

18. THE SPONTANEOUS POTENTIAL LOG

18.1 Introduction

The *spontaneous potential* log (SP) measures the natural or *spontaneous potential difference* (sometimes called *self-potential*) that exists between the borehole and the surface in the absence of any artificially applied current. It is a very simple log that requires only an electrode in the borehole and a reference electrode at the surface. These spontaneous potentials arise from the different access that different formations provide for charge carriers in the borehole and formation fluids, which lead to a spontaneous current flow, and hence to a spontaneous potential difference. The spontaneous potential log is given the generic acronym SP.

The SP log has four main uses:

- The detection of permeable beds.
- The determination of R_w .
- The indication of the shaliness of a formation.
- Correlation.

The log has a low vertical resolution, is rarely useful in offshore environments, and is always recorded in the leftmost track of the log suite, together with the GR log.

It is very important to recognize that this log has no absolute scale – only relative changes in the SP log are important. This is reflected in the design of the log header, which shows only a bar that represents a change of, say, 10 mV.

18.2 Principles

There are three requirements for the existence of an SP current:

- A conductive borehole fluid (i.e., a water based mud).
- A sandwich of a porous and permeable bed between low porosity and impermeable formations.
- A difference in salinity between the borehole fluid and the formation fluid, which are the mud filtrate and the formation fluid in most cases. Note, however, that in some special cases an SP current can be set-up when there is no difference in salinity, but where a difference in fluid pressures occurs.

The origin of the spontaneous potential has four different components. These are shown in Fig. 18.1. The spontaneous potential is composed of contributions that are *electrochemical* (arise from electrical interactions between the various chemical constituents of the rocks and fluids), and *electrokinetic* (arise from the movement of electrically charged ions in the fluid relative to the fixed rock).

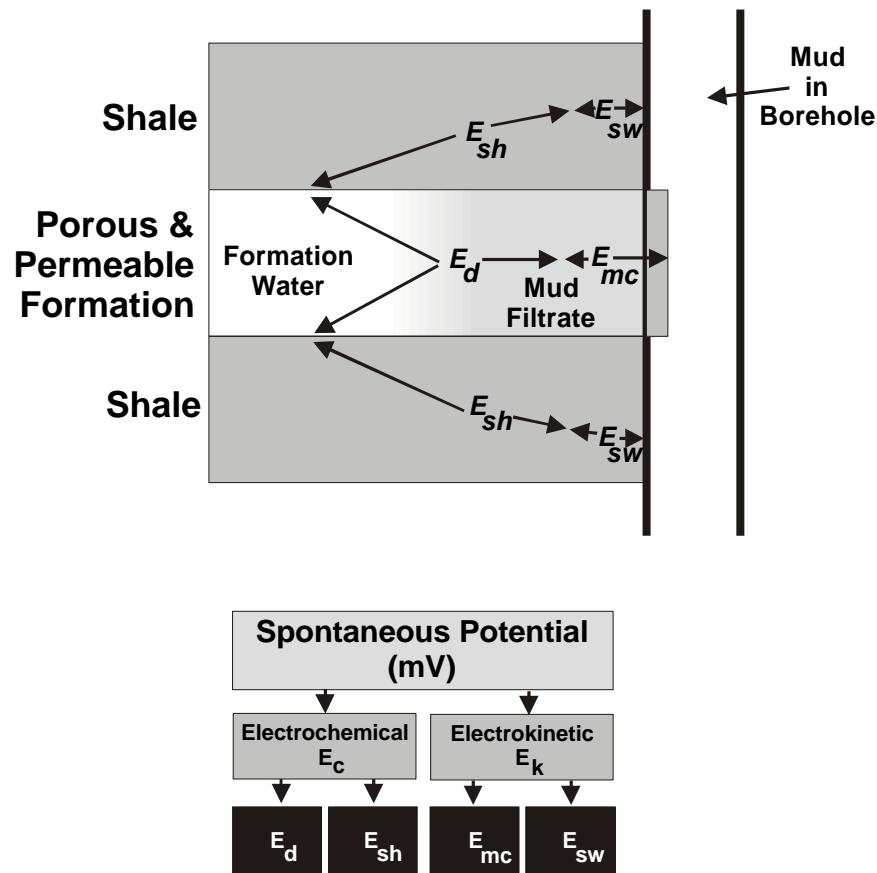


Figure 18.1 Electromotive components of the spontaneous potential.

18.2.1 Electrochemical Components

These components arise from the electrochemical interaction of ions in the mud filtrate and formation fluids.

The electrochemical contribution, itself, consists of two effects:

1. **The diffusion potential (sometimes called the liquid-junction potential).** This potential exists at the junction between the invaded and the non-invaded zone, and is the direct result of the difference in salinity between the mud filtrate and the formation fluid.

Assume that the formation fluid is more saline than the mud filtrate for a moment, and that the only dissolved ions in the system are Na^+ and Cl^- , as NaCl . The chloride ions have a higher mobility than the sodium ions. When the two fluids come into contact across the interface between the invaded and non-invaded zones, diffusion will occur. Ions from the high salinity mud filtrate will diffuse into the invaded zone to try to balance the salinities out. The chloride ions are more mobile and so more of them diffuse into the invaded zone than sodiums. The net result is a flow of negative charge into the invaded zone, which sets up a charge imbalance (potential difference) called the diffusion potential. The diffusion potential causes a current to flow (from negative to positive) from the invaded zone into the non-invaded zone. This scenario is illustrated in Fig. 18.2 for an analogue system, and is applied to the borehole environment in Fig. 18.3.

Of course, if the mud filtrate has a higher salinity than the formation fluid, the same argument applies but in reverse, and leads to a reverse diffusion potential and current flow.

The same arguments also apply for more complex fluid compositions because some ions always have a greater mobility than others.

For NaCl solutions at 25°C, the diffusion potential, E_d , is given by; $E_d = -11.81 \times \log(R_1/R_2)$, where R_1 is the resistivity of the diluter solution, and R_2 is the resistivity of the more saline solution.

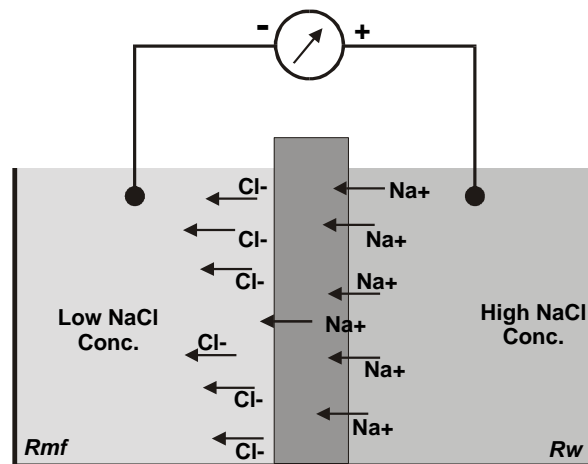


Figure 18.2 Laboratory demonstration of the diffusion potential.

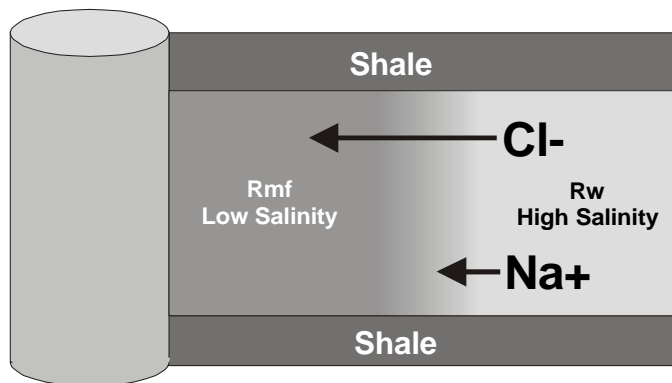


Figure 18.3 The diffusion potential in a borehole.

2. **The membrane potential (sometimes called the shale potential).** This potential exists at the junction between the non-invaded zone and the shale (or other impermeable rock) sandwiching the permeable bed. These beds are usually shale, and the argument that follows applies mainly to shales, but is also valid to a less extent for other low permeability rocks.

Shales have the property that they can preferentially retard the passage of anions. This is called *anionic permselectivity* or *electronegative permselectivity* and is a property of *membranes*. It is due to an electrical double layer that exists at the rock-fluid interface, and that has the ability to exclude anions from the smaller pores in the rock (sometimes called *anion exclusion*). The

strength of this effect depends upon the shale mineralogy, the fluid concentration and the fluid pH. Most other rocks exhibit the same behaviour but to a lower degree for geologically feasible fluid concentrations and pHs, but cationic permselectivity is possible, if rare. Most subsurface shales are such efficient anionic permselecting membranes that they repel almost all anions (say, chloride ions). This results in the shale being more positive than the non-invaded zone, and hence there is an electrical membrane potential, which causes current to flow from the invaded zone into the shale (and hence borehole). This scenario is illustrated in Fig. 18.4 for an analogue system, and is applied to the borehole environment in Fig. 18.5.

For NaCl solutions at 25°C, the membrane potential, E_m , is given by; $E_d = 59.15 \times \log(R_1/R_2)$, where R_1 is the resistivity of the diluter solution, and R_2 is the resistivity of the more saline solution.

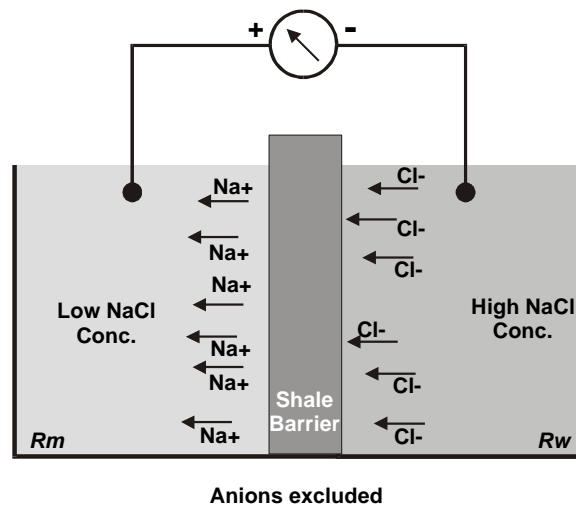


Figure 18.4 Laboratory demonstration of the membrane potential.

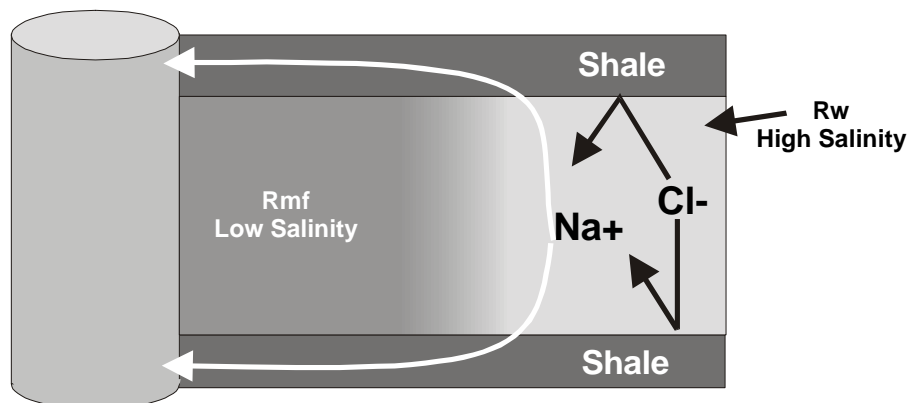


Figure 18.5 The membrane potential in a borehole.

The total electrochemical component of the SP at 25°C for NaCl solutions is therefore;

$$E_c = E_d + E_m = -11.81 \log\left(\frac{R_1}{R_2}\right) + (-) 59.15 \log\left(\frac{R_1}{R_2}\right) = -71 \log\left(\frac{R_1}{R_2}\right) = -71 \log\left(\frac{R_{mf}}{R_w}\right) \quad (18.1)$$

for our situation where the mud filtrate is lower salinity than the formation fluid.

Equation (18.1) can be generalized by the formula;

$$E_c = -K \log \left(\frac{A_w}{A_{mf}} \right) \quad (18.2)$$

where; K is a coefficient that depends upon temperature, A_w is the activity of the formation water, and A_{mf} is the activity of the mud filtrate. This relationship breaks down for very saline solutions ($R_{mf} < 0.08 \Omega m$), when corrected formation and mud filtrate resistivities must be obtained from charts. In this circumstance Eq. (18.2) is rewritten as

$$E_c = -K \log \left(\frac{A_w}{A_{mf}} \right) = -K \log \left(\frac{R_{mfe}}{R_{we}} \right) \quad (18.3)$$

where R_{mf} and R_{mfe} are corrected resistivities obtainable from charts.

18.2.2 Electrokinetic Components

These components arise from the movement of fluids containing conducting ions.

The electrokinetic contribution, itself, consists of two effects, which are usually very small and act in opposite ways such that they cancel each other out. These contributions depend upon fluid flow, and hence are larger when there is a substantial difference in pressure between the borehole and the formation. Thus, these contributions may be significant for depleted and under-pressured reservoirs where the differential pressure is high (>500 psi). The contributions also depend upon the development of an electrical double layer at mineral surfaces, which is larger for low salinity fluids. Hence, these contributions are also more important for fresh formation waters or mud filtrates.

1. **The mudcake potential.** This potential is produced by the movement of charged ions through the mudcake and invaded zone in a permeable formation. Its size depends upon the hydraulic pressure drop, and since most of this is across the low permeability mudcake, the great majority of electrokinetic potential is also generated across the mudcake, with an insignificant amount in the invaded zone.

The surface of clay minerals carry a negative charge when in contact with fluids of pH and salinities that are geologically feasible. The surface negative charge attracts cations from the fluid, which become adsorbed to the surface and are fixed. The now apparent positive surface charge is balanced out by an excess of negative ions in the fluid close to the surface. This "layer" of excess negative fluid close to the surface ensures global charge balance and is mobile. If there is no fluid flow the situation is electrically balanced. However, if there is fluid movement due to passage of mud filtrate through the mudcake the mobile layer moves setting up a *streaming potential*. Since the mudcake is anionically permselective (like shales), the potential that arises is always negative, with current flowing from the borehole into the formation through the mudcake.

2. **The shale wall potential.** This potential is the same in origin to the mudcake potential, but applies to the flow of fluids from the borehole into shale formations. It is usually very small because the flow into impermeable shales is small. It also acts to set up a current flow into the formation. We will see how this tends to cancel out the mudcake potential.

The total electrokinetic potential is $E_k = E_{mc} + E_{sw}$, and because E_{mc} and E_{sw} have the same polarity, the value of E_k is the difference between their absolute values, i.e., $E_k = |E_{mc}| + |E_{sw}|$.

18.2.3 The Combined Spontaneous Potential Effect

Figure 18.6 shows the scenario with the formation water more saline than the mud filtrate. We will combine the previously described contributions to the SP step-by-step, which can be followed in both parts of the figure.

- First assume that point A in the borehole has some unknown potential relative to the surface E_o .
- The mudcake potential E_{mc} induces a current flowing into the formation through the mudcake. Therefore at point B, the potential is $E_o + E_{mc}$ and current has flowed from A to B.
- The diffusion potential E_d across the interface between the invaded and non-invaded zones induces a current flowing from the invaded zone into the non-invaded zone. Therefore at point C, the potential is $E_o + E_{mc} + E_d$ and current has flowed from A through B to C.

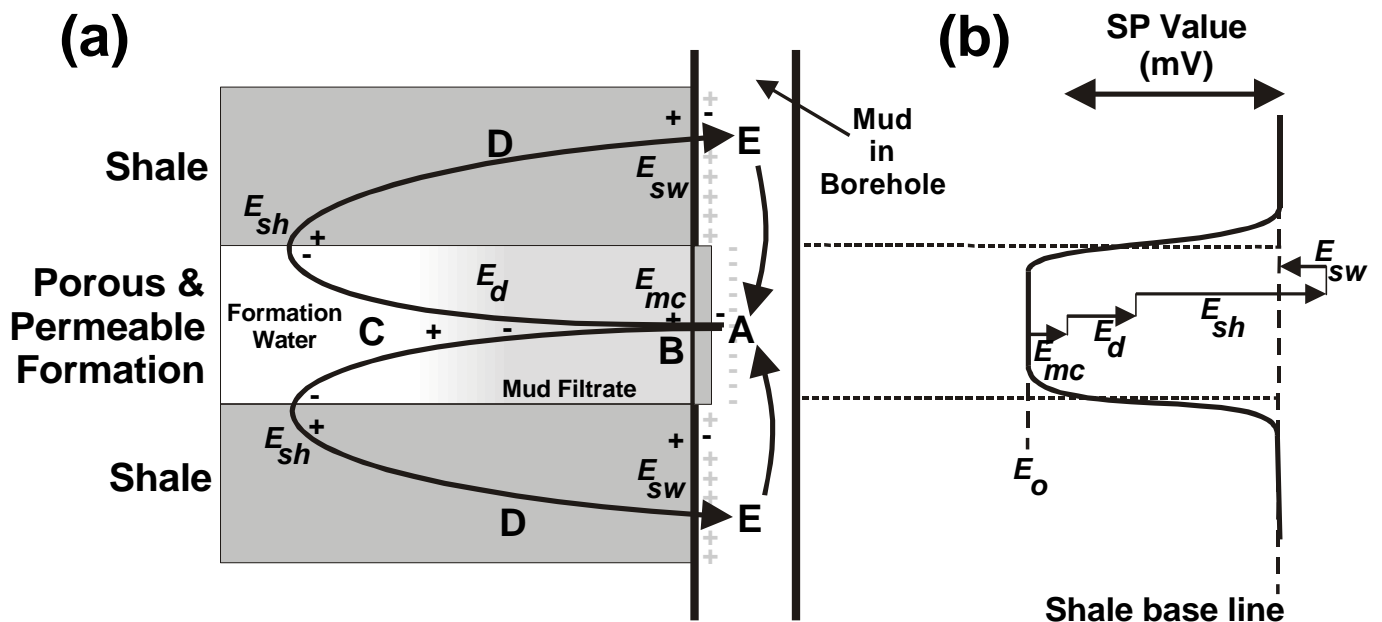


Figure 18.6 Combination of the electromotive components of the spontaneous potential for the formation water more saline than the mud filtrate.

- The membrane potential E_m across the interface between the permeable formation and the shale above it induces a current flowing into the shale from the non-invaded zone. Therefore at point D, the potential is $E_o + E_{mc} + E_d + E_m$ and current has flowed from A through B and C to D.

- The shale wall potential E_{sw} induces a current flowing into the shale from the borehole. This current counteracts the current flow set-up in the previous steps. Therefore at point E, the potential is $E_o + E_{mc} + E_d + E_m - E_{sw}$ and the current has flowed from A through B and C to D, and has been slightly reduced there by the small countercurrent due to the shale wall potential. The overall effect is for a net current to flow from A through B, C and D to E.
- The overall effect is for point E in the borehole opposite the shale wall to have a more positive potential than that at point A opposite the permeable formation. Hence there will also be a current flow in the borehole between the borehole opposite the shale beds and the borehole opposite the permeable bed to close the loop.

The arrows in Fig. 18.6a show the flow of currents and the black charge symbols indicate the local relative potential due to each of the contributions to the SP. The grey charge symbols indicate the overall potential set-up by the combined process. Figure 18.6b shows the summation of the potentials.

Note, since the value of E_o is arbitrary, there is no absolute value of spontaneous potential – what matters is the relative change in spontaneous potential.

So, is the SP opposite a permeable formation always less than that opposite the shale above (or below) it? **NO**. This is for the particular case where the formation fluid is more saline than the mud filtrate.

If the formation fluid is less saline than the mud filtrate, the opposite applies, and the SP opposite the permeable formation is **GREATER** than that opposite the shale above (or below) it. This situation is shown in Fig. 18.7, and described in the step-by-step list below.

- First assume that point A in the borehole has some unknown potential relative to the surface E_o .
- The mudcake potential E_{mc} induces a current flowing into the formation through the mudcake. Therefore at point B, the potential is $E_o + E_{mc}$ and current has flowed from A to B. This is the same as in the previous case because nothing has changed locally. The mud filtrate is still passing through the mudcake and sets up the same potential difference.
- The diffusion potential E_d across the interface between the invaded and non-invaded zones now induces a current flowing from the non-invaded zone into the invaded zone (i.e., the opposite way to the previous case). Therefore at point C, the potential is $E_o + E_{mc} - E_d$ and current has flowed from C to B. Since this current is generally larger than that flowing from A to B in the opposite direction due to the mudcake potential, the net current flow is from C through B to A.
- The membrane potential E_m across the interface between the permeable formation and the shale above it now induces a current flowing out of the shale and into the non-invaded zone (i.e., again the opposite way to the previous case). Therefore at point D, the potential is $E_o + E_{mc} - E_d - E_m$ and the net current has flowed from D through C and B to A.
- The shale wall potential E_{sw} induces a current flowing into the shale from the borehole as it did in the previous scenario. This is because the local situation has not changed – mud filtrate is still flowing into the shale and setting up the associated streaming potential. This current now does not counteract the current flow, but contributes to it. Therefore at point E, the potential is $E_o + E_{mc} - E_d - E_m - E_{sw}$ and current has flowed from E through D, C and B to A, and has been slightly reduced by the small countercurrent due to the mud cake potential between B and A.

- The overall effect is for point E in the borehole opposite the shale wall to have a more negative potential than that at point A opposite the permeable formation. Hence there will also be a current flow in the borehole between the borehole opposite the permeable bed and the borehole opposite the shale beds to close the loop.

The arrows in Fig. 18.7a show the flow of currents and the black charge symbols indicate the local relative potential due to each of the contributions to the SP. The grey charge symbols indicate the overall potential set-up by the combined process. Figure 18.7b shows the summation of the potentials.

Note, if the mud filtrate and the formation fluids have the same or similar salinities, there is no change in the SP Log between shaly and permeable formations.

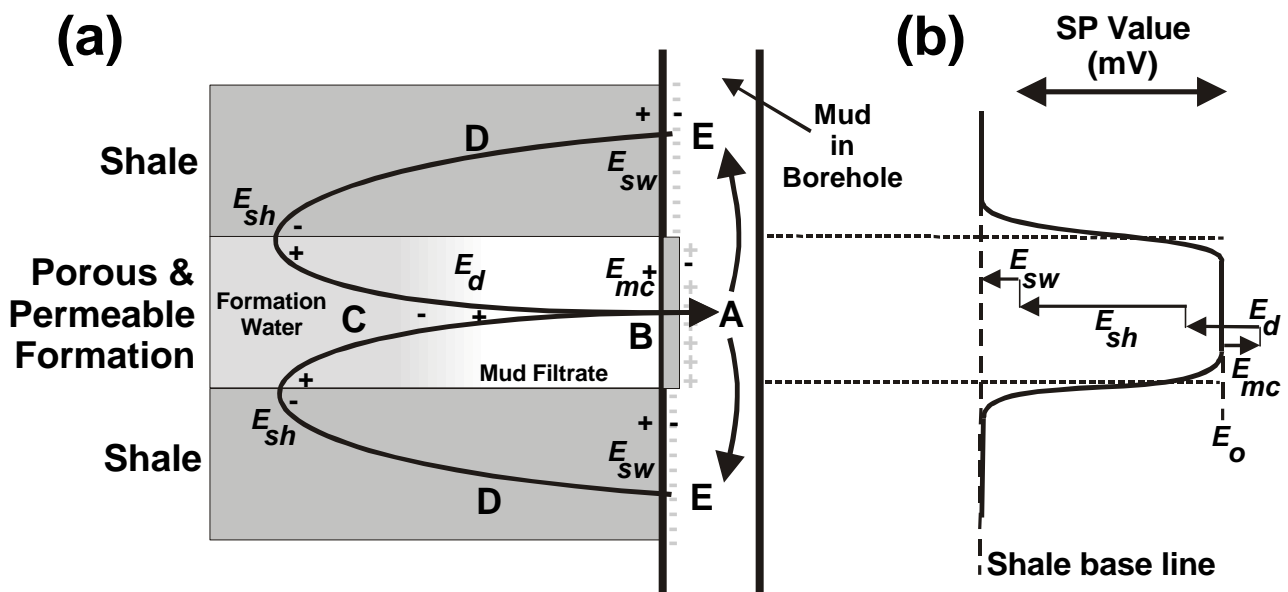


Figure 18.7 Combination of the electromotive components of the spontaneous potential for the formation water more saline than the mud filtrate.

18.3 Measurement Tools

The tool is extremely simple, consisting of a single electrode that is connected to a good surface earthing point *via* a galvanometer for the measurement of DC potential (Fig. 18.8). A small 1.5 V battery is also included commonly to ensure that the overall signal is measured on the correct scale. The simplicity of the log means that it is extremely cheap, and therefore give tremendous value for money.

Only relative changes in potential are measured because the absolute value of the SP is meaningless. Changes of the order of 50 mV are typical. For the log to be good, a good earth is necessary, which is often a metal spike driven 1 m into the ground.

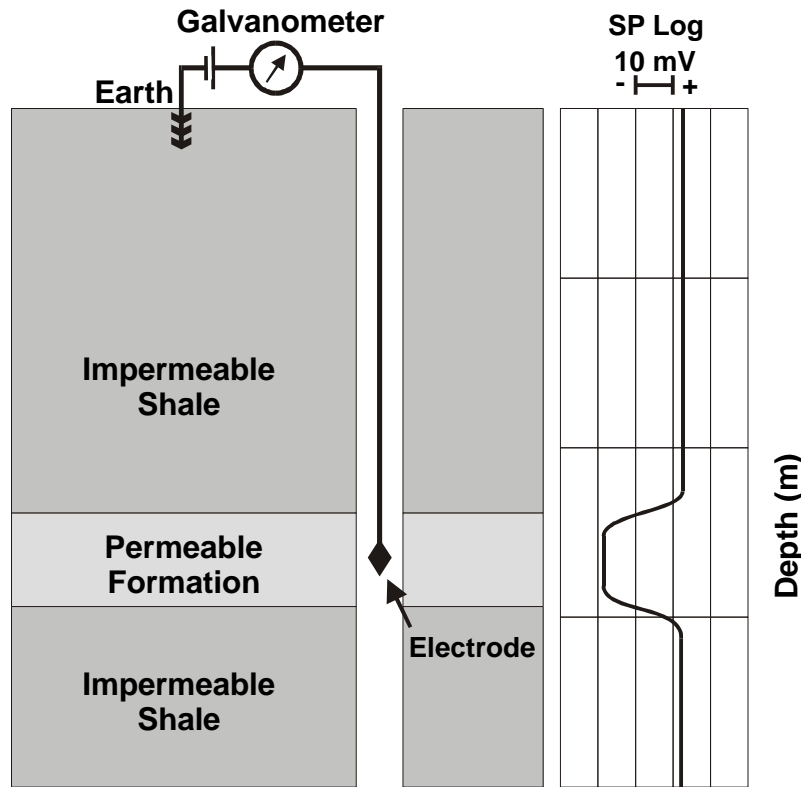


Figure 18.8 The SP tool arrangement.

The SP log is difficult to run offshore because (i) a good earth is difficult to find, and (ii) the amount of electrical noise on board a rig often causes problems for accurately measuring signals that commonly change by less than a millivolt. Sometimes the riser is used as the earth, but often the riser is in connection with the rig, and therefore a source of electrical noise. Sometimes the rig legs or an anchor chain are used, which is a big mistake because (i) the legs of oil platforms are given a specific electrical potential to help combat the effects of corrosion, and (ii) the operation of sea waves on the rig legs induces potentials in the rig legs that give rise to wavy patterns in the recorded SP log which cannot be removed.

18.4 Log Presentation

SP is shown in millivolts in Track 1, with negative deflections to the left and positive ones to the right (Fig. 18.9). Figure 18.9 shows the general presentation of the SP log, and Fig. 18.10 shows a schematic diagram of typical SP log responses.

In reading the SP log it is best to first define a *shale base line*. This is the typical SP level for shales and can be found by comparing the SP log with the GR log response. Permeable formations will then have excursions of variable intensity to the left or right of this line, depending upon the relative salinities of the formation water and the mud filtrate. It is useful to know the salinity or resistivity of the mud filtrate from the log header, if available, as this will indicate whether the formation water is likely to fall at a higher or lower salinity. For example, if the mud filtrate is known to be very fresh, the likelihood is that that the formation water will be saltier, and the SP will likely kick left.

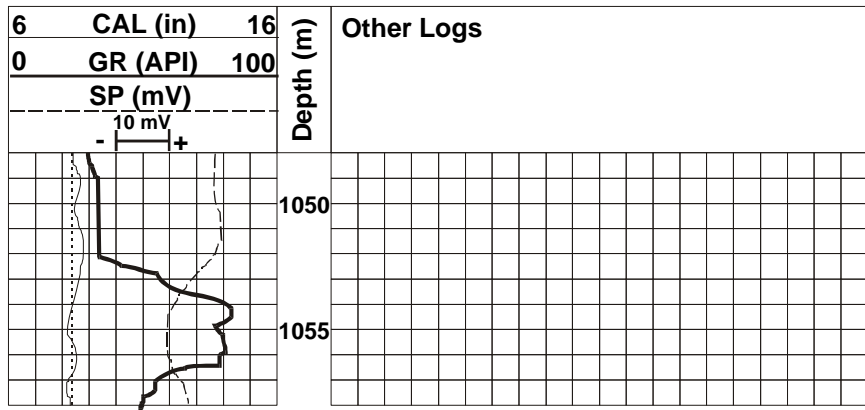


Figure 18.9 Presentation of the SP log.

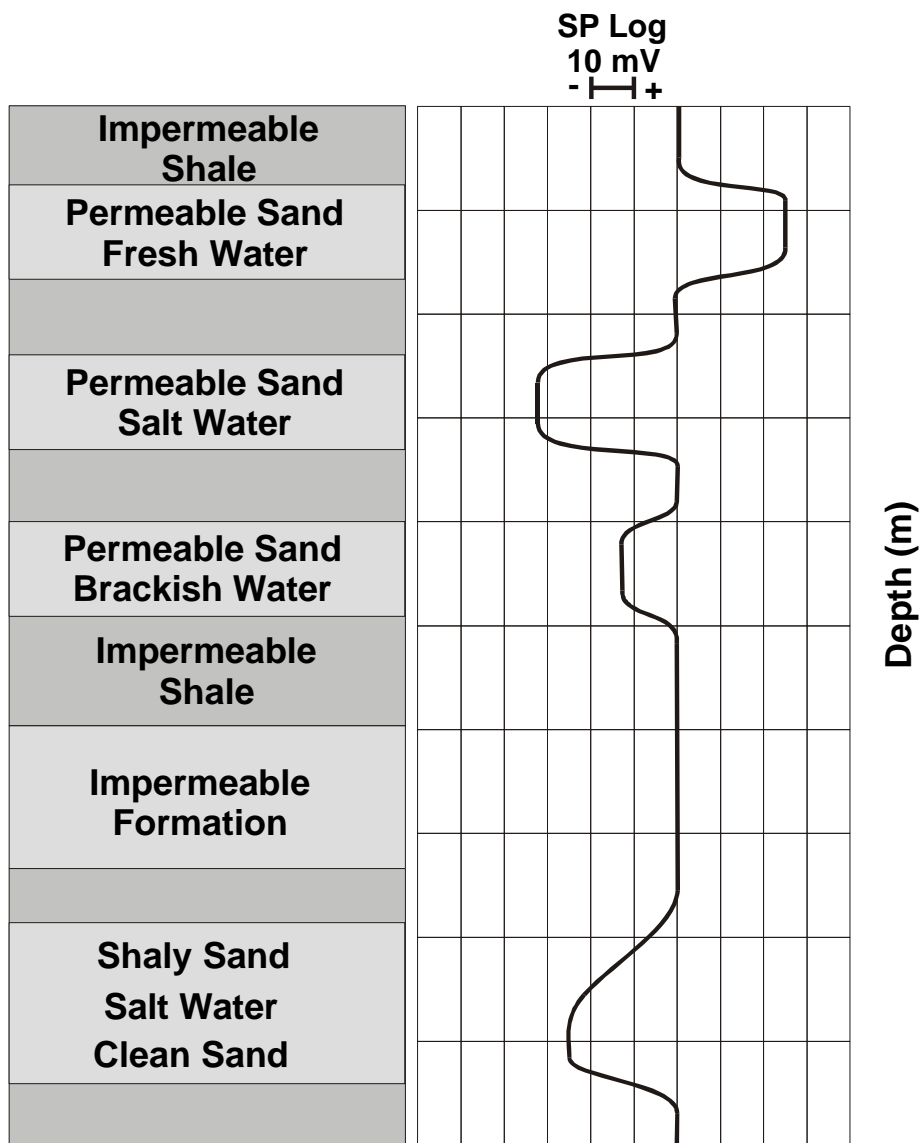


Figure 18.10 Typical responses of the SP log.

18.5 Vertical Resolution and Bed Resolution

The SP tool has a poor resolution. Although it can be used for correlation, it is best not to rely solely upon it. If it has to be used for defining a bed boundary, it is best to take the inflexion point in the SP change as the boundary depth.

Bed resolution is bad, and one would not expect it to show beds less than about 20 times the borehole diameter.

18.6 The Amplitude of the SP Deflection

Several factors govern the amplitude of the SP deflection opposite a permeable bed. This is because the size of the deflection and the change in the SP curve between beds depends upon the distribution of the current flux and the potential drops taking place in each part of the formation. The following parameters are important:

- The thickness of the permeable bed, h .
- The true resistivity of the permeable bed, R_t .
- The diameter of the invaded zone, d_i .
- The resistivity of the invaded zone, R_{XO} .
- The resistivity of the bounding formations.
- The resistivity of the mud, R_m .
- The diameter of the borehole, d_h .
- The relative salinities of the mud filtrate and the formation fluids.

The recorded SP log represents the potential drop in the borehole, only. To use the SP curve quantitatively, a value for the total potential drop around the circuit must be derived. This is called the *static spontaneous potential* (SSP). This value may be derived from correction charts. However, a direct reading of the SSP may be obtained directly from the SP log opposite *thick, clean, shale-free, 100% water-bearing* formations. The SSP is the value in millivolts of the difference between the SP log at the shale base line and that in the centre of the thick clean formation, as shown in Fig. 8.11.

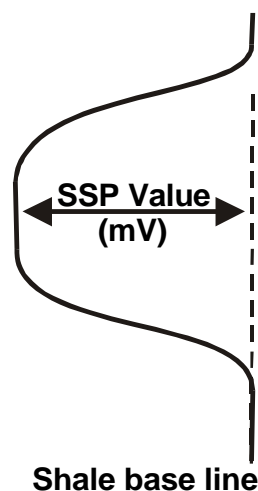


Figure 18.11 Definition of SSP.

The SP deflection obtained for homogeneous shaly formations or thin shaly beds after correction for bed thickness is called the *pseudo-static spontaneous potential* (PSP). The SSP is the value in millivolts of the difference between the SP log at the shale base line and that in the centre of the thick homogeneous shaly formation, or a thinner bed if a bed thickness correction has been carried out.

If there is a proportion of shale in the permeable bed, the SP deflection is reduced from what it would be if the bed were clean and contained the same fluids. Hydrocarbon saturation also decreases SP deflections.

The present understanding of the electrical effect of clays and shales in reservoir rocks depends largely upon the concept of *cation exchange capacity*, Q_v , which is the cation concentration in milliequivalents of exchange sites for sodium ions per cubic centimetre of pore volume. Laboratory investigations have used this concept to develop a method for calculating the formation water resistivity from SP log data in a way that takes account of the shaliness of a formation.

To use this method a value of Q_v is needed from the shale beds above or below the formation of interest, and a value of Q_v for the formation of interest. These values are normally obtained from standard chemical methods carried out in the laboratory upon cores or sidewall cores. More information concerning Q_v is given in Chapter 20.

18.7 Uses of the Spontaneous Potential Log

The main uses of this log are:

- The detection of permeable beds.
- The determination of R_w .
- The indication of the shaliness of a formation.
- Correlation.

18.7.1 Permeable Beds

The SP log is an extremely useful quick-look indicator of bed permeability. It is not quantitative, and opinions differ to the extent to which one can associate the size of the deflection with the degree of permeability. Given the large number of other parameters that might affect the SP log, I prefer to say that one should not associate very large permeabilities necessarily with large deflections and *vice versa*. However, the SP log is quite sensitive, and even a small deflection in the SP log indicates that the bed has reasonable permeability. It should be noted that some permeable beds might give no deflection, such as those where there is no difference in salinity between the formation fluids and the mud filtrate. These cases are rare however. Figure 18.12 shows an example of permeability recognition by SP log.

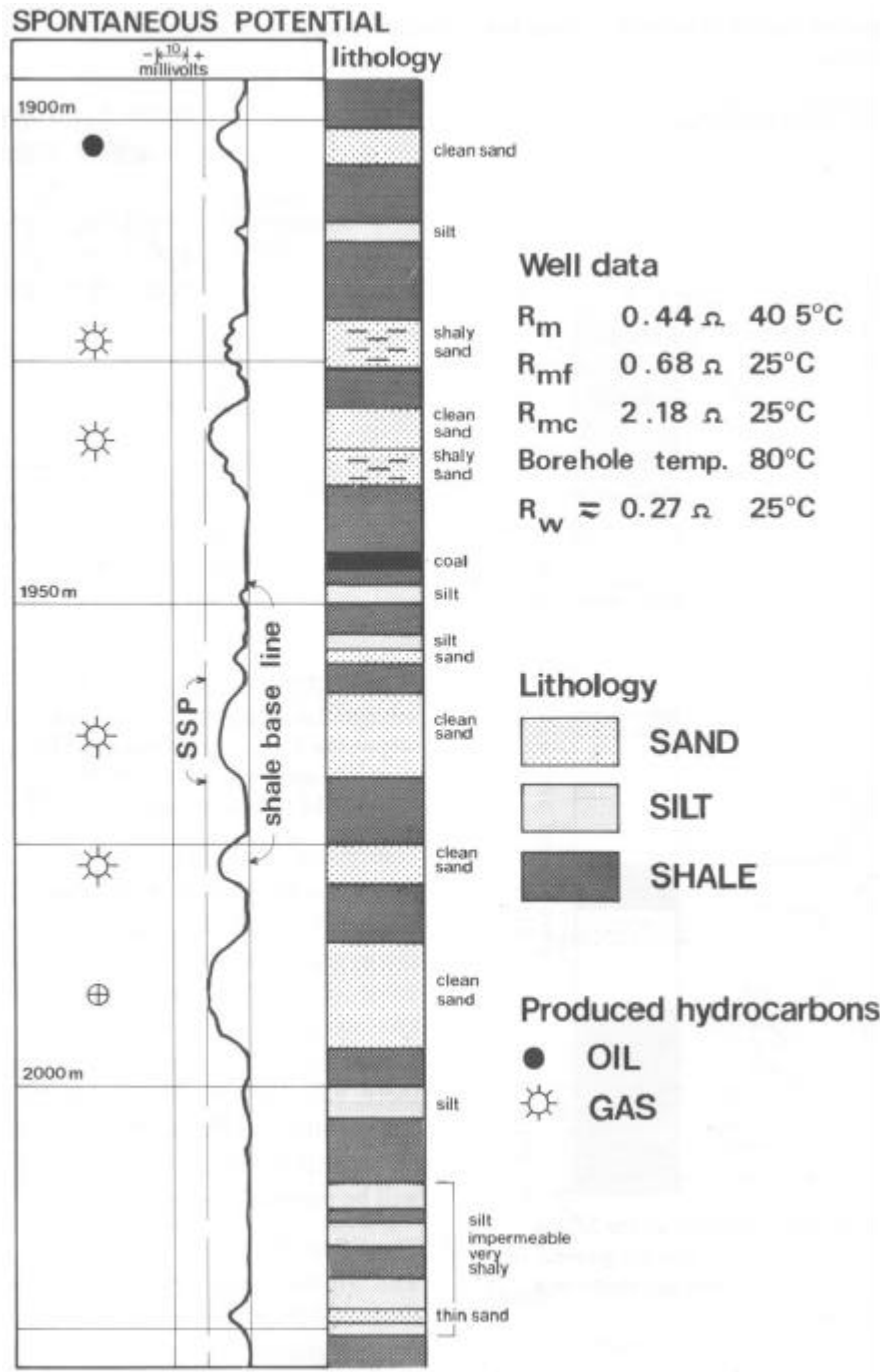


Figure 18.12 Permeability recognition by SP log.

18.7.2 Correlation and Facies

The SP log is sometimes a useful additional log to use in correlation, but is rarely used alone. If used, the wells should be close together and drilled with the same mud, and the salinities in the formations should be constant between wells.

The SP log can be used to follow facies changes. However, it has been largely replaced by the GR log, which has a higher resolution and is more reliable.

18.7.3 Mineral Recognition

Though not as good as some other logs, the SP log does react unusually to a few minerals and formations, and is therefore sometimes useful in mineral recognition. The most common occurrences are as follows, but are not reliable:

- Coals Large negative kick (or none at all!)
- Pyrite Very large negative kick.
- Rhyolite Large negative kick.
- Black shale Positive kick.

18.7.4 Calculation of R_w

This is one of two quantitative use of the SP log. However, it is extremely useful when no formation water samples or water-bearing sands are available to otherwise obtain R_w from during an analysis for OOIP.

There are three methods which will be described here.

18.7.4.1 The Quick-Look Method - Procedure

This is the quickest and most common method, and does not require knowledge of Q_v . As the method ignores the complicating effects of electrokinetic potentials and the possible presence of clay, it is to be used with caution as errors in R_w will translate into errors in OOIP that may represent tens of millions of dollars.

The following procedure is followed:

- [1] Obtain mud resistivity at formation temperature. It will either be directly available, or given at some other temperature, such as at 75°C. If the latter is the case, use a resistivity-salinity-temperature correction chart, such as that shown in Fig. 18.13). [If the chart is used, enter the chart on the left y-axis with the value of mud resistivity at the starting temperature, and scan across to the point represented by that temperature. This may lie on a curve or between curves. At this point the equivalent salinity of the mud (which is constant) may be read off the chart. Now follow the curve (or parallel to the curves if lying between them) until the new temperature is reached. The value for the mud resistivity at this temperature can then be read off the right-hand y-axis.]
- [2] Read off the difference in millivolts between the shale base line and the SP curve in the centre of the formation of interest.
- [3] Correct the SP reading from [2] for bed thickness using the correction chart shown in Fig. 18.14. Enter the bed thickness, read off the correction factor, and multiply the correction factor by the reading from [2]. This gives the SSP for the depth concerned.
- [4] Enter this value into the correction chart in Fig. 18.15 x-axis, and intersecting the relevant temperature curve, read off the value of the ratio R_{mf}/R_{we} from the y-axis.
- [5] Now go back to the initial data provided by the log header to find R_{mf} @ 75°F.

- If R_{mf} @ 75°F (24°C) > 0.1 Ωm, correct R_{mf} to the formation temperature using Fig. 18.13 as in [1], and use $R_{mfe} = 0.85 \times R_{mf}$
 - If R_{mf} @ 75°F (24°C) < 0.1 Ωm, determine the value of R_{mfe} at the formation temperature using the correction chart shown in Fig. 18.13 as in [1].
- [6] With the known value of R_{mfe} at the formation temperature, calculate the value of R_{we} at the formation temperature from the R_{mfe}/R_{we} ratio calculated in [4].
- [7] Determine the value of R_w at the formation temperature from calculated R_{we} at the formation temperature using the correction chart shown in Fig. 18.16.

This is essentially the same method as described in Rider [1996].

18.7.4.2 The Quick-Look Method - Example

INPUT DATA	
Parameter	Value
Bed of interest	Shaly sand, homogeneous, 5ft thick
Bounding beds	Thick shale
Measured SP in centre of bed of interest	-25 mV
Formation temperature	200°F
Borehole diameter	8.75 inches
Diameter of invaded zone	20 inches
Mud resistivity, R_m @ 75°F	1.80 Ωm
Mud filtrate resistivity, R_{mf} @ 75°F	1.35 Ωm
Resistivity of invaded zone, R_{XO}	4.00 Ωm
True resistivity of formation, R_t	10.0 Ωm

- [1] Mud resistivity, R_m @ 75°F = 1.80 Ωm. Therefore use Fig. 18.13 to give Mud resistivity, R_m @ 200°F = 0.68 Ωm.
- [2] Value of SP log (difference between shale base line and value in centre of formation) = -25 mV.
- [3] Find correct correction curve in available literature for your parameters. These are: (i) diameter of invasion $\approx 2 \times$ diameter of borehole, (ii) ratio of resistivity of surrounding beds (shale) to the resistivity of the mud (clay based), $R_s/R_m = 1$, (iii) borehole diameter = 8.75 inches. Then calculate the ratio of the resistivity of the invaded zone, R_{XO} (sometimes R_i) to the resistivity of the mud R_m ; $R_{XO}/R_m \equiv R_i/R_m = 4/0.68 = 6$ in this case. The chart in Fig. 18.14 is close enough to these parameters to use reliably. Enter the plot from the appropriate x -axis, intersect the curve at the appropriate curve (or interpolated curve) for $R_i/R_m = 6$, and read off the correction factor on the y -axis. Correction factor = 1.2. Multiply this by the SP value gives the bed corrected SSP for the formation: $SSP = 1.2 \times -25 \text{ mV} = -30 \text{ mV}$.

- [4] Use the correction chart in Fig. 18.15 to obtain the value of R_{mfe}/R_{we} (on the y-axis) from input of the SSP into the x-axis by intersecting the appropriate formation temperature curve. This gives $R_{mfe}/R_{we} = 2.1$.
- [5] We are given $R_{mf} @ 75^{\circ}\text{F} = 1.35 \Omega\text{m}$, which is $> 0.1 \Omega\text{m}$. So, first correct the value of $R_{mf} @ 75^{\circ}\text{F}$ to that at 200°F using Fig. 18.12. This gives $R_{mf} @ 200^{\circ}\text{F} = 0.51 \Omega\text{m}$. The value of $R_{mfe} @ 200^{\circ}\text{F}$ can be calculated by simply multiplying this value by 0.85. So, $R_{mfe} @ 200^{\circ}\text{F} = 0.85 \times 0.51 = 0.43 \Omega\text{m}$.
- [6] As $R_{mfe}/R_{we} = 2.1$ and $R_{mfe} @ 200^{\circ}\text{F} = 0.43 \Omega\text{m}$, we can find $R_{we} = 0.43/2.1 = 0.21 \Omega\text{m} @ 200^{\circ}\text{F}$.
- [7] Now this value of $R_{we} = 0.21 \Omega\text{m} @ 200^{\circ}\text{F}$ can be entered into the correction chart shown in Fig. 18.16 to read off the value of $R_w @ 200^{\circ}\text{F}$, by intersecting the appropriate temperature curve. Here $R_w = 0.31 \Omega\text{m} @ 200^{\circ}\text{F}$

This is the resistivity of the formation water in the formation at depth at the formation temperature.

18.7.4.3 The Single Chart Method - Procedure

This is a method used by Halliburton. It should be used with caution for the same reasons stated for the quick-look method. For more information see Silva *et al.* [1985]. The name indicates that a single chart is used for the main calculations, however all the input data need to be corrected for formation temperature and bed thickness. Hence, more than one chart is actually needed. The full procedure is given below.

The following procedure is followed:

- [1] Read off the difference in millivolts between the shale base line and the SP curve in the centre of the formation of interest.
- [2] Correct the SP reading from [1] for bed thickness using the correction chart shown in Fig. 18.14. Enter the bed thickness, read off the correction factor, and multiply the correction factor by the reading from [1]. This gives the SSP for the depth concerned.
- [3] Now go back to the initial data provided by the log header to find $R_{mf} @ 75^{\circ}\text{F}$.
 - If $R_{mf} @ 75^{\circ}\text{F} (24^{\circ}\text{C}) > 0.1 \Omega\text{m}$, correct R_{mf} to the formation temperature using Fig. 18.13 as in [1], and use $R_{mfe} = 0.85 \times R_{mf}$
 - If $R_{mf} @ 75^{\circ}\text{F} (24^{\circ}\text{C}) < 0.1 \Omega\text{m}$, determine the value of R_{mfe} at the formation temperature using the correction chart shown in Fig. 18.13 as in [1].
- [4] Enter the known value of R_{mfe} at the formation temperature into the x-axis of the “single chart” (Fig. 18.17) and using the appropriate formation temperature curve, read off a value for apparent SSP on the y-axis.
 - If the value of the true SSP calculated in [2] is positive, then leave the value of apparent SSP read off the chart also positive.

- If the value of the true SSP calculated in [2] is negative, then take the value of apparent SSP read off the chart as a negative number.
 - If you are working with positive SSPs, add the real and apparent SSPs to give a modified SSP.
 - If you are working with negative SSPs, subtract the real value of SSP calculated in [2] above from the apparent SSP to give the modified SSP.
- [5] Take the value of the modified SSP on the y-axis and project across horizontally to the appropriate formation temperature curve, then read off on the x-axis the value of R_w at the formation temperature.

18.7.4.4 The Single Chart Method – Example

INPUT DATA	
Parameter	Value
Bed of interest	Shaly sand, homogeneous, 5ft thick
Bounding beds	Thick shale
Measured SP in centre of bed of interest	-25 mV
Formation temperature	200°F
Borehole diameter	8.75 inches
Diameter of invaded zone	20 inches
Mud resistivity, R_m @ 75°F	1.80 Ωm
Mud filtrate resistivity, R_{mf} @ 75°F	1.35 Ωm
Resistivity of invaded zone, R_{XO}	4.00 Ωm
True resistivity of formation, R_t	10.0 Ωm

- [1] Value of SP log (difference between shale base line and value in centre of formation) = -25 mV.
- [2] Find correct correction curve in available literature for your parameters. These are: (i) diameter of invasion $\approx 2 \times$ diameter of borehole, (ii) ratio of resistivity of surrounding beds (shale) to the resistivity of the mud (clay based), $R_s/R_m = 1$, (iii) borehole diameter = 8.75 inches. Then calculate the ratio of the resistivity of the invaded zone, R_{XO} (sometimes R_i) to the resistivity of the mud R_m ; $R_{XO}/R_m \equiv R_i/R_m = 4/0.68 = 6$ in this case. The chart in Fig. 18.14 is close enough to these parameters to use reliably. Enter the plot from the appropriate x-axis, intersect the curve at the appropriate curve (or interpolated curve) for $R_i/R_m = 6$, and read off the correction factor on the y-axis. Correction factor = 1.2. Multiply this by the SP value gives the bed corrected SSP for the formation: $SSP = 1.2 \times -25 \text{ mV} = -30 \text{ mV}$.
- [3] We are given R_{mf} @ 75°F = 1.35 Ωm, which is $> 0.1 \text{ Ωm}$. So, first correct the value of R_{mf} @ 75°F to that at 200°F using Fig. 18.13. This gives R_{mf} @ 200°F = 0.51 Ωm. The value of R_{mfe} @ 200°F can be calculated by simply multiplying this value by 0.85. So, R_{mfe} @ 200°F = $0.85 \times 0.51 = 0.43 \text{ Ωm}$.

- [4] Take R_{mfe} @ 200°F = 0.43 Ω m from [3] and enter the single chart (Fig. 18.17) on the x -axis. Project vertically to the curve for formation temperature = 200°F, and then horizontally to read apparent SSP = -170 mV from the y -axis. Note that this axis looks positive, but we have taken the negative value, because the true SSP calculated in [2] is negative. If it were positive, we would have left the apparent SSP read from the graph as a positive value. Subtract the true SSP value from [2] from the apparent SSP just read off the graph, which gives a value of $(-170) - (-30) = -140$ mV. Enter this value back into the y -axis, project horizontally to the relevant temperature curve, and down to the x -axis, where the value of R_w @ 200°F can be read directly. In this case R_w @ 200°F = 0.19 Ω m.

18.7.4.5 The Smits Method – Procedure

This is a complex method that is the most accurate we have. It accounts for both electrokinetic potentials and the effect of the shaliness of the formation, but does not account for the possible presence of hydrocarbons.

- [1] Read off the difference in millivolts between the shale base line and the SP curve in the centre of the formation of interest.
- [2] Correct the SP reading from [1] for bed thickness using the correction chart shown in Fig. 18.14. Enter the bed thickness, read off the correction factor, and multiply the correction factor by the reading from [1]. This gives the SSP for the depth concerned.
- [3] Determine the mudcake potential E_{mc} for your particular mud (Fig. 18.18).
- [4] Determine the shall wall potential E_{sw} for the correct pressure differential between the borehole and the formation using $E_{sw} = \Delta P/100$, where the pressure difference is in psi.
- [5] Derive the total electrokinetic contribution to the SP using $E_k = SSP + |E_{mc}| - |E_{sw}|$ at the appropriate formation temperature.
- [6] Carry out the following temperature corrections:
 - If the temperature is measured in °F, calculate E_k @ 77°F using the following relationship, where T_F is the formation temperature in °F: $E_k @ 77°F = E_k @ T_F \times 537 / (460 + T_F)$.
 - If the temperature is measured in °C, calculate E_k @ 25°C using the following relationship, where T_F is the formation temperature in °C: $E_k @ 25°C = E_k @ T_F \times 298 / (273 + T_F)$.
- [7] Obtain the mud filtrate salinity in g/l NaCl equivalent from the mud filtrate resistivity value.
- [8] Select the correct “ Q_v – shale” chart (Figs. 18.19 and 18.20) depending upon the value for your formation in meq/cm³. Enter the mud filtrate resistivity on the x -axis, project vertically to intersect the appropriate Q_v reservoir curve, project horizontally to read the “ E ” value.
- [9] If E_k is negative, subtract the absolute value of E_k calculated in [6] from the E value from [8].
- [10] If E_k is positive, add the absolute value of E_k calculated in [6] to the E value from [8].

- [11] Enter the new value into the y-axis of the chart, projecting horizontally to the appropriate Q_v reservoir curve and down to the x-axis again. read off the formation water salinity.
- [12] Convert the formation water salinity to formation water resistivity using a chart (Fig. 18.13).

18.7.4.6 The Smits Method – Example

INPUT DATA	
Parameter	Value
Bed of interest	Shaly sand, homogeneous, 5ft thick
Bounding beds	Thick shale
Measured SP in centre of bed of interest	-25 mV
Formation temperature	200°F
Borehole diameter	8.75 inches
Diameter of invaded zone	20 inches
Mud resistivity, R_m @ 75°F	1.80 Ω m
Mud filtrate resistivity, R_{mf} @ 75°F	1.35 Ω m
Resistivity of invaded zone, R_{XO}	4.00 Ω m
True resistivity of formation, R_t	10.0 Ω m
Q_v shale	1 meq/ml
Q_v formation	0.04 meq/ml
Formation depth	5500 ft.
Mud pressure gradient	0.49 psi/ft.
Formation fluid pressure gradient	0.435 psi/ft.

- [1] Value of SP log (difference between shale base line and value in centre of formation) = -25 mV.
- [2] Find correct correction curve in available literature for your parameters. These are: (i) diameter of invasion $\approx 2 \times$ diameter of borehole, (ii) ratio of resistivity of surrounding beds (shale) to the resistivity of the mud (clay based), $R_s/R_m = 1$, (iii) borehole diameter = 8.75 inches. Then calculate the ratio of the resistivity of the invaded zone, R_{XO} (sometimes R_i) to the resistivity of the mud R_m ; $R_{XO}/R_m \equiv R_i/R_m = 4/0.68 = 6$ in this case. The chart in Fig. 18.14 is close enough to these parameters to use reliably. Enter the plot from the appropriate x-axis, intersect the curve at the appropriate curve (or interpolated curve) for $R_i/R_m = 6$, and read off the correction factor on the y-axis. Correction factor = 1.2. Multiply this by the SP value gives the bed corrected SSP for the formation: $SSP = 1.2 \times -25 \text{ mV} = -30 \text{ mV}$.
- [3] $E_{mc} = -12 \text{ mV}$ from Fig. 18.18 using the curves for untreated mud, $R_m = 1.8 \text{ } \Omega\text{m}$ and a pressure difference of 303 psi, calculated below in [4].
- [4] The pressure difference is $5500 \times (0.49 - 0.435) = 303 \text{ psi}$. So $E_{sw} = 303/100 = +3 \text{ mV}$.
- [5] $E_k @ 200^\circ\text{F} = -30 + |-12| - |+3| = -21 \text{ mV}$.
- [6] $E_k @ 77^\circ\text{F} = -21 \times 537/(460 + 200) = -17 \text{ mV}$.

- [7] As $R_{mf} = 1.35 \Omega\text{m}$ @ 77°F, use of Fig. 18.13 shows this to be for a solution of about 4 g/l NaCl equivalent.
- [8] Chose the correct Q_v – shale chart (Fig. 18.19 in this case for Q_v – shale = 1 meq/ml). Read off an $E = 57$ mV for the input of a salinity of 4 g/l NaCl equivalent and a Q_v for the formation of 0.04 meq/ml.
- [9] As E_k is negative, subtract the absolute value of E_k calculated in [6] from the E value from [8]. Hence the new $E = 57 - |-17| = 40$ mV.
- [10] Entering this into Fig. 18.19 again, and using the $Q_v = 0.04$ meq/ml curve, gives a formation water salinity of 9.5 g/l NaCl equivalent.
- [11] This corresponds to a water resistivity R_w @ 200°F = 0.23 Ωm , from using Fig. 18.13.

18.7.5 Calculation of Shale Volume

The shale volume is sometimes calculated from the SP log using the relationship:

$$V_{sh} = \left(1 - \frac{\text{PSP}}{\text{SSP}} \right) \quad (18.4)$$

PSP = SP log read in a thick homogeneous shaly sand zone, SSP = SP log read in the thick clean sand zone.

This assumes a linear mixing relationship between the SP log and shale volume, and has no theoretical basis. It probably overestimates the shale volume.

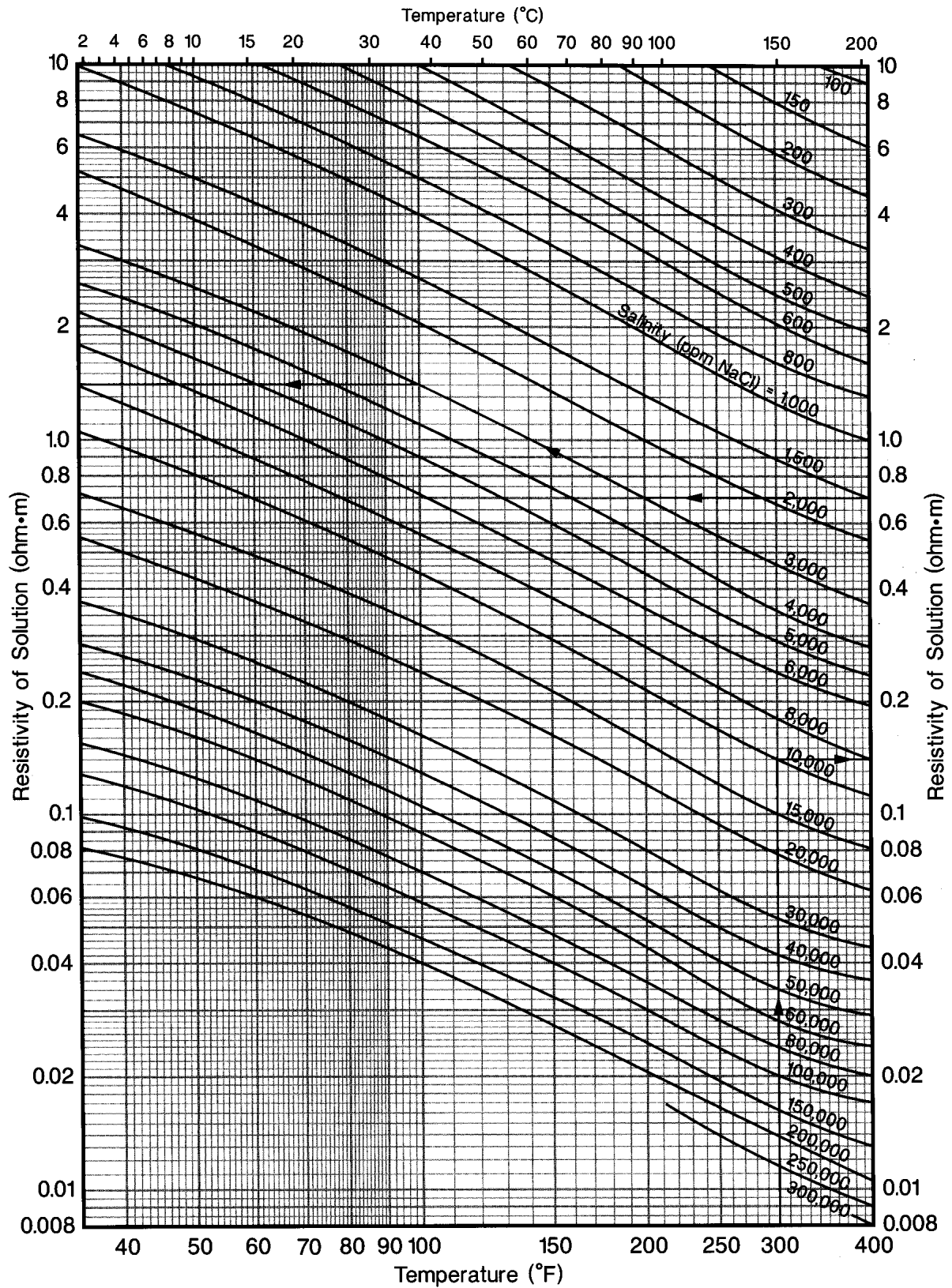


Figure 18.13 Correction chart for fluid resistivity-salinity-temperature.

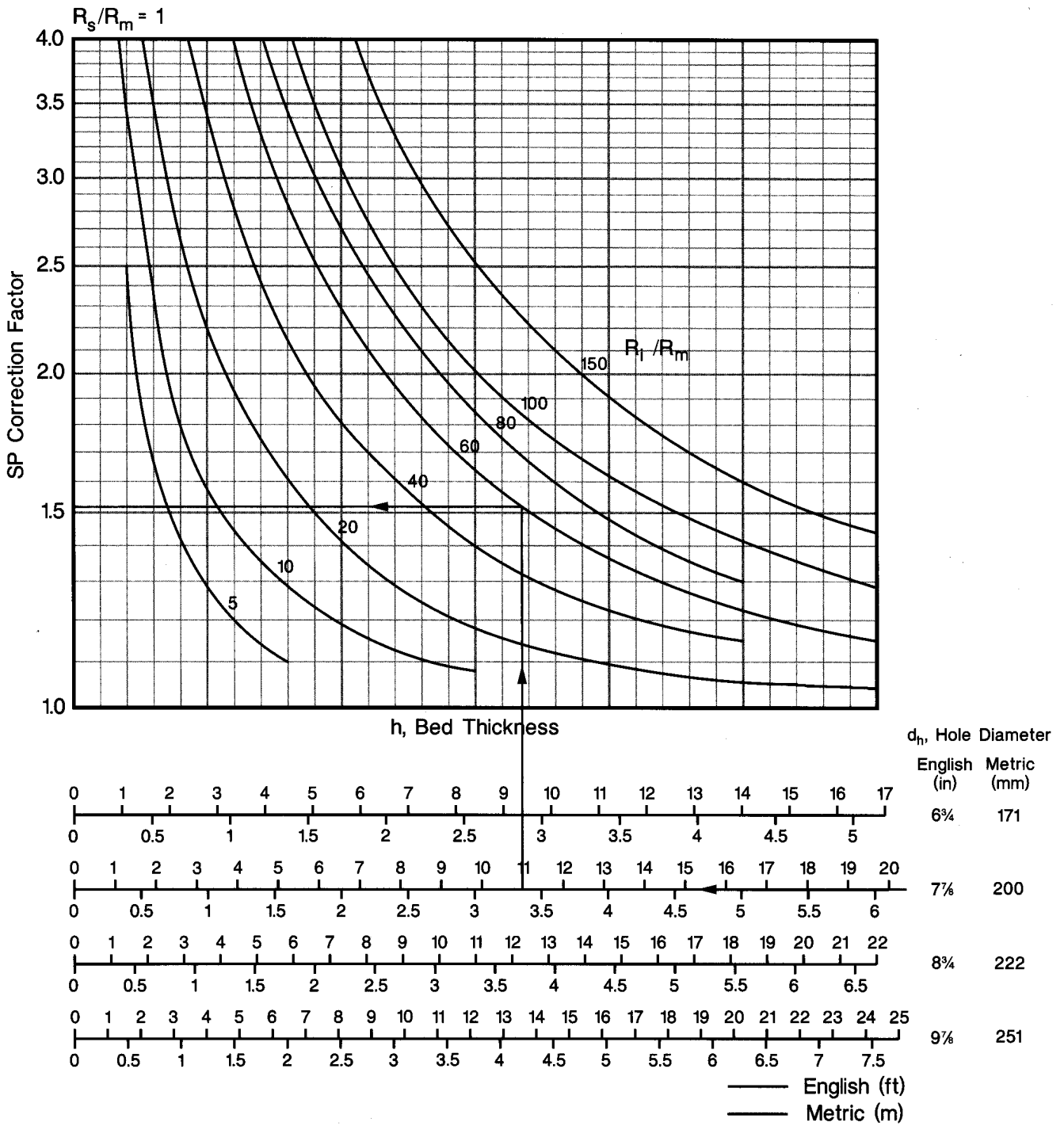


Figure 18.14 Correction chart bed thickness for diameter of invasion equals twice the borehole diameter.

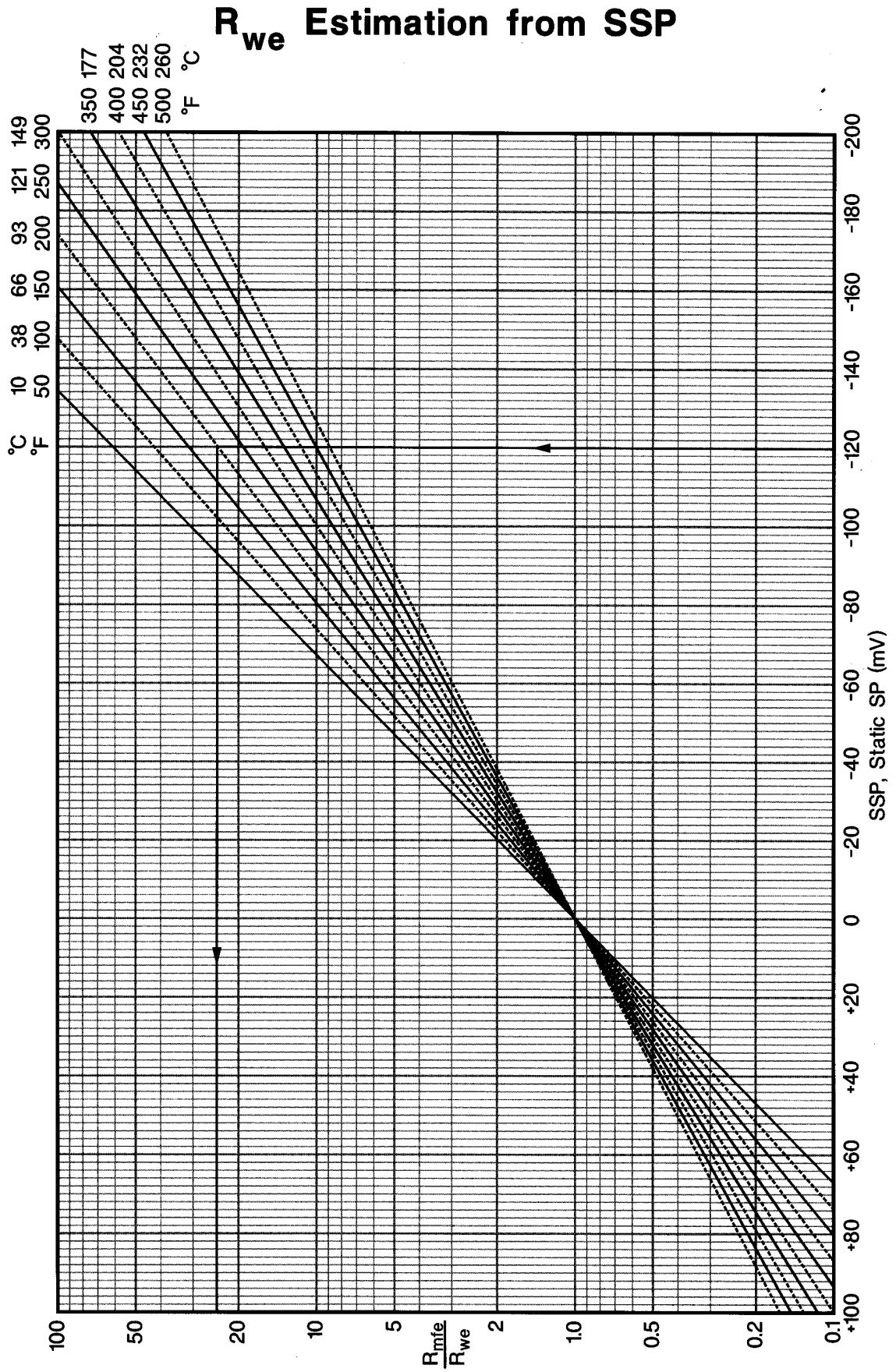


Figure 18.15 Correction chart for the R_{mfe}/R_{we} ratio from SSP for various formation temperatures.

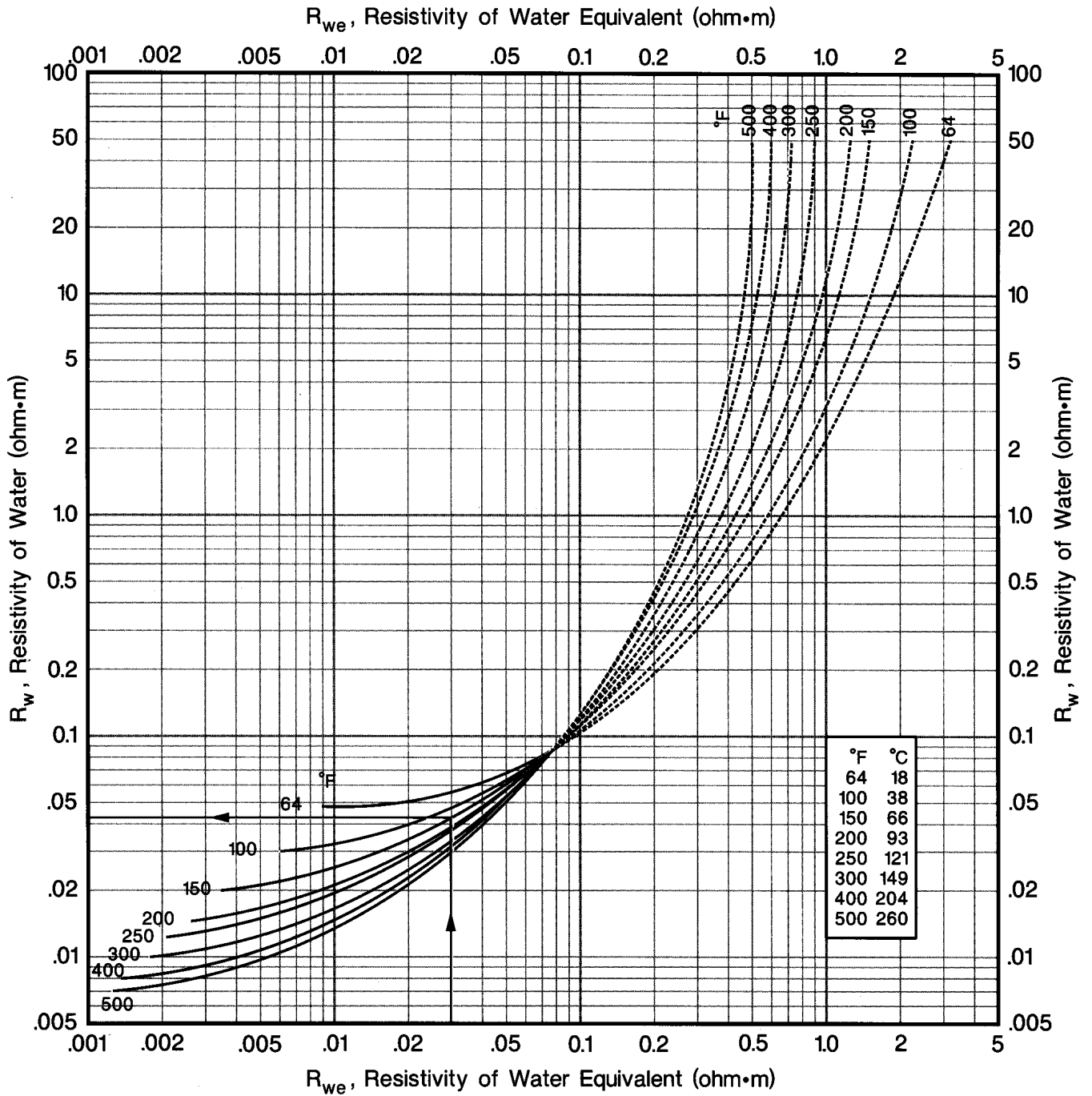


Figure 18.16 Correction chart for the R_w from R_{we} for various formation temperatures.

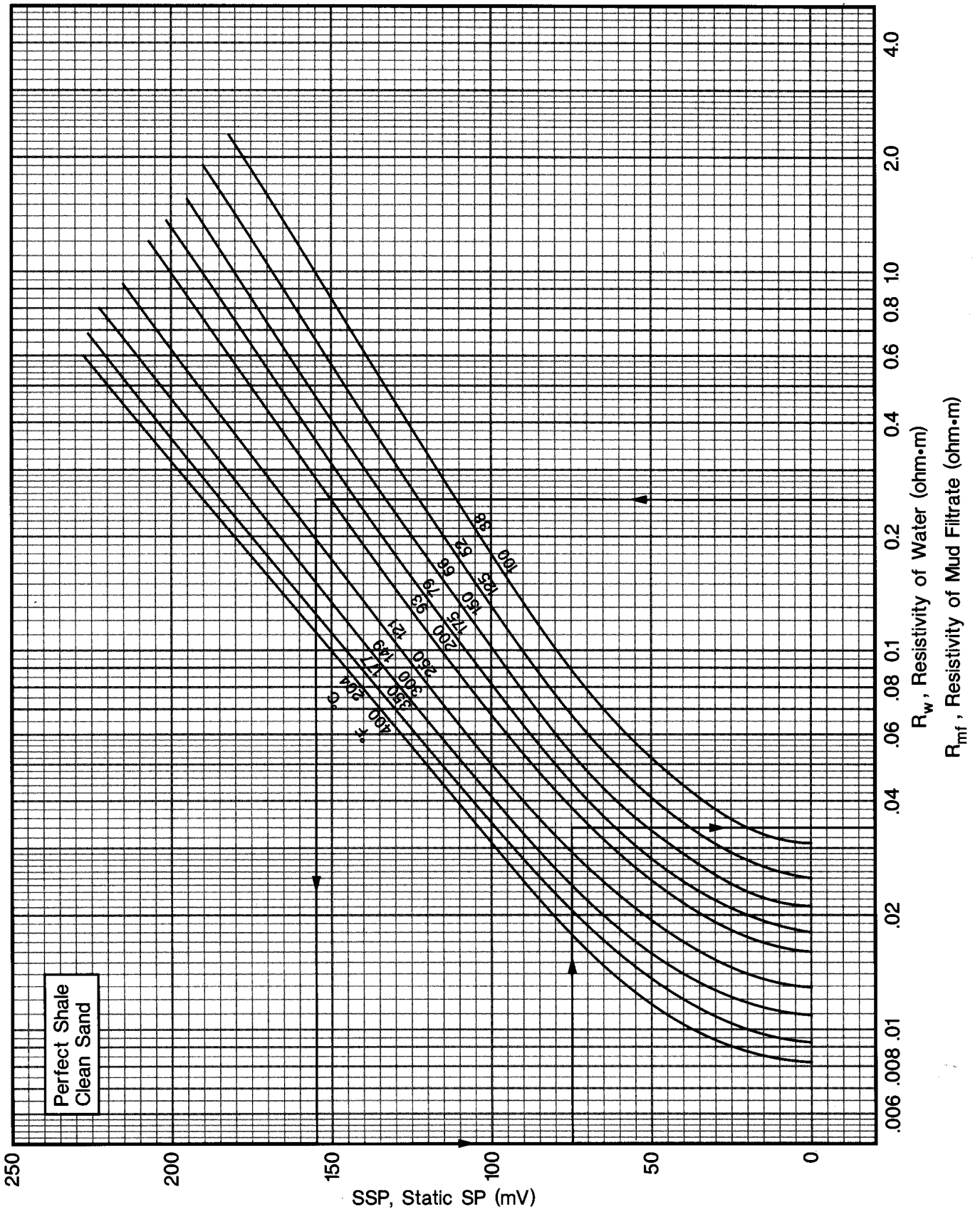


Figure 18.17 Single chart correction chart for obtaining water resistivity from SSP for various formation temperatures.

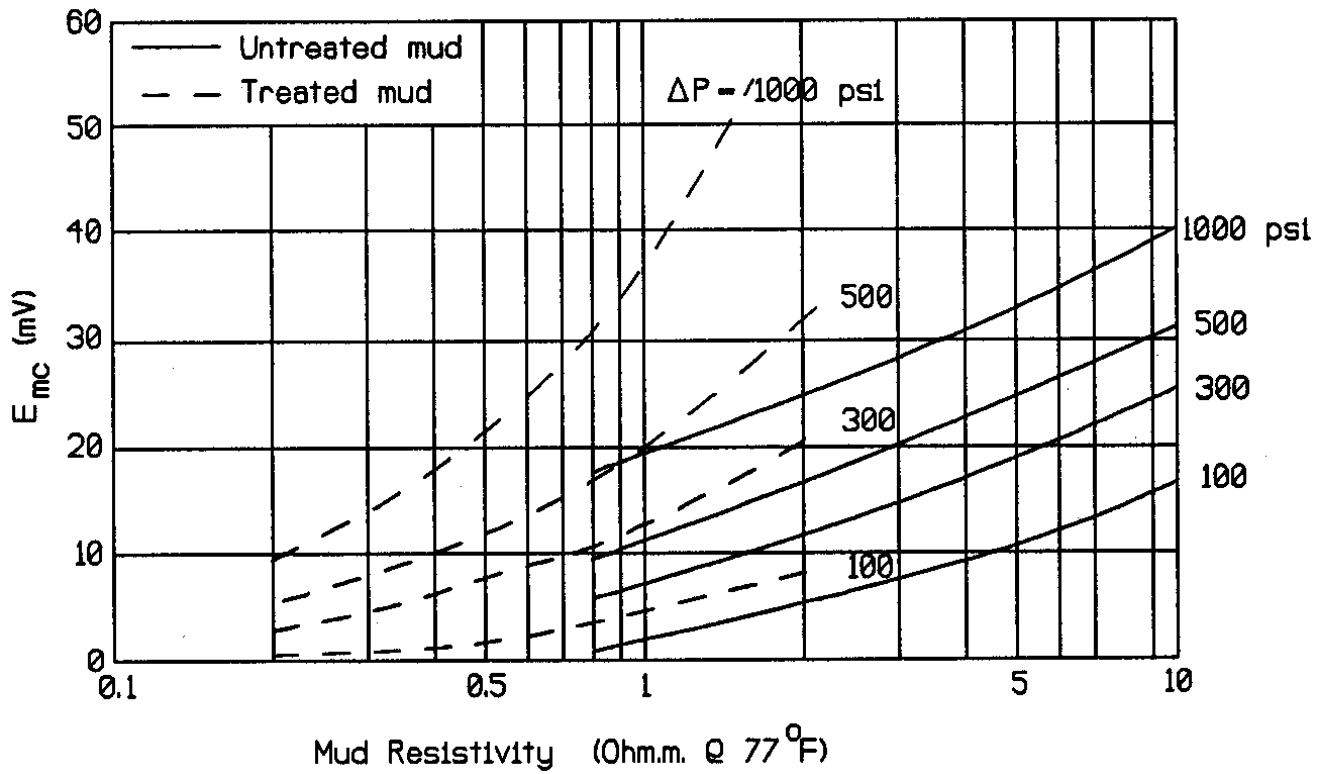


Figure 18.18 The electrokinetic mudcake potential for treated and untreated drilling muds as a function of mud resistivity for various fluid pressure differentials (mud pressure minus formation fluid pressure). This data has been derived from laboratory measurements.

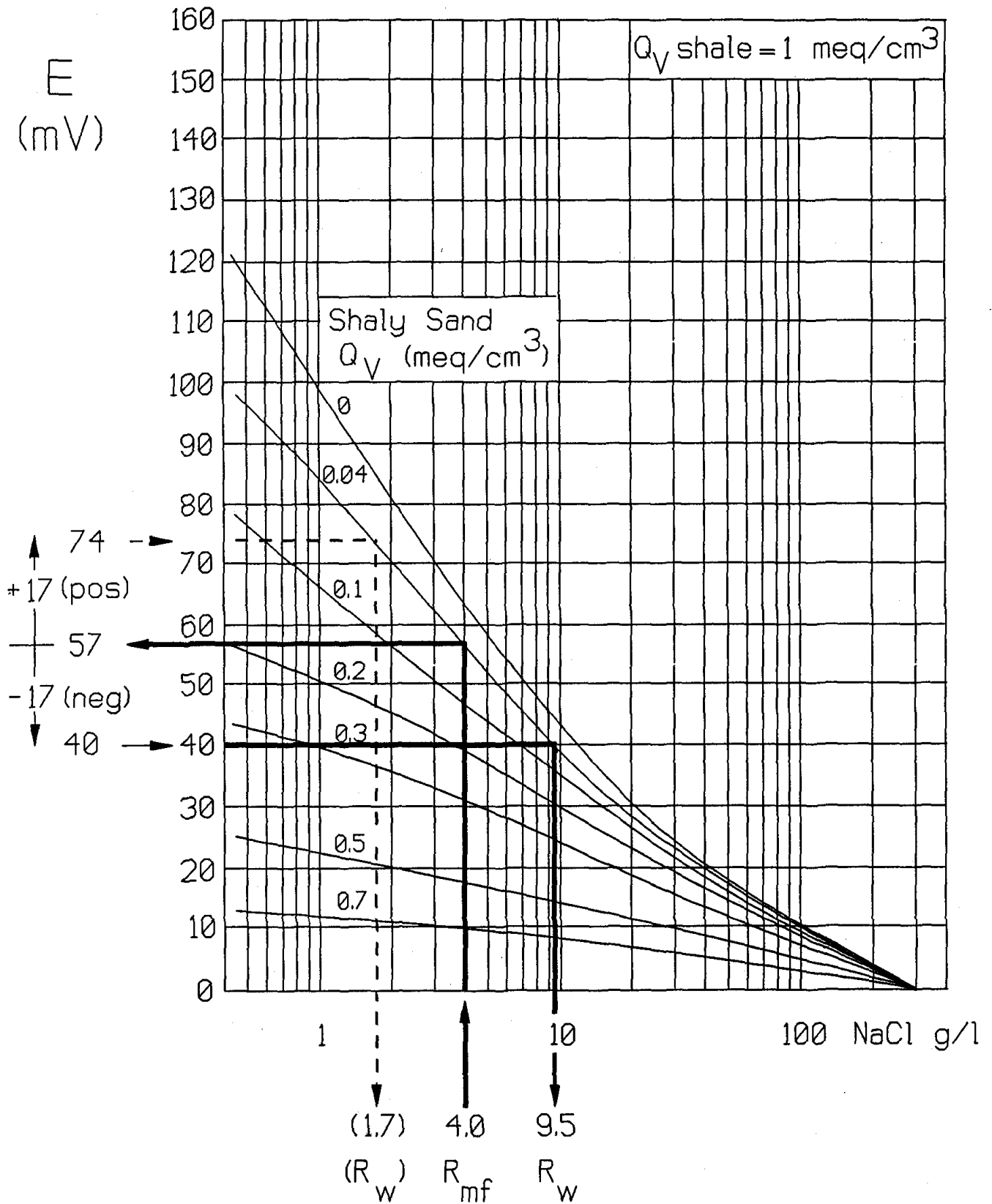


Figure 18.19 Smit method correction chart for obtaining water resistivity from SSP for various formation temperatures. This chart is for a shale $Q_v = 1 \text{ meq/cm}^3$, and plots electrochemical potential against equivalent NaCl concentration in g/l.

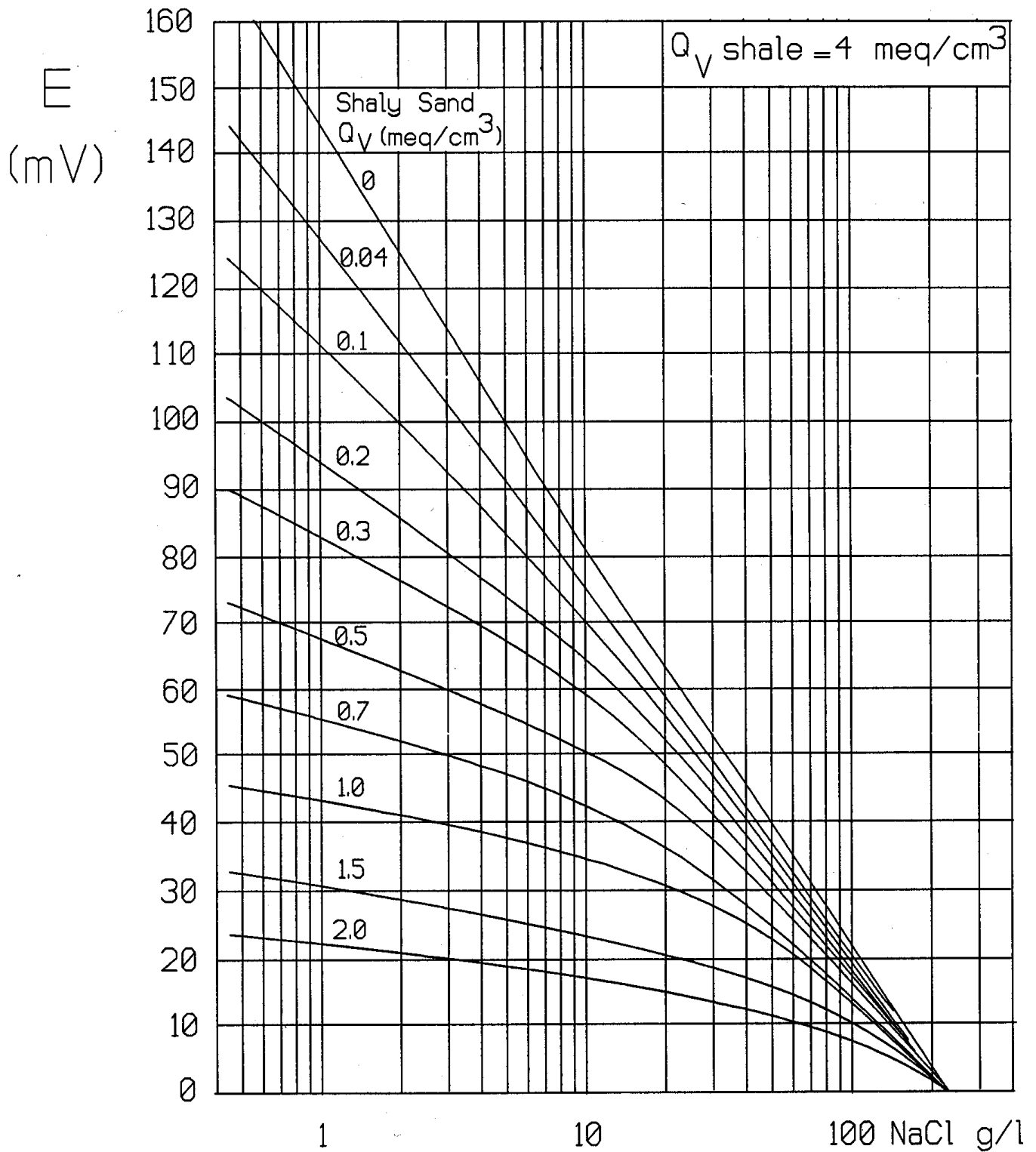


Figure 18.19 Smit method correction chart for obtaining water resistivity from SSP for various formation temperatures. This chart is for a shale $Q_v = 4 \text{ meq/cm}^3$, and plots electrochemical potential against equivalent NaCl concentration in g/l.