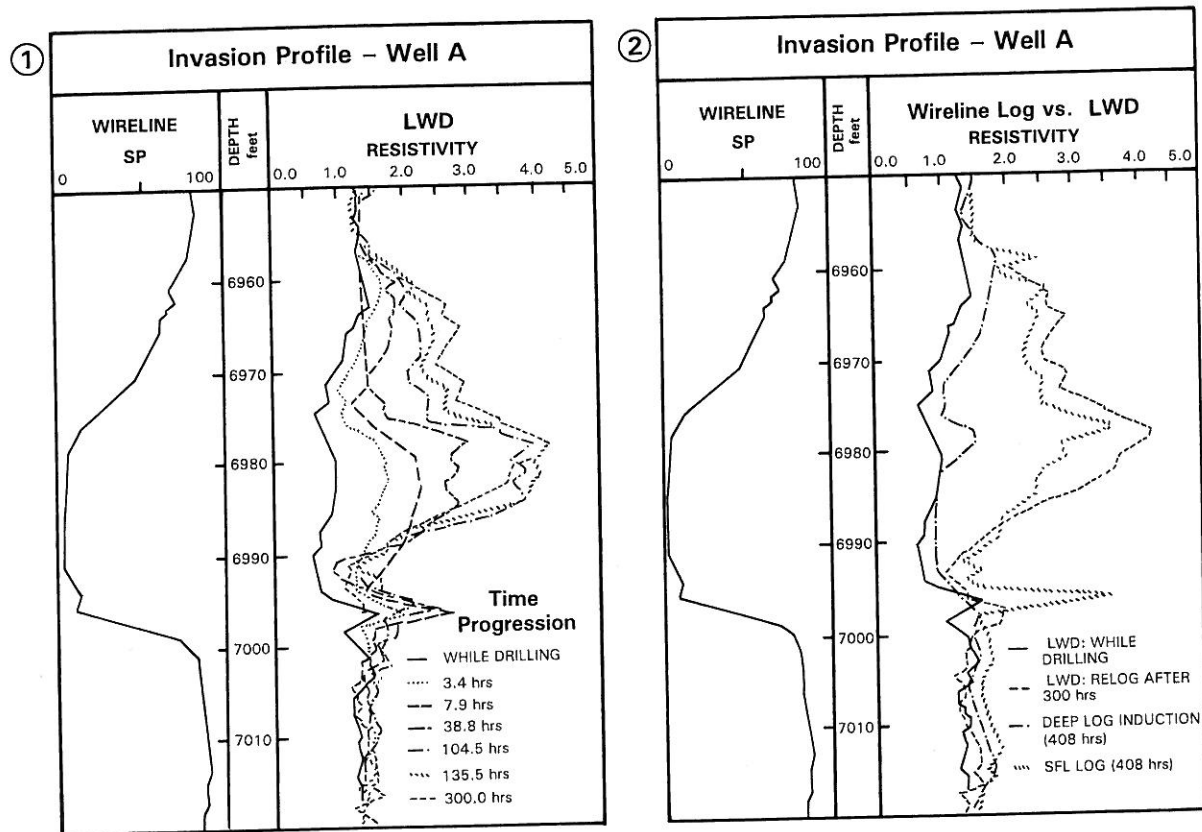


Figure 6.10 Progressive formation invasion demonstrated by LWD and wireline resistivity logs run over a porous, salt water bearing sandstone interval.

1. LWD resistivity logs measured repeatedly over the interval from 3.4 hrs after drilling to 12.5 days (300 hrs). 2. LWD logs (first and last) compared to wireline resistivity logs run 17 days (408 hrs) after drilling. The deep induction wireline measurement compares with the first LWD measurement (no invasion, R_t), the shallow wireline SFL measurement compares with the final LWD measurement (flushed zone, R_{xo}) (from Cobern and Nuckols, 1985).

depicted by a graph of resistivity against distance from the borehole at a constant depth (Figure 6.8,3). The variations are due entirely to changes in fluid content, it being the same rock formation (thus F is constant).

This effect can be 'brought to life' by comparing LWD resistivity measurements, made before significant invasion takes place, with wireline resistivities made when invasion is near its maximum. The example, of a saltwater bearing sandstone (Figure 6.10, 1), shows LWD measurements, one taken immediately during drilling and a series at intervals over the next 300 hours (12.5 days). The resistivity progressively increases for the first 104.5 hours (4.3 days) as invasion increases, the invading fluid having a higher resistivity than the in-place, salty formation water. After 4.3 days the invasion stabilises and logs taken over the next 8 days are similar (Figure 6.10, 1) (Cobern and Nuckols, 1985). For comparison, wireline logging took place 17 days after drilling (407 hours). The wireline resistivity representing the flushed zone (the SFL) is similar to the stabilised LWD log (maximum invasion), while the wireline log representing the virgin formation (deep induction) is similar to the first LWD log

measured before any invasion (i.e. when the reservoir contained salt water). It is truly with such a set of logs that invasion can be monitored (it takes a surprisingly long time in this case) and the depth of investigation characteristics of the resistivity tools empirically evaluated.

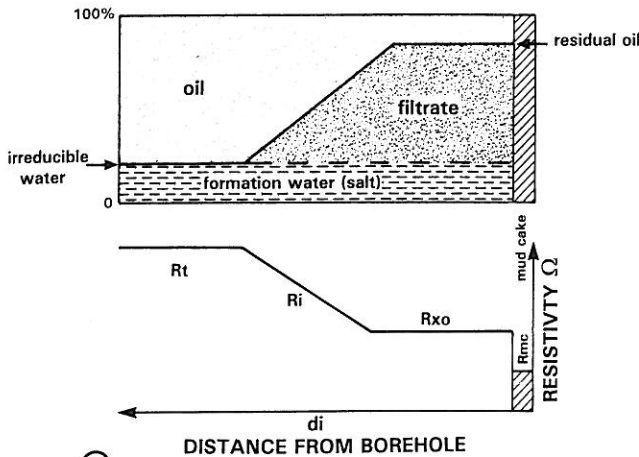
The zones of invasion, associated fluid resistivities and corresponding zone resistivities all have accepted notations (Table 6.4). These will be used henceforth.

Resistivity profile variations

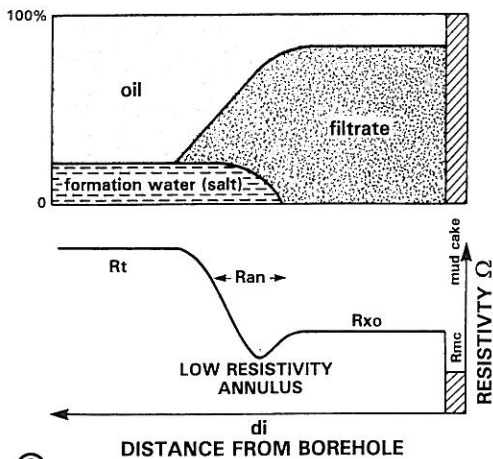
Since the variations in resistivity about a borehole are due to the mixing of two fluids, mud filtrate and formation fluid, it is as well to know their average characteristics. Formation-water characteristics have already been described (Chapter 2). Essentially, three types of mud are used; saltwater mud, freshwater mud and, in certain cases, oil-based mud. The different resistivity regimes caused by the combinations of muds and formation waters are shown in Table 6.5 and Figure 6.9. When interpreting the resistivity logs, care should be taken to note the fluids used in the borehole and their characteristics. They appear on the log heading.

Table 6.5 Variations in filtrate and formation-water resistivity values, as read by resistivity tools (see also Figure 6.9).

		Formation-water salinity	
		Fresh formation water	Saline formation water
Saltwater mud (usual offshore)	$R_{mf} < R_w$	$R_{mf} = R_w$	$R_{mf} \geq R_w$
Freshwater mud	$R_{mf} \geq R_w$	$R_{mf} \gg R_w$	$R_{mf} > R_w$
Oil-based mud (special cases)	Oil filtrate contamination Only R_i induction is usable		



①



②

Figure 6.11 Schematic oil zone resistivity profiles. 1. Simple invasion model. 2. Model with low resistivity annulus. R_{an} = annulus resistivity. For symbols see Table 6.4.

Oil (hydrocarbon) zone resistivity profiles

All previous examples have assumed 100% water saturation in the porous and permeable bed, the resistivity variations being due to mud filtrate and formation water mixing, a two phase system of miscible fluids. When hydrocarbons are present, the system becomes three phase and much more complex. The mud filtrate will

replace the oil and gas immediately around the borehole, essentially replacing them through the flushed zone, while the original saturation in hydrocarbons is only found in the virgin formation (Figure 6.11,1). A resistivity profile across a hydrocarbon zone will show a flushed zone with a moderate to low resistivity, filled with mud filtrate (with resistivity depending on mud type) and the virgin formation with an extremely high resistivity because of the high saturation in hydrocarbons. Both oil and gas are infinitely resistive and show the same effect on resistivity logs. The resistivity profile then, shows a big increase away from the borehole, the exact reverse of a water zone. (Figure 6.11,1). This increase in resistivity deeper into the formation, away from the borehole, is expressed very distinctly on the logs. Shallow looking tools which read in the flushed zone show low (relatively) resistivity values, while deep reading tools show very high resistivities (Figure 6.12) The separation between the curves from the shallow and deep tools, plotted on the same resistivity scale, is diagnostic of hydrocarbons. It is sometimes called the *hydrocarbon separation* and is used in the 'quick look' technique for locating oil or gas. A quick look, however, must be verified by calculation since curve separation can be caused by fresh water and many hydrocarbon zones do not give any obvious separation.

In practice, the behaviour of fluids in a drill encountered hydrocarbon zone is not simple. Theoretically there is a differential rate of flushing of formation water and of oil or gas by the mud filtrate. This is supposed to create a zone where there is a high volume of formation water with only residual hydrocarbons, the so-called low

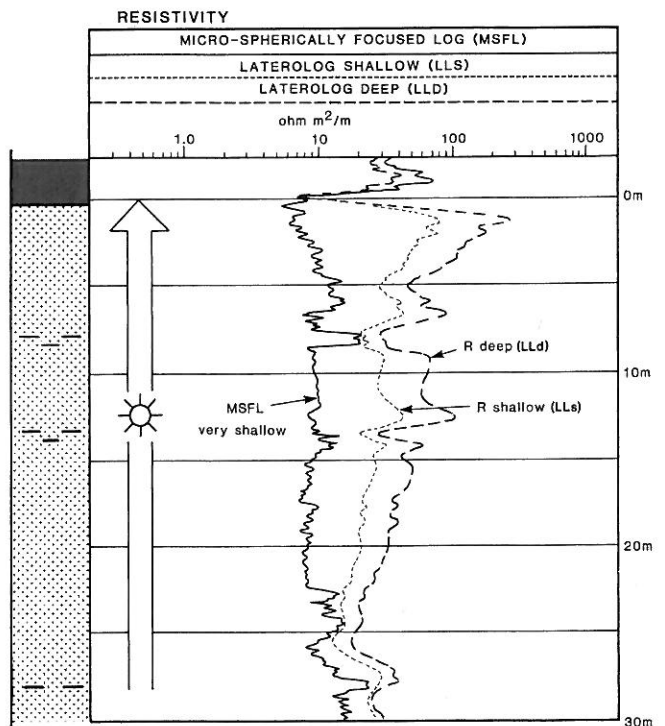


Figure 6.12 Strong separation of resistivity logs in a gas zone. Porosity is around 15%.

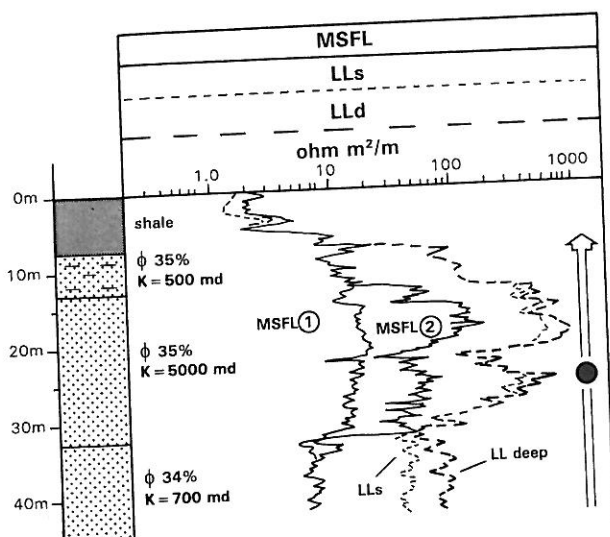


Figure 6.13 Active fluid movement during logging shown by a comparison between a main run and 'repeat' section. MSFL 1, the 'repeat' section, was run 1.5 hours before MSFL 2, the main run. The comparison shows that hydrocarbons are re-migrating into the flushed zone, measured by the MSFL, over the extremely permeable section (see text for explanation).

resistivity annulus on the outer fringe of the flushed zone (Figure 6.11,2). Doubt was always cast on the stability of such a zone, even if it was created (Threadgold, 1971). From the data sets now accumulating from LWD measurements (i.e. Figure 6.10), it is clear that there is considerable fluid movement not only during drilling when invasion occurs, but also when drilling ceases. The fluid equilibrium which existed before drilling attempts to re-establish itself, especially in gas filled reservoirs or those with very high permeabilities. The example (Figure 6.13) shows a highly permeable reservoir containing oil found in an offshore well drilled with a saltwater mud and logged by a resistivity tool combination of shallow, medium and deep devices (DLL-MSFL of Schlumberger). A 'repeat' run of the tool was made and completed 1.5 hours before the same interval was logged during the main run. In that 1.5 hours, the re-migration of the hydrocarbons back towards the well was taking place. This is shown by the increasing flushed zone resistivity (MSFL) over the central part of the reservoir. The two deep logs (LLd and LLs) are unchanged as is the shallow reading (MSFL) in the upper and lower reservoir zones (Figure 6.13). In this case, no doubt, the re-migration of the hydrocarbons was helped by the huge permeability of 5000 mD in the affected reservoir. However, hydrocarbon movement after drilling is nicely demonstrated.

Oil-based mud resistivity profiles

Many modern wells are now drilled with oil-based mud. It helps stop water loss, is a good lubricant and often reduces drilling time considerably. Clearly, the invasion behaviour of an oil filtrate is quite different from a water filtrate. The oil filtrate will mix with the hydrocarbons in a hydrocarbon zone while the water filtrate will be immiscible: the water filtrate will mix with the formation water

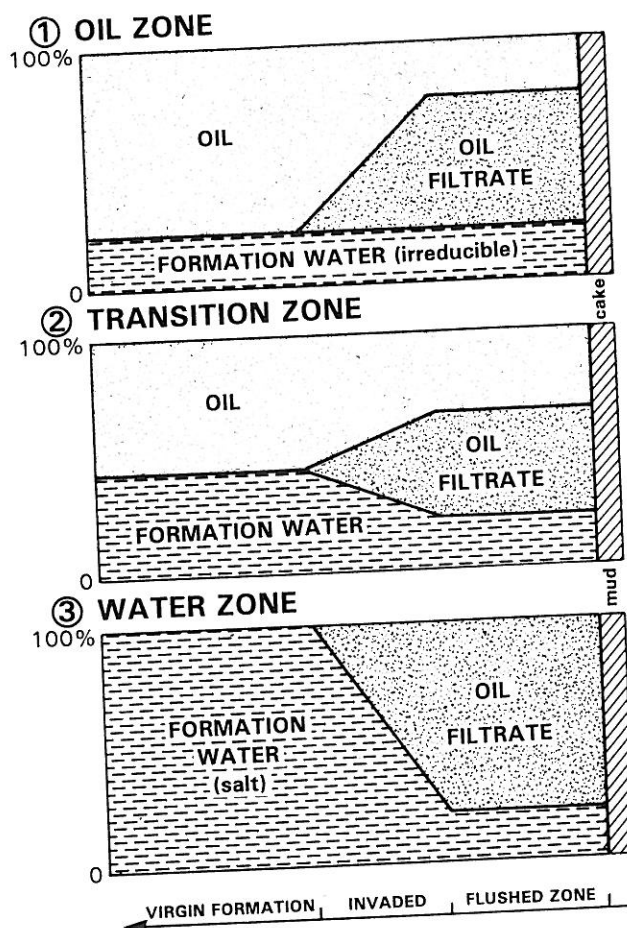


Figure 6.14 Fluid mixing in a well drilled with oil-based mud. 1. Oil zone. 2. Transition zone. 3. Water zone. (Modified after Boyeldieu *et al.*, 1984).

in a water zone while it is the oil filtrate which will be immiscible (Figure 6.14). Thus, in an oil zone the effects of invasion will be difficult to identify while high resistivities will be present close to the boreholes in water zones.

As will be discussed below, boreholes in which oil-based muds are used cannot be logged with the standard resistivity tools: only induction devices are effective. It is only recently, with the modern array induction tools (see Section 6.5, Induction tools) that the invasion behaviour of oil-based muds can be monitored by logs.

6.4 Resistivity tools

Standard tools

The basic circuitry of the resistivity tools was established by Conrad Schlumberger in 1927. He passed a current between two electrodes in the earth and measured the potential drop between two other electrodes. Modern tools are considerably more complex than this, especially because emitted currents are 'focused' by contiguous guard currents (Figures 6.15, 6.16). Focused currents are less prone to borehole effects and can be directed at required areas of the formation.

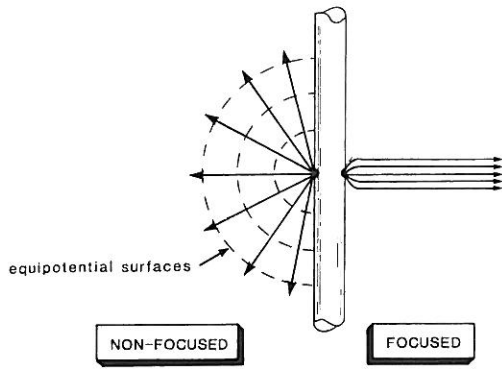


Figure 6.15 Schematic drawing of focused and non-focused electrical current distribution about a logging tool. The old Electrical Survey tools were not focused: modern Laterologs are focused.

Resistivity tools exist with diverse capabilities as a result of the need to measure formation resistivity from anywhere between the immediate vicinity of the borehole wall and the flushed zone, to the distant, uninvaded formation (Figure 6.18). The deeper looking devices are hole-centred (Figure 6.16) while the shallow investigating devices, like the microlog, are mounted on a pad pressed against the borehole wall (Table 6.6, Figure 6.17). It should be noted here that in the literature, measured depth of investigation usually refers to the detection of 50% of the emitted signal.

In the modern logging suite, the focused laterologs are the deepest 'looking' and most likely to give the virgin formation resistivity, R_v . Slightly shallower, invaded zone resistivities, R_i , are measured by shallow focused laterologs and body mounted devices such as the SFL. All

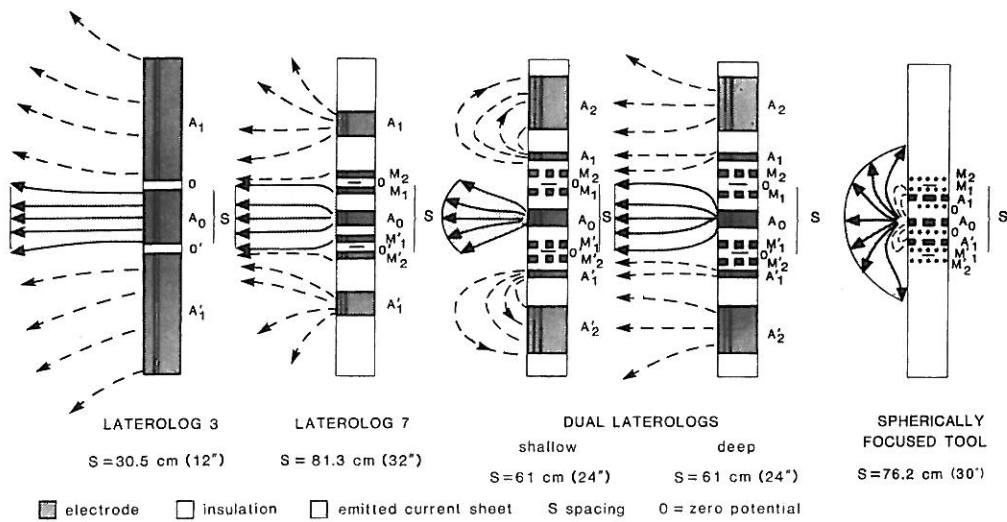


Figure 6.16 Schematic electrode disposition in several body mounted, focused resistivity tools from Schlumberger. A = electrode, M = monitoring electrode. (From Schlumberger, re-drawn).

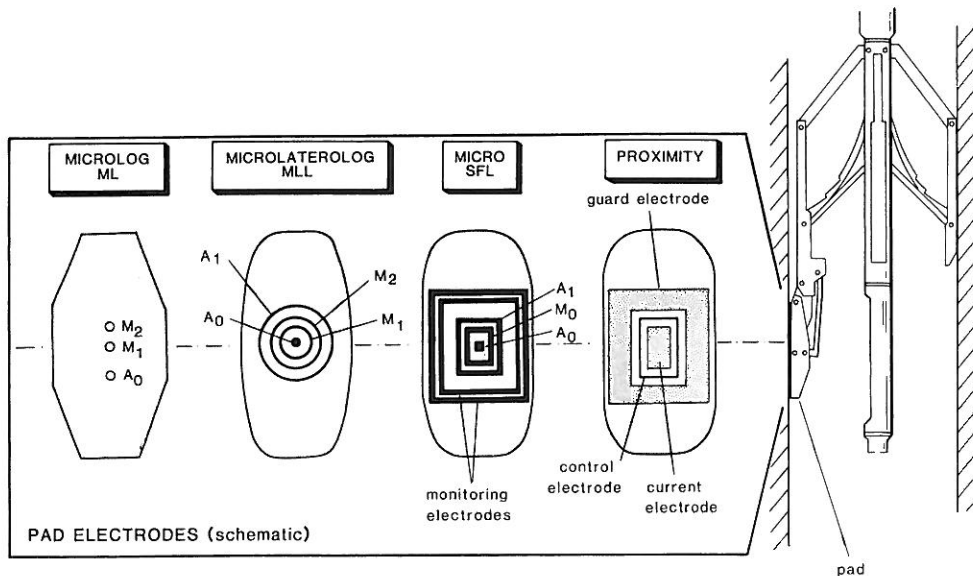


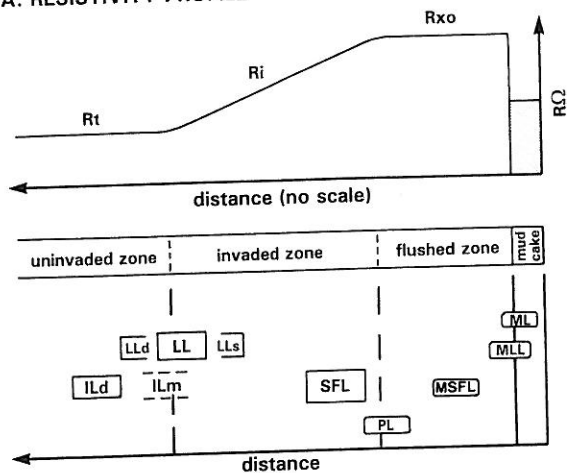
Figure 6.17 Schematic drawings of electrode dispositions on pad-type resistivity tools. One tool (MSFL) is shown in the hole. SFL = spherically focused log. A, M, electrodes. (Modified from Schlumberger documents).

Table 6.6 Resistivity (conductivity) measuring tools (see also Figures, 6.14, 6.17 and symbols in Table 6.4).

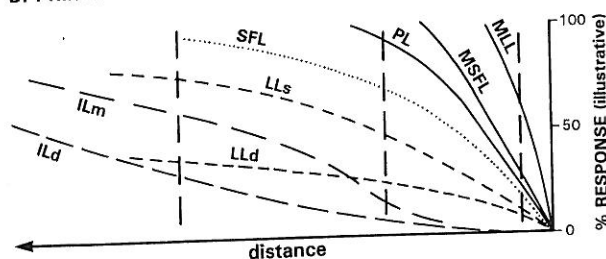
Tool		Symbol	Resistivity	
Pad tool	†Micro-log normal	ML2"	$R_{mc} + R_{xo}$	
	inverse	ML1" × 1"		
	Micro-laterolog	MLL	$R_{xo} (+ R_{mc})$	
	Proximity log	PL	$R_{xo} + R_i$	
	*Micro-spherically focused log	MSFL	R_{xo}	
Hole centred	*Spherically focused log	SFL	R_i	
	Laterolog	shallow	LLs	R_i
		deep	LLd	R_i
	Induction log	medium	ILm	$R_i - R_t$
		deep	ILd	R_i
	Array Induction	shallow to deep		$R_i - R_t$ (profile)

†Minilog - Dresser
*Schlumberger

A. RESISTIVITY PROFILE



B. PRINCIPAL RESISTIVITY INDICATED (schematic)



C. GEOMETRIC TOOL RESPONSE (schematic)

Figure 6.18 The type of resistivity measured by the various tools (after Schlumberger). IL = induction log, deep-medium; LL = laterologs, deep-shallow; SFL = spherically focused log; MSFL = micro-spherically focused log; PL = proximity log; MLL = microlaterolog; ML = microlog.

these tools are best used in holes drilled with conductive (salt) muds. (see Section 6.6). Of the very shallow 'looking', pad mounted devices, the Micro-spherically focused log of Schlumberger (MSFL) or equivalent from other companies, is the one most frequently used for a good measurement of flushed zone resistivity, R_{xo} (Table 6.6, Figure 6.18). The pad devices can only be run in holes with conductive muds.

Recent developments

There has been very little change in the basic, standard 'hardware' of resistivity logging over the last 20 years, such as the laterologs and the microlaterologs. Perhaps the only new departure in this area is the array laterolog of BPB which gives a pad micro-resistivity, intermediate resistivity and conventional shallow and deep resistivities. With four measurements an invasion profile can be built up. There has however been change in the way that the data are presented so that presently profile colour images, and even colour images of simple logs are available.

Considerable new development is occurring in the more specialist fields and the present effort in resistivity logging seems to be centred on such aspects as thin bed deep resistivity evaluation, oriented (directed) resistivity measurements for horizontal drilling (i.e. the Azimuthal Resistivity Imager, ARI of Schlumberger, see Chapter 16) and improved signal processing (cf. Maute, 1992). These efforts are directed at petrophysical problems and a geological evaluation of the new tools and processing techniques is continuing.

6.5 Induction tools

Standard tools

The induction tool was introduced to the industry by Henri Doll of Schlumberger in 1949. It was based on the design of a mine detector. A basic induction tool consists of an emitting coil and a receiving coil separated along the length of the tool by an electrically isolated section (mandrel). A constant amplitude sinusoidal current is applied to the transmitter coil. This creates a magnetic field around the tool which in turn induces eddy currents in the formation, flowing in a circular path around the tool (Figure 6.19). The eddy currents create their own magnetic field and induce an alternating current in the receiver coil. The eddy currents are 90° out of phase with the emitter current and the receiver current a further 90°: the emitter and receiver therefore, show a 180° phase shift. This measured current is the so called *R-signal*. There is also a much stronger current caused by a direct coupling of the emitter and receiver coils which is 90° out of phase with the emitting current: this is the *X-signal*.

The standard modern induction tool, such as the Dual Induction of Schlumberger, was introduced in 1963, although the technology had already existed in separate tools for some time. These dual induction tools consisted of emitting and receiving coils along with a series of paired, reverse wound coils, precisely placed to eliminate

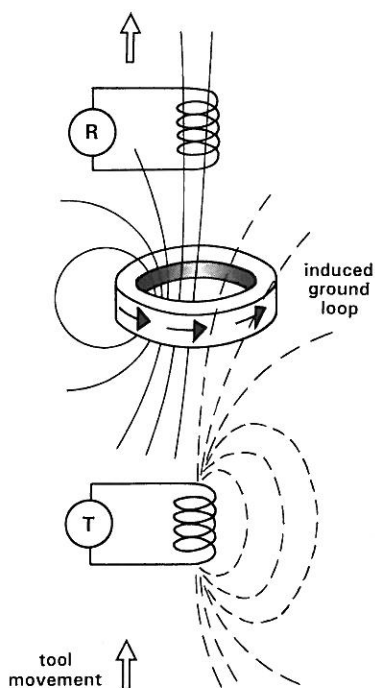


Figure 6.19 The principle of the simple induction tool. The vertical component of the magnetic field from the transmitting coil, T, induces a ground loop in the formation which in turn is detected by the receiver coil, R (re-drawn, modified from Ellis, 1987).

or buck out the unwanted X-signal. The typical tool used today, the dual induction (combined with other modules) has been improved but has the same basic construction as the earlier ones. The principal coils are set 1 m (40") apart and it is considered that the induced current comes from the formation between 1 m and 5 m (Western Atlas, 1.6 m) away from the borehole, the exact depth of investigation depending on formation and mud conductivities. The corresponding average depth of investigation for the medium or shallow induction is 80 cm (i.e. detection depth of 50% of the tool signal).

Recent developments, Array induction tools

Advances have been made in recent years in induction logging. A significant new tool is the array induction. For example the Array Induction Tool (AIS) of BPB, who were the first to introduce such a tool in 1983 (Martin *et al.*, 1984), consists of one emitter coil and four receiver coils. The raw signals are processed mathematically using the laws of electromagnetics, to produce a log value or formation signal. The multiple investigation depths calculated from the tool response can be reconstructed into an invasion profile (Figure 6.20) impossible with 2 value tools, although the shallowest reading is probably not generally into the flushed zone (Head *et al.*, 1992).

A second advance in induction tool design is that modern tools measure both the R- and X-signals, principally because the X-signals are used in subsequent signal

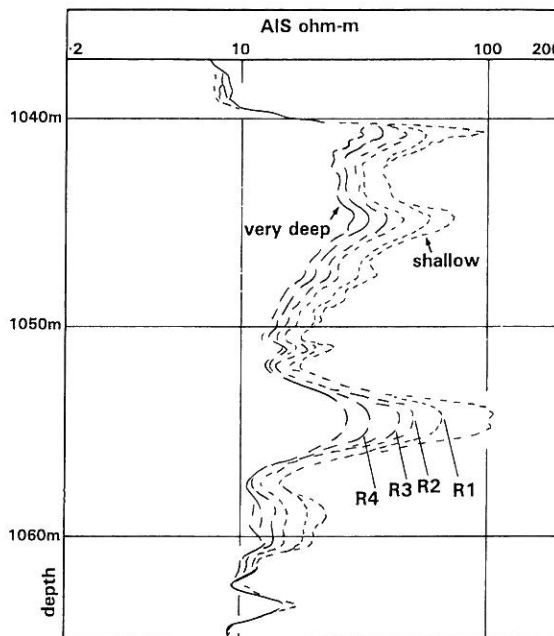


Figure 6.20 Invasion profile indicated by the BPB AIS, array induction tool in a water-filled limestone drilled with oil-based mud. The 4 raw induction tool readings (R1 – R4) have been resolution matched and modelled to give the invasion profile. The results may be presented as a colour image (from Elkington, 1995).

processing (*see below*). The modern tools also have the possibility of using different current frequencies. The older tools used a fixed frequency of 40 kHz while modern tools give a choice of 10, 20 and 40 kHz.

The other area of advance in induction logging is in signal processing. Induction tool responses can be very satisfactorily modelled mathematically. This means that the difference between tool derived values and real formation values can be 'modelled out'. It is, effectively, the 'reconstruction of a formation property profile consistent with the measured data' (Dyos, 1987). This technique, inversion, can be applied in several ways, but essentially consists of predicting realistic formation values from the tool recorded values, by satisfying mathematically, the calculated distortion to the tool signal that the proposed formation would have. This is in fact forward modelling. The Phasor Induction tool of Schlumberger uses signal processing to improve the conventional induction tool measurements using one set of log values to correct the other (Maute, 1992).

The induction tools are important because they provide the only resistivity measurement in wells drilled with oil-based mud. With the older standard tools, signal distortion was common and it was not possible to have a flushed zone resistivity, only a deep reading. Inversion is diminishing signal distortion and with the new array tools a spectrum of resistivities can be presented (Figure 6.20).

The basic equations of petrophysics

Below, the fundamental equations of petrophysics appear in a specific order, followed by explanation and comment on their computation. In fact, these equations have applications beyond resistivity measurement, but their use is not discussed here. Such information is found in logging company handbooks and specialist publications (see references).

$$R_o = F.R_w \tag{1}$$

Overall rock resistivity = the formation resistivity factor \times resistivity of the formation fluid (see 'Rock resistivity', p.44). Rock resistivity consists of two elements, the passive but constricting formation and the conductive formation fluids. As Wyllie said in 1956 (Wyllie, 1963), *This is perhaps the most important single relationship in electric log interpretation and must be committed to memory.*

$$I = \frac{R_t}{R_o} \tag{2}$$

The resistivity index = the resistivity of a rock containing hydrocarbons divided by the resistivity of a rock with 100% water. The equation introduces the notion of the ratio (in one particular reservoir) of the resistivity when entirely water-saturated, as opposed to the resistivity in the presence of hydrocarbons.

The Archie Equation

$$S_w^n = \frac{F.R_w}{R_t} \tag{3}$$

where S_w = water saturation;
 n = saturation exponent, usually 2.
 $F.R_w = R_o$ when the formation is 100% water-saturated (see equation 1). Thus, equation (3) is usually written

$$S_w^2 = \frac{R_o}{R_t} \tag{3a}$$

The water saturation (squared) = the rock resistivity with 100% water saturation divided by the rock resistivity with possible hydrocarbons. The equation is more commonly written

$$S_w = \sqrt{\frac{R_o}{R_t}} \text{ or } \sqrt{\frac{F.R_w}{R_t}} \tag{3b,c}$$

This equation, due to G.E. Archie of Shell, makes use of the ratio of resistivities from equation (2).

Invaded zone resistivities - movable hydrocarbons

$$S_{xo} = \sqrt{\frac{R_{xo}(100\% \text{ mud filtrate})}{R_{xo}(\text{with residual hydrocarbons})}} \tag{4}$$

Flushed zone saturation = the square root of the flushed zone resistivity in a 100% water zone divided by the flushed zone resistivity with possible residual hydrocarbons. Residual hydrocarbon saturation, $S_{hr} = 1 - S_{xo}$. The equation gives the saturation in unmoved or residual hydrocarbons of the invaded zone. This is the same Archie Equation as above, but here uses the resistivity ratio in the flushed zone. Comparison of S_w and S_{xo} in a hydrocarbon zone is considered to give movable hydrocarbons. $S_{xo} - S_w$ is equal to the fraction of movable hydrocarbons in the formation. The percentage volume in terms of the reservoir is given by multiplying the term by the porosity, i.e. % volume of reservoir with movable hydrocarbons = $(S_{xo} - S_w) \times \phi$ (where ϕ = porosity).

Formation resistivity factor-porosity relationships

$$F = \frac{a}{\phi^m} \tag{5}$$

where F = formation resistivity factor
 ϕ = porosity
 m = so-called cementation factor, dependent on rock type, and more closely related to texture than to cementation (Figure 6.5), and
 a = a constant.

The equation indicates that the formation resistivity factor is a function of porosity and rock type (m). Archie discovered this relationship between F and porosity (see Figure 6.5) and equation (5) is the result. Subsequent research and empirical correlations show that the global relationship varies; average figures used for the relationship are:

$$F = \frac{0.81}{\phi^2} \text{ in most sandstones} \tag{5a}$$

$$F = \frac{0.62}{\phi^{2.15}} \text{ (best average for sandstones)} \tag{5b}$$

- this is the *Humble Formula*

$$F = \frac{1}{\phi^2} \text{ compact formations, chalks} \tag{5c}$$

$$F = \frac{1}{\phi^m} \text{ where } m = \text{variable (usually 1.8 to 3)} \tag{5d}$$

The most frequently-used formula is (5b) which is applicable to sandstones. In limestones, the F -porosity relationships are quite variable.

Practical average Archie Equation

$$S_w = \sqrt{\frac{0.62 \times R_w}{\phi^{2.15} \times R_t}} \tag{6}$$

This is the general equation for finding the water saturation,

- RESISTIVITY AND CONDUCTIVITY LOGS -

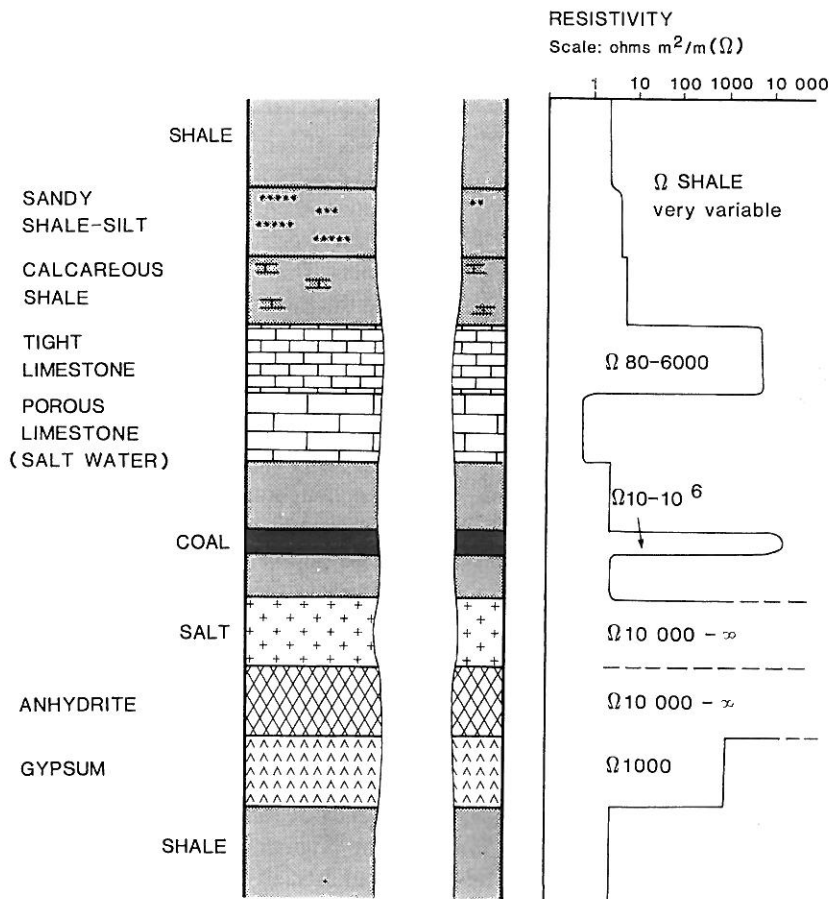


Figure 6.28 Responses on a deep resistivity log of some minerals and some typical, distinctive lithologies. To these mineral values should be added the following fluid values: pure, fresh water (26.7°C) = α , salt-saturated water (26.7°C) = 0.032Ω , methane = α .

Table 6.10 Some typical diagnostic resistivity values (mainly from Serra, 1972).

Lithology/ Mineral	Resistivity	Resistivity Range ohm m ² /m
Shale	Moderate	Extremely variable (0.5000-1000.0)
Limestone	Generally high	Variable - depends on porosity and formation water salinity
Dolomite	"	
Sandstone	Moderate-low	
Salt	Very high	10,000 - infinity
Anhydrite	"	10,000 - infinity
Gypsum	High	1000
Coal	High (variable)	10 - 1,000,000
Pyrite	Very low	0.0001 - 0.1

This sensitivity of the resistivity logs is brought out by a second example in which there are bulk changes in a shale, probably in texture as well as composition, brought about by a series of marine flooding events (Figure 6.31).

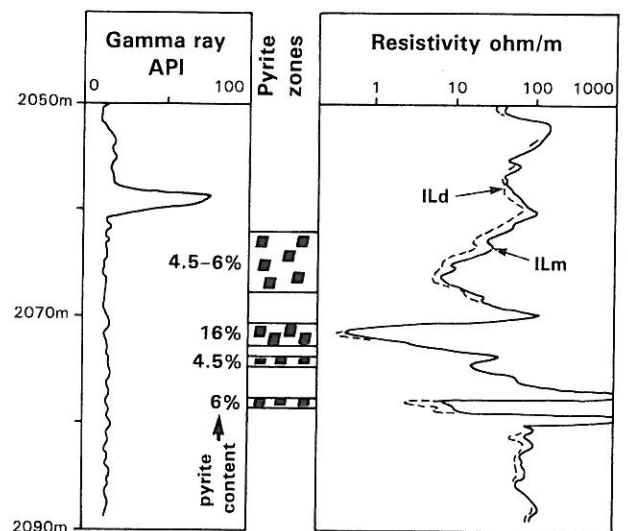


Figure 6.29 The effect of pyrite on induction logs. At high concentrations the electrical conductivity of pyrite is seen and log resistivity values are significantly lowered (re-drawn, modified from Theys, 1991, attributed to Clavier *et al.*, 1976).

The shale rich in organic matter shows a low resistivity; it is probably well laminated (*see below*) and was deposited in deep water (actually condensed deposits). Analysis of palynodebris shows that most of the organic material is