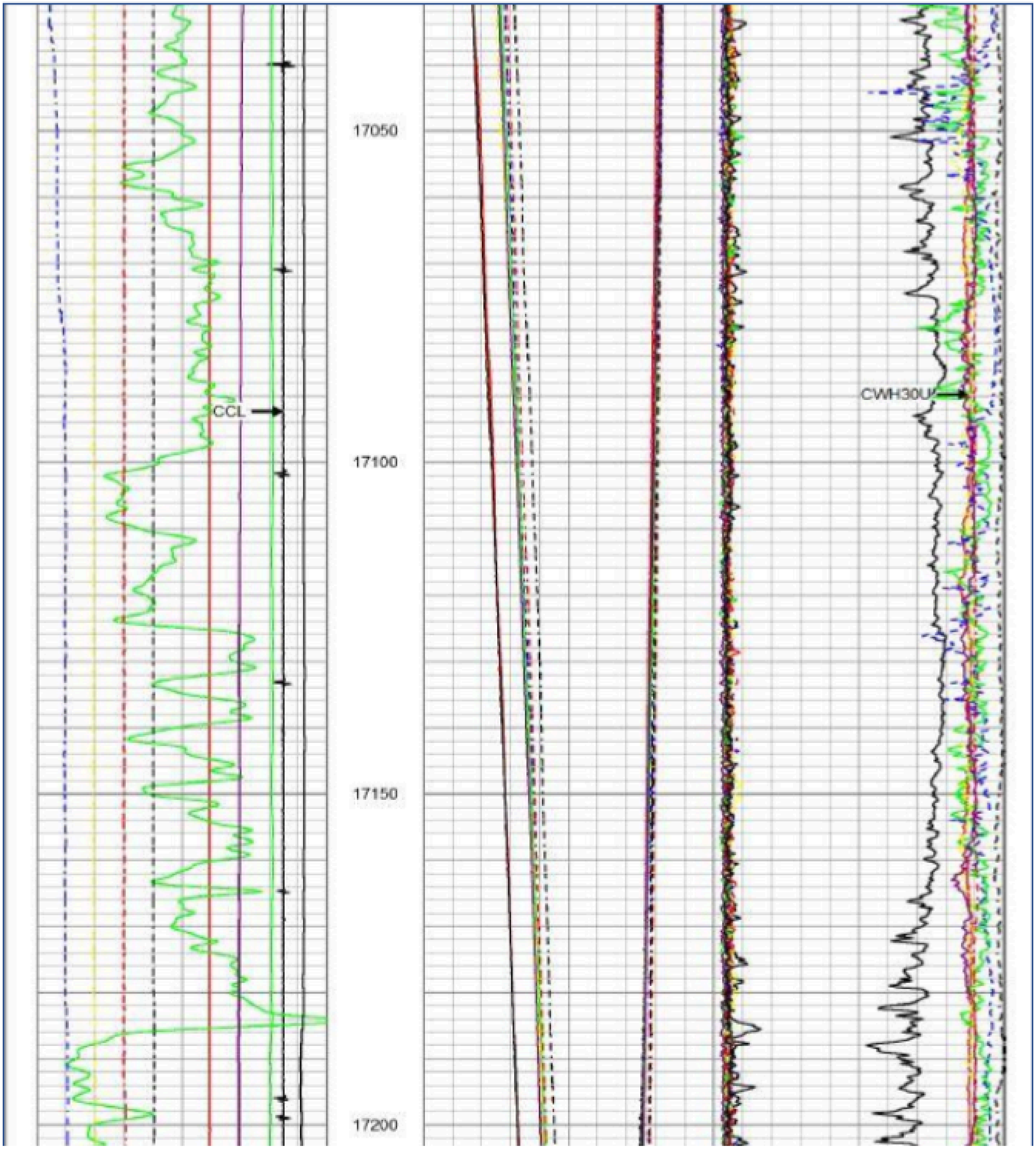
Chapter 2 - Spontaneous Potential

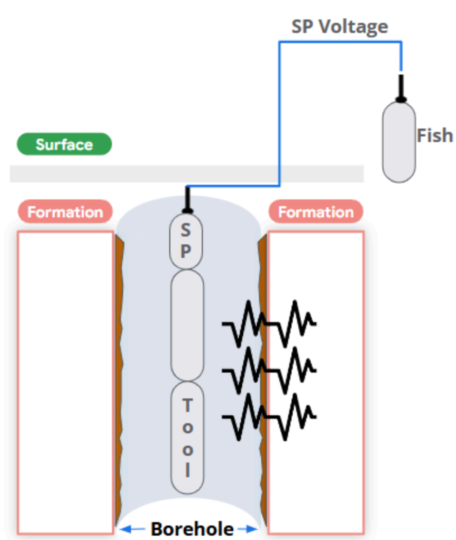


Content

Chapter 2 - Spontaneous Potential

The spontaneous potential (SP) tool is designed to measure a natural—or spontaneous—current flow in the borehole and formation resulting from ionic imbalances that exist between different subsurface fluids and ionic movement near the borehole/formation interface. The exchange of ions (primarily chlorine, Cl-, and sodium, Na+) between fluids of different salinities creates a voltage drop in a fluid-filled borehole. This natural current flow is measured as the potential difference between a downhole electrode in the SP tool and a reference electrode (or fish) at the surface (Fig. 1).

Figure 1. The basic principle of the SP measurement: a multi-meter with extremely long leads.



Ionic imbalances can occur where fluids of different salinities are in close proximity to one another, such as within an invaded formation or where a permeable formation is in contact with shale. Impermeable formations such as shale are characterized by a relatively straight, or static, SP curve response. Permeable formations that have experienced invasion by mud filtrate often exhibit deflections on the SP curve resulting from relative differences in the ionic concentrations of invaded mud filtrate and the original formation water.

In a sense, the SP measurement provides an indication of ionic permeability which, in many cases, can be closely related to fluid permeability. The primary objective of logging the SP is to obtain a qualitative indicator of permeability.

Applications

Natural current flow in the borehole and formation is also related to the effects of shale on the diffusion of ions. Clay minerals in shale have charge imbalances that can restrict ionic movement, thus influencing the amount of current generated. Because of these effects related to clay minerals, the SP measurement can be used to estimate the volume of shale (or VSH) in a formation. Other logging measurements commonly suited for this application include gamma ray, neutron porosity and density porosity.

Another important application of the SP measurement is the estimation of formation water resistivity (Rw), a critical variable used to estimate water saturation using the Archie equation:

$$S_w{}^n = \frac{a}{\Phi^m} \times \frac{R_w}{R_t}$$

Where: S_w = water saturation of the uninvaded zone
n = saturation exponent
a = tortuosity factor
Φ = porosity
m = cementation exponent
R_w = formation water resistivity
R_t = true resistivity of the uninvaded zone

The preferred source of Rw is its measurement from a sample of formation water. However, if no other source is available, then the SP response in a water-bearing formation can be used for this purpose. The magnitude of the SP deflection observed on a log is a function of the resistivity contrast between mud filtrate and formation water (Rmf/Rw). With a measure of Rmf from the API mud test performed at the wellsite, a value of Rw can be determined.

In areas where permeable formations are found associated with impermeable shale, the SP response can be used for well-to-well correlation. It may also be used to define formation boundaries where contrasting lithologies meet, and to determine formation thickness. Because the SP response is dependent mainly on fluid characteristics, it may not provide the best means of accomplishing these objectives.

Logging Conditions

The usefulness of the SP response is, in large part, dependent upon the borehole fluid. The measurement is not valid in wells drilled with oil-based mud or air because there is no electrical continuity between the formation and the downhole electrode. The SP measurement is also not valid in casing because of the conductivity of steel.

Best results are provided in water-based drilling fluids where there is a large contrast between Rmf and Rw. The SP measurement does not provide useful information where the salinities of mud filtrate and formation water are comparable. Examples of where this might become a problem are formations containing saline water that are drilled with salt water-based mud, and formations containing very fresh water that are drilled with very fresh water-based mud.

Origin of Spontaneous Potentials

Deflections on the SP curve are caused by currents flowing in the mud-filled borehole and the formation. These currents are driven by electromotive forces (emfs) that result from electrochemical and electrokinetic processes.

Electrochemical processes relate to ionic imbalances between fluids. Where two fluids exist having different ionic concentrations, the natural tendency is for ions to migrate to the fluid of lowest concentration. Electrokinetic processes relate to the movement of fluid at the borehole/formation interface. Moving fluids transport ions. In both cases, the exchange of ions between different fluids or the movement of ions represents a current flow.

Electrochemical Processes

A large majority of SP currents measured in logging originate by electrochemical processes. These processes involve ionic exchange between fluids of different salinities. Each process results in the generation of a potential at the downhole electrode that is different from that measured at the surface electrode (or fish).

These specific potentials originate within the formation, and include:

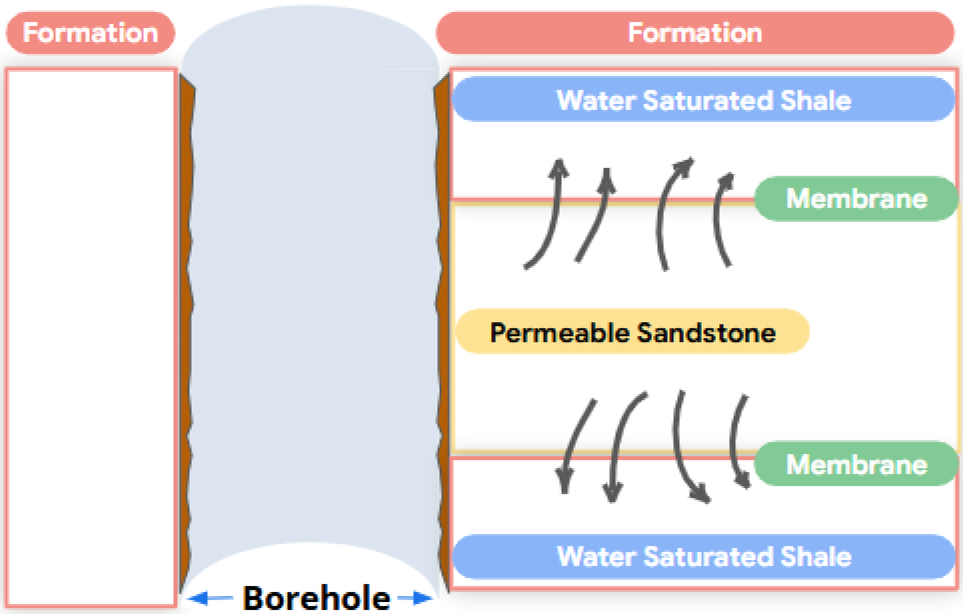
- The membrane potential
- The liquid junction potential

Membrane Potential

In permeable and invaded formations that are in contact with shale, a potential exists across the formation boundary (Fig. 2). Shale consists of microscopic clay minerals that can have negative charges on their surfaces. These negatively charged clay minerals tend to repel negatively charged ions such as chlorine (Cl^-). However, positively charged ions such as sodium (Na^+) are allowed to migrate through the shale from a fluid of higher ionic concentration (more saline) to one of lower ionic concentration (less saline).

The ionic exchange across the shale produces an electromotive force in the formation called the membrane potential. The clay minerals of the shale act as a membrane that preferentially allows the passage of positively charged Na^+ ions. This potential causes current flow across the membrane.

Figure 2. Ionic exchange across the boundary between a permeable formation and impermeable shale creates a membrane potential.



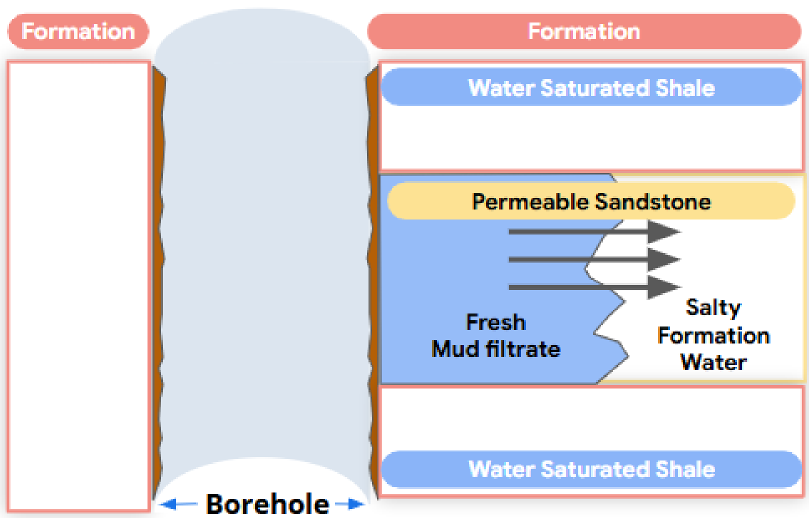
Clay minerals, apart from existing in shale, can also be dispersed throughout the pore space of a permeable formation. These dispersed clays also produce a membrane potential; however, its magnitude is smaller and its polarity is opposite that created by overlying and underlying shale. Therefore, in shaly formations, the membrane potential related to dispersed clays will counteract the membrane potential related to adjacent shale, and result in a suppression of the SP curve deflection.

Liquid Junction Potential

A permeable formation is often invaded during the drilling process by mud filtrate. This mud filtrate may have a salinity that is much different from that of the original formation water. At the margin of the invaded zone there will exist a boundary where mud filtrate and formation water are in contact. This boundary is called liquid junction (Fig. 3). Ions will be free to migrate from one solution to the other if the mud filtrate and formation water have different ionic concentrations or salinities. In the typical case where a salt water-bearing formation is invaded by fresh mud filtrate, chlorine ions (because of their greater mobility) will migrate from the formation water (more saline) to the mud filtrate (less saline).

The ionic exchange across the liquid junction produces an electromotive force in the formation called the liquid junction potential. This potential causes current flow across the liquid junction.

Figure 3. Ionic exchange between invaded filtrate and formation water at different salinities produces a liquid-junction potential.



Electrokinetic Processes

Most of the deflection observed on an SP curve is the product of electrochemical processes such as the liquid junction potential and the membrane potential. Depending upon well conditions, some of this deflection can also be the result of electrokinetic processes that involve the flow of fluids through the mudcake. The magnitude of SP deflections resulting from these electrokinetic processes is a function of several factors, including:

- Differential pressure that causes the fluid flow across the mudcake
- Salinities of the solutions involved

An electrokinetic potential is created as fluid flows through some porous and permeable medium. An example of this is the flow of mud filtrate through the mudcake. In most cases, hydrostatic pressure in the borehole balances formation pressure and very little fluid flow occurs. However, in the case of a depleted formation or a borehole drilled with very heavy mud, a situation may arise where there is sufficient differential pressure to cause fluid flow through the mudcake.

As fluid flows through the mudcake, the migration of ions creates an electromotive force called the streaming or electrofiltration potential. Normally, very little streaming potential is present because any pressure differential between the borehole and the formation is reduced across the mudcake.

Where hydrostatic pressure is significantly greater than formation pressure, the resulting migration of ions in the fluid that flows through the mudcake can be great enough to produce a rather large streaming potential. A similar current flow is generated in wells drilled with very heavy mud that is capable of penetrating mudcake and invading the formation.

Physics of the Measurement

Spontaneous potentials existing in formations and the borehole create a natural current flow. This current loop flows through a permeable formation, into adjacent shale, and returns via the mud filled borehole. The SP measurement is simply taken as the potential difference between a downhole electrode and a reference electrode (or fish) at the surface.

Because the downhole electrode is suspended in the mud column, the SP deflection observed on a log represents only the potential drop in the borehole as current passes the downhole electrode. It does not necessarily represent the potential drops occurring within a permeable formation. Therefore, the observed SP response reflects only a fraction of the total electromotive force (emf).

Ideally, the surface fish should be located in a place that is isolated from any potentials at the surface. Because the SP measurement is the potential difference between two electrodes, any excess potential on one of those electrodes (for example, the fish) will cause errors in the measurement. The effects of these spurious potentials are unpredictable and cannot be corrected for when setting up the tool.

Sources of excess spontaneous potential at the surface fish may include:

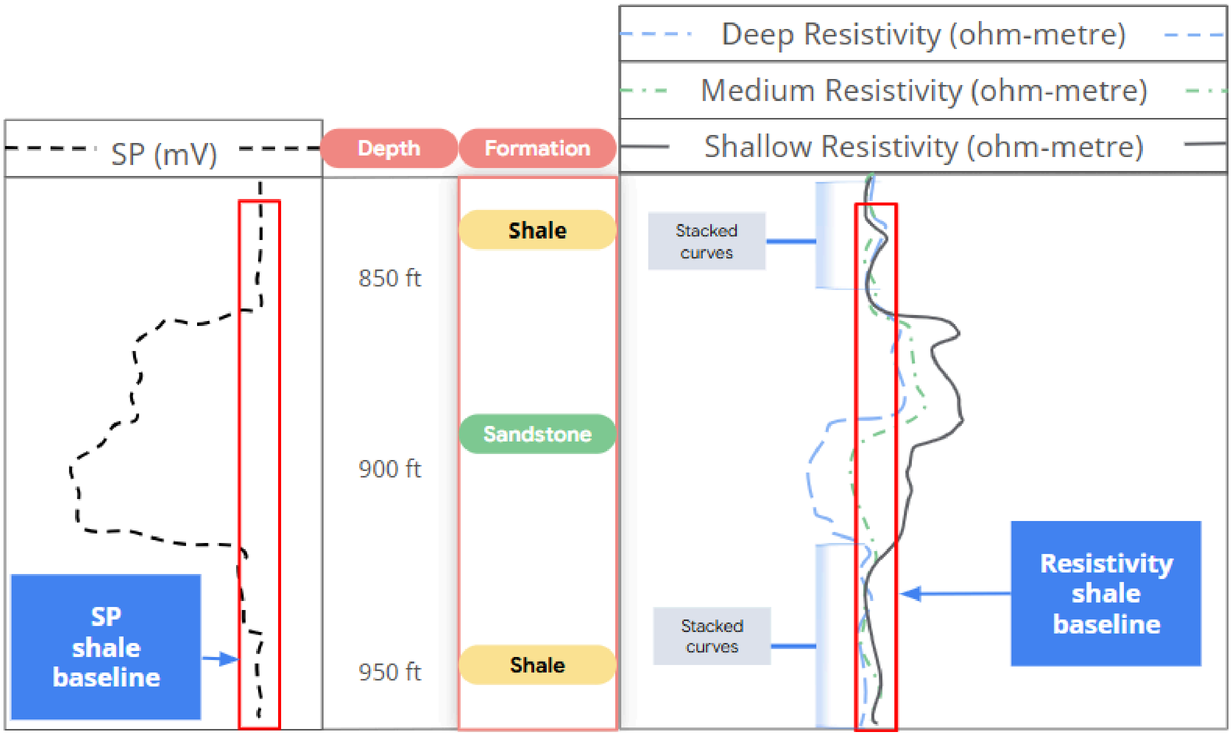
- Magnetism of measuring wheels or the drum.
- Line leakage or poor fish connections.
- Non-static fish conditions such as running water.
- Stray current such as that experienced during lightning storms, welding operations on the rig, or when cathodic protection or power generators are active.
- Telluric currents like the aurora borealis

Every effort should be taken to ensure that the surface fish obtains a good Earth ground reference. This helps to minimize the possibility of error in the SP measurement.

Baseline Responses in Shale

Shale can be easily recognized on a resistivity log because of its baseline responses on spontaneous potential (SP) and resistivity curves. The SP curve in shale is usually static, relatively straight and showing little deflection. If the SP curve is properly positioned, then its baseline is commonly found near the right side of the track (Fig. 4). In permeable rocks, any salinity difference between invaded mud filtrate and original formation water causes a deflection away from the SP shale baseline. As a quick-look method, scanning the SP curve can help distinguish permeable formations of interest from impermeable shales.

Figure 4. SP baseline and resistivity baseline response in shale



Shale also exhibits a baseline response on resistivity curves (Fig.4) Because of their very low permeabilities, shales are not usually invaded and resistivity values at all depths of investigation are equal (the curves "stack", meaning $R_{shallow} = R_{deep}$). Furthermore, because clay minerals in shale are conductive, the resistivity baseline is usually found at some low value (average range 1-10 Ω-m)

SP Response to Rmf/Rw Contrasts

Deflections of the SP curve away from its shale baseline are driven primarily by contrasting fluid salinities. Ionic exchange between invaded mud filtrate and original formation water in a permeable rock gives rise to a natural current flow. This current creates a potential drop in the borehole that is measured by the SP electrode. The measured voltage depends upon the Rmf/Rw contrast; greater contrasts result in larger voltage drops and larger deflections of the SP curve away from its shale baseline.

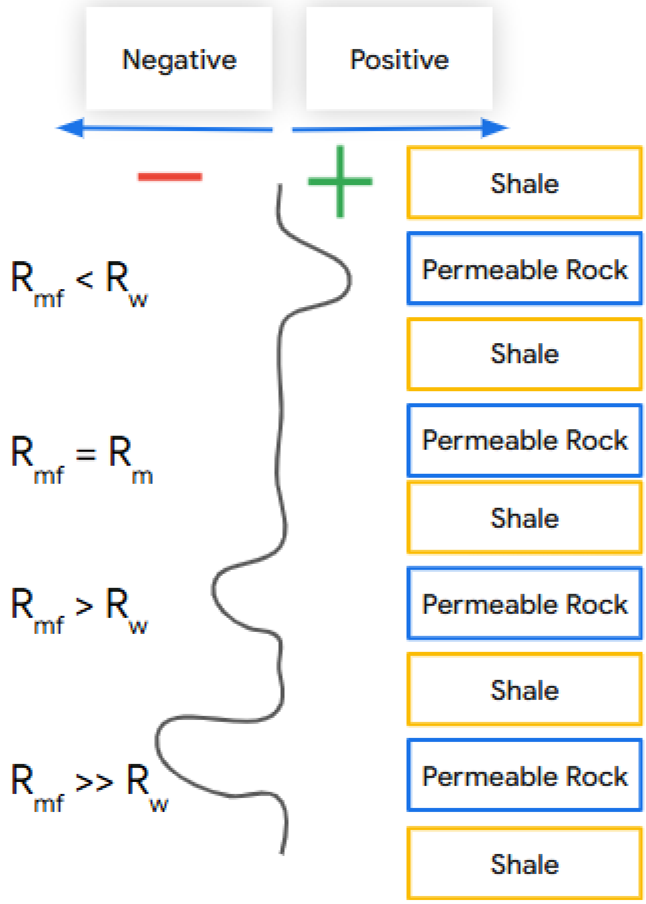
The direction the SP curve deflects away from its shale baseline – either left or right – is controlled by the polarity of the natural current flow in the formation which, in turn, is determined by the absolute relationship between Rmf and Rw. If Rmf is greater than Rw (e.g., fresh mud invading salty formation water), then current flows into the permeable formation and returns through adjacent shales and into the borehole. On the other hand, if Rmf is less than Rw (e.g., salty mud invading fresh formation water), then the current loop is reversed.

Negative SP deflection describes curve deflections to the left of the shale baseline (Fig.5), indicating that mud filtrate is more resistive than formation water (Rmf > Rw). This is the common SP response observed on induction logs in water-based mud where fresh mud filtrate invades formation containing salty water.

Positive SP deflection describes curves deflections to the right of the shale baseline (Fig.5), and are observed when mud filtrate is less resistive than formation water (Rmf < Rw). Positive deflection where water is fresh enough to cause positive deflection occur at shallower depths and are already behind casing.

Where there is no salinity contrast between mud filtrate and formation water (Rmf = Rw). The SP curve shows very little – if any – deflection away from the shale baseline. This highlights one limitation of the SP curve as a permeability indicator: permeable water-saturated rocks where Rmf/Rw = 1 can easily be mistaken as shale.

Figure 5. SP response under conditions of different Rmf/Rw contrast. The magnitude of deflection is a function of the amount of salinity difference, while the direction of deflection is determined by which fluid is more resistive – Rmf or Rw.



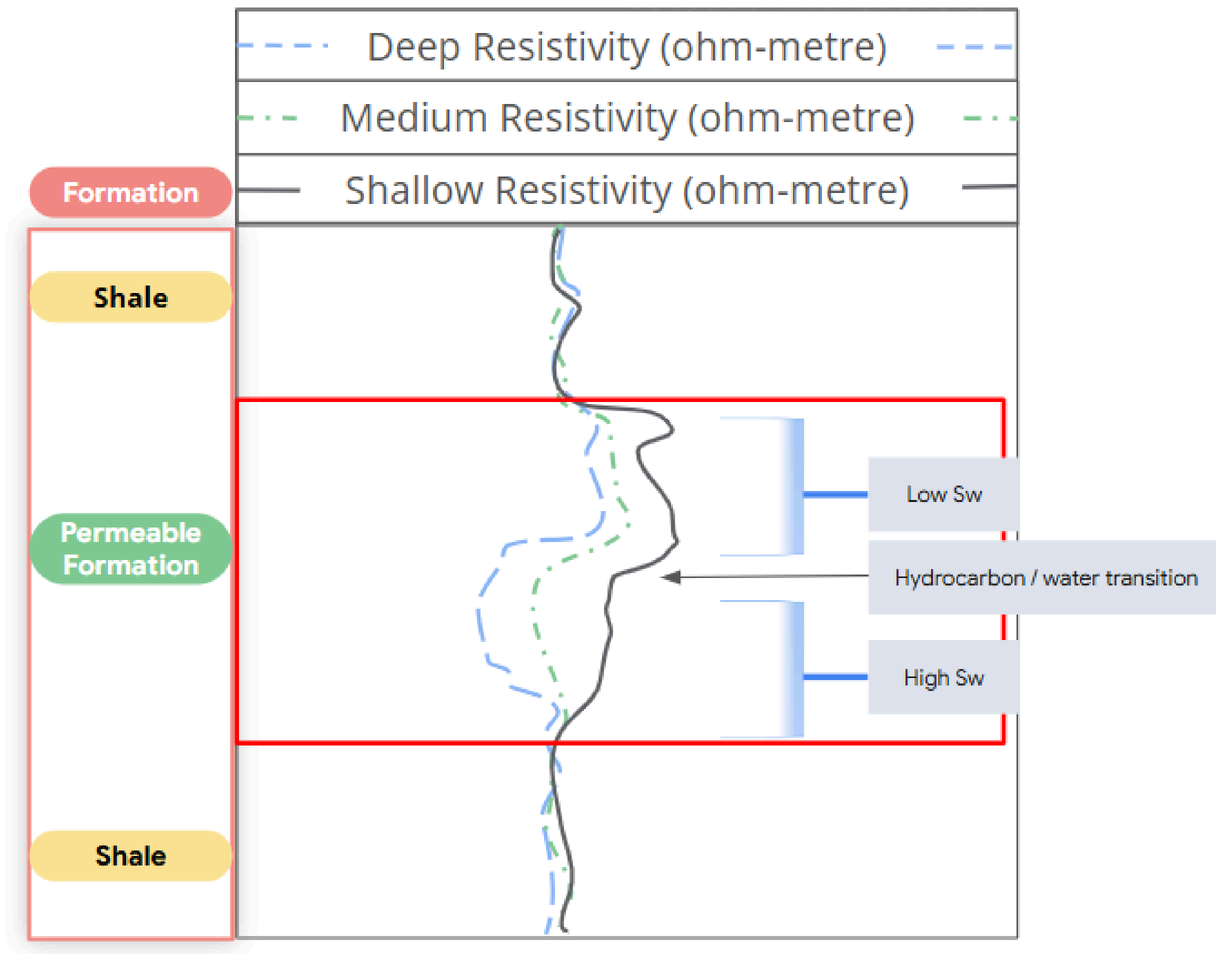
Resistivity shale baseline method

The resistivity shale base line can also be used to qualitatively estimate a formation's water saturation S_w. A common practice in wellsite interpretation is to use a resistivity shale baseline method for judging whether a formation contains mostly water or at least some hydrocarbon. Given the effects of porosity and saturation on R_{deep} measurements, the generalities apply:

1. Porous formations at high S_w usually exhibit R_{deep} values that are less than the resistivity shale baseline.

2. Porous formations containing high hydrocarbons (lower S_w)usually exhibit R_{deep} values that are greater than the resistivity shale baseline.

Figure 6. Comparison of R_{deed} to the resistivity shale baseline provides a qualitative estimate of water saturation. High S_w is indicated where R_{deep} is less than the resistivity shale baseline, while low S_w is indicated where R_{deep} is greater than the shale baseline



The resistivity shale baseline method works best in “clean” formations. In shaly rocks, the conductivities of clay minerals cause resistivity to be abnormally low and possibly less than the shale baseline, even when a significant volume of hydrocarbon is present. Given this effect, it is possible for a shaly hydrocarbon-bearing formation to be mistaken for one with high Sw when using the resistivity shale baseline method.

A convenient first-step toward identifying water-saturated formations and potential hydrocarbon reservoirs is to establish the SP and resistivity shale baselines. Quickly scan the log, looking for zones of interest where these curves depart from their baselines. This approach helps eliminate impermeable shale intervals so that attention can then be focused on more interesting zones.

Resistivity Response to Rmf/Rw Contrasts

With knowledge of Rmf/Rw conditions from the SP response, it is possible to predict an expected relationship between Rshallow and Rdeep in an invaded formation. For any water-saturated formation, the following relationship can be made:

$$\frac{R_{mf}}{R_w} \propto \frac{R_{xo}}{R_t}$$

R_{mf} = Mud filtrate resistivity
R_w = Formation water resistivity
R_{xo} = Flushed Zone resistivity
R_t = Formation True resistivity

Given their depths of investigation, Rshallow and Rdeep provide the best approximations for Rxo and Rt, respectively. Therefore, for any water-saturated formation, it is correct to say:

$$\frac{R_{mf}}{R_w} \propto \frac{R_{shallow}}{R_{deep}}$$

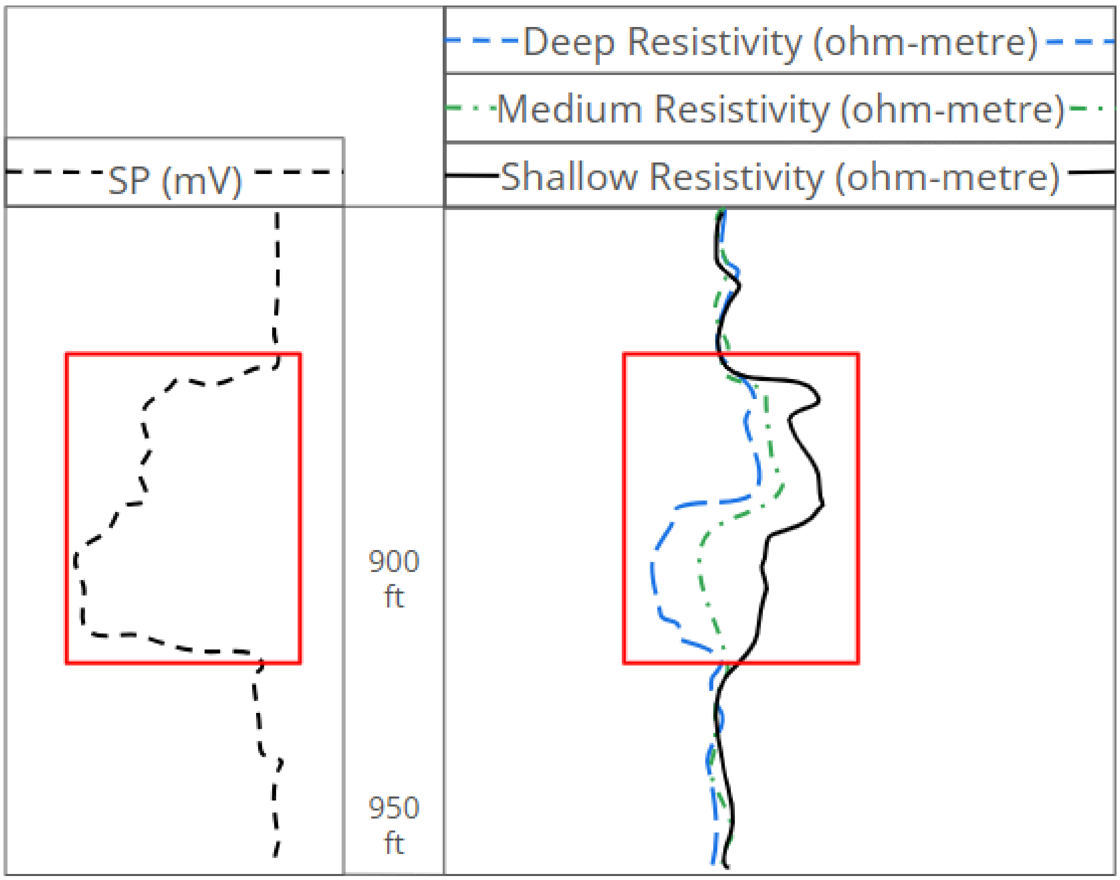
In water-saturated formations, the relationship between Rmf and Rw determined from the SP deflection will be reflected by the relative comparison of Rshallow and Rdeep. If a water-saturated formation is invaded by mud filtrate of equal salinity (Rmf/Rw = 1, no SP deflection), then there will be no separation of resistivity curves (Rshallow = Rdeep). If that same formation is invaded by a fresh mud filtrate (Rmf/Rw > 1, negative SP deflection), then Rshallow > Rdeep will result. The difference between Rshallow and Rdeep depends upon the Rmf/Rw ratio; therefore, larger SP deflections are usually accompanied by greater separation of resistivity curves.

The presence of hydrocarbons in permeable formations makes it more difficult to predict how Rshallow will respond to invasion and what relationship will be observed between Rshallow and Rdeep. The mixing of mud filtrate and formation water along with the displacement of moveable hydrocarbons both combine to determine the relationship between Rshallow and Rdeep. To develop a better understanding of invasion in hydrocarbon-bearing rocks and how it influences resistivity responses, it is first necessary to classify different types of invasion and examine the effects of mixing and displacement in each.

Classifying Invasion

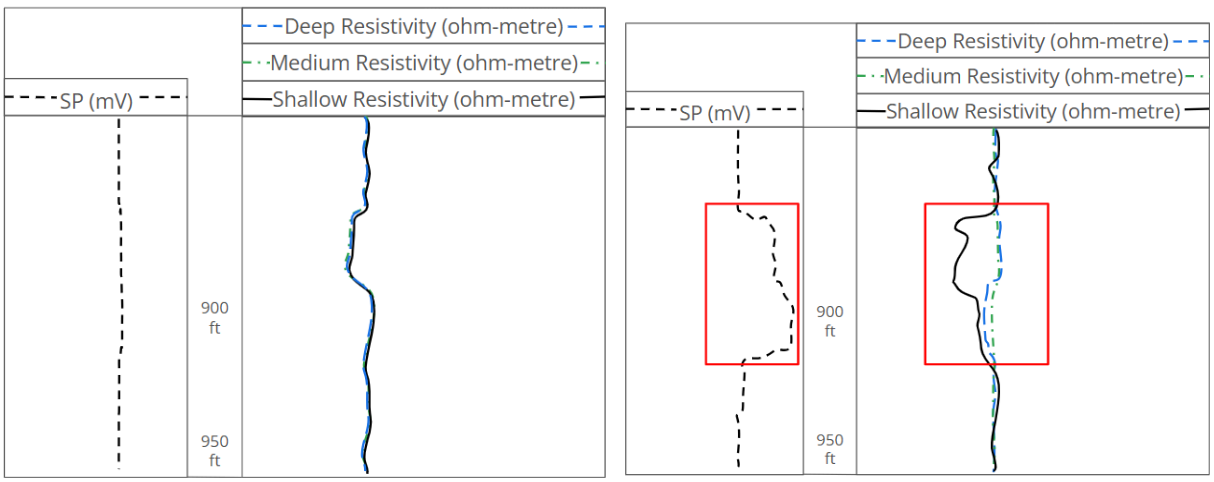
The type of invasion experienced by a permeable rock – and, therefore, the type of profile observed – is defined by the Rmf/Rw ratio. Resistive invasion occurs when the invaded mud filtrate is more resistive than original formation water (Rmf > Rw). Resistive invasion of a water saturated formation produces a resistive profile (Rshallow > Rdeep; Fig. 7). In a hydrocarbon bearing formation, the resulting profile is dependent upon the mixing of mud filtrate and formation water in addition to how efficiently hydrocarbons were displaced during invasion.

Figure 7. Example of a resistive invasion profile in a water-saturated formation. Negative SP deflection indicates $R_{mf} > R_w$ so the invasion of mud filtrate will result in $R_{shallow} > R_{deep}$



Conductive invasion occurs when the invaded mud filtrate is approximately the same resistivity as original formation water ($R_{mf} \approx R_w$), or when mud filtrate resistivity is less than that of the original formation water ($R_{mf} < R_w$). Conductive invasion of a water-saturated formation produces a conductive profile ($R_{shallow} \approx R_{deep}$ or $R_{shallow} < R_{deep}$) (Fig. 8), depending upon the absolute R_{mf}/R_w contrast. In a hydrocarbon-bearing formation the resulting profile is not so much dependent upon the mixing of mud filtrate and formation water as it is upon the efficiency of hydrocarbon displacement during invasion.

Figure 8. Examples of conductive invasion profiles in water-saturated formations. At the left, the lack of SP deflection indicates $R_{mf} \approx R_w$ so $R_{shallow} \approx R_{deep}$ At right, positive SP deflection indicates $R_{mf} < R_w$ so $R_{shallow} < R_{deep}$



Validating resistivity tool response sometimes is as simple as determining Rmf/Rw conditions from the SP curve and verifying whether or not the separation and relative arrangement between Rshallow and Rdeep is in agreement. In water-saturated formations, negative SP deflection is usually accompanied by a resistive profile, while lack of deflection or positive SP deflection are accompanied by conductive profiles. In water-saturated formations, the exact relationship between Rshallow and Rdeep depends only upon the mixing of invaded mud filtrate and original formation water. In hydrocarbon-bearing formations, the displacement of any moveable hydrocarbon during invasion will also have an effect on the Rshallow vs. Rdeep relationship.

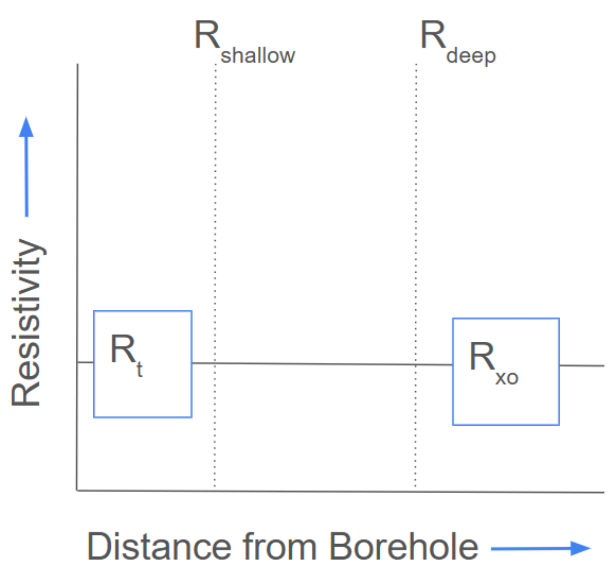
Model Invasion Profiles

Invasion of mud filtrate in a permeable formation creates a distribution of different fluid types – invaded and original – in the pore space radiating outward from the borehole. Resistivity of the uninvaded zone (Rt) is a function of the types and relative amounts of original fluids (water and hydrocarbon), while resistivity of the flushed zone (Rxo) is determined by both the Rmf/Rw ratio and how efficiently any moveable hydrocarbon, if present, was displaced. Ignoring the need for any borehole or invasion corrections to resistivity measurements, it is generally said that Rshallow provides a good approximation of Rxo while Rdeep provides a good approximation of Rt. Accordingly, the observed relationship between Rshallow and Rdeep provides clues about how the distribution of original fluids in the formation changed as a result of invasion, and why.

To this point invasion profiles have been discussed with respect to the relative arrangement of resistivity curves at multiple depths of investigation, and examples have been presented of how these profiles would appear on a log. Invasion profiles can also be depicted as X-Y diagrams, illustrating changes in resistivity with respect to distance from the borehole (i.e., depth of investigation).

Model invasion profiles are helpful for developing an understanding of how resistivity measurements change in response to mud filtrate invasion. If a permeable water-saturated formation could be logged before invasion began, then resistivity values at all depths of investigation would be low and equal, resulting in a "flat" profile (Fig. 9). A similar flat profile is expected in shale which, because of its low permeability, is not invaded.

Figure 9. "Flat" resistivity profile in a water-saturated formation that has nos yet been invaded. Resistivity curves show no separation. A similar profile describes the resistivity response in shale where diameter of invasion d_i equals 0.



Mixing and Displacement as Causes of Invasion Profiles.

Invasion profiles observed on resistivity logs are the result of two processes occurring during invasion. These processes include:

1. The mixing of water-based mud filtrate and original water in pores of the flushed zone. This mixing occurs in both water-saturated and hydrocarbon-bearing formations.

2. The displacement of moveable hydrocarbons by mud filtrate in pores of the flushed zone. Displacement occurs only in hydrocarbon-bearing formations.

Considered individually, the effects of mixing and displacement are relatively straightforward. At question is how Rshallow changes in response to each. Mixing of mud filtrate and formation water produces mixed water, the resistivity of which can be less than, equal to, or greater than that of the formation water itself (Rw). As a result of mixing alone, Rshallow can decrease, remain unchanged, or increase with respect to Rdeep. The amount of change depends upon the Rmf/Rw ratio, while the direction of change depends upon which is greatest – Rmf or Rw.

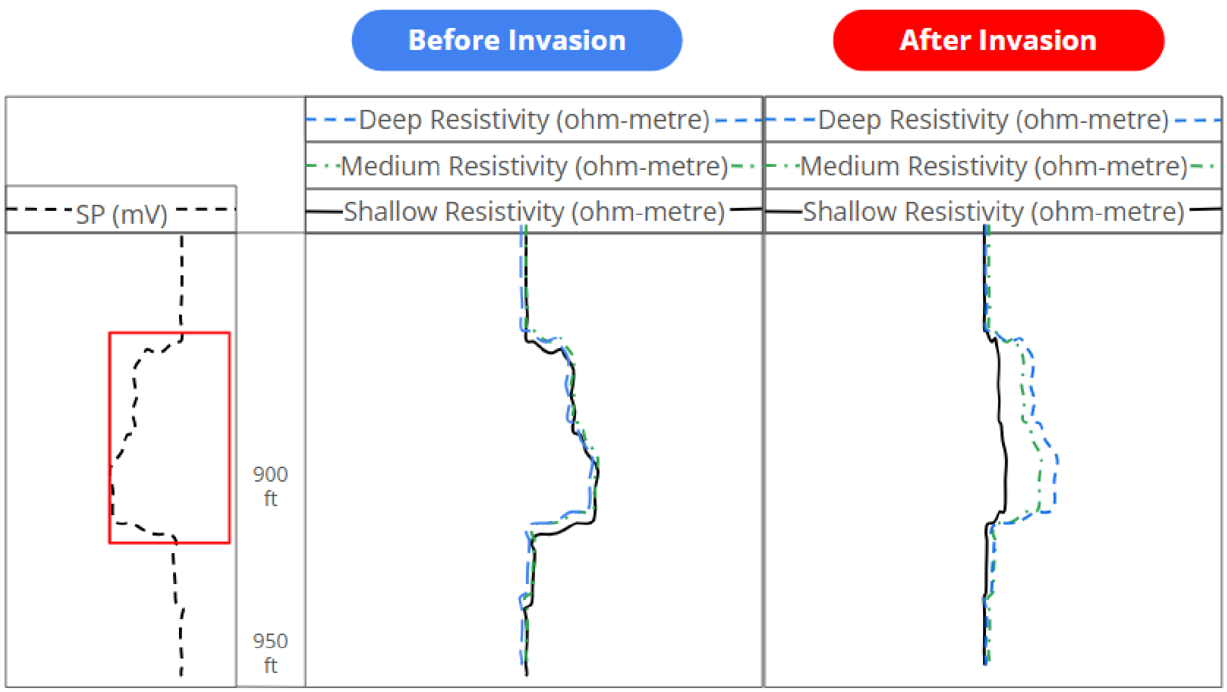
Displacement of moveable hydrocarbons, if present, causes an increase in flushed zone saturation (Sxo). As a result of displacement alone, Rshallow must decrease because of the larger fraction of pore space filled by mud filtrate after invasion. The amount of decrease depends upon the volume of hydrocarbon displaced.

Invasion profiles in water-saturated formations are easy to interpret because they develop in response to mixing alone. This mixing can cause either a resistive or a conductive profile to be apparent. In hydrocarbon-bearing formations the interpretation might not be so simple. Mixing and displacement both occur in formations where hydrocarbon is present, so the possibility arises where the two processes have competing effects on Rshallow.

The potential difficulty involved with interpreting profiles in hydrocarbon-bearing formations can be demonstrated by a common sense approach to invasion. A porous and permeable hydrocarbon-bearing rock at some low value of water saturation will show Rdeep greater than the shale baseline.

Before invasion, Rshallow = Rdeep (Fig. 10). During the invasion of water-based mud filtrate, at least some volume of moveable hydrocarbon is displaced from pores in the flushed zone. Some residual hydrocarbon remains behind, unable to be displaced. The increase in flushed zone water saturation (Sxo) must cause a corresponding decrease in Rshallow. Therefore, in a formation containing moveable hydrocarbons that is invaded by water-based mud filtrate, it is common sense to expect a conductive profile (Rshallow < Rdeep; Fig. 10). The amount of decrease experienced by Rshallow depends upon the volume of moveable hydrocarbons displaced.

Figure 10. "Common sense" conductive profile in a hydrocarbon-bearing formation invaded by water-based mud filtrate. $R_{shallow}$ decreases in response to the displacement of movable hydrocarbons



The problem with this common sense approach to invasion profiles is that it completely ignores the effect of mixing. It is true that the flushed zone contains a smaller volume of hydrocarbons after invasion than it did before. This, after all, is what causes Rshallow to decrease. However, the flushed zone pore space previously occupied by movable hydrocarbons is, after invasion, occupied by mixed water. This mixed water can have a resistivity greater than that of the original formation water (which, by itself, would cause an increase in Rshallow). Mixing and displacement in this case would have competing effects on Rshallow, one causing an increase, and the other a decrease. As a result, the decrease in Rshallow might not be as significant as expected, particularly when mud filtrate is very resistive.

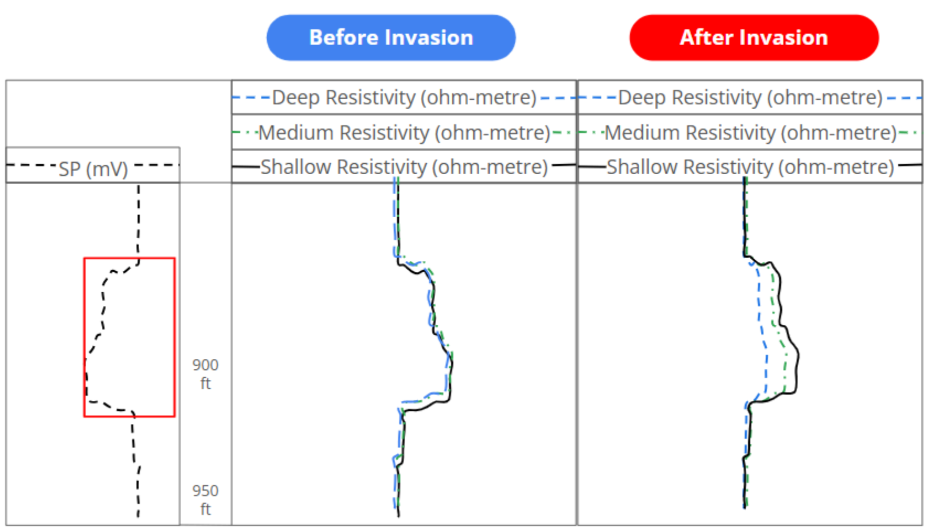
What happens to Rshallow as a result of invasion in hydrocarbon-bearing formation depends upon two factors:

1. The Rmf/Rw ratio.

2. The volume of moveable hydrocarbons displaced.

It is a balancing act between mixing (the Rmf/Rw ratio) and displacement (how much hydrocarbon was moved) which ultimately determines the invasion profile observed. Hydrocarbon-bearing formations that experience conductive invasion, intuitively, should show conductive profiles. Those that experience resistive invasion might also show conductive profiles if significant volumes of hydrocarbons were moved. However, when resistive invasion occurs where there is a significant Rmf/Rw contrast and an average volume of hydrocarbons is moved, resistive profiles (Fig.11) can be the rule rather than the exception.

Figure 11. Resistive profile in a hydrocarbon-bearing formation invaded by water-based mud filtrate. Large negative SP deflection indicates R_{mf} >> R_w Under such conditions of extreme R_{mf}/R_w contrast and average hydrocarbon moveability, any decrease in $R_{shallow}$ caused by displacement can be counteracted by the effect of mixing.

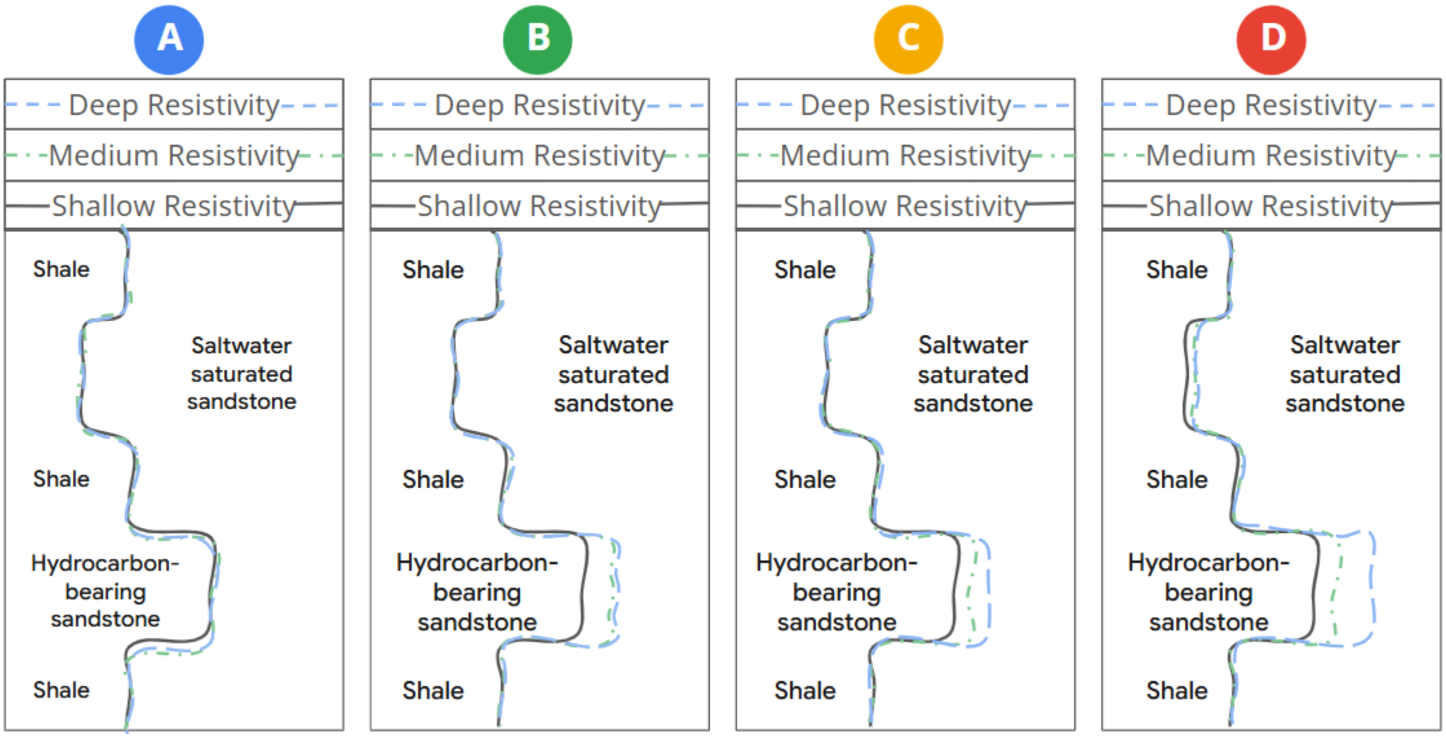


To demonstrate this possibility of a resistive profile in hydrocarbon-bearing formations, it is helpful to apply actual numbers to the R_{mf}/R_w ratio. The preferred operating environment for an induction tool is when $R_{mf}/R_w \geq 2.5$, a condition that is satisfied by most fresh water-based mud systems. Corrected for temperature, $R_{mf} \approx 1.2$ Ω-m in average fresh water-based mud and $R_w \approx 0.05$ Ω-m for average formation waters. The average environment for an induction tool is $R_{mf}/R_w = 24$ which is not only greater than 2.5, but significantly greater. A very fresh mud might have $R_{mf} \approx 3.0$ Ω-m resulting in $R_{mf}/R_w = 260$

Given that mixed water can have a resistivity 24 to 60 times greater than formation water alone, it is entirely possible for a $R_{shallow}$ increase resulting from mixing to counteract and even overcome any $R_{shallow}$ decrease caused by displacement. Because of this, resistive invasion profiles are the most common type of profile observed on induction logs run in their preferred environment. Conductive profiles might also be observed on induction logs when significant volumes of hydrocarbon were moved, but are more commonly seen on laterologs where $R_{mf}/R_w < 2.5$

Interpreting conductive invasion profiles ($R_{shallow} \approx R_{deep}$ or $R_{shallow} < R_{deep}$) is rather intuitive, owing to the fact that water-based mud filtrate is at least somewhat conductive while hydrocarbon is not. Recall that conductive invasion occurs whenever $R_{mf} \approx R_w$ or $R_{mf} < R_w$ (both of which are satisfied when $R_{mf}/R_w < 2.5$). A good example of this condition is when a well is drilled with saltwater-based mud and formations contain the usual salty water.

Figure 12 illustrates resistivity responses across an interval comprising impermeable shales and permeable sandstones. The permeabilities of both sandstones are assumed to be equal. From left to right, the sequence of logs depicts the progressive invasion of conductive (i.e., salty) mud filtrate. In Figure 12A invasion has not yet begun, so resistivities at all depths of investigation are equal.



At the onset of invasion (Fig. 12B), mud filtrate is introduced into the flushed zone of the permeable sandstones. Mixing of mud filtrate and salty formation water causes no change to Rshallow in the water-saturated sandstone, but displacement of moveable hydrocarbon in the hydrocarbon-bearing sandstone causes a decrease in Rshallow.

With deeper invasion (Fig. 12C) of salty mud filtrate, there is little change to the curve response in the water-saturated sandstone, again because Rmf ≈ Rw. In the hydrocarbon-bearing sandstone, as invasion becomes deeper and a larger volume of hydrocarbon is moved, the separation of curves becomes greater. At some depth of invasion Rmedium begins to be influenced by this displacement, and decreases relative to Rdeep.

Ultimately, the invasion of salty mud filtrate displaces a considerable volume of hydrocarbon, resulting in significant separation of curves in the hydrocarbon-bearing sandstone (Fig. 12D). The amount of separation observed is a function of how much hydrocarbon was moved. Mixing of salty mud filtrate and salty formation water does not cause much – if any – separation of curves in the water-saturated sandstone. Any separation that does develop is a function of small salinity differences between the two fluids.

For the case of conductive invasion (Rmf/Rw < 2.5), conductive invasion profiles are observed in both the water-saturated sandstone and the hydrocarbon-bearing sandstone. These types of profiles are commonly observed on dual laterologs in their preferred operating environment (salty mud filtrate and salty formation water). Porous hydrocarbon-bearing formations at some low value of water saturation (Sw) will likely show Rdeep greater than the resistivity shale baseline. When Rmf/Rw < 2.5, the separation of resistivity curves can be used as an indication of the presence of moveable hydrocarbon