3

Spontaneous Potential and Natural Gamma Ray Logs

The spontaneous potential (SP) curve and the natural gamma ray (GR) log are recordings of naturally occurring physical phenomena in in-situ rocks. The SP curve records the electrical potential (voltage) produced by the interaction of formation connate water, conductive drilling fluid, and certain ion-selective rocks (shale). The GR log indicates the natural radioactivity of the formations. Nearly all rocks exhibit some natural radioactivity and the amount depends on the concentration of potassium, thorium, and uranium. There are two types of GR logs. One, the standard GR log, measures only the total radioactivity. The other, the NGS* natural gamma ray spectrometry log, measures the total radioactivity and the concentrations of potassium, thorium, and uranium producing the radioactivity.

Both the SP curve and GR log are generally recorded in Track 1 (left track) of the log. They are usually recorded in conjunction with some other log — such as the resistivity or porosity log. Indeed, nearly every log now includes a recording of the SP curve and/or GR log.

Although relatively simple in concept, the SP curve and GR logs are quite useful and informative. Among their uses are the following:

- Differentiate potentially porous and permeable reservoir rocks (sandstone, limestone, dolomite) from nonpermeable clays and shales.
- Define bed boundaries and permit correlation of beds.
- Give a qualitative indication of bed shaliness.
- Aid in lithology (mineral) identification.
- In the case of the SP curve, permit the determination of formation water resistivity, R_w.
- In the case of the GR and NGS logs, detect and evaluate deposits of radioactive minerals.
- In the case of the NGS log, define the concentrations of potassium, thorium, and uranium.

THE SP CURVE

The SP curve is a recording versus depth of the difference between the electrical potential of a movable electrode in the borehole and the electrical potential of a fixed surface electrode.

Opposite shales the SP curve usually defines a more-or-less straight line on the log, called the shale baseline. Opposite permeable formations, the curve shows excursions from the shale baseline; in thick beds, these excursions (deflections) tend to reach an essentially constant deflection defining a sand line. The deflection may be either to the left (negative) or to the right (positive), depending primarily on the relative salinities of the formation water and of the mud filtrate. If the formation water salinity is greater than the mud filtrate salinity, the deflection is to the left. For the reversed salinity contrast, the deflection is to the right.

The position of the shale baseline on the log has no useful meaning for interpretation purposes. The SP sensitivity scale is chosen and the shale baseline position is set by the engineer running the log so that the curve deflections remain in the SP track. The SP log is measured in millivolts (mV).

An SP curve cannot be recorded in holes filled with nonconductive muds because such muds do not provide electrical continuity between the SP electrode and the formation. Furthermore, if the resistivities of the mud filtrate and formation water are about equal, the SP deflections will be small and the curve will be rather featureless.

Origin of the SP

The deflections on the SP curve result from electric currents flowing in the mud in the borehole. These SP currents are caused by electromotive forces in the formations, which are of electrochemical and electrokinetic origins.

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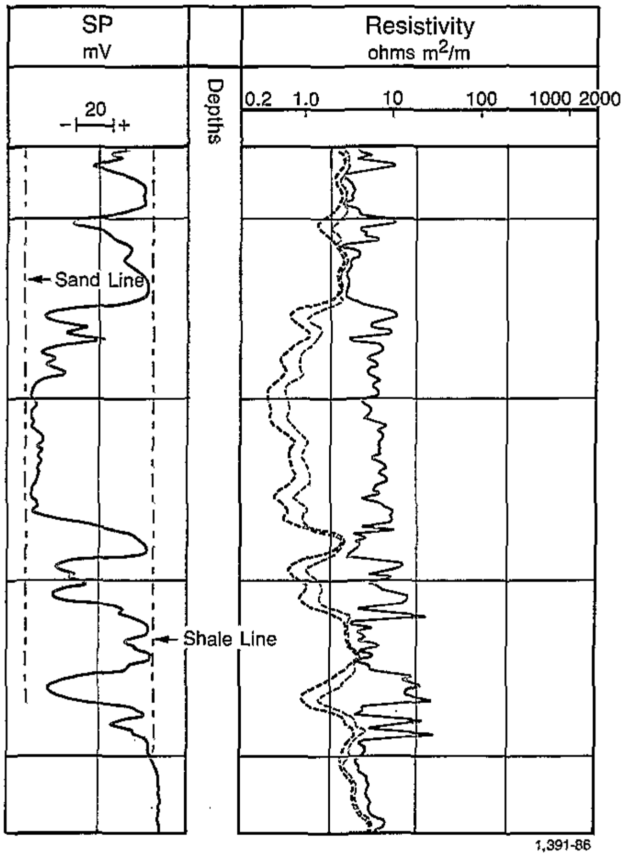

Fig. 3-1—Example of SP log in a sand-shale series.

Electrochemical Component of the SP

Consider a permeable formation with thick shale beds above and below; assume, too, that the two electrolytes present, mud filtrate and interstitial formation water, contain sodium chloride (NaCl) only. Because of the layered clay structure and the charges on the layers, shales are permeable to the Na^+ cations but impervious to the Cl^- anions. Only the Na^+ cations (positive charges) are able to move through the shale from the more concentrated to the less concentrated NaCl solution. This movement of charged ions is an electric current, and the force causing them to move constitutes a potential across the shale.

The curved arrow in the upper half of Fig. 3-2 shows the direction of current flow corresponding to the passage of Na^+ ions through the adjacent shale from the more saline formation water in the bed to the less saline mud.

Since shales pass only the cations, shales resemble ion-selective membranes, and the potential across the shale is therefore called the membrane potential.

Another component of the electrochemical potential is produced at the edge of the invaded zone, where the mud filtrate and formation water are in direct contact. Here Na^+ and Cl^- ions can diffuse (move) from either solution to the other. Since Cl^- ions have a greater mobility than Na^+ ions, the net result of this ion diffusion is a flow of negative charges (Cl^- ions) from the more concentrated to the less concentrated solution. This is equivalent to a conventional current flow in the opposite direction, indicated by the straight Arrow A in the upper half of Fig. 3-2. The current flowing across the junction between solutions of different salinity is produced by an electromagnetic force (emf) called liquid-junction potential. The magnitude of the liquid-junction potential is only about one-fifth the membrane potential.

If the permeable formation is not shaly, the total electrochemical emf, E_c, corresponding to these two phenomena, is equal to

$$E_c = -K \log \frac{a_w}{a_{mf}}, \qquad \text{(Eq. 3-1)}$$

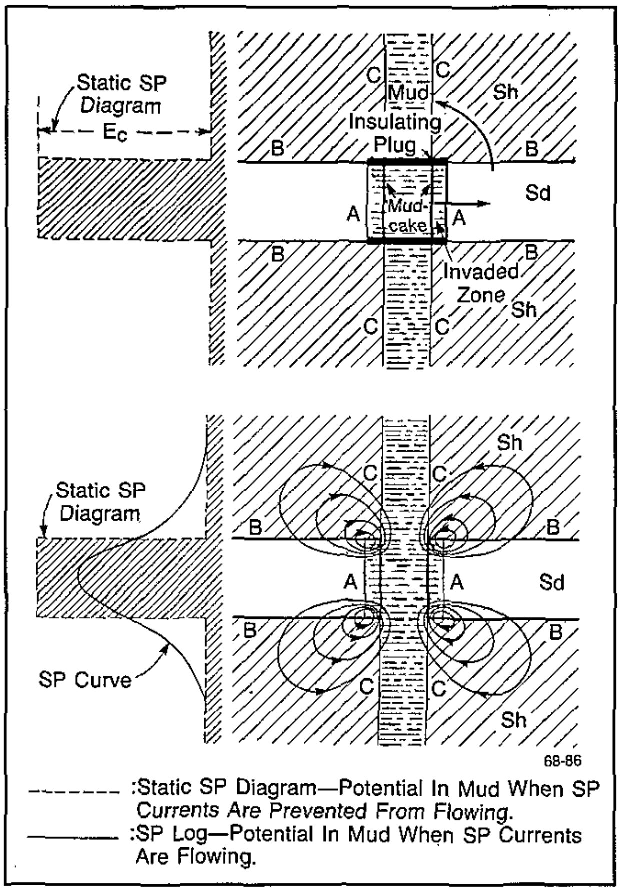

Fig. 3-2—Schematic representation of potential and current distribution in and around a permeable bed.

where a_w and a_{mf} are the chemical activities of the two solutions (formation water and mud filtrate) at formation temperature; K is a coefficient proportional to the absolute temperature, and, for NaCl formation water and mud filtrate, is equal to 71 at 25° C (77° F). The chemical activity of a solution is roughly proportional to its salt content (i.e., to its conductivity). If the solutions contain substantial amounts of salts other than NaCl, the value of K at 77° F may differ from 71.

If the permeable formation contains some shale or dispersed clay, the total electrochemical emf and, hence, the SP deflections will be reduced since the clay in the permeable formation produces an electrochemical membrane of opposite polarity to that of the adjacent shale bed.

Electrokinetic Component of the SP

An electrokinetic potential, E_k (also known as streaming potential or electrofiltration potential), is produced when an electrolyte flows through a permeable, nonmetallic, porous medium. The magnitude of the electrokinetic potential is determined by several factors, among which are the differential pressure producing the flow and the resistivity of the electrolyte.

In the borehole, an electrokinetic emf, E_{kmc}, is produced by the flow of mud filtrate through the mudcake deposited on the borehole wall opposite permeable formations. In practice, little or no electrokinetic emf is actually generated across the permeable formation itself. This is because practically all the differential pressure between the borehole and undisturbed virgin formation is expended across the less permeable mudcake. Any remaining differential pressure across the formation is normally not great enough to produce any appreciable electrokinetic emf.

An electrokinetic emf, E_{ksh}, may, however, be produced across the shale, since it may have sufficient permeability to permit a tiny amount of filtration flow from the mud.

Each of these electrokinetic emf's contributes to a more negative SP reading opposite the permeable bed and opposite the shale, respectively. The net contribution to the SP deflection (measured from the shale line) is, therefore, the difference between the contributions of the mudcake and the shale electrokinetic effects. In practice, these electrokinetic emf's are similar in magnitude, and the net electrokinetic contribution to the SP deflection is therefore usually small, normally regarded as negligible. This is particularly true if the formation water is rather saline (resistivity less than 0.1 ohm-m) and the differential pressure has a normal value of only a few hundred pounds per square inch (psi) or less.

It is, however, possible for electrokinetic effects to become more important in cases of unusually large pressure differentials (e.g., in depleted formations of low pressure or when very heavy drilling muds are used). In these cases, the electrokinetic emf's may be quite significant and the mudcake and shale electrokinetic effects may not cancel each other.

Important electrokinetic effects may also be seen in very low-permeability formations (less than a few millidarcies) in which an appreciable part of the pressure differential is applied across the formation itself. If formation permeability is so low that little or no mudcake is formed, most of the pressure differential between the formation pore pressure and hydrostatic head of the mud column is applied to the formation. If the formation water is brackish, if the mud is resistive, and if the formation is clean and has some porosity, the electrokinetic effect may be quite large, sometimes exceedng −200 mV.

These infrequent effects are difficult to detect, but conditions favoring their existence should alert us to the possibility of a large electrokinetic potential. When a significant electrokinetic potential exists the SP deflection cannot be used to calculate a reliable value of formation water resistivity, R_w.

SP Versus Permeability and Porosity

The movement of ions, which causes the SP phenomenon, is possible only in formations having a certain minimum permeability. (A small fraction of a millidarcy is sufficient.) There is no direct relationship between the value of permeability and the magnitude of the SP deflection, nor does the SP deflection have any direct relation to the porosity.

Static SP

The lower portion of Fig. 3-2 depicts how the SP currents flow in the borehole and formations. The current directions shown correspond to the more usual case where the salinity of the formation water is greater than that of the mud filtrate. Thus, the potential observed opposite the permeable sandstone bed is negative with respect to the potential opposite the shale. This negative variation corresponds to an SP curve deflection toward the left on the SP log (also illustrated on the figure).

If the salinity of the mud filtrate is greater than that of the formation water, the currents flow in the opposite direction. In that case, the SP deflection opposite a permeable bed is positive (to the right). Positive deflections are usually observed in freshwater-bearing formations. If the salinities of the mud filtrate and formation water are similar, there is no SP potential or current flow and, hence, no SP deflection opposite a permeable bed.

As shown on Fig. 3-2, the SP currents flow through four different media: the borehole, the invaded zone, the noninvaded part of the permeable formation, and the surrounding shales. In each medium, the potential along a line of current flow drops in proportion to the resistance encountered; the total potential drop along a line of current flow is equal to the total emf.

The deflections on the SP curve are, however, a measurement of only the potential drop in the borehole resulting from the SP currents. This potential drop represents only a fraction (although usually the major fraction) of the total emf because there are also potential drops in the formation. If the currents could be prevented from flowing by means such as the insulating plugs schematically indicated in the upper part of Fig. 3-2, the potential differences observed in the mud would equal the total emf. The SP curve recorded in such an idealized condition is called the static SP curve. The static SP, or SSP, is the SP deflection opposite a thick, clean formation. The deflection is measured from the shale baseline and its magnitude, from Eq. 3-2, is

$$\mathrm{SSP} = -K \log \frac{a_w}{a_{mf}} . \qquad \text{(Eq. 3-2)}$$

Fortunately, because the borehole presents a much smaller cross-sectional area to current flow relative to the formations, most of the SP voltage drop does occur in the borehole provided formation resistivities are low to moderate and beds are moderately thick. Therefore, the recorded SP deflection does approach the static SP value in most thick permeable beds.

Determination of SSP

The value of SSP can be determined directly from the SP curve if, in a given horizon, there are thick, clean, water-bearing beds. A line is drawn through the SP (negative) maxima opposite the thick permeable beds, and another line (shale baseline) is drawn through the SP opposite the intervening shale beds (see Fig. 3-1). The difference, in millivolts, between these lines is the SSP; any SP anomalies should be discounted.

Many times, it is difficult to find thick, clean, permeable invaded beds in the zone under study. When beds are thin but still clean, the SP must be corrected to find a value of SSP. Corrections for the effect of bed thickness and/or invasion are given in Charts SP-3 or SP-4. Additional information on SP bed thickness corrections is provided in Refs. 14 and 15.

Shape of the SP Curve

The slope of the SP curve at any level is proportional to the intensity of the SP currents in the borehole mud at that level. As illustrated on Fig. 3-2, the intensity of the currents in the mud is maximum at the boundaries of the permeable formation, and, accordingly, the slope of the curve is maximum (and there is an inflection point) at these boundaries.

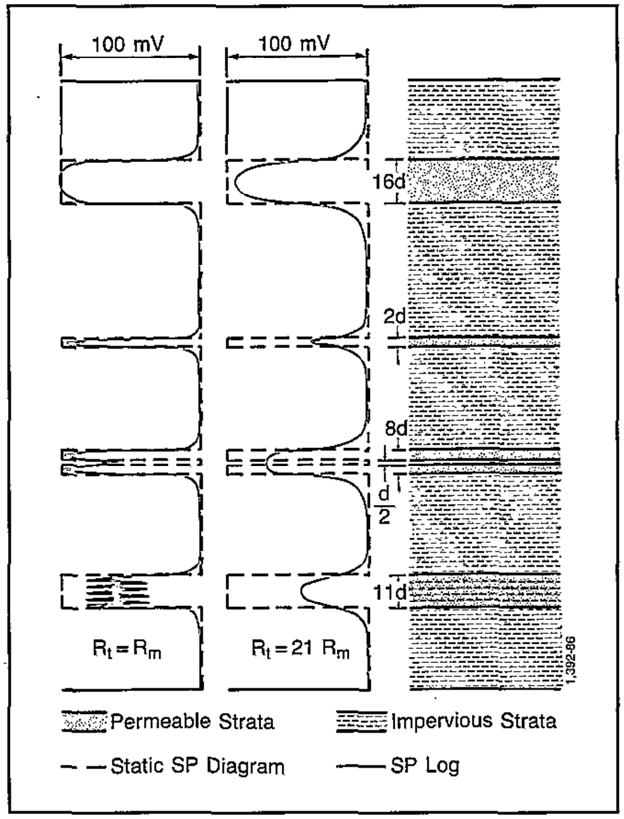

Fig. 3-3—SP curve in beds of different thickness for $R_t = R_m$ (left) and $R_t = 21\ R_m$ (center).

The shape of the SP curve and the amplitude of the deflection opposite a permeable bed depend on several factors. The factors, which affect the distribution of the SP current lines and the potential drops taking place in each of the media through which the SP current flows, are the following:

- Thickness, h, and true resistivity, R_t, of the permeable bed.
- Resistivity, R_{xo}, and diameter, d_i, of the zone contaminated by mud filtrate invasion.
- Resistivity, R_s, of the adjacent shale formation.
- Resistivity, R_m, of the mud and diameter, d_h, of the borehole.

Fig. 3-3 shows a few examples of SP curves computed for $R_t = R_s = R_m$ (left side) and $R_t = R_s = 21\ R_m$ (center); the static SP, SSP, represented by the crosshatched diagrams is assumed to be 100 mV in these examples. In the case of $R_t = R_s = R_m$, the SP curve gives a much sharper definition of the boundaries of the permeable beds, and the SP deflections are greater and more closely approach the SSP value than in the case where the formation-to-mud resistivity ratio is 21.

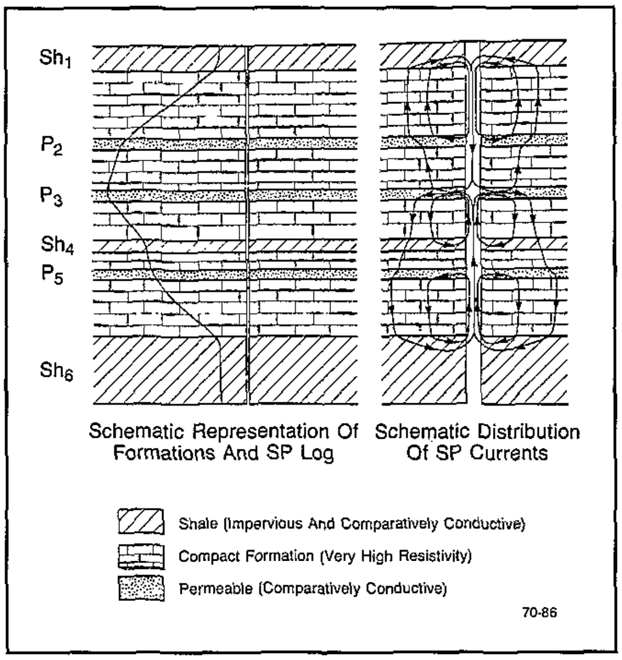

Fig. 3-4—Schematic representation of SP phenomena in highly resistive formations.

Highly Resistive Formations

In some formations, resistivities may be very high except in the permeable zones and in the shales. These high resistivities can significantly alter the distribution of the SP currents and, hence, the shape of the SP curve. As illustrated in Fig. 3-4, the currents flowing from shale bed Sh_1 towards permeable bed P_2 are largely confined to the borehole between Sh_1 and P_2 because of the very high resistivity of the formation in this interval. Accordingly, the intensity of the SP current in the borehole in this interval remains constant. Assuming the hole diameter is constant, the potential drop per foot will be constant, and the SP curve will be a straight sloped line.

In these formations, SP current leaves or enters the borehole only opposite the lower resistivity permeable beds or the shales. Therefore, the SP curve shows a succession of straight portions with a change of slope opposite every permeable interval (with the concave side of the SP curve towards the shale line) and opposite every shale bed (with the convex side of the SP curve towards the shale line). The SP cannot easily be used to define the boundaries of the permeable beds in these situations.

Shale Baseline Shifts

The shale baseline (from which the SP deflections are measured) is usually fairly well defined on the SP log (Fig. 3-1). However, in some wells, baseline shifts are observed. A baseline shift occurs whenever formation waters of different salinities are separated by a shale bed that is not a perfect cationic membrane. Large shifts make definition of the shale baseline and determination of the SSP value quite difficult.

Fig. 3-5 shows a simplification of a field case. The well penetrates a series of sandstones (B, D, F, H) separated by thin shales or shaly sandstones (C, E, G). The SSP of Interval B is indicated by the deflection at the upper boundary to be −42 mV. Shale C is not a perfect cationic membrane and the SP opposite C does not come back to the shale baseline of A. The SP deflection of Interval D, measured from Shale E, indicates that E is a better membrane than C. The shale baseline for Sandstone D is shown by the dashed line farther to the left; the SSP of Interval D is 44 mV or more. Similarly, it can be seen that Shale G is not as good a membrane as E; the SSP of Interval F is negative and equal to at least −23 mV.

When there is no shale bed to separate waters of different salinities in a permeable bed, there is also an SP baseline shift. In such a case, the SP curve shows little

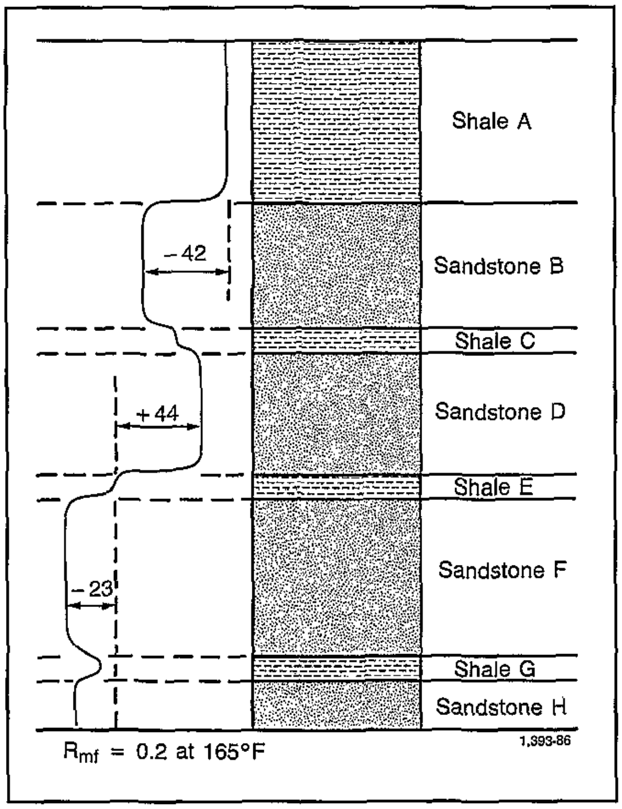

Fig. 3-5—SP baseline shift.

or no variation at the level where the salinity change occurs, but the SP deflections at the upper and lower boundaries of the permeable bed exhibit quite different amplitudes. Indeed, they may exhibit different polarities if the salinity of the mud filtrate is between the salinities of the two different interstitial formation waters. If the permeable bed is not shaly and if the permeable bed and the surrounding shales are sufficiently thick, the SP deflections at the two boundaries are the static SP deflections corresponding to the two different waters.

In all cases, the SP deflection at the shale-permeable bed boundary gives the polarity of the static SP deflection and, generally, a lower limit of its magnitude.

SP Anomalies Related to Invasion Conditions

In very permeable formations, SP anomalies, if not understood or recognized, may cause errors in the evaluation of the SSP.

When a high-porosity saltwater sand with good vertical permeability is invaded by fresh mud filtrate, the lighter filtrate floats up toward the upper boundary of the sand. An invasion profile, such as shown on the right *side of Fig. 3-6, develops. Invasion is very shallow near* the lower boundary of each permeable interval and deeper near the upper boundary. The SP is affected as follows:

- At the upper boundary the curve is rounded because of the deep invasion.
- At impervious shale streaks the SP may have a sawtoothed profile, as illustrated on the left side of Fig. 3-6; just below the shale streak the SP deflection is less than the SSP, and above the shale streak the SP deflection exceeds the SSP. This anomaly is caused by the accumulation of filtrate below the shale streak. Encircling the hole is a horizontal disk-shaped cell consisting of a shale disk sandwiched between salt water and mud filtrate. The emf of this cell superimposed on the normal SSP produces the anomalous profile.

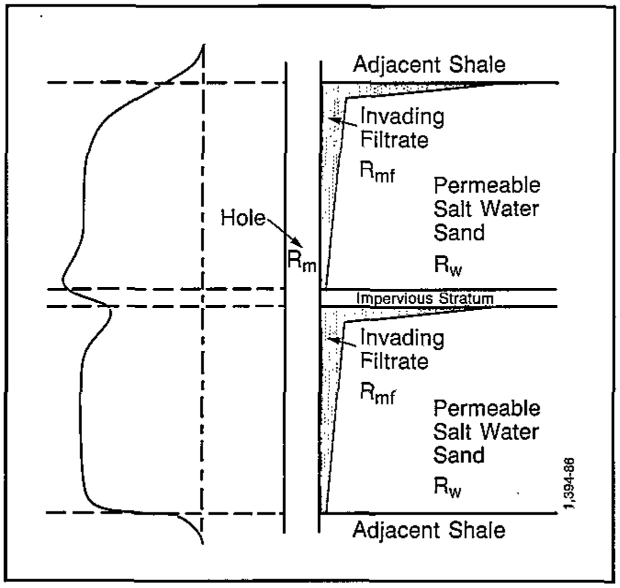

Fig. 3-6—Sawtooth SP.

The invasion may vanish completely in the lower portion of a very permeable bed, producing an invasion profile as shown on Fig. 3-7. Where there is no invasion, a reduced SP deflection is observed; there, the filtrate and the interstitial water are no longer in direct contact. As a result, there is no liquid-junction potential E_j to add to the shale-membrane potential E_{sh}, as is the case where there is invasion. Furthermore, the mudcake now acts as a cationic membrane to produce a mudcake membrane potential E_{mc}, which is of opposite direction to the shale-membrane potential. The efficiency of the mudcake as a membrane is usually much less, however, than that of a good shale so only a reduced SP deflection, as shown on Fig. 3-7, occurs. Since the diameter of invasion in the lower part of a permeable bed may decrease or increase with time, dependent upon mud and hole conditions, this reduced SP phenomenon may also appear and disappear with time. *Sometimes the SP is decreased over most of* the bed because invasion exists only in a thin plane at the top.

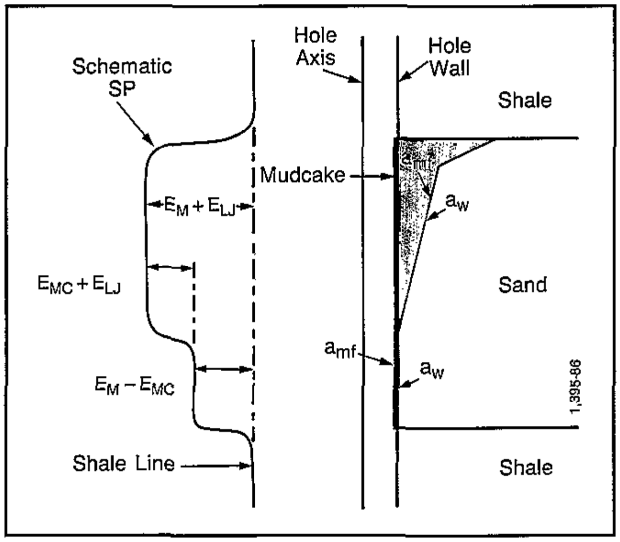

Fig. 3-7—SP reduction by mudcake membrane emf.

Field experience has shown that when there is a significant change in the mud used during drilling, it takes a long time for the recorded SP curve to reflect characteristics of the new mud. Therefore, when the SP curve is needed for R_w determinations, the mud characteristics should be kept fairly constant during drilling. In fact, if the characteristics of the mud must be changed, it is desirable to log the well *just prior to the change.*

SP Anomalies—Noise

Sometimes a small-amplitude sine-wave signal is superimposed on the SP; this happens when some mobile part of the winch becomes accidentally magnetized. An intermittent contact between casing and cable armor may also cause spurious spikes on the SP curve. In these situations, the SP curve should be read in such a way that the sine-wave amplitude or spike is not added to, or subtracted from, the authentic SP deflection.

Direct currents flowing through the formations near the SP electrode can also result in erroneous SP values, particularly when formation resistivities are high. These currents may be caused by bimetallism, which occurs when two pieces of different metals touch each other and, surrounded with mud, form a weak battery. These currents are small and are not likely to affect the SP except in highly resistive formations. Accordingly, if an SP curve in very resistive formations looks questionable, the SP deflections should preferably be read opposite nonshaly intervals where the resistivities are as low as possible.

It is sometimes difficult to record a good SP on offshore or barge locations; passing ships, cathodic protection devices, and leaky power sources may all contribute to a noisy SP. On land, proximity to power lines and pumping wells may have a similar effect on the SP curve. Many of these disturbances can be minimized by a careful choice of the ground-electrode location.

THE GR LOG

The GR log is a measurement of the natural radioactivity of the formations. In sedimentary formations the log normally reflects the shale content of the formations. This is because the radioactive elements tend to concentrate in clays and shales. Clean formations usually have a very low level of radioactivity, unless radioactive contaminant such as volcanic ash or granite wash is present or the formation waters contain dissolved radioactive salts.

The GR log can be recorded in cased wells, which makes it very useful as a correlation curve in completion and workover operations. It is frequently used to complement the SP log and as a substitute for the SP curve in wells drilled with salt mud, air, or oil-based muds. In each case, it is useful for location of shales and nonshaly beds and, most importantly, for general correlation.

Properties of Gamma Rays

Gamma rays are bursts of high-energy electromagnetic waves that are emitted spontaneously by some radioactive elements. Nearly all the gamma radiation encountered in the earth is emitted by the radioactive potassium isotope of atomic weight 40 (K^{40}) and by the radioactive elements of the uranium and thorium series.

Each of these elements emits gamma rays; the number and energies of which are distinctive of each element. Fig. 3-8 shows the energies of the emitted gamma rays: potassium (K^{40}) emits gamma rays of a single energy at 1.46 MeV, whereas the uranium and thorium series emit gamma rays of various energies.

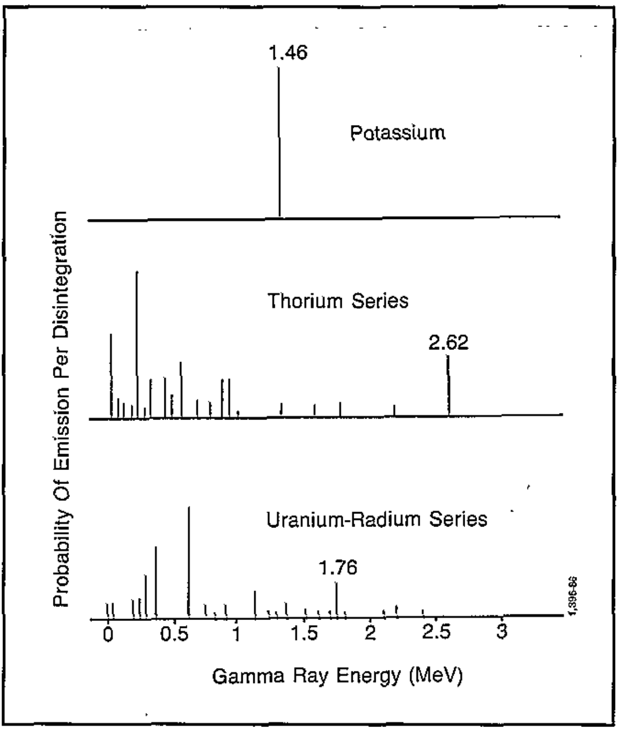

Fig. 3-8—Gamma ray emission spectra of radioactive minerals.

In passing through matter, gamma rays experience successive Compton-scattering collisions with atoms of the formation material, losing energy with each collision. After the gamma ray has lost enough energy, it is absorbed, by means of the photoelectric effect, by an atom of the formation. Thus, natural gamma rays are gradually absorbed and their energies degraded (reduced) as they pass through the formation. The rate of absorption varies with formation density. Two formations having the same amount of radioactive material per unit volume, but having different densities, will show different radioactivity levels; the less dense formations will appear to be slightly more radioactive. The GR log response, after appropriate corrections for borehole, etc., is proportional to the weight concentrations of the radioactive material in the formation:

$$\mathrm{GR} = \frac{\Sigma\, \varrho_i V_i A_i}{\varrho_b}, \qquad \text{(Eq. 3-3)}$$

where

ϱ_i are the densities of the radioactive minerals,

V_i are the bulk volume factors of the minerals,

A_i are proportionality factors corresponding to the radioactivity of the mineral,

and

ϱ_b is the bulk density of the formation.

In sedimentary formations, the depth of investigation of the GR log is about 1 ft.

Equipment

The GR sonde contains a detector to measure the gamma radiation originating in the volume of formation near the sonde. Scintillation counters are now generally used for this measurement. They are much more efficient than the Geiger-Mueller counters used in the past. Because of its higher efficiency, a scintillation counter need only be a few inches in length; therefore, good formation detail is obtained. The GR log may be, and usually is, run in combination with most other logging tools and cased hole production services.

Calibration

The primary calibration standard for GR tools is the API test facility in Houston. A field calibration standard is used to normalize each tool to the API standard and the logs are calibrated in API units. The radioactivities in sedimentary formations generally range from a few API units in anhydrite or salt to 200 or more in shales.

Prior to the API calibration procedure, GR logs were scaled in micrograms of radium-equivalent per ton of formation. Conversions from these units to API units are shown in Table 3-1.

Table 3-1

Conversion from old units to API units for Schlumberger gamma ray logs.

Equipment	Old Unit	API Units Per Old Unit
GNT-F or -G Gamma Ray	1 μgm Ra-eq/ton	16.5
GNT-J, -K Gamma Ray, GLD-K	1 μgm Ra-eq/ton	11.7

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Borehole Correction Curves

The GR log deflection is a function not only of the radioactivity and density of the formations but also of hole conditions (hole diameter, mud weight, tool size, and tool position) since the material interposed between the counter and the formation absorb gamma rays. Chart Por-7 is used to make these borehole corrections. As might be expected, the corrections are quite significant in large boreholes and in heavy muds.

Many older GR logs were calibrated so that a 3⅝-in. sonde eccentric in a 10-in. uncased borehole filled with 10-lb/gal nonradioactive mud would read directly the true radioactivity of the formations. Chart Por-7, with some minor shifting, is applicable for logs calibrated in this manner.

Applications

The GR log is particularly useful for defining shale beds when the SP is distorted (in very resistive formations), when the SP is featureless (in freshwater-bearing formations or in salty mud; i.e., when $R_{mf} \approx R_w$), or when the SP cannot be recorded (in nonconductive mud, empty or air-drilled holes, cased holes). The bed boundary is picked at a point midway between the maximum and minimum deflection of the anomaly.

The GR log reflects the proportion of shale and, in many regions, can be used quantitatively as a shale indicator. It is also used for the detection and evaluation of radioactive minerals, such as potash or uranium ore. Its response, corrected for borehole effect, is practically proportional to the K_2O content, approximately 15 API units per 1% of K_2O. The GR log can also be used for delineation of nonradioactive minerals.

This traditional correlation log is part of most logging programs in both open and cased hole. Furthermore, because it is readily combinable with most other logging tools, it permits the accurate correlation of logs made on one trip into the borehole with those made on another trip.

THE NGS LOG

Like the GR log, the NGS natural gamma ray spectrometry log measures the natural radioactivity of the formations. Unlike the GR log, which measures only the total radioactivity, this log measures both the number of gamma rays and the energy level of each and permits the determination of the concentrations of radioactive potassium, thorium, and uranium in the formation rocks.

Physical Principle

Most of the gamma ray radiation in the earth originates from the decay of three radioactive isotopes: potassium 40 (K^{40}), with a half-life of 1.3 x 10^9 years; uranium 238 (U^{238}), with a half-life of 4.4 x 10^9 years; and thorium 232 (Th^{232}), with a half-life of 1.4 x 10^{10} years.

Potassium 40 decays directly to stable argon 40 with the emission of a 1.46-MeV gamma ray. However, uranium 238 and thorium 232 decay sequentially through a long sequence of various daughter isotopes before arriving at stable lead isotopes. As a result, gamma rays of many different energies are emitted and fairly complex energy spectra are obtained, as Fig. 3-8 shows. The characteristic peaks in the thorium series at 2.62 MeV and the uranium series at 1.76 MeV are caused by the decay of thallium 208 and bismuth 214, respectively.

It is generally assumed that formations are in secular equilibrium; that is, the daughter isotopes decay at the same rate as they are produced from the parent isotope. This means that the relative proportions of parent and daughter elements in a particular series remain fairly constant; so, by looking at the gamma ray population in a particular part of the spectrum it is possible to infer the population at any other point. In this way, the amount of parent isotope present can be determined.

Once the parent isotope population is known, the amount of nonradioactive isotope can also be found. The ratio of potassium 40 to total potassium is very stable and constant on the earth while, apart from thorium 232, the thorium isotopes are very rare and so can be neglected. The relative proportions of the uranium isotopes depend somewhat on their environment, and there is also a gradual change because of their different half-lives; at present, the ratio of uranium 238 to uranium 235 is about 137.

Measurement Principle

The NGS tool uses a sodium iodide scintillation detector contained in a pressure housing which, during logging, is held against the borehole wall by a bow spring.

Gamma rays emitted by the formation rarely reach the detector directly. Instead, they are scattered and lose energy through three possible interactions with the formation; the photoelectric effect, Compton scattering, and pair production. Because of these interactions and the response of the sodium iodide scintillation detector, the original spectra of Fig. 3-8 are degraded to the rather "smeared" spectra shown in Fig. 3-9.

The high-energy part of the detected spectrum is divided into three energy windows, W1, W2, and W3; each covering a characteristic peak of the three radioactivity series (Fig. 3-9). Knowing the response of the tool and the number of counts in each window, it is possible to determine the amounts of thorium 232, uranium 238, and potassium 40 in the formation. There are relatively few counts in the high-energy range where peak discrimination is best; therefore, measurements are subject to large statistical variations, even at low logging speeds. By including a contribution from the high-count rate, low-energy part of the spectrum (Windows W4 and W5), these high statistical variations in the high-energy windows can be reduced by a factor of 1.5 to 2. The statistics are further reduced by another factor of 1.5 to 2 by using a filtering technique that compares the counts at a particular depth with the previous values in such a way that spurious

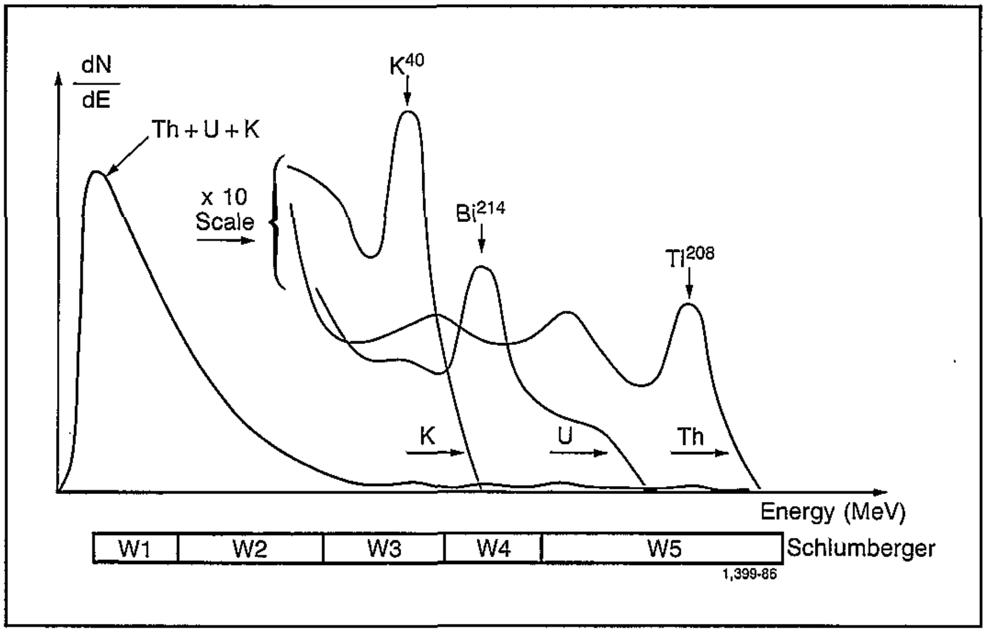

Fig. 3-9—Potassium, thorium, and uranium response curves (NaI crystal detector).

changes are eliminated while the effects of formation changes are retained. Normally, only the final filtered data are presented on film, but the unfiltered raw data are always recorded on tape.

Log Presentation

The NGS log provides a recording of the amounts (concentrations) of potassium, thorium, and uranium in the formation. These are usually presented in Tracks 2 and 3 of the log (Fig. 3-10). The thorium and uranium concentrations are presented in parts per million (ppm) and the potassium concentration in percent (%).

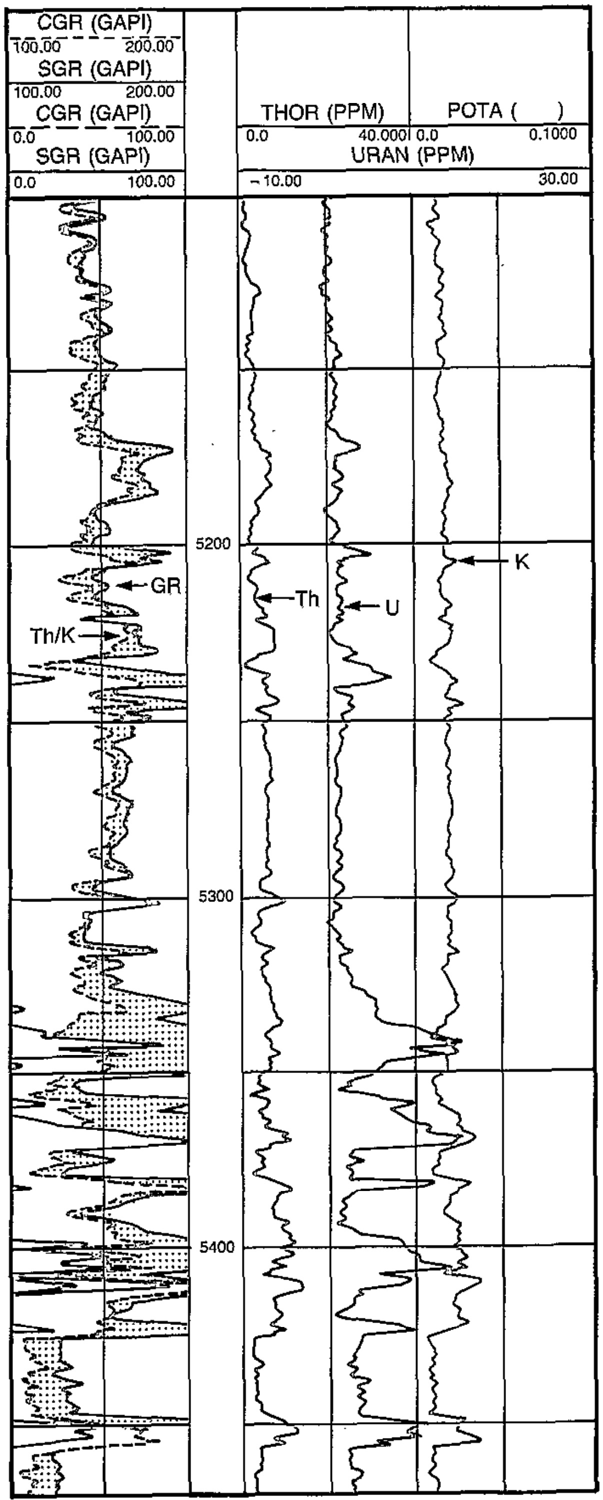

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Fig. 3-10—NGS* natural gamma ray spectrometry log.

In addition to the concentrations of the three individual radioactive elements, a total (standard) GR curve is recorded and presented in Track 1. The total response is determined by a linear combination of the potassium, thorium, and uranium concentrations. This standard curve is expressed in API units. If desired, a "uranium-free" measurement (CGR) can also be provided. It is simply the summation of gamma rays from thorium and potassium only.

Borehole Correction Curves

The response of the NGS tool is a function not only of the concentration of potassium, thorium, and uranium but also of hole conditions (hole size and mud weight) and of the interactions of the three radioactive elements themselves.

Interpretation

The average concentration of potassium in the earth's crust is about 2.6%. For uranium, it is about 3 ppm; for thorium, it is about 12 ppm. Obviously, individual formations may have significantly greater or lesser amounts and specific minerals usually have characteristic concentrations of thorium, uranium, and potassium. Therefore, the curves of the NGS log can often be used individually or collectively to identify minerals or mineral type. Chart CP-19 shows a chart of potassium content compared with thorium content for several minerals; it can be used for mineral identification by taking values directly from the recorded curves.

Often, the result is ambiguous so other data are needed. In particular, the photoelectric absorption coefficient in combination with the ratios of the radioactive families are helpful: Th/K, U/K, and Th/U. Care needs to be taken when working with these ratios; they are not the ratios of the elements within the formation but rather the ratio of the values recorded on the NGS log, ignoring the units of measurement. Chart CP-18 compares the photoelectric absorption coefficient with the potassium content or the ratio of potassium to thorium for mineral identification.

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*Mark of Schlumberger

Applications

The NGS log can be used to detect, identify, and evaluate radioactive minerals. It also can be used to identify clay type and to calculate clay volumes. This, in turn, can provide insight into the source, the depositional environment, the diagenetic history, and the petrophysical characteristics (surface area, pore structure, etc.) of the rock.

The thorium and potassium response or the thorium-only response of the NGS log is often a much better shale indicator than the simple GR log or other shale indicators. Shaly-sand interpretation programs such as GLOBAL* and ELAN* can thereby benefit from its availability. The NGS log can also be used for correlation where beds of thorium and potassium content exist.

The combination of the NGS log with other lithology-sensitive measurements (such as photoelectric absorption, density, neutron, sonic) permits the volumetric mineral analysis of very complex lithological mixtures. In less complex mixtures, it allows the minerals to be identified with greater certainty and volumes to be calculated with greater accuracy.

The uranium response of the NGS log is sometimes useful as a "moved fluid" indicator for in-field wells drilled into previously produced reservoirs. Also, permeable streaks may have higher uranium salt content than less permeable intervals.

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