Geophysical Well Logging

We can gain direct access to rocks beneath the earth's surface by drilling. The best samples are obtained by core drilling, but this method is very costly and is seldom practical for depths of more than a few thousand feet. In addition, the conventional methods of deep drilling produce rock cuttings that are flushed from the borehole by drilling fluids. Because these rock cuttings become mixed and contaminated by the drilling fluid, they can be difficult to interpret. Furthermore, these broken fragments tell us little about

the porosity and permeability of the unbroken matrix of rock, or the natural fluid
the pore space. Therefore, instruments have been developed for measuring certa
erties directly, while they are lowered in a borehole. The operation of such instrun
well logging, and the strip chart on which the measurements are plotted is called a

Geophysical well logging was introduced in 1928 by two brothers, Conrad and M
berger. They devised a probe that could be lowered in a well, continuously measu
resistivity as it moved past different rock formations. A strip chart, the electrical
produced while the operation was underway. Variations in resistivity indicated th
tween different lithologic units more clearly than the rock cuttings obtained while
being drilled.

In the decades that followed, the inventory of well logging instruments expanc
improvements increased the variety of electrical measurements. Resistivity was me
different electrode configurations, and natural voltages were recorded. Several va
recorded simultaneously by means of a probe, called a *sonde*, on which several el
mounted. These values could be analyzed in different combinations to estimate f
rosity and to make inferences about the natural fluids filling the pore space.

Later improvements included the addition of devices to log radioactivity. Thes
levels of natural gamma radiation, and they measure radiation produced by bomb
mation with atomic particles. At about the same time, other logging tools were d
measuring seismic wave speeds close to the wall of the well. This is called sonic loggi
combinations of radioactivity and sonic logs have proved very useful for determin
density, and porosity. On a more limited scale, borehole gravimeters and magnet
been used in well logging operations.

In this chapter, we begin with a discussion of well drilling to point out certai
must be considered in interpreting well logs. Then we will describe the conventio
and introduce methods for interpreting them. The general objective of well logg
formation evaluation. Well logs are used to discover as much as possible about the
rock formations penetrated by a drill.

WELL DRILLING

Most modern well drilling is done with rotary drills and with percussion drills. The rotary drill can be used for both shallow and deep wells. The record depth reached with a rotary drill is more than 40,000 feet. A percussion drill is faster, but it cannot be operated if the well becomes flooded by groundwater while drilling is in progress. This problem restricts its use for the most part to depths of less than a few thousand feet.

Rotary Drilling

The basic parts of a rotary drill a
in Figure 14–1. Drilling is done v
tached at the bottom of a colum
hollow pipe. The top of this colu
to a square hollow bar, the *kelly*
through a square hole in the rota
engine turns the rotary table, cau
tire column to rotate at speeds o
rpm. The teeth on the rotating bit
rock, working the hole deeper int

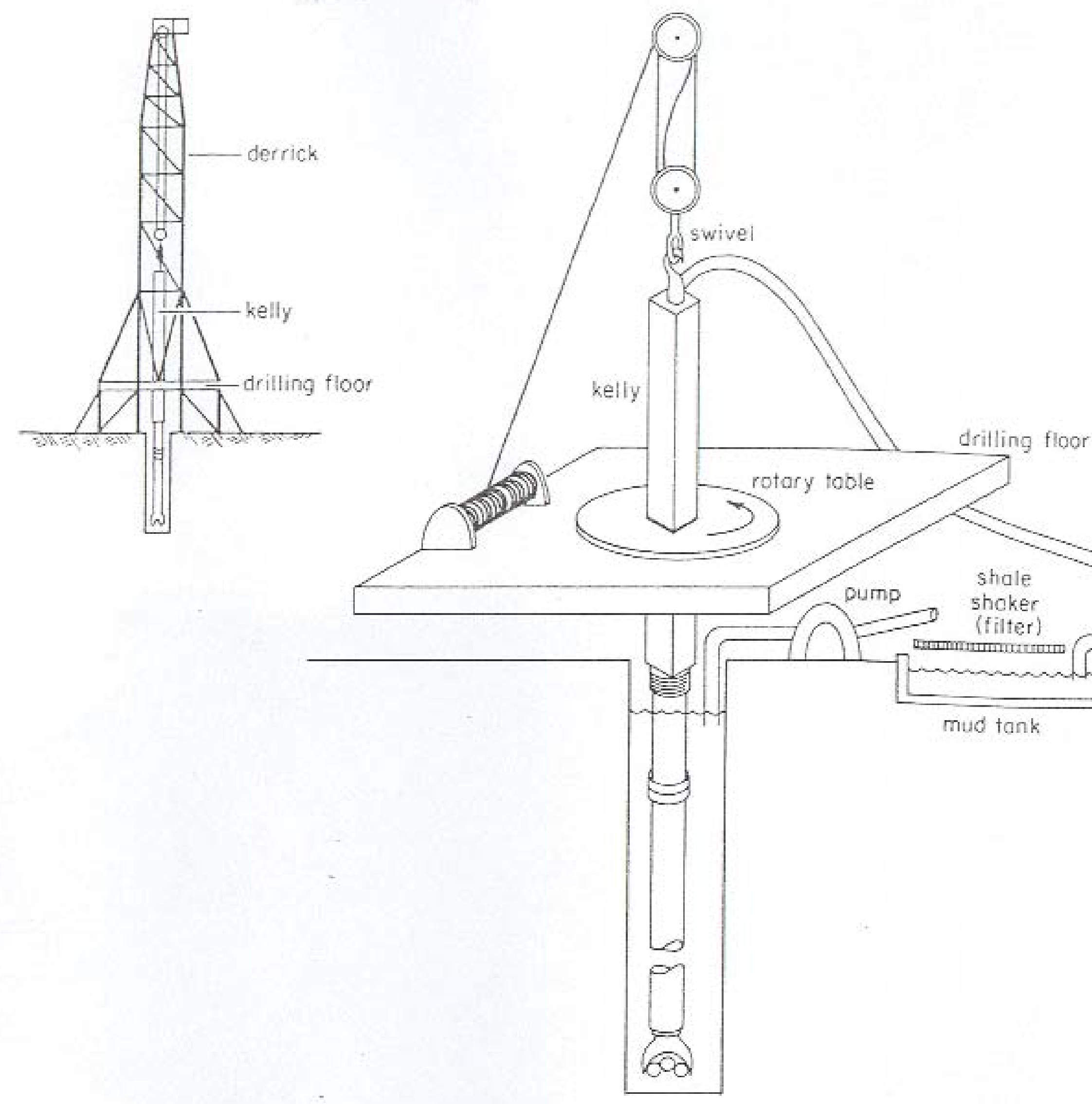

Figure 14–1
Principal parts of a rotary drill. The power system turns the rotary table, which then rotates the entire column of drilling pipe. The bit grinds the rock at the bottom of the hole. Mud
down through the column of pipe th
hole, flushing out the rock cuttings.

At the same time drilling fluid, stored in the mud tank, is pumped down the column of pipe. It flows out through holes in the bit and rises in the well, carrying the rock cuttings up to the land surface. On the surface the cuttings are filtered out, and the flui
the mud tank.

As the well deepens, additional
round pipe, threaded at the ends,
beneath the kelly to lengthen t

Drilling continues until the bit becomes dull. To replace it requires that the entire column be raised by means of the cable and pulleys hooked to the swivel at the top of the kelly. The column is lifted, unscrewed section by section, and stacked in the derrick tower. A new bit is attached and the column is reassembled, after which drilling resumes. The task of disassembling the pipe, changing the bit, and reconnecting the pipe is called "making a trip." In a deep well, this operation can require at least several hours and perhaps more than a day.

Drilling fluid serves several purposes. We have already mentioned that it carries rock cuttings out of the well. For shallow depths water itself is suitable, but in deeper wells a more viscous fluid is desirable to hold the cuttings in suspension. The fluid also lubricates the rotating column of pipe, and it cools the bit. Another important function of the fluid is to seal the rock surface so that pore fluids cannot seep into the well. In this capacity, the drilling fluid acts to prevent gushers and blowouts that would otherwise occur when the bit penetrates high-pressure oil and gas-bearing zones. To seal the rock surface effectively, the drilling fluid must exert pressure against it that exceeds the pressure of the groundwater, oil, or gas which fills the pores in the rock.

Pressure on the wall of the well depends on the weight of the drilling fluid, which increases with depth. To increase the weight at some particular depth, we must increase the density of the drilling fluid. Particles of different substances are added to turn the drilling fluid into a thicker and more viscous mud. Considerable thought goes into the choice of additives to achieve the desirable weight, viscosity, and lubrication.

By sealing the rock surface, the drilling fluid acts to hide the nature of the pore fluids that would otherwise seep or g
well. Oil- and gas-bearing zone
completely sealed that we have n
cation they have been drilled int
principal objectives of well loggi
detect the presence of these hyd
ter the well has been drilled. No
natural pore fluids prevented f
into the well, but because of its
sure the drilling fluid itself seeps
displacing the natural pore fluids

The zone surrounding the w
drilling fluid has infiltrated is call
invasion; its structure is illustrat
14–2. At the side of the well w
fluid first begins to seep into the
the additive particles are filtered
remaining filtrate with its dissol
ents passes into the rock. Close to
filtrate completely replaces the
fluids, creating the *flushed zone.* B
annulus of invasion where the prop
trate diminishes gradationally w
from the well. As seepage progre
ditive particles build up a coating
of the well called the *mud cake.* It
til it forms an impermeable barrie
vents further invasion.

In relatively impermeable r
shale, the entire zone of invasion
a few inches into the rock. Poro
meable sandstones and carbonate
vaded to distances of several fe
The mud cake may reach a thick
tenths of an inch, and the flush
extend several inches to more tha
the rock. To "see through" the
vasion into the undisturbed fo
quires combinations of several
devices.

Coring is done using a
equipped with a special hollow an

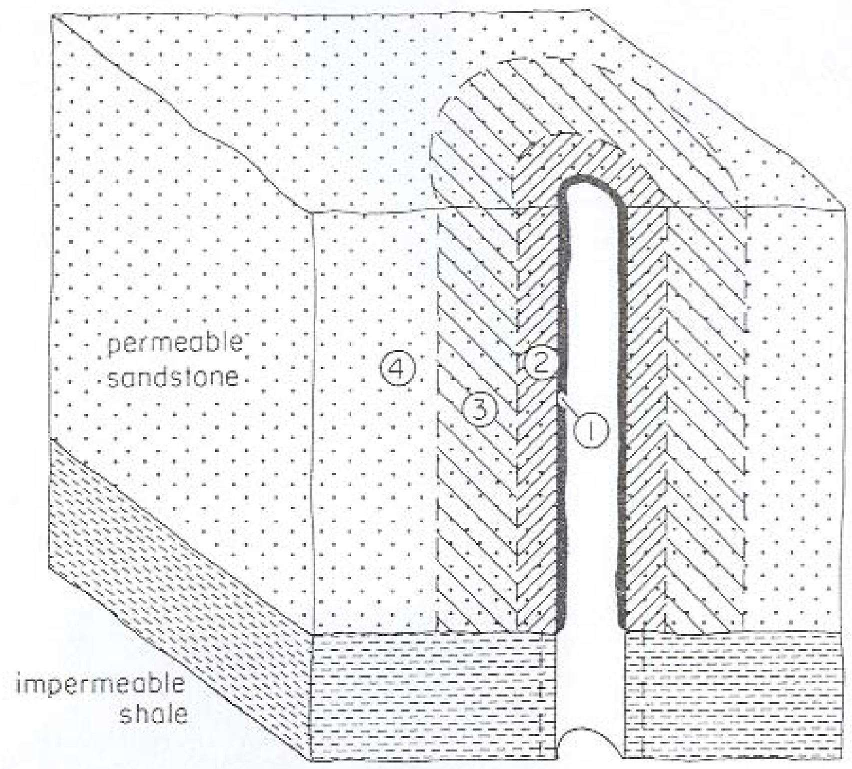

Figure 14–2
The zone of invasio
the mud cake, (2) th
zone, and (3) the ar
partial invasion. Be
of invasion is (4) th
formation. The zon
extends much farth
well in permeable s
in relatively imperm

(Figure 14–3). The end of the bit is studded with fragments of industrial diamond or some other very hard substance. As the bit turns, it cuts a tubular hole around a solid core of rock which moves into a container, the *core barrel,* inside the column of drill pipe. When the core barrel is full, it is retrieved by "making a trip." This process is carried out much more frequently in core drilling than in noncore drilling, because of the limitation imposed by the length of the barrel, which is ordinarily less than 20 feet. In addition, drilling must proceed more slowly and carefully to minimize core breakage. For these reasons, core drilling is very expensive compared with other noncoring operations. The core drill produces the best rock samples, but the natural formation fluids are flushed out by the drilling field.

Percussion Drilling

Modern percussion drilling is
hammer activated by an air com
principle is not unlike that of a
commonly used to break up pa
drill rig includes a hammer bit,
Figure 14–4, mounted at the bo
umn of pipe. Air from a com
through a high-pressure hose in
the column and then down th
drive the hammer.

A simplified sketch (Figure 14-
the principal features of a bit asse
sists of a hammer attached to a
moves up and down in a cyl
pressed air, pumped into the t
forces the piston downward. Thi

Figure 14–3
Coring bits studdec
industrial diamond
(Courtesy of Sprag
Henwood, Inc.)

presses the air that is sealed in the bottom chamber. When the piston is pushed down far enough, the compressed air in the top chamber escapes through holes in the side of the cylinder. Upon release of pressure in the top chamber, the compressed air in the bottom chamber expands, driving the piston upward. This closes the holes, allowing pressure to build up once again in the top chamber. The cycle is repeated several times per second. The rapid pounding of the hammer, which is studded with knobs of tungsten carbide or other hard materials, pulverizes the rock into a fine dust. Air escaping from the upper chamber blows the dust out of the well.

As drilling progresses, lengths of pipe, threaded at the ends, are added to the column. Eventually, the studding on the hammer wears away, and it is necessary to "make a trip" to replace the bit. Percussion drilling usually proceeds faster than rotary drilling. But a depth is reached beyond which the escaping air can no longer remove the rock dust. The depth that can be drilled is also limited by the effect of groundwater seepage, which obstructs the upward flow of air and rock dust.

Casing

Several difficulties in drilling and
wells are overcome by means of
is cased by lining it with a colu
which is lowered into the hole a
ing pipe has been removed. Ce
pumped into the well to fill the s
the casing pipe and to fix it soli
This seals the well, preventing na
tion fluids from seeping into it
loose rock from collapsing and
hole. After the casing has been s
perforated at particular depths to
from an aquifer, or oil and gas fr
rock, to flow into the well. The
sometimes be set before a well is
drilled, for example, when groun
age floods the well so that a per
cannot be operated. In rotary d
lems with collapsing rock and exc
drilling fluid into fracture zones c
by casing. After the casing is set,
resume with a smaller bit tha
through the casing pipe.

Casing creates some serious p
well logging. Electric logs canno
run in wells with steel casing. So

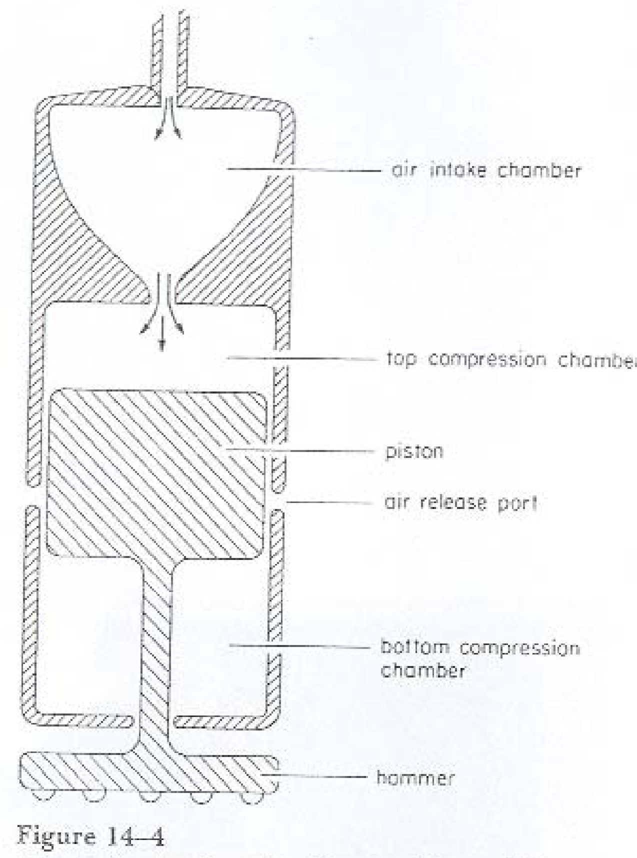

Figure 14–4
Schematic drawing of a bit assembly used for percussion drilling. The hammer is driven by compressed air, which is pumped down through the column of drilling pipe into the air intake chamber. Rock cuttings are blown out of the hole by compressed air escaping from the air release ports.

also be severely distorted. But, certain radioactivity logs can be run effectively where casing prevents other kinds of logging.

FORMATION EVALUATION

The properties of a formation that can be estimated from well log measurements include lithology and bed thickness, porosity, perme-

ability, and the proportions of
drocarbons occupying the pore
kinds of information are needed
these properties? We will answer
first, before describing the lo
ments and techniques used to
formation.

Lithology and Bed Thickness

Electrical resistivity, natural vo
ences, natural radioactive emissi
mic wave speed can all help us
different lithologies. None of the
uniquely characterizes particul
rock, however. We already know
some overlap in the ranges of
sured in typical sandstones, shale
and other lithologies. Neverthele
differences usually exist for p
quences of interbedded litholog
particular areas. For example, in
alternating sandstone and shale
of natural voltage, radioactivity,
travel time over a fixed interval
high in shale and low in sandstone
terns (Figure 14–5) exist almost
even though the actual values
one area can be quite different fr
another area.

Cuttings produced by drilling
tially, what kinds of rock are penet
well. Because of the mixing that
these cuttings are carried in suspe
drilling fluid, they do not provide
formation about bed thicknesses a
tions of bed boundaries. But they
what patterns we should look f
those in Figure 14–5, so that we
for accurate measurement of these
and thicknesses.

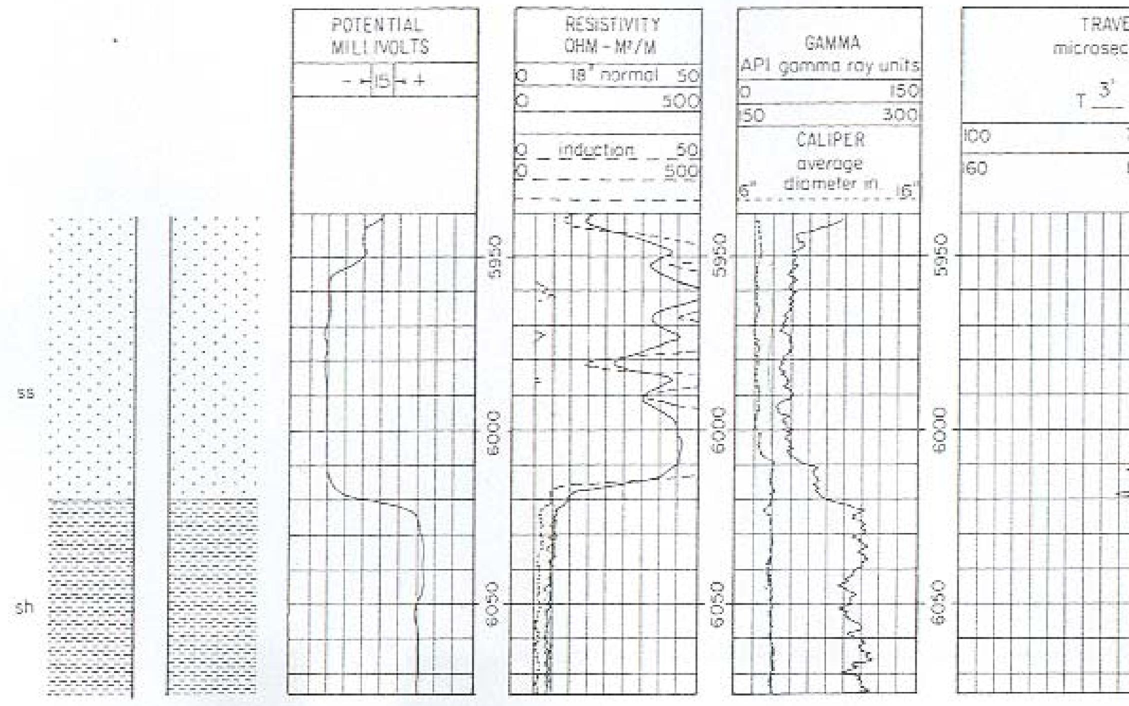

Figure 14–5
Representative well logs illustrating the variation across the boundary between sandstone and shale layers of spontaneous potential (natural voltage), electrical resistivity, natural gamma sonic transit time (*P*-wave travel tim receivers one foot apart.

The usual practice is to interpret lithology in a well by comparing logs from that well with reference logs from another well in the area in which lithology is already known from careful study of cuttings and, perhaps, rock cores. Patterns of variation corresponding to these lithologic units are recognized by visual correlation of the logs (Figure 14–6). It is useful to know that peaks and troughs on well logs are not usually recorded exactly at bed boundaries. Rather, these boundaries are located by more subtle inflections between the high and low points on a log. The reasons for these subtle indications are discussed in a later section.

For correlation purposes, it i necessary to understand exact duces the patterns of variation t ize different rock layers. More the ability to recognize the pa within a pattern that marks a la Because different types of loggi cord different patterns of variat quite difficult to correlate, say, a from one well with a radioactivity other well. Accurate identificatio layer boundary in different wells by comparing logs recorded w kind of instrument. No particula turns out to be generally super

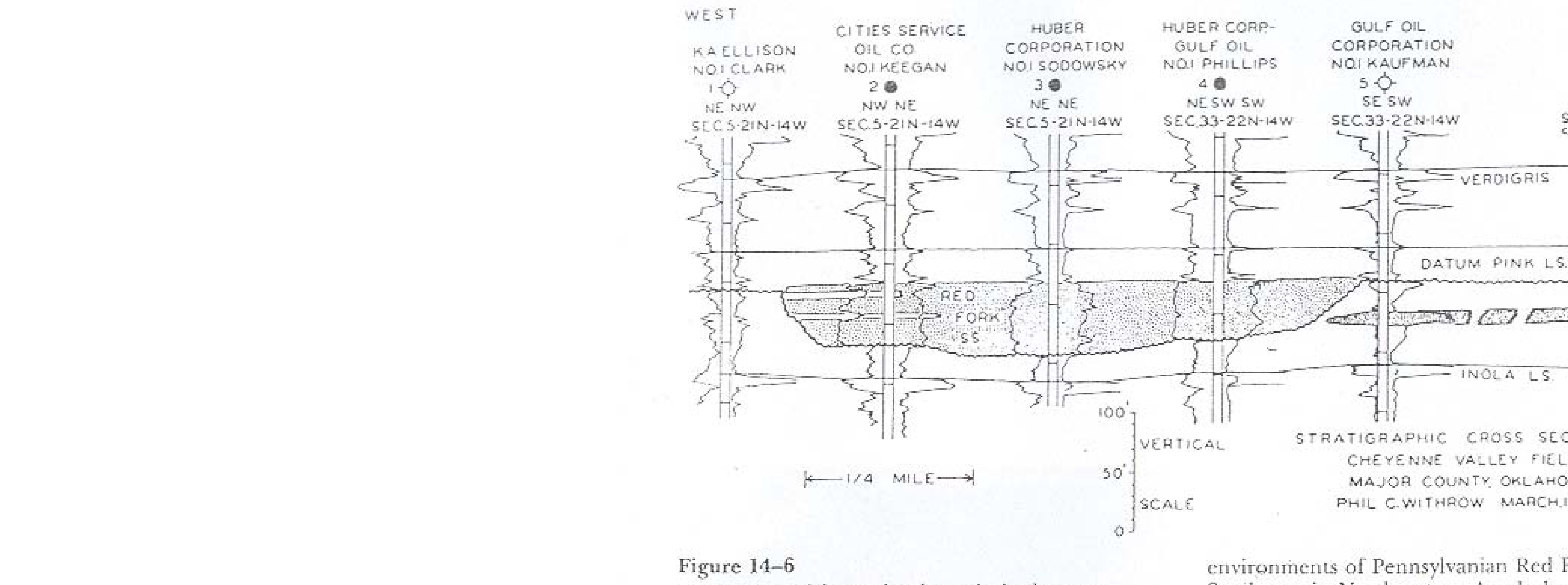

Figure 14–6
Correlation of formation boundaries between different wells based on similar patterns of variation identified on logs from these wells. (From Phillip C. Withrow, Depositional environments of Pennsylvanian Red F Sandstone in Northeastern Anadarko Oklahoma, *Bulletin of the American Ass Petroleum Geologists*, v. 52, n. 9, pp. 16 September 1968.)

areas, resistivity logs are easiest to compare, but in other places the correlation patterns are clearer on radioactivity logs.

Porosity

In a sample of a rock formation, the proportion of the volume that consists of openings between grains, along fractures, and in cavities is the *porosity*. The porosity of reservoir rocks containing petroleum, natural gas, or fresh water is especially important because it indicates the volume of fluid that can be stored in the rock. Methods for estimating porosity from well log measuremen mostly on experiments that have trical resistivity, *P*-wave travel ti clear emissions in rock specimen the porosity is known from indep surements.

Insofar as the pore fluid resis from the solid matrix resistivity, w a relationship between formatic and porosity. In 1942 G. E. Arch such a relationship. It was deter laboratory measurements of the r sandstone cores that had been sa water containing different conce dissolved NaCl. The porosities of were measured by a method independent of resistivity. Archie introduced a property called the *formation resistivity factor F*, which depends on the formation resistivity R_0 and the pore fluid resistivity R_w:

$$F = R_0/R_w \qquad (14–1)$$

He then plotted values of F and porosity φ that had been found for the different cores on a logarithmic graph (Figure 14–7). Because a straight line could be fitted to this logarithmic plot, he recognized that φ and F could be related by an equation of the form

$$\varphi = aF^{-m} \qquad (14–2)$$

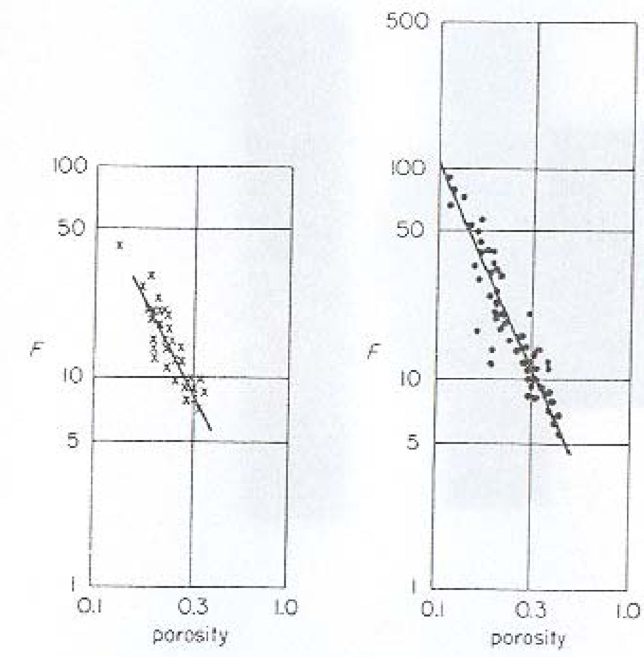

Figure 14–7
Graphs of the variation of formation factor (F) with porosity (φ), based on values measured in sandstone cores from two regions. (From G. E. Archie, *Transactions of the AIME*, v. 146, pp. 54–62, 1942.)

where m is a constant that depen mentation of the reservoir rock a stant that must be found by test in an area of interest. This equa known as the Archie formula, ha most widely used equation in for uation. Tests for many different a that values for a are mostly betw 1.0, and values for m are mostly and 3.0.

Another property of a formati lated to porosity is the compre speed, which well loggers usually wave speed. The sonic wave through the pore fluid is usually ent from speed (V_m) through the Because the sonic wave speed (V_0) acteristic of the formation depe proportions of these two parts, i lated to porosity:

$$\frac{1}{V_0} = \frac{\varphi}{V_w} + \frac{1 - \varphi}{V_m}$$

The formation wave speed (V_0) c from the travel time (T_0) betwee that are a known distance apart (Eq Because these points remain a fi apart on a sonic logging instrum rosity can be related directly to the

$$T_0 = \varphi T_w + (1 - \varphi)T_m$$

where T_w and T_m are travel time same distance through a fluid in wave speed is V_w and through a so the wave speed is V_m. This form rearranged to find the porosity:

$$\varphi = \frac{T_0 - T_m}{T_w - T_m}$$

The last porosity relationship t consider concerns the formation

This physical property depends on the proportion of pore fluid, which has the density of ρ_w, and the proportion of solid matrix, which has the density of ρ_m. Therefore, it can be related to the porosity:

$$\rho_0 = \varphi\rho_w + (1 - \varphi)\rho_m \qquad (14\text{–}6)$$

This equation can be rearranged to obtain

$$\varphi = \frac{\rho_m - \rho_0}{\rho_m - \rho_w} \qquad (14\text{–}7)$$

We know that density of formation water is close to 1 g/cm^3, and that the matrix density is typically between 2.6 and 2.7 g/cm^3. Radioactivity can be used to estimate the formation density in two ways. The first employs a device for bombarding the formation with electromagnetic photons, which become scattered by collisions with electrons in the formation. As a result of the scattering process, a certain proportion of these photons are returned to a detector. This proportion depends on the concentration of electrons, hence the density (ρ_0) of the formation. The other method bombards the formation with neutrons which become absorbed into atomic nuclei in the formation; this causes the nuclei to emit gamma rays. The level of gamma radiation reaching a detector depends on the formation density. Values of ρ_0 measured in these ways can be used in Equation 14–7 to calculate porosity.

Water and Hydrocarbon Saturation

The pore space in rocks is almost everywhere filled with water. Except at shallow depths, this water ordinarily contains some dissolved NaCl and other ions. Because of these dissolved constituents, the water becomes a good electric conductor with low resisti… trast, the common rock-formin… making up the solid matrix of a fo… poor conductors with high resisti… quently, the flow of electric curre… mation is almost entirely through … ter.

Very sparsely distributed in the… imentary rocks are zones contai… leum and natural gas. These zo… elusive targets of the exploration … Petroleum and natural gas, like th… ing minerals, are poor conductor… resistivity. Therefore, when thes… bons percolate into a reservoir roc… some of the pore water, the electr… ity of the formation increases.

A typical reservoir rock contair… of water and hydrocarbon fluids. … their lower densities, the hydrocar… migrate upward, becoming more c… in the upper part of the reservoir. … is the water completely replaced, … diminish gradationally to an irred… mum. Therefore, a reservoir co… drocarbon fluids tends to have a… upward increase in electrical resis…

For purposes of estimating p… duction from a well, it is useful t… the proportions of water and hyd… different parts of the reservoir by … sistivity measurements. In 1942 … proposed a formula for finding th… portion, otherwise called the *wa…* *(S)*. It is based on laboratory meas… the resistivities of sandstone core… different proportions of petroleu… ter having a fixed salinity. Loga… of S and the fraction R_0/R_t could… straight lines, indicating that

$$S = (R_0/R_t)^{1/n}$$

where R_t is the resistivity of rock containing a mixture of hydrocarbons and water, and R_0 is the resistivity of the same rock matrix completely saturated with water. Because the formation factor F is defined in terms of rock that is completely water-saturated, the formula can also be written as

$$S = (FR_w/R_t)^{1/n} \qquad (14\text{–}9)$$

where R_w is the resistivity of the water that partly fills the pore space. In a reservoir where the water saturation *(S)* decreases gradationally upward, the value of R_0 must be measured from well log readings in the lower part that is completely saturated with water.

Permeability

The capacity of a formation to transmit fluid is called its *permeability*. It depends on the extent to which the pores are interconnected and on the diameter of the openings. It is the most difficult property to estimate from well log measurements.

The permeability of a core sample of rock can be measured with the apparatus shown schematically in Figure 14–8. Fluid is forced to flow through the specimen by applying different pressures at either end. The permeability *(k)* can be expressed in terms of the discharge (q, volume per unit of time) through the core, the length (L) of the core, the pressure difference ($P_1 - P_2$), and the viscosity (μ) of the fluid:

$$k = \frac{q\mu L}{P_1 - P_2} \qquad (14\text{–}10)$$

The permeability has units of area, the most common being the *darcy*, which has as its value 1 darcy = 0.987×10^{-8} cm^2; and the *millidarcy*, with the value 1 darcy = 1000 millidarcies.

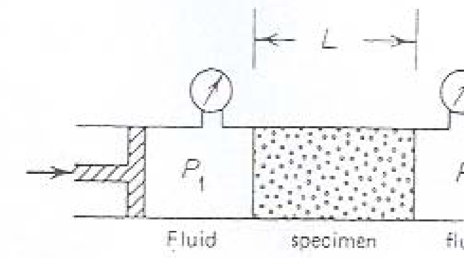

Figure 14–8

Schematic diagram of the apparatus
permeability in rock cores. Pushing i
on the left and drawing out the plun
right makes the pressure P_1 in the le
higher than the pressure P_2 in the ri
This pressure difference causes fluid
through the specimen from the left c
the right chamber.

Using permeability measureme
stone cores, G. E. Archie showed
of *k* and the corresponding forma
ity factors *(F)* plotted close to a str
a logarithmic graph (Figure 14–9
other factors such as the capillary
depends on the diameters of the
interconnected pores, also influen
other factors cause the inclinatio
straight line to change too much f
place to obtain a reliable relation
only on *k* and *F*.

Additional experimentation h
that capillary force effects can be
in terms of the capacity of the ro
water. We know that migrating h
fluids are able to displace all but a
minimum amount of water. This
fraction of water is called the *irre*
saturation (S_{irr}). The value of S_{irr}
mated from resistivity measureme
a reservoir formation in which w
tion is decreased to the irreducibl
by hydrocarbon displacement.

A relation between permeabili
formation resistivity factor is evide

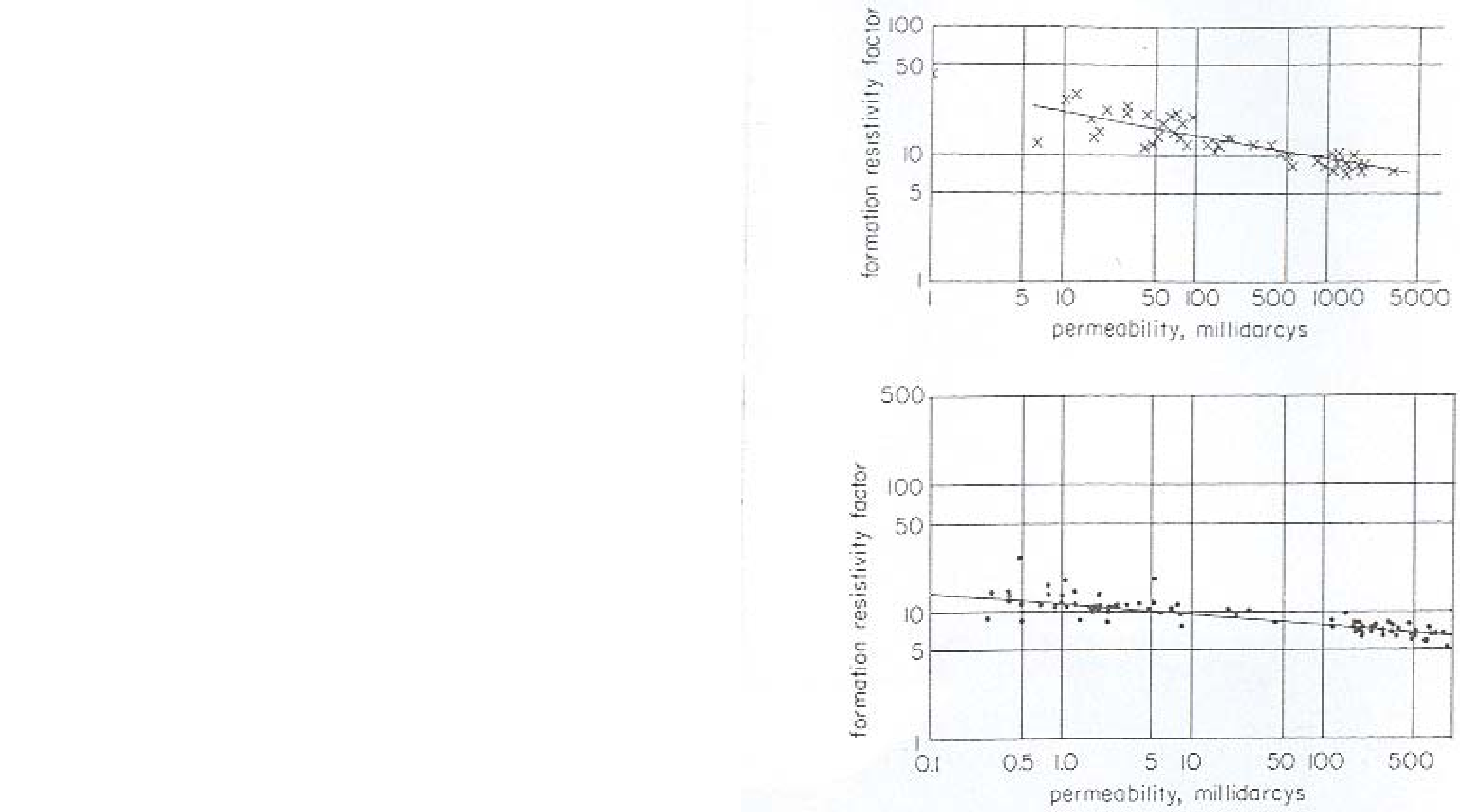

Figure 14–9
Graphs of the variation of formation factor (F) with permeability (k), based on values measured in sandstone cores from two regions. (From G. E. Archie, *Transactions of the AIME*, v. 146, pp. 54–62, 1942.)

14–9. We know from Equation 14–2 that the formation resistivity factor also depends on porosity. These two facts suggest that permeability is influenced by porosity. Measuring permeability in rock cores having different porosity and water saturation tests the combined effects of porosity and capillary force. Graphs of the results indicate the following approximate relation,

$$k \cong (C\varphi^3/S_{irr})^2 \qquad (14\text{–}11)$$

where the constant C depends on the lithology and average grain size of the rock. The problem with using this formula permeability is that values of φ, must first be estimated from well ments. Any error in φ will be m fold, and errors in S_{irr} and C will b twofold in the estimate of k. Thes out why permeability is a difficult measure.

We have now introduced some mulas that are used for quantitati evaluation. To use these formulas able to measure electrical propert tivity, and sonic wave speeds in We turn now to the well logging p provide this information.

ELECTRIC LOGGING

Electric logging is the procedure ing the resistivity and the natural tential in the formations penetrate The measurements are made wi the sonde, which moves in the wel on a wire line. Electrodes on th connected in different circuits t signed to test the resistivity in dif of the formation and to detect the tential, more commonly called the *potential* (SP). It is necessary to test ity in different zones to correct fo of invasion by a drilling fluid that tivity different from that of the r fluid. We now describe each of used in conventional electric log tions.

Special Forms of Ohm's Law

The basis for resistivity logging is which was introduced in Chapte again at Equation 13–8, which is

Ohm's law used in the analysis of resistivity measurements made with the electrodes placed on the land surface. Recall that in a homogeneous material, current spreads out from the source electrode through concentric hemispherical shells (Figure 13-3). The factor 2π in Equation 13–8 originates from the expression of the area of a hemispherical surface of radius r, which is $2\pi r^2$.

The situation will be different if the electrodes are placed underground so that current can spread out through concentric spherical shells (Figure 14–10) rather than hemispherical shells. Because the area of a sphere of radius r is $4\pi r^2$, the factor 2π in Equation 13–8 must be changed to 4π in the equation we use in the analysis of resistivity measurements made in wells. Otherwise, the same reasoning is used to obtain the following expression of Ohm's law,

$$v_{MN} = \frac{IR}{4\pi}\left(\frac{1}{AM} - \frac{1}{AN} - \frac{1}{BM} + \frac{1}{BN}\right) \qquad (14\text{–}12)$$

where v_{MN} is the change in potential between two electrodes M and N, I is the current flowing between a source electrode A and a sink electrode B, R is the resistivity of the material in which the electrodes are embedded, and AM, AN, BM, and BN are distances between the electrodes (Figure 14–11).

Let us consider the zone that is tested with the electrode arrangement in Figure 14–11. Observe that electrodes M and N are situated on two equipotential surfaces. The potential difference v_{MN} is related to the flow of current I and the resistivity R everywhere in the shaded zone between these two surfaces. If the electrodes M and N were placed at any other points on these surfaces, the same value of v_{MN} would be measured. The entire shaded zone between these equipotential surfaces is tested.

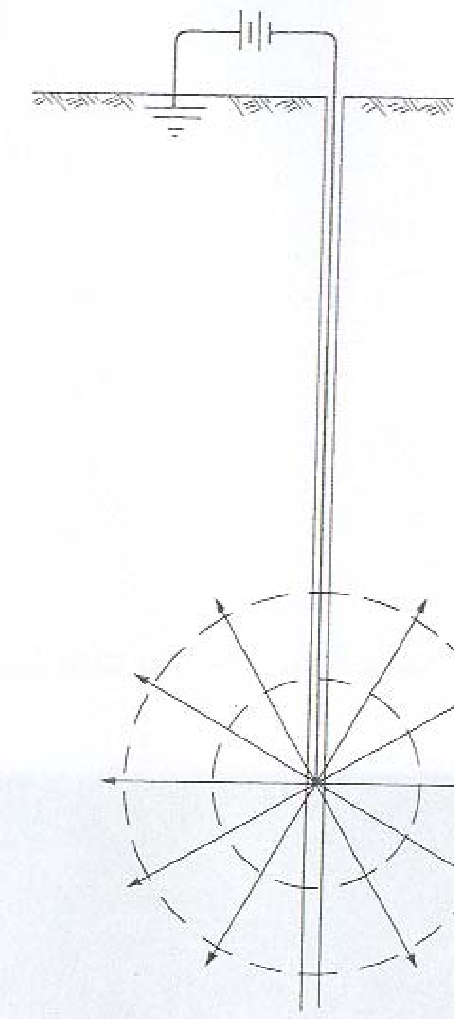

Figure 14–10
Spherical radiation of electric current
a homogeneous formation from a sou
situated underground, far from the s
situated on the land surface.

We can express Ohm's law in
that apply to particular electro
ments. It is common practice in
ging to place the sink electrode
surface far from the other electroc
this practice makes the distances I
very large, the terms 1/BM and 1/

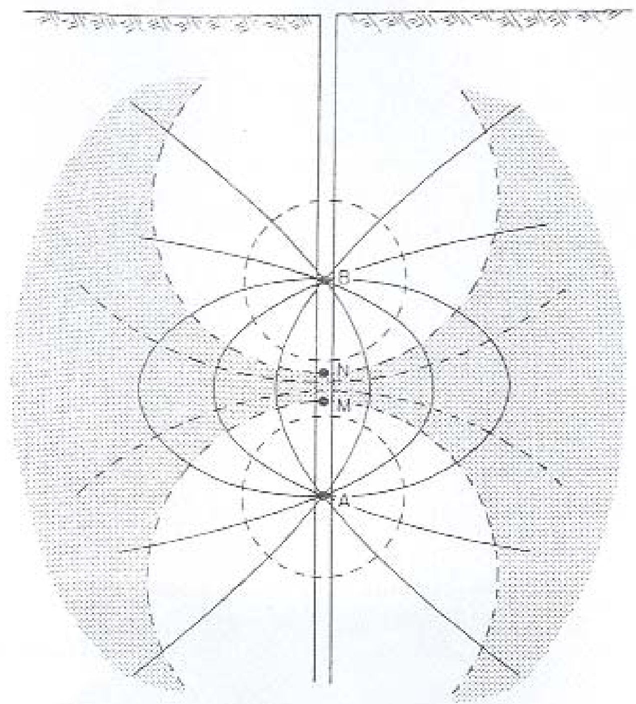

Figure 14–11

Current rays (solid lines) and equipotential surfaces (dashed lines) illustrating the flow of current and the electric field between a source electrode (A) and a sink electrode (B) situated underground in a homogeneous formation. The difference in potential measured between two other electrodes M and N is affected by all the material in the shaded zone between the equipotential surfaces on which M and N are located.

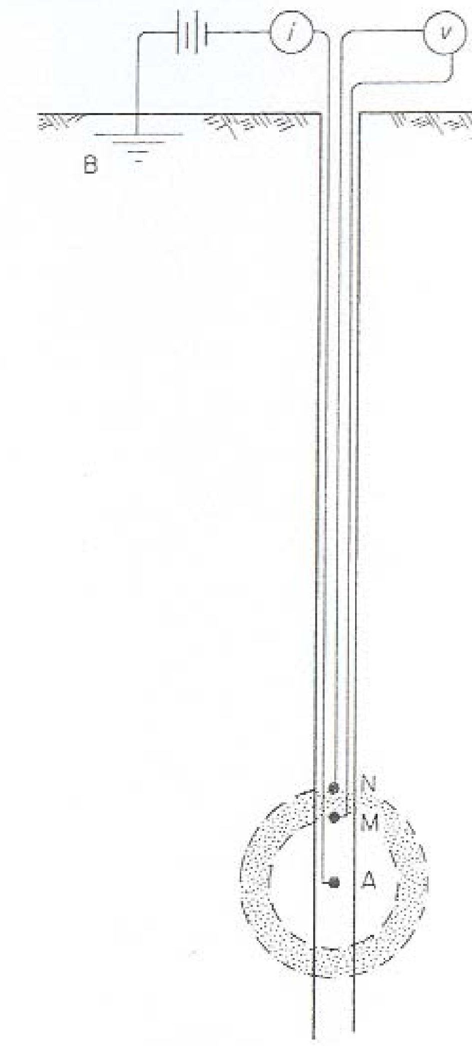

Figure 14–12

Electrode arrangement in which the so electrode (A) is located far from the sin (B), and the difference in potential (v) between the M and N electrodes that a close to A and far from B. The value o affected by all the material in the spher having an inner radius AM and an out AN.

very small and can be neglected. Equation 14–12 can then be modified to the form

$$v_{\mathrm{MN}} = \frac{IR}{4\pi}\left(\frac{1}{\mathrm{AM}} - \frac{1}{\mathrm{AN}}\right) \quad (14\text{–}13)$$

In this arrangement, the M and N electrodes are situated on nearly spherical equipotential surfaces, with the A electrode at the center. Therefore, the zone being tested is a spherical shell with inner radius AM and outer radius AN (Figure 14–12).

Let us consider another electrode arrangement in which A and M are close together, and both B and N are placed far away. Because AN is very large, the term 1/AN becomes small enough to neglect. Equation 14–13 can then be modified to obtain

$$v_{MN} = IR/4\pi\ \mathrm{AM} \qquad (14\text{–}14)$$

The zone tested by this electrode arrangement is a thick shell with inner radius AM and a very large outer radius (Figure 14–13). However, most of the change in potential occurs in the innermost part of this shell. We can understand why by considering the change in potential that would be measured if the N electrode were placed at the distance AN = 2AM. By substituting 2AM for AN in Equation 14–13, we obtain $v_{MN} = 0.5 \times IR/4\pi\mathrm{AM}$, which is one-half the value of v_M given by Equation 14–14. This tells us that one-half of the change in potential found from Equation 14–14 occurs within a distance of 2AM from the source electrode. If the N electrode is placed at the distance AN = 10AM, the same analysis indicates that 90 percent of the potential change found from Equation 14–14 occurs within a distance of 10AM from the source electrode. It is clear, then, that even when the N electrode is placed far from A and M, measurements are the most strongly influenced by rock in a relatively thin spherical shell with the inner radius AM. The gradational shading in Figure 14–13 illustrates how the effect of rock within this zone diminishes with distance from the inner equipotential surface.

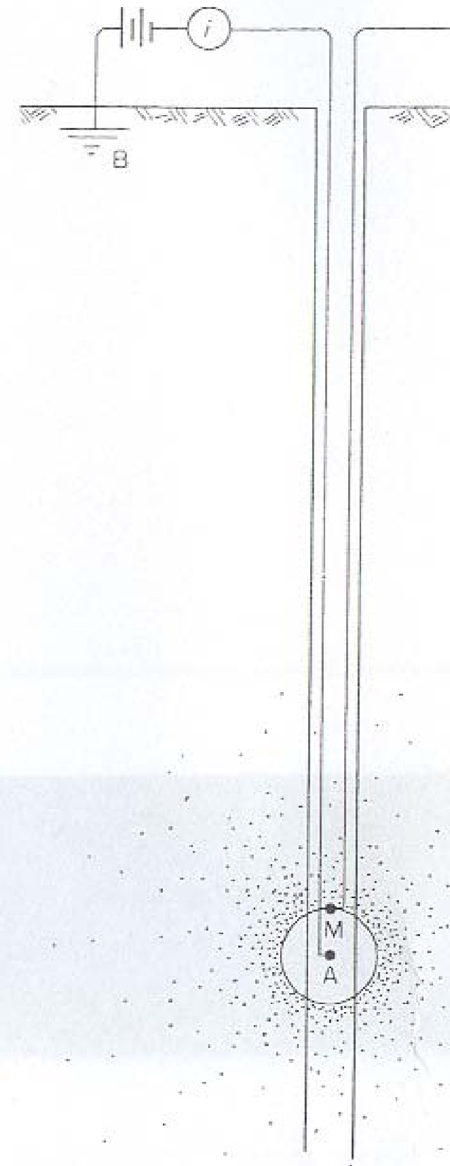

Figure 14–13
Electrode arrangement in which the s
(A) is located far from the sink electro
difference in potential (v) is measured
M electrode, placed near A, and the N
which is placed far from M. The value
by all the material in a spherical shell o
AM and outer radius AN, but material
has a much larger influence than mate
from M, as illustrated by the gradation

Normal Logs

One of the most widely used electrode arrangements for logging resistivity is called the *normal* electrode configuration (Figure 14–14). Only the source electrode A and the potential electrode M are mounted on the sonde. The sink electrode B and the other potential electrode N are situated far from the sonde. A

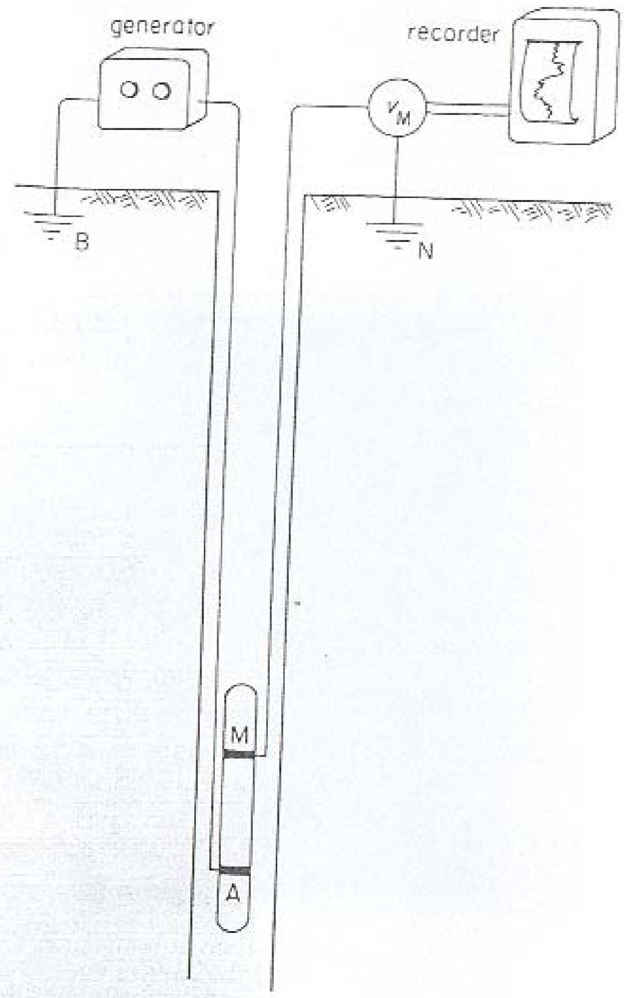

Figure 14–14
Schematic diagram of a normal logging circuit. The source electrode A is far away from the sink electrode B, and the electrode M is far away from the electrode N. The difference in potential v_M is measured between M and N.

generator connected betweer
plies a constant current I, an
potential v_M is measured con
voltmeter connected between
voltmeter output is plotted c
the *normal log,* as the sonde m
For this electrode configuratio
R is found by rearranging I
into the form

$$R = \frac{4\pi AM}{I} v_M$$

Because the A amd M electro
distance apart on the sonde an
held constant, we see that R
with v_M. Therefore, the strip
scaled in resistivity units (usua
or ohm-feet) rather than in vo
possible to read resistivity dir
log.

A normal logging sonde mov
very thick homogeneous format
a continuously changing zone
illustrated in Figure 14–13. But
logging is not done in a homo
ronment. The zone of testing in
contrasting resistivity, and the s
operated in a well filled with
which has yet another resistivity.
anating from the A electrode
through the drilling mud and t
formation. Rays representing thi
rent refract into different direc
boundary where the resistivity c
ure 14–15). Observe how the c
equipotential surfaces, which mus
dicular to these rays, are distort
spherical shapes. Because these e
surfaces indicate the shape of the
ing, it is clear that this zone will n
ically symmetrical, and that its
change as the sonde moves throu

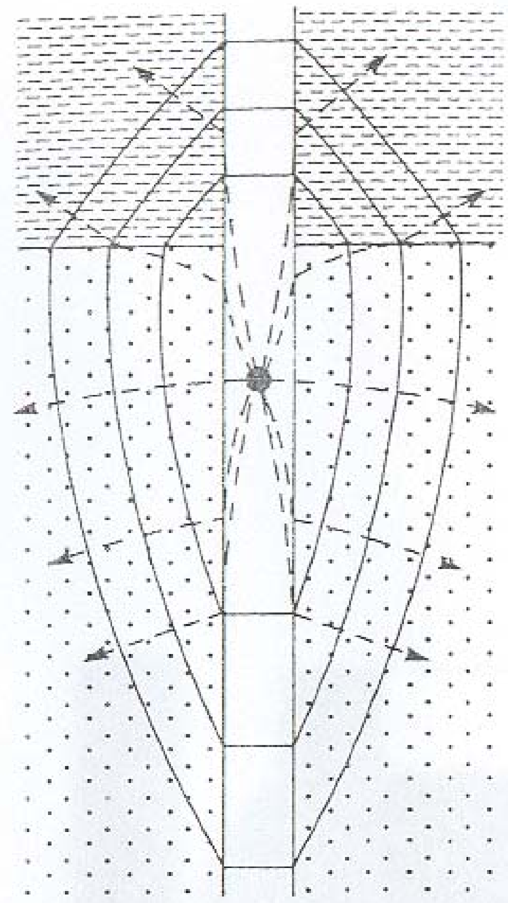

Figure 14–15

Refraction of current rays at the side of the well and at a boundary between two formations of different resistivities. (From Interpretation Handbook for Resistivity Logs, *Schlumberger Document No. 4,* Schlumberger Well Surveying Corporation, 1951.)

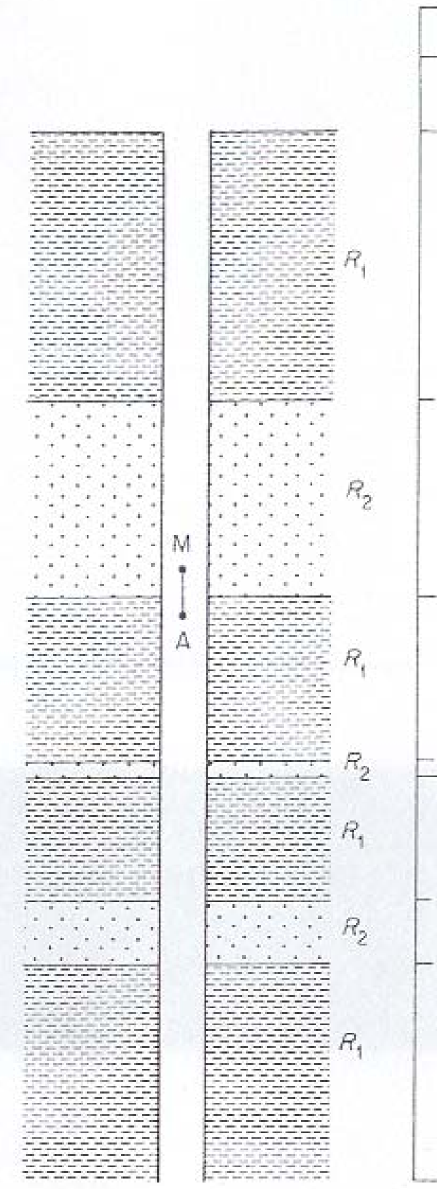

Figure 14–16

Idealized normal log variation at bo
between beds of different thicknesse
contrasting resistivities. Contrasts be
and low resistivity are properly indic
considerably thicker than the distanc
and M. For the thin bed, the respon
which gives an incorrect indication o
resistivity contrast.

this heterogeneous environment, Equation 14–15 expresses only an apparent resistivity that depends on the proportions of the zone of testing which have contrasting resistivities.

Suppose that we obtain a normal log in a well that penetrates beds of contrasting resistivities. An idealized example (Figure 14–16) illustrates how the apparent resistivity changes as the sonde moves through the well. Observe that there are no abrupt changes in R as the sonde passes bed boundaries. Rather, we see gradational changes. The reason why is that the A and M electrodes mark the inner radius of a zone of testing that reaches beyond the dimensions of the sonde. Therefore, the zone of testing moves through a bed boundary before the sonde actually passes this boundary. Therefore, a nearby bed influences the apparent resistivity measurements, even though the sonde is still moving through another bed.

Observe in Figure 14–16 that the apparent resistivity measured with the sonde near the center of a thick bed comes closest to the true formation resistivity R_t. Here the bed occupies most of the zone of testing, and distortion caused by the beds above and below is at a minimum. For beds that are thicker than 10AM, the measured resistivity should differ from R_t by less than 10 percent near the center of the bed. For thinner beds, the value of R_t is not accurately indicated on a normal log.

There is a particular problem when a bed thinner than AM is encountered. Look at the apparent resistivity variation near the thin layer in Figure 14–16. Small increases appear at its upper and lower boundaries, but low apparent resistivity is indicated near the center where R_t is high. This distortion results from refraction of current rays, which occurs when the A electrode is below the layer and the M electrode remains above it. The proportion of current flowing in the layer is reduced so that an incorrect measure of resistivity is recorded.

Another factor affecting the measurement of apparent resistivity is invasion. Insofar as the resistivity of the drilling mud differs from that of the natural pore fluid it has displaced, the resistivity in the invaded zone will be different from R_t. Therefore, where invasion is deep, even the apparent resistivity

measured near the middle of a th
quite different from the true fo
tivity.

One aim of electric logging is
for purposes of calculating the
ration, and permeability of a f
the problems posed by thin bed
prevent us from obtaining accu
ments? To overcome these diffi
gin by finding bed thickness a
the depth of invasion. We do th
ing electric logs recorded with
trode spacings. The comm
throughout most of the petrole
to record a short normal log with
ing of 16 inches, and a long no
an AM spacing of 64 inches, as
logs, which we will discuss later.

What can we learn from lo
normal logs? Consider first the
sion. Suppose that resistivity in
fluid is higher than the resistivit
ral pore fluid. The effect of inva
increase the resistivity R_i in the
so that $R_i > R_t$. Next, consid
tested by long and short norma
the long normal log, this zone
reaches farther into the undistu
the formation. Invasion affects a
portion of this zone compared
portion of the zone tested by the
log. Therefore, the long normal
cate a lower value of apparent re
difference can be seen in Figure
both long and short normal lo
high-resistivity bed between th
1750 and 1820 feet. The appar
values indicated by these logs
pared with values read from sta
tion charts that have been calcula
els consisting of beds wi
thicknesses, resistivity contrasts, a

invasion.[1] The true resistivity R_t and the depth of invasion are found from the particular chart that best reproduces the apparent resistivities on the 16- and 64-inch normal logs.

Even though the short normal log is more adversely affected by invasion, it is useful for detecting thin beds, which are incorrectly represented on a long normal log. Compare the logs in Figure 14–17 near 6677 feet. Here only the short normal log properly indicates the presence of a high-resistivity bed which must be between 16 and 64 inches thick.

The Lateral Log

Another way to measure resistivity is with the *lateral* electrode configuration (Figure 14–18). The M and N electrodes are placed near each other on the sonde. Farther away in the well is the A electrode, and very far away at the land surface is the B electrode. In the petroleum industry the M and N electrodes are usually spaced 32 inches apart and the A electrode 18 feet, 8 inches from the point O situated midway between M and N. Because it is impractical to operate a sonde of this length, the A electrode is mounted on the wire line above a shorter sonde. The lateral log is almost always operated in combination with normal logs or other kinds of electric logs.

As with normal logging, the procedure in lateral logging is to supply constant current I from the generator connected between A and B. The potential difference v_{MN} is measured continuously with a voltmeter connected between M and N, as the sonde moves through

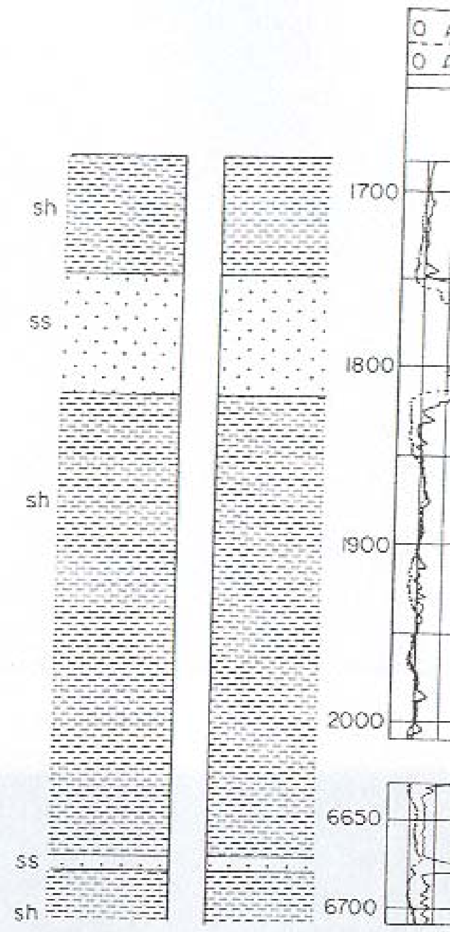

Figure 14–17
The effect of invasion on apparent r
measured with 16-inch and 64-inch
logging devices. The 16-inch normal
strongly influenced by the high-resis
zone in the thick sandstone layer. Th
normal log does not properly detect
sandstone bed near 6680 feet.

the well. Because the spacing of
remains fixed, this potential diff
in direct proportion with resistiv
to Equation 14–13. The lateral lo
by recording the voltmeter outp
chart scaled in resistivity units.

In a very thick, homogeneou

[1]Interested readers can find correction charts for normal logs and other kinds of well logs in George B. Asquith and Charles B. Gibson, *Basic Well Log Analysis for Geologists*, Tulsa, Okla., American Association of Petroleum Geologists, 1982.

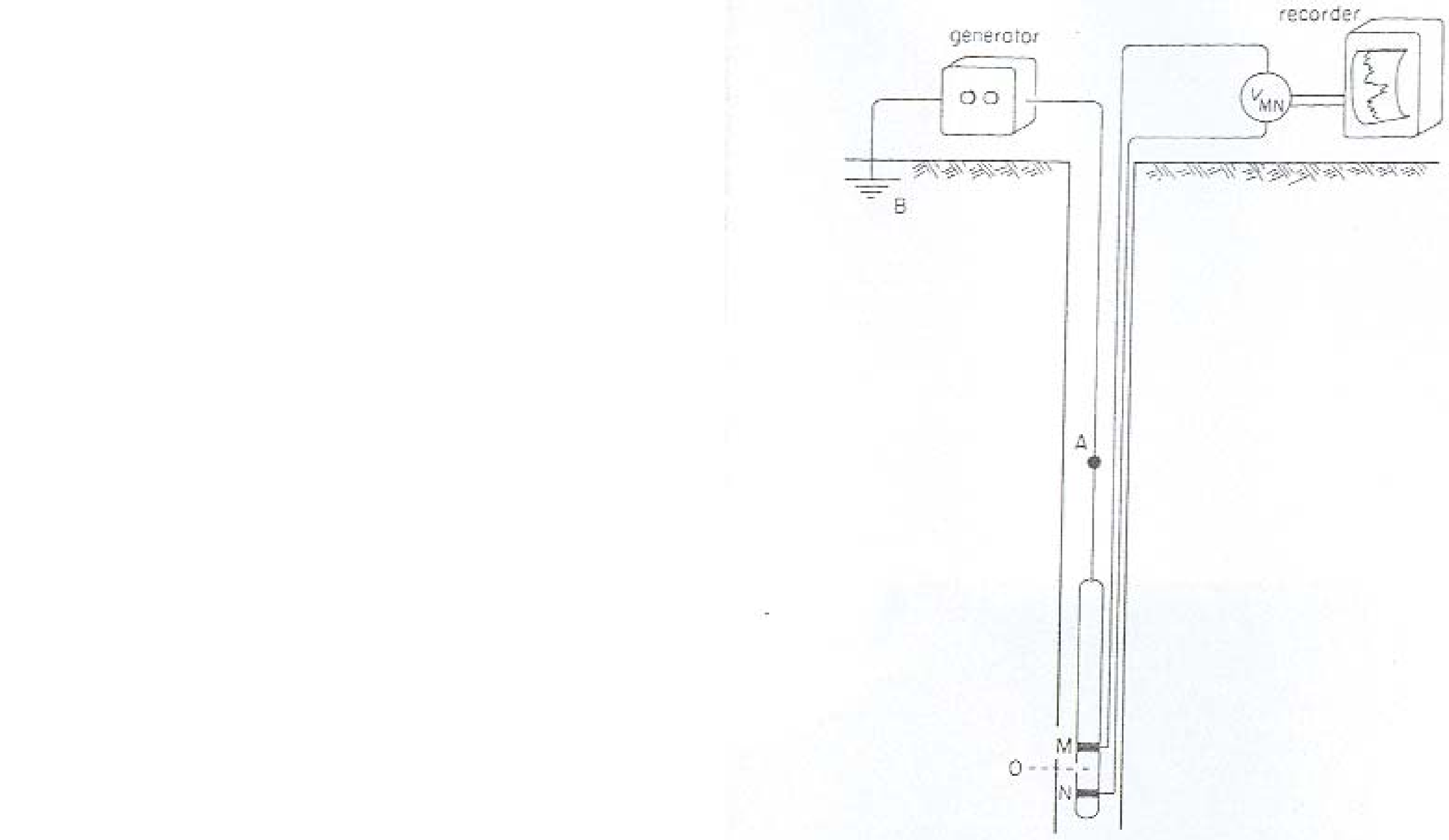

Figure 14–18

Schematic diagram of a lateral logging circuit. The M and N electrodes are quite close to the source electrode A but remain far away from the sink electrode B.

the lateral log would test a spherical shell with inner radius AM and outer radius AN (Figure 14–12). However, in an environment consisting of beds of contrasting resistivities, the zone of testing is distorted into a nonspherical shell because of the refraction of current rays (Figure 14–15). Regardless of this distortion, the zone tested by lateral logging reaches much farther from the well than the zones tested by conventional normal logging. For this reason, a much larger proportion of the

lateral zone occupies formatio
contaminated by invasion. Ther
parent resistivity measured in a
lateral logging tends to be closer
values obtained from normal log

Lateral logs have peculiar var
parent resistivity near bed boun
distortions are related to the refr
rent rays that occurs where the M
trodes are moving through one b
A electrode is still moving thro
overlying bed. This refraction p
typical features of a lateral log t
trated in Figure 14–19.

First, let us examine the variati
ent resistivity related to the thick
high resistivity. Observe the sm
that appears close to its upper bo
occurs because the M electrode ha
low the boundary while the N e
mains above it, where the current
ented differently. Apparent
increases gradually after N move
boundary, and then increases m
when the A electrode passes be
change ceases in the middle part
where the apparent resistivity le
value close to R_t. A sharp rise is re
the base of the bed, reaching a ma
close to its lower boundary as the
moves below. After N passes thi
the apparent resistivity decreases
mediate level and then diminishe
ter A, too, moves below the bed.

A different pattern of variation
the thin, high-resistivity layer in Fi
The small decrease that is recorde
then N pass the upper boundary
by a sharp increase, reaching a pe
these electrodes pass the lower bou
log decreases sharply after M a
moved below the bed. Then, at t

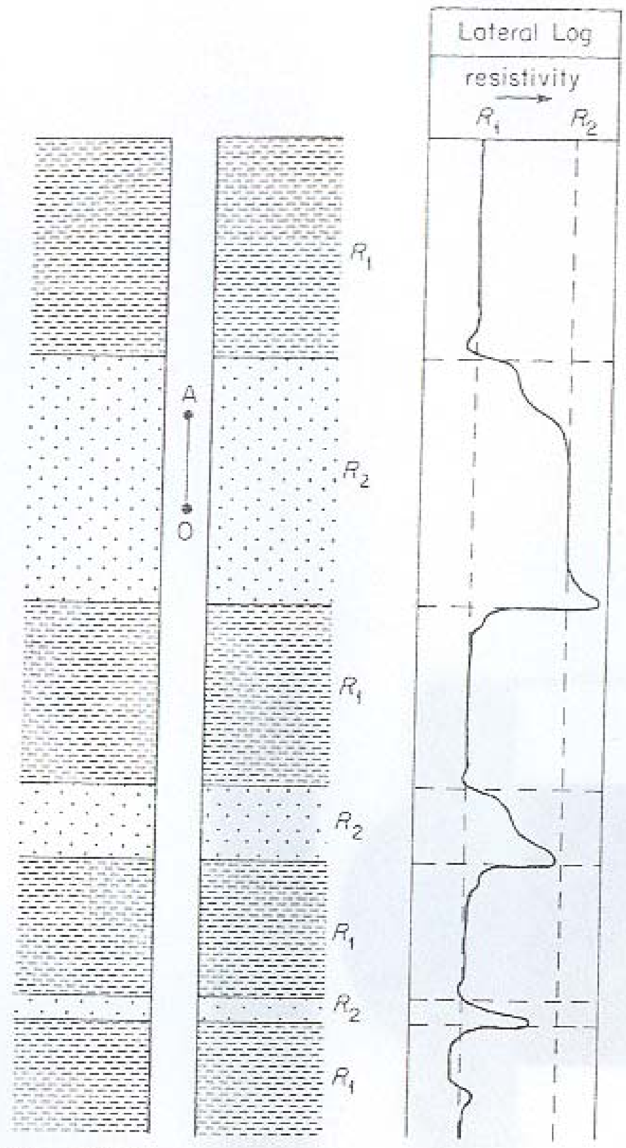

Figure 14–19

Idealized lateral log variation at boundaries between beds of different thicknesses and contrasting resistivities. The spurious effects are measured close to the bed boundaries and at a distance below a thin bed that is equal to the AO electrode spacing.

AO beneath the bed, a small r
crease is indicated. This effect is
change in current refraction as
trode moves through the thin bed
pletely spurious variation that sh
mistaken for the effect of another

The advantages of a lateral lo
with normal logs are (1) a more ac
sure of R_t in the middle part of
and (2) a much sharper indication
bed boundary. A similarly sharp i
the upper bed boundary can be
lateral logging with the A electrod
neath M and N. Deep invasion ca
some distortion in the resistivity r
lateral log, albeit less severe than t
mal logs. Corrections for the effe
sion can be estimated from stand
similar to those used in normal l
The spurious resistivity variations
corded below thin beds are a seriou
tage of lateral logging. When clo
thin beds are encountered, it can
ficult to interpret lateral logs.

The Laterolog

The electric logs that we have been
are often referred to as unfocuse
cause no attempt is made to contro
tion of current flow. It spreads out
directions from the A electrode
fracted at boundaries where resis
trasts exist (Figure 14–15). There
procedure, called *laterologging*, in
cuits are designed to focus the curr
ticular ways.

The most widely used laterologgi
direct the current in a sheet that sp
izontally outward from the well. O
accomplishing this is illustrated

14–20. The sonde consists of a short electrode centered between two long electrodes, called the *guard* electrodes, which are connected to each other. Current, which can be controlled separately for the guards and the central electrode, is adjusted automatically to maintain all of these electrodes at the same fixed potential. It then becomes impossible for current to flow

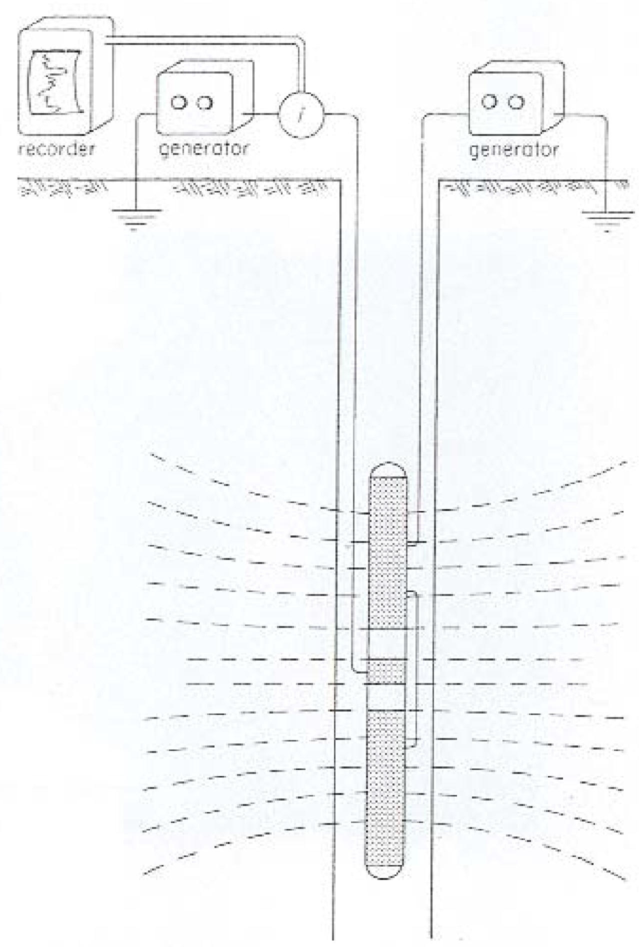

Figure 14–20
Schematic diagram of a laterologging circuit. The effect of the guard electrodes above and below, which are held at the same potential, is to make nearly horizontal current rays (dashed lines) flow outward from the center source electrode.

from any one of these electrode
other. Therefore, current from
electrode must move outward in
sheet. Because the potential i
amount of current from the cent
varies in proportion to the resis
formation into which it flows. Th
plotted on a strip chart scaled
units to obtain the *laterolog*.

Laterologging sondes ordinarily
electrodes that are more than fi
The length of the central elect
from as short as three inches to
one foot. The zone tested by the l
circular disk (Figure 14–21) with
approximately equal to the centr
length. Within this zone, the ro
the well has the greatest effect on
measurement. Closely spaced rays
greatest current intensity. The ef
farther from the well diminishes
spread apart.

Compared with unfocused elec
laterolog is much more sensitive t
It can properly detect a bed as thi
tral electrode length. If the effect
is small, the apparent resistivity re
laterolog is close to R_t. However,
sion can introduce significant dis
cause the invaded zone is close to
has a proportionally larger effect o
olog than on unfocused electric l
the principal disadvantage of th
Corrections can be determined fro
charts if the depth of invasion can b
independently from normal and

Induction Logging

Up to this point, we have been con
logging devices that introduce curr

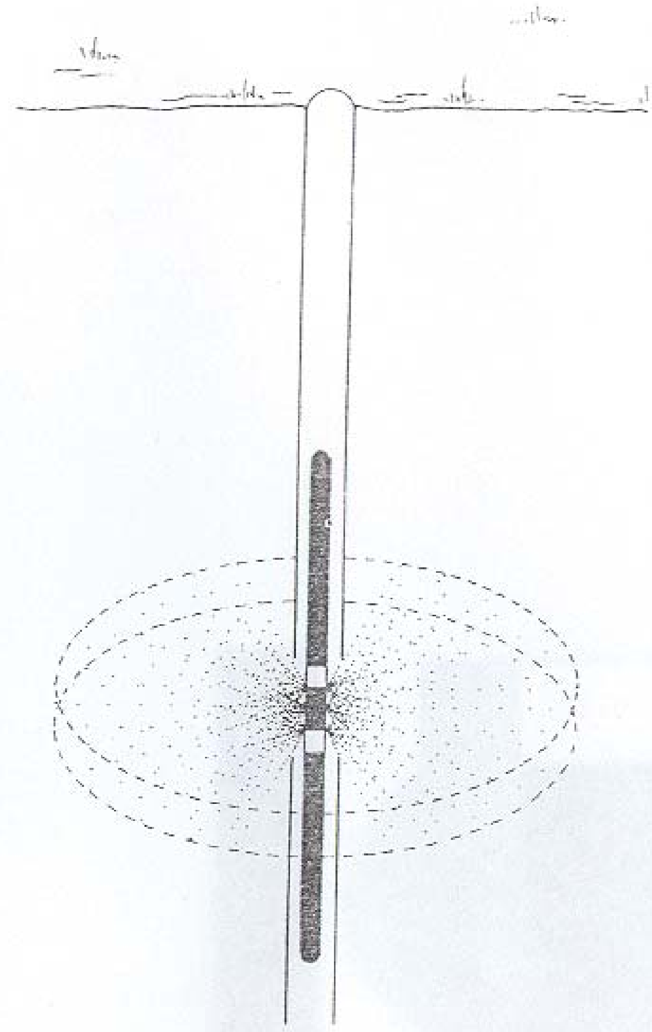

Figure 14–21
The zone tested by a laterolog is a circular disk with a thickness equal to the length of the central electrode. The material closest to the well has the strongest influence on the resistivity measurement. Influence diminishes gradationally with distance from the well, as illustrated by the gradational shading.

formation by means of electrod
a sonde. To reach the formatio
first flow from the electrode thr
ing fluid to the side of the wel
that the well is filled with nonco
the sonde will be insulated and
of introducing current into t
This difficulty can be encou
crude oil rather than water is us
the drilling mud.

A different procedure, *indu*
has been developed for opera
filled with nonconducting fluids.
of coils rather than electrode
mounted on the sonde. Electr
duction is the means for introd
into the formation and for mea
fects. Unfocused induction log
done with a two-coil sonde (Figu
generator produces alternating c
transmitting coil. This alternatin
ates an alternating magnetic fie
gion surrounding the coil, which
the formation. Electromagnetic
sociated with this field compels cu
through the formation in circula
tered on the well. This alterna
current creates a secondary magn
compels current to flow in the r
again by electromagnetic inducti
tensity of the ground current vari
tivity, and so do the secondary m
intensity and the induced curren
ceiving coil. The induced curren
ceiving coil is recorded on a strip
tain an unfocused induction log.

Suppose that the sonde is plac
thick homogeneous formation. Th
sible to calculate the intensity of
magnetic field and the correspon
sity of the ground current at any
formation. Such calculations hel

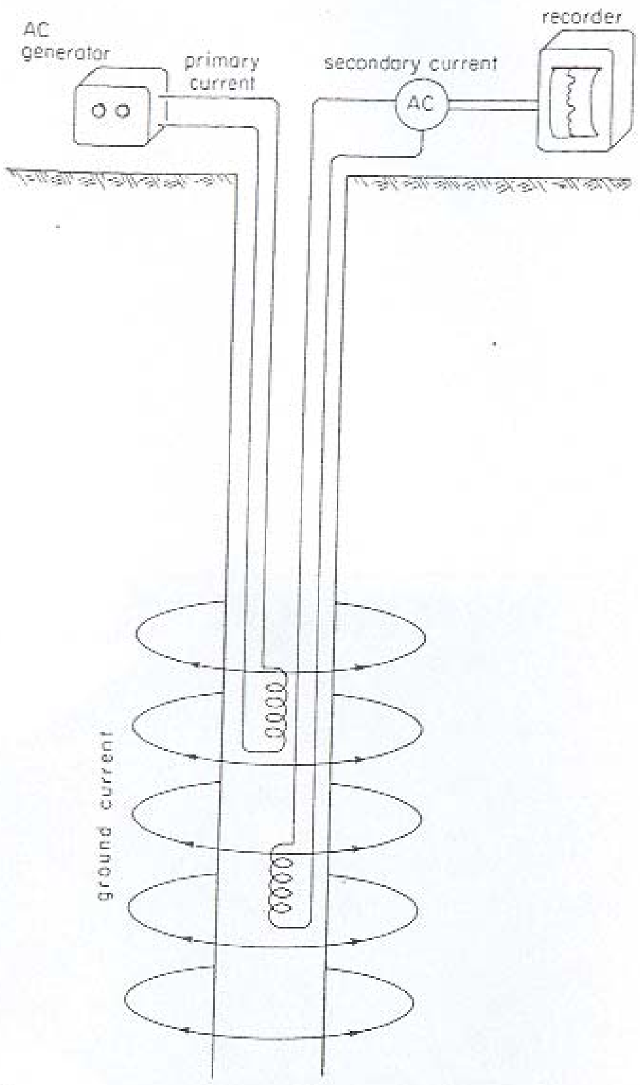

Figure 14–22
Schematic diagram of an unfocused two-coil induction logging circuit, showing the ground currents induced by the alternating magnetic field of the primary coil. The alternating magnetic field associated with these ground currents induces alternating current in the secondary coil.

mine the zone that is tested by t
logging procedure. Graphs in Fig
lustrate how the effect of differen
formation vary with distance fro
They show that the ground curre
trated mostly in the zone within
about three times the coil spacing

An unfocused induction log r
dational change in apparent resi
sonde passes the boundary betw
of contrasting resistivity. This is s
ure 14–24. In a thick bed in whi
is more than three times the coil
either the upper or lower bounda
sured apparent resistivity should
unless the results are distorted
Corrections for invasion can be
from standard charts, but additio
tion is required; this information
be obtained from other kinds of l

Observe in Figure 14–24 th
points on the induction log lie clos
boundaries. These inflections can
to identify. A sharper indicati
boundaries can be obtained by n
cused induction logging. This
quires additional control on th
ground currents, which is accon
adding more coils to the transmitt
ceiving circuits. The simplest focu
are shown in Figure 14–25. Two
coils are used. One is in series wit
nal transmitting coil but is situated
original receiving coil; the other
with the original receiving coil bu
near the original transmitting coil.
tained with this arrangement is
with the unfocused log in Figure
focusing coils produce a sharper in
bed boundaries, but they introduc
oscillations in apparent resistivity.
focusing coils can be arranged in

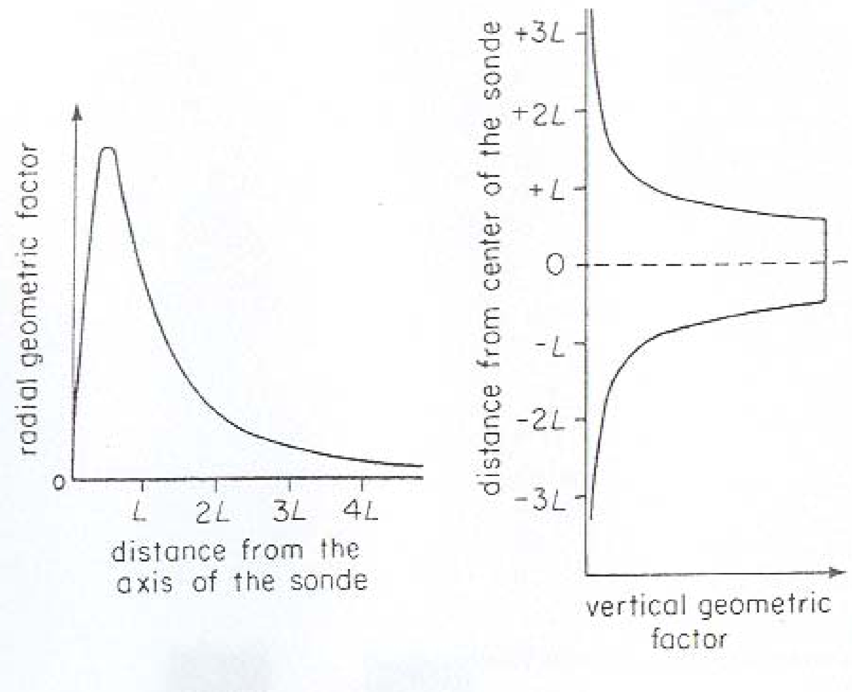

Figure 14–23
Graphs illustrating th
by an unfocused two-
logging circuit. Geom
read from these grap
the relative influence
different distances aw
well and above or bel
(From H. G. Doll, Int
induction logging anc
to logging of wells dr
base mud, *Journal of P*
Technology, AIME, p.
1949.) The distance is
units of coil spacing.

plicated circuits to suppress these oscillations while retaining the steeper change in apparent resistivity at the bed boundary.

The induction log was introduced for the purpose of testing wells filled with nonconducting drilling mud. This logging procedure can also be used in wells containing mud that does conduct current.

Spontaneous Potential Logging

Natural potential differences have been found to exist near bed boundaries. The circuit for measuring these so-called *spontaneous potentials* (SP) is quite simple. A voltmeter is connected between an electrode mounted on a sonde and another electrode fixed at the land surface (Figure 14–26). The SP log is obtained by recording the voltmeter output on a strip chart.

Why do spontaneous potentia
though their origin is not clearly
we have some ideas about the c
pore water solutions that have c
concentrations are in contact, i
move across the boundary to equa
centration. Insofar as some ion
more easily than others, charge
can develop, creating potential di

Consider the situation in whic
able sandstone is in contact with
impermeable shale. Suppose tha
contain the same saline pore wat
is much deeper in the sandstone
shale, however, and the NaCl conc
the mud filtrate is different from
tration in the natural pore water
near the well, along the bound
these beds, the mud filtrate in th
is in contact with the natural pore
shale.

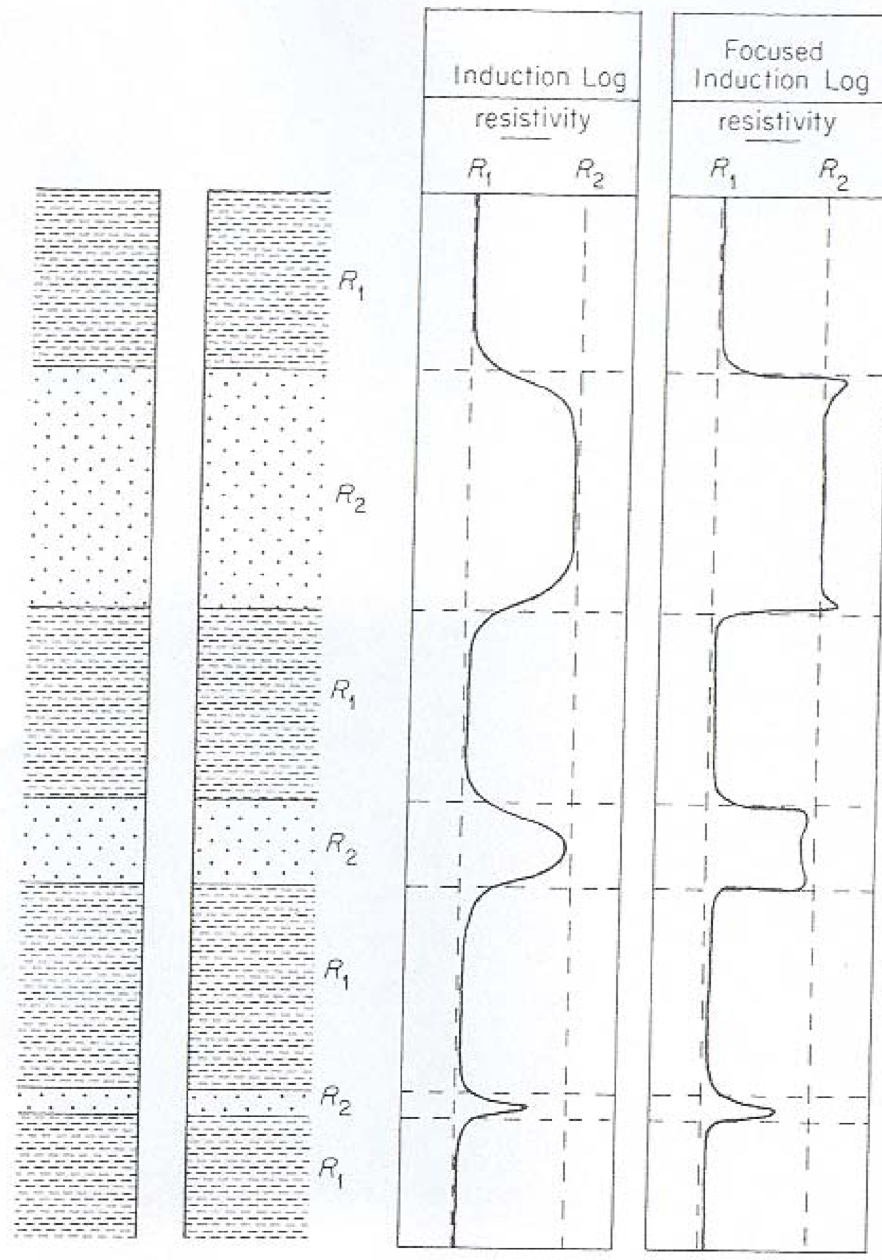

Figure 14–24
Idealized unfocused
induction log variati
boundaries between
different thicknesses
contrasting resistiviti
spurious effects are
close to the bed bou

The movement of ions to equalize the concentrations in these two solutions is impeded by surface charges on the clay particles in the shale. These charges tend to immobilize the negative chloride ions but have little effect on the positive sodium ions. Therefo
imbalance develops across the bou
a spontaneous potential is created.

In the permeable sandstone, b
and chloride ions are mobile, but

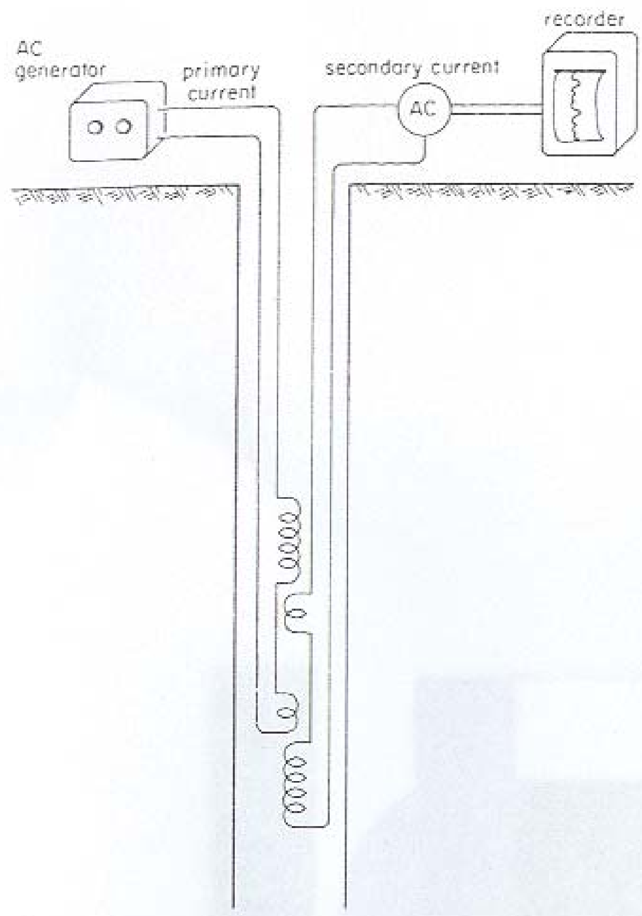

Figure 14–25
Schematic diagram of a focused four-coil induction logging circuit. Both the primary circuit and the secondary circuit contain two coils. The small secondary coil is placed close to the large primary coil, and the small primary coil is placed close to the large secondary coil.

ions tend to move more freely. Therefore, another source of spontaneous potential is the transitional boundary between the mud filtrate near the well and the natural pore water beyond the invaded zone. We do not fully understand the nature of these and other processes that contribute to spontaneous potential variations. But we can measure their combined effect; it produces a few tens to a few hundr volts.

Some important features of S seen in Figure 14–27. In a sequ stone and shale beds, a negative tential is recorded as the sor passes from shale into sandston with conventional resistivity log

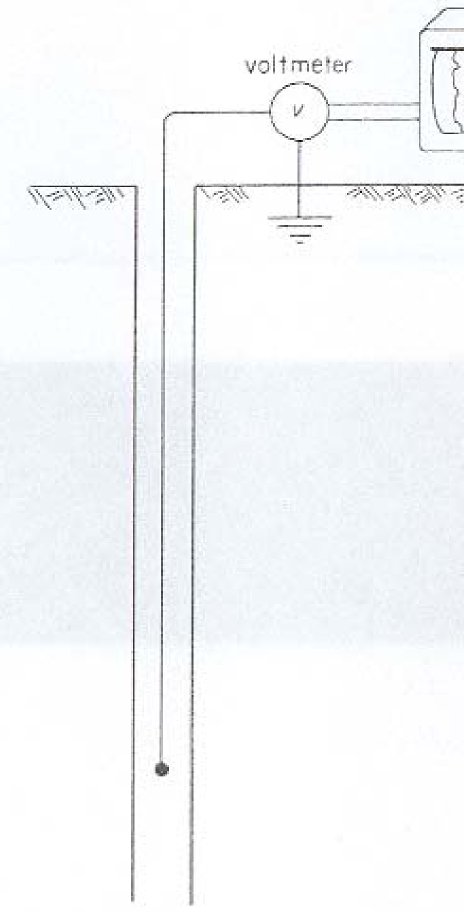

Figure 14–26
Schematic diagram of a circuit for m spontaneous potential. The potential measured between an electrode mou sonde and another electrode placed

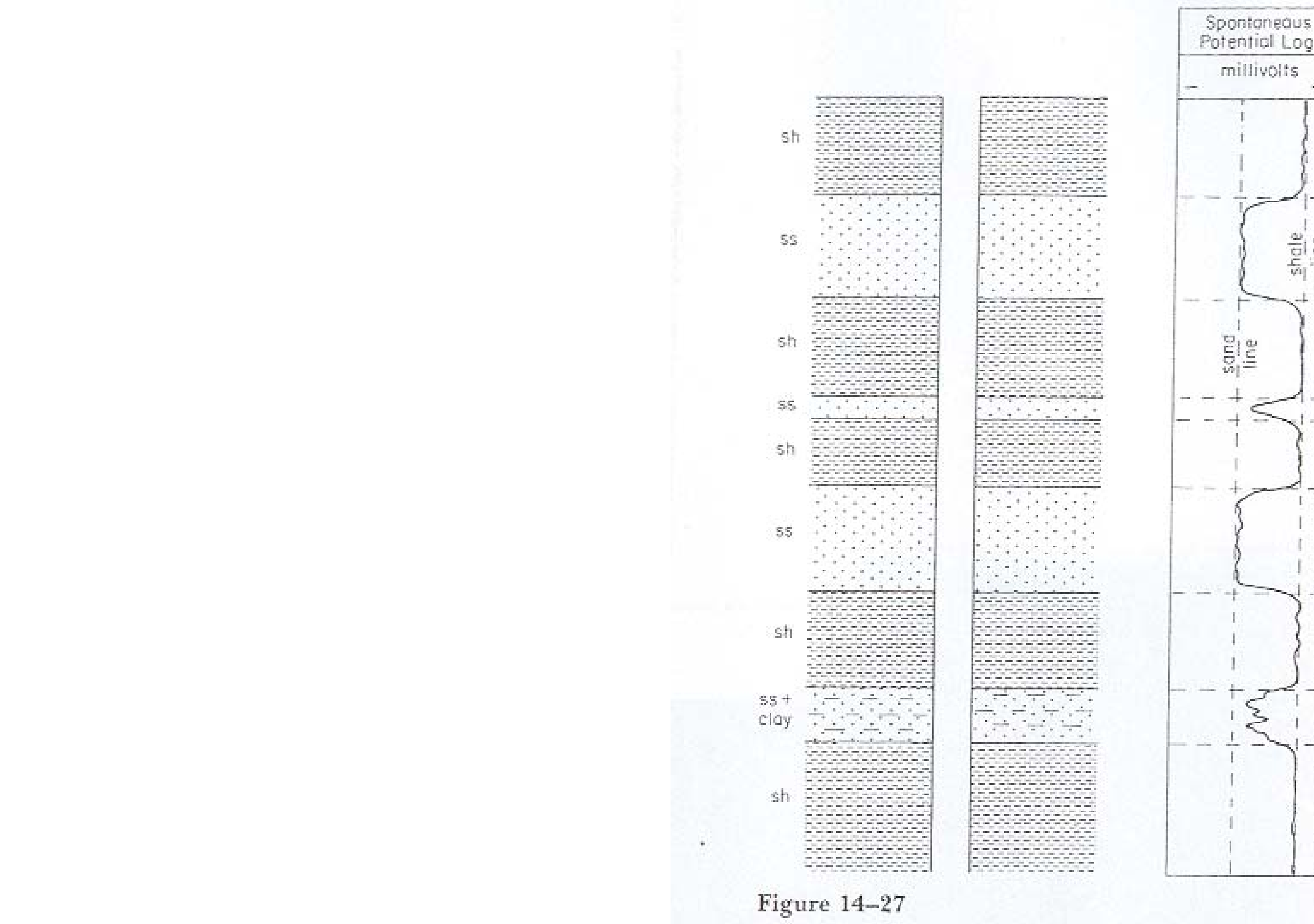

Figure 14–27

Idealized spontaneous potential variations in alternating beds of sandstone and shale. The inflection points on the log occur close to the bed boundaries.

change more steeply, with the inflection point on the curve occurring at the boundary. This feature of the SP log provides an accurate means of locating bed boundaries.

A feature observed in many regions is that all the shale beds are at approximately the same spontaneous potential. Then it is possible to draw a straight line, called the *shale line*

(Figure 14–27), along the right- the SP log, showing the alignmen of the log that were recorded in well also encounters relatively t sandstone uncontaminated by cla is not unusual to measure the s neous potential in these beds. Th *sand line* (Figure 14–27), can be the left-hand side to show the a these parts of the SP log. Hav these two SP extremes, we can clay contamination in other beds termediate spontaneous potentia sured. If an uncontaminated san thin, the sharp peak recorded on not reach the sand line. Neverthe boundaries are correctly indicate flection points above and below su

Micrologs

Special sondes have been design suring resistivity with very closely trodes. These electrodes are plac which can be pressed firmly agains a well (Figure 14–28). These electr are usually one or two inches apa nected into different circuits to o *normal* logs, *microlateral* logs, and *ogs.*

These micrologs can detect ver However, their principal purpose sure the resistivity of the mud ca well and the resistivity in the inv These measurements are of crit tance for determining correction are needed to calculate true resisti standard normal, lateral, and induc

Because the microlog electrod pressed against the side of the well has to move very slowly. It is ge

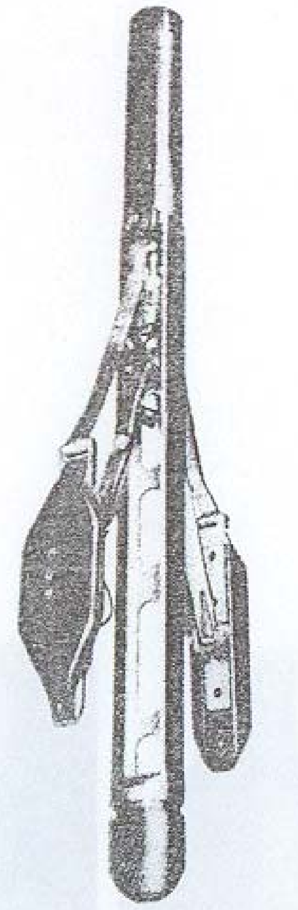

Figure 14–28
A micrologging sonde with electrodes mounted on a pad which can be pressed against the side of the well. (Courtesy of Schlumberger, Limited.)

practical to run micrologs through the entire depth of a well. Only zones of particular interest are logged.

Electric Log Combinations

The apparent resistivity measured by an electric log depends on the true resistivity R_t in a bed, the resistivity in the invaded zone, and

the resistivities in other nearby b
electrode configurations test zon
ferent proportions of these resi
by combining apparent resistivit
sured with different electrode c
can we calculate R_t.

The electric logging appara
consists of a sonde with several e
are automatically switched into
cuits, so that several logs can be
taneously on the same strip ch
sonde moves through the well.
erations, the recording equipme
tronic controls are mounted in a
also carries the winch and wire li
ing and raising the sonde (Figure
offshore operations, the same equ
stalled in a small vessel or is airlif
shore drilling platform. Differen
be attached to the wire line, each
ing a different combination of lo

The combination most widely
petroleum industry includes the
inch and 64-inch normal logs, and
8-inch lateral log (Figure 14–
very common combination incl
log, the laterolog, and two induc
both of these combinations, the S
used to locate bed boundaries, a
logs provide data for estimating
tional resistivity measurements
different sondes equipped for
can be attached to the wire line.

The trucks used for electric
usually equipped for radioactivit
well as for sonic logging. In add
chart recorders, these trucks have
recording on magnetic tape, wh
suitable for later computer pro
some carry small computers for o
sis.

Not all electric logging is don
trucks designed to operate seve

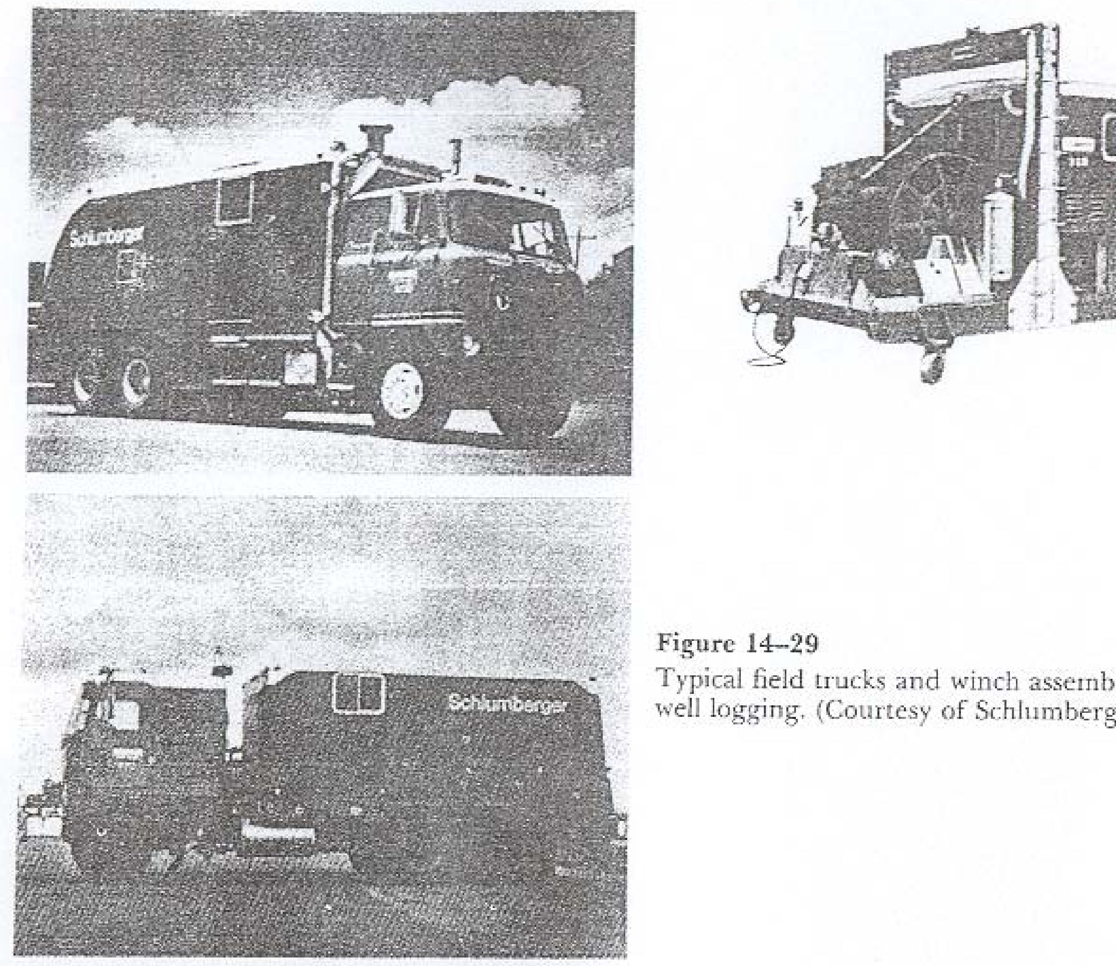

Figure 14–29
Typical field trucks and winch assemb
well logging. (Courtesy of Schlumberg

sondes. There are small, portable units that can be backpacked into remote areas for obtaining SP and normal logs and natural radioactivity logs.

RADIOACTIVITY LOGGING

The process by which particles of mass or energy are spontaneously emitted from an atom is called radioactivity. These emissions consist of protons, neutrons, electrons, and photons of electromagnetic energy that are called

gamma rays. In nature they co
unstable nuclei or radioactive ele
uranium, thorium, rubidium, a
40. Similar emissions from the st
other elements can be stimulated
ing them with gamma rays or n
dioactivity logging methods mak
natural and stimulated emissions
at three methods of radioactivity
first uses a detector mounted o
measure the gamma rays produ
active elements in a formation. I
method gamma radiation is int

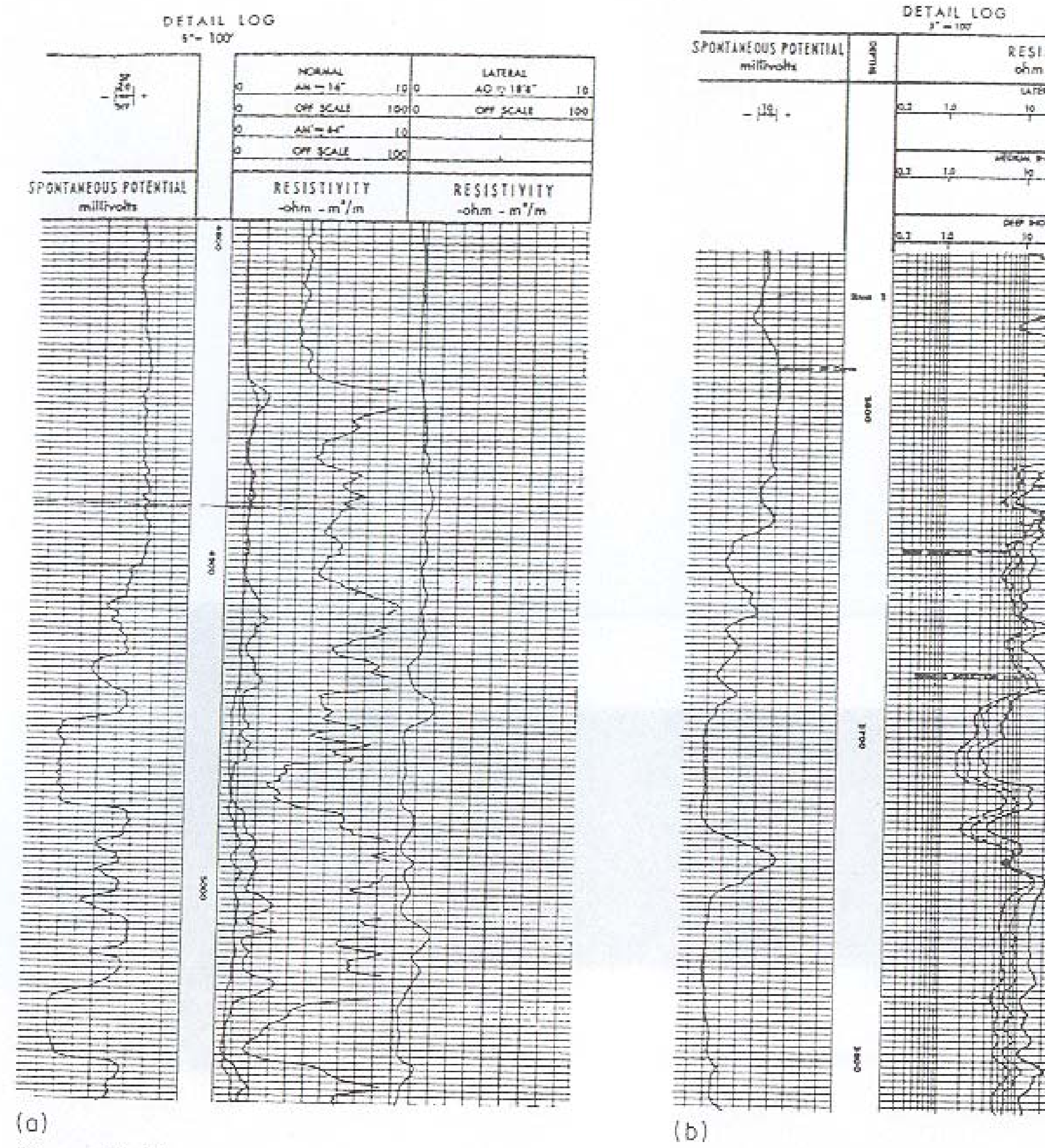

Figure 14–30

Typical electric log combinations: (a) SP log, 16-inch and 64-inch normal logs, and 18-foot, 8-inch lateral log; (b) SP log, induction logs, laterolog.

the formation from a source mounted at one point on the sonde, and the intensity of this radiation is measured by a detector mounted at another point a fixed distance from the source. In the third method neutron bombardment of the formation stimulates gamma radiation. The neutron source is placed at one point on the sonde, and a gamma-ray detector is mounted at another point.

Common to these three kinds of radioactivity logging is the detection of gamma rays. A device called a *scintillation counter* is the usual instrument; it consists of a special crystal and a photoelectric tube. Certain crystals, such as sodium iodide crystals, emit flashes of light as they absorb gamma-ray photons. A flash of light produced in this way can be converted into a pulse of electric current by a photoelectric tube. Radioactivity logs are obtained by plotting the scintillation counter output on a strip chart.

Natural Gamma Radiation Logging

Small concentrations of radioactive elements exist in most shale beds. Potassium in the micas and the clay minerals produced by decomposition of micas and alkali feldspars includes small proportions of the radioactive isotope potassium-40. Trace amounts of uranium and thorium also occur in shale. These unstable elements produce measurable levels of gamma radiation. Quartz sandstones and carbonate beds have much lower concentrations of these radioactive impurities. Therefore, the principal use of natural gamma-ray logging is to distinguish shale beds and to estimate the clay content in impure sandstones and carbonates.

The scintillation counter used for natural gamma-ray logging counts the number of

light flashes that occur in the cry
fixed interval of time. This is the
recorded on the log. Because of
and sporadic nature of radioa
gamma-ray emissions can vary
one moment to the next. Therefo
strument counting time is brief,
ond, the log can register conside
larity as the sonde passes throug
shale bed. Over larger periods o
ever, the number of emissions be
regular. With the instrument co
set at, say, five seconds, a much m
level of radiation would be indic
same bed.

The sensitivity of natural gam
ging to boundaries between shal
less radioactive beds depends on
ment counting time and the spe
the sonde is moving. Each value
log represents the average radioa
rock through which the sonde has
ing the interval of counting time.
sider the three logs in Figure 14–
obtained with a short counting ti
sonde speed, log b with a long co
and fast sonde speed, and log c
counting time and slow sonde spe
that if the counting time is too sh
ural irregularity of emissions may
boundary between shale and ar
This irregularity can be reduced b
the counting time, but if the sond
too fast, the log will indicate a
rather than a sharp change in r
near the boundary. This gradatio
can be sharpened by slowing the so
but for practical reasons, we cann
the sonde too slowly. Therefore,
must be made in choosing the cou
and the sonde speed that will yie
log. Typically, good results can b

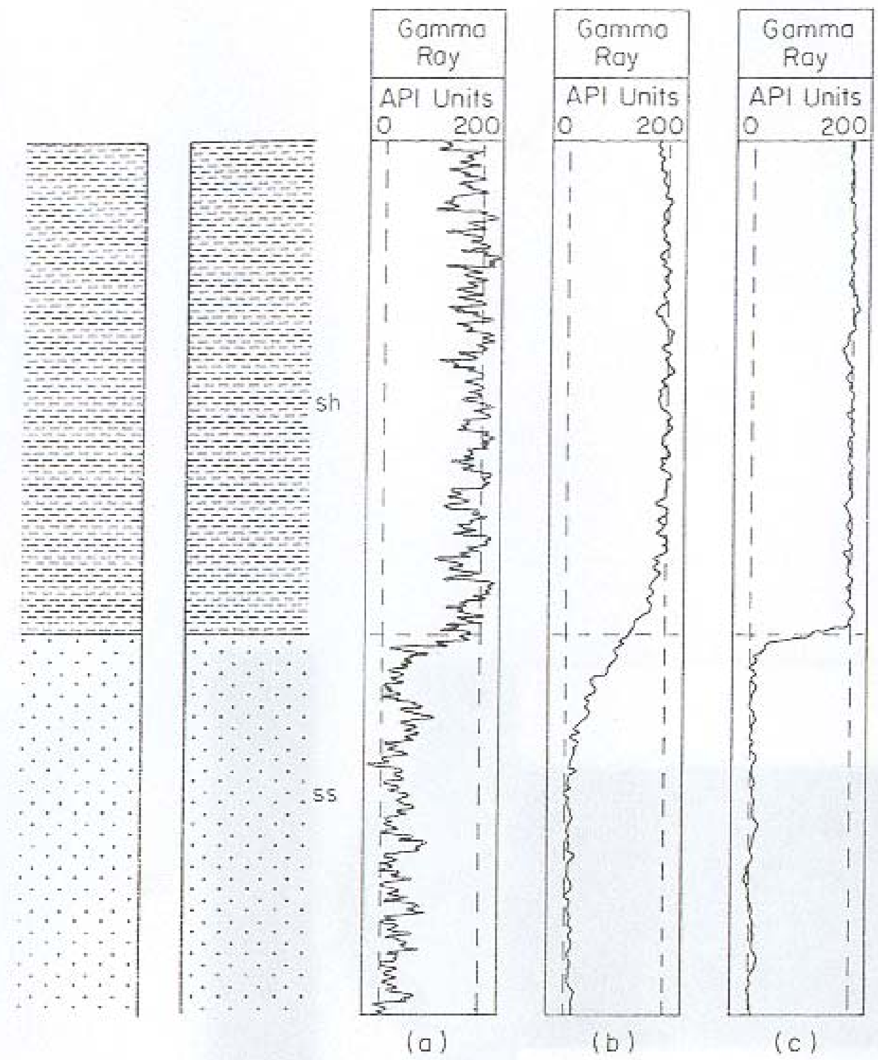

Figure 14–31
Idealized diagram sh
variation of natural g
radiation near the bo
between sandstone a
beds obtained by (a)
counting time and fa
speed, (b) a long cou
and fast sonde speed
long counting time a
sonde speed.

with a counting time of 2 seconds and a sonde speed of about 30 feet per minute.

An important advantage of natural gamma radiation logging is that it can be done in cased wells. Electric logging cannot be done in cased wells because most of the current flows in the highly conductive casing pipe rather than through the formation. Gamma radiation detected at the sonde comes from the formation within a few feet from the well.

Gamma-Ray Density Logging

Gamma radiation is emitted in c
tions of electromagnetic energy
tons. We can think of these phot
cles of energy. While traveling
substance, they frequently collid
trons. At each collision, some ene
ferred to the electron, thus reduc
ergy of the photon. This proce

Compton scattering. The number of collisions occurring during a fixed interval of time depends on the abundance of electrons, which is proportional to the density of the substance.

Gamma-ray density logging is the procedure for estimating formation density ρ_0 by measuring gamma radiation that has undergone Compton scattering. A source element mounted on the sonde emits gamma radiation into the formation. A scintillation counter mounted at another point on the sonde detects the portion of this gamma radiation that has been returned to the sonde by Compton scattering. This level of gamma radiation is proportional to the electron density index ρ_e of the formation. The gamma rays produced by the source have a different range of wavelengths than that of natural gamma radiation emitted within the formation. The scintillation counter output is plotted on a strip chart to obtain a log of the electron density index.

The relation between formation density ρ_0 and the electron density index ρ_e depends on the chemical elements present. The number of electrons possessed by each atom of an element is specified by the atomic number N of that element. By summing the atomic numbers of all elements in the formation, we can calculate ρ_0,

$$\rho_0 = \rho_e w / 2\Sigma N \qquad (14\text{–}16)$$

where w is the molecular weight of the combined constituents of the formation, and ρ_e is read from a log. The value of ρ_0 obtained in this way can be used in Equation 14–7, together with estimated values of pore fluid density and solid matrix density, to calculate formation porosity.

Good results can be obtained only if the source element and the detector are pressed firmly against the side of the well. The sonde must be equipped with a blade for cutting through any mud cake to ensure the rock surface. To maintain thi sonde must move quite slowly well at speeds of less than 30 fee Therefore, in deep wells, gamm logging is usually restricted to zo ular interest.

Neutron–Gamma-Ray Loggin

Nonradioactive elements in a fo be stimulated to emit gamma rad are bombarded by neutrons. yields neutron–gamma-ray logs information about porosity. The tains a neutron source and a counter mounted a fixed distanc source consists of a small amoun tive material such as plutoniu which emits neutrons during th radioactive decay.

Neutrons emitted from the s through the formation, colliding nuclei. The nuclei of most elemen mation, such as silicon, oxygen, potassium, are much more mas neutron. Therefore, a colliding n to bounce away with almost no lo energy. Of all the elements in th only hydrogen possesses approx same mass. For this reason, upo neutron can transfer a significan kinetic energy to a hydrogen nucl a proton. Such collisions reduce a neutron until its kinetic energy enough for it to be absorbed int larger nuclei. Absorption, or ca neutron stimulates the emission gamma radiation. A portion of gamma radiation reaches the sond detected by the scintillation count

The intensity of capture gamma radiation detected at the sonde depends on its distance from points of neutron capture. If neutrons travel a considerable distance before capture, only a small portion of the capture gamma rays manages to reach the sonde. But when the neutrons are quickly absorbed close to the well, a high level of capture gamma radiation is recorded.

The concentration of hydrogen in a formation is, by far, the most important factor affecting the distance that a neutron travels before it is captured. Where hydrogen content is high, neutron capture occurs close to the well, and a high level of capture gamma radiation is detected. The neutron–gamma-ray log, then, indicates variations in hydrogen concentration.

What influences hydrogen concentration? Hydrogen exists in molecules of water and petroleum and in crystals of hydrated minerals such as the silicate clays, micas, amphiboles, and gypsum. Therefore, in quartz sandstones and carbonate rocks, hydrogen occurs almost entirely in the pore water or petroleum. Its concentration depends on the formation porosity. In shale, however, micas and clay minerals as well as pore water contribute to the content of hydrogen.

It can be difficult to distinguish a shale bed from porous sandstone or carbonate beds by means of a neutron–gamma-ray log. These different beds may all contain the same concentration of hydrogen. Other kinds of logs, such as the natural gamma-ray log, must be used to make these lithologic distinctions. The principal use of the neutron–gamma-ray log is to detect porosity variations within sandstone beds or carbonate beds, as illustrated in Figure 14–32. We can identify the sandstone and shale beds by means of the natural gamma-ray log. Then we can look at the neutron–gamma-ray log variation within an in[...] stone bed. The log in this exa[...] the highest hydrogen content, [...] the highest porosity, near the [...] bed.

The neutron–gamma-ray log [...] cased or uncased wells. The be[...] obtained with a skid mounting [...] source and detector against th[...] well. Capture gamma radiation [...] from neutron capture at distanc[...] 2 feet from the well. Typicall[...] speed is about 30 feet per min[...] counting time of the scintillation [...] at 2 seconds. The scintillation co[...] structed to detect wavelengths [...] gamma radiation, which are di[...] the wavelengths of natural gamm[...]

SONIC LOGGING

The final logging procedure we wi[...] volves a small-scale seismic refrac[...] ment. This experiment can be con[...] a source and two receivers mo[...] sonde (Figure 14–33a). In the s[...] sign, the receivers are placed one[...] with the source three feet from the[...] ceiver. Sound pulses are emitted[...] source at 0.1-second intervals. Beca[...] speed is faster in the formation [...] fluid filling the well, the wave refra[...] rock at the side of the well is the [...] at the receivers. Each pulse activat[...] circuit that records the difference i[...] times to the two receivers. This val[...] the *interval transit time* T_0. The inte[...] times are plotted on a strip chart [...] sonic log.

The procedure we have describ[...] without problems. If the sonde is ti[...]

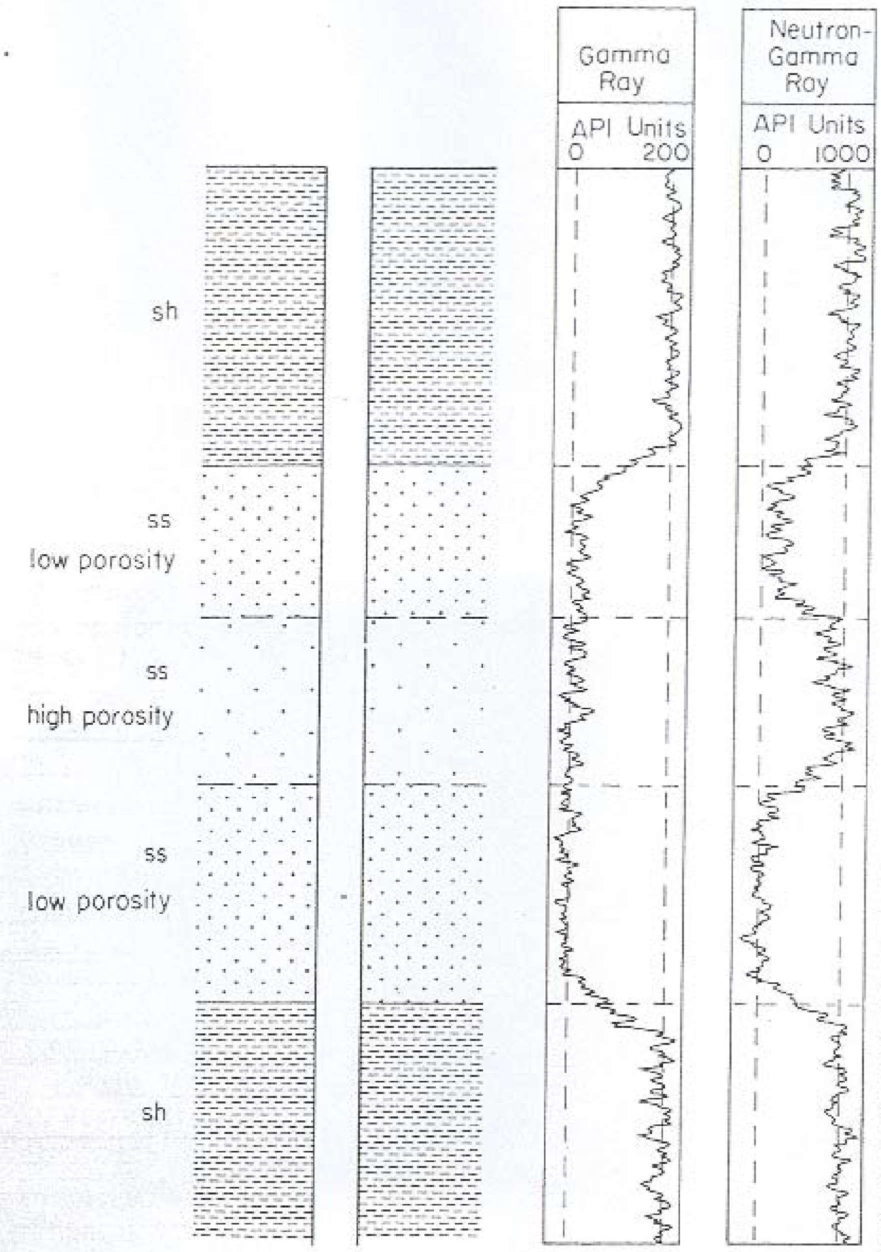

Figure 14–32
Idealized diagram sh
effect of lithology (sl
sandstone) and poro
gamma radiation an
gamma radiation log
gamma radiation de
concentration of rad
elements in a rock u
neutron–gamma rad
depends principally
proportion of water-
space in a rock unit.

well, or if the well diameter varies, travel paths through the fluid filling the well to the two receivers will have different lengths (Figure 14–33b). This problem is similar to that with dipping layer refraction (Figure 3-10), which means that an apparent interval being measured rather than the T_0 in the formation. To overco culty, we can mount another source on the sonde in a positio

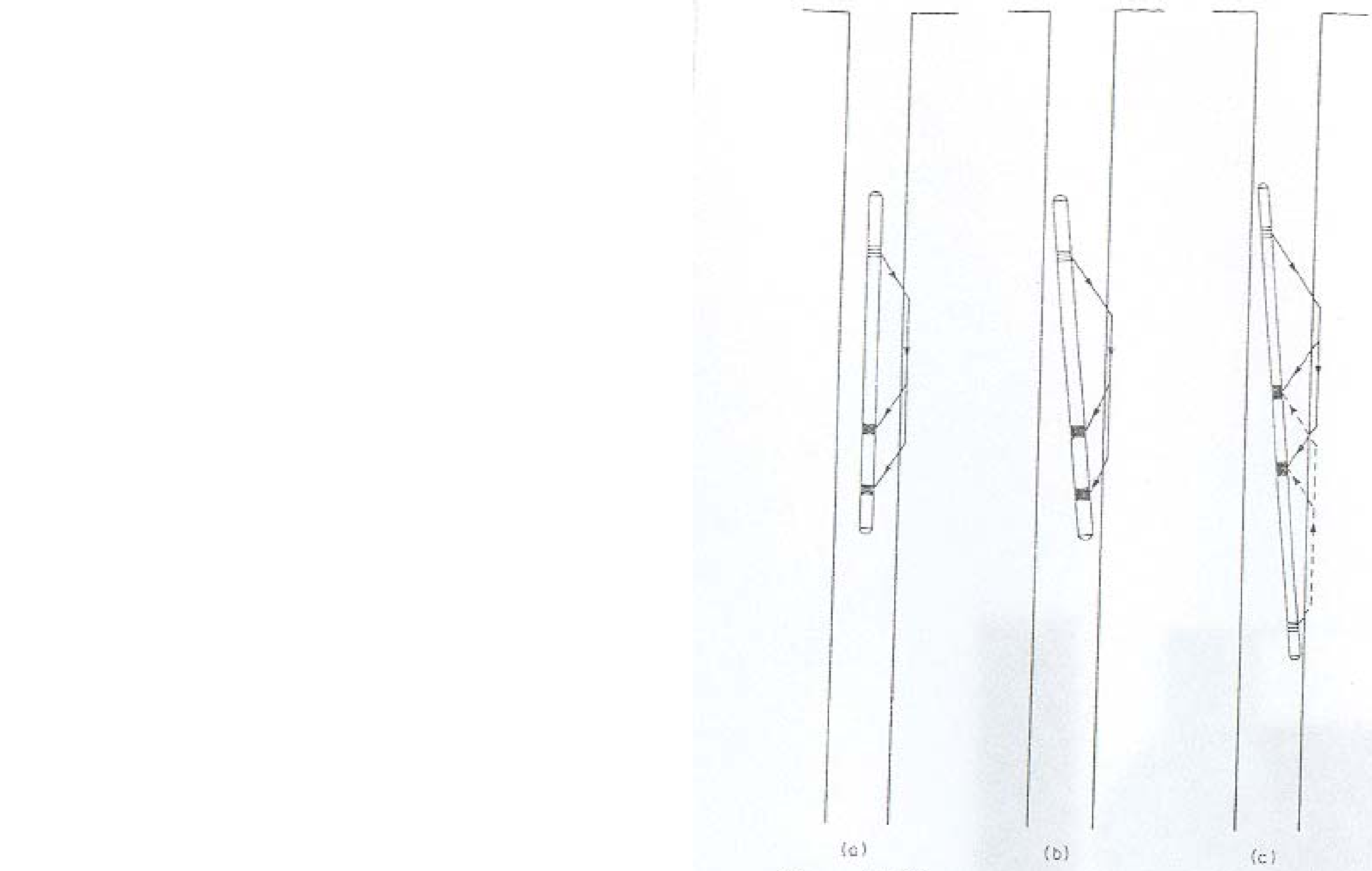

Figure 14–33
Schematic diagram of source–receiver configurations for (a) a nonborehole-compensated single-transmitter device aligned vertically and (b) tilted in the well, and (c) a two-transmitter borehole-compensated device which plots the average of the transit times measured from the two sources.

the original source (Figure 14–33c). Now we have a *borehole-compensated sonde.* Sound pulses are emitted alternately from the sources, and the apparent interval transit times from the two oppositely traveling refracted waves are averaged electronically to obtain the true value of T_0. This practice is sim recording along reversed refracti order to obtain the apparent velo to solve the dipping layer proble aged interval transit times are strip chart to obtain a borehole- (BHC) sonic log.

The *P*-waves reaching the rece ically refracted at the side of the fore, the sonic log tests only the very close to the well. Interval (T_0) read from a log depend on tions of solid matrix and fluid wit These readings together with esti transit times in the solid (T_m) an parts are used in Equation 14–4 t ues of formation porosity. The es is based on information about li tained from drill cuttings and oth logs. The values given in Table 1 ical for the kinds of rock commo tered in oil and gas wells. The est requires some independent know the formation fluid, which might

TABLE 14–1 Sonic Transit Time an Speeds in Different Materials

MATERIAL	TRANSIT TIME (μs/foot)	*P*-V
Sandstone	51–55.5	18
Limestone	43.5–47.6	21
Dolomite	43.5	
Anhydrite	50.0	
Salt	66.7	
Shale	62.5–167	6,
Water (pure)	218	
Water (10% NaCl)	208	
Oil	238	
Methane	626	

from electric logs. Typical values of T_w are also given in Table 14–1.

Sonic logs have proved very useful for correlation between nearby wells. Beds as thin as the spacing of the two receivers, commonly one foot, can be detected. Sonic logs are also very useful in the interpretation of seismic surveys of nearby areas. The variations in interval transit time indicate boundaries from which reflections might be expected. By summing the transit time through a continuous succession of intervals reaching to such a boundary, we can calculate the probable reflection travel time.

SUMMARY STATEMENT

Well logs are essential for discovering the nature of rock formations penetrated by a drill. The drill itself does not provide unambiguous information about these formations. Rock cuttings tell us what lithologies are present but are unclear about exactly where they occur. Even core drilling, which can be prohibitively expensive, yields incomplete information about formation fluids, and 100 percent core recovery is seldom possible. Therefore, we need an assortment of well logs for more complete evaluation of the formations.

Electric logs have proved the most useful for evaluating formation fluid properties. But the results from any individual log are distorted by the electrode configuration and by effects of invasion. Only in combination with other logs do they yield reliable information

for estimating the salinity of p
the proportions of water and
natural gas. Because both petro
ural gas are nonconductors, th
to distinguish from each othe
electric logs. Their elastic prope
are very different, so that sonic
for making this distinction.

We cannot unambiguously i
ent kinds of rock by any single
as resistivity, density, radioacti
time. A much clearer picture
these properties are consider
Electric logs, gamma density
gamma logs, and sonic logs ar
gether for this purpose.

Formation porosity can be e
pendently from electric logs, a g
log, a neutron–gamma log, an
Nonetheless, each separate resu
error introduced by invasion,
mud cake, and irregularity in th
ter. To the extent that results f
ferent logs confirm one anothe
tain reliable values.

For more than half a centur
well logging has played a centr
discovery and development of p
natural gas resources. These r
not been so fully used for minin
in the search and development
resources, and as a part of en
drilling operations. Today mod
ging techniques are being used
for these purposes.

STUDY EXERCISES

1. The cross section in Figure 14–34 shows a borehole that crosses the boundary between two rock layers. The dashed line is an equipotential surface related to the current source shown in the well. From the shape of this surface, determine which resistivity value is largest and which is smallest, where R_m is the resistivity of the drilling fluid filling the well, and R_1 and R_2 are resistivities in the upper and lower layers.

Figure 14–34
Cross section showing a borehole that penetrates two formations, a source of electric current, and an equipotential surface (dashed line).

2. Describe the conditions that cause an annulus of invasion to form in the rock surrounding a borehole. Sketch a graph showing the approximate variation in resistivity with distance away from the center of the hole, assuming that the resistivity of the drilling fluid is higher than the resistivity of the natural fluid filling the pores of the formation.

3. In a sandstone layer, suppose that the resistivity is 30 ohm-m, and that the resistivity of the fluid filling the pores is 6 ohm-m. What is the highest value for porosity that you would culate for this rock by means of t mula?

4. In a layer of quartz sandstone, as sonic transit time is 82 μs/foot. U of 20,000 feet/s as the *P*-wave velo calculate the porosity of the sands

5. A layer of relatively impermeabl foot thick lies between two layers sandstone, each of which is 50 fe well penetrating these layers, a 1 log, an 18-foot, 8-inch lateral log olog were obtained. The central el laterologging sonde was 10 inches ity in the limestone is higher thar the sandstone.

   a. Which log or logs indicate a h resistivity in the limestone? Exp swer.

   b. Which log will produce the r value of limestone resistivity? Exp swer. .

   c. Which log or logs will produce curate value of the sandstone resist your answer.

6. Suppose that a layer of sandston nated by clay mineral grains simila dinarily found in shale. Both a ga and a neutron–gamma-ray log fro etrating this layer show an increas with depth through the layer. Do that porosity changes with depth contamination changes with dept property that is changing increase with depth? Explain your answers.

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