SESSION 20

BOREHOLE GEOPHYSICS

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1. Introduction to Borehole Geophysics techniques

Geophysical well logging techniques can be subdivided into static and dynamic logging techniques. **Static techniques** measure the resident energy field, while **dynamic techniques** record the response to injected fluxes.

- **Static techniques:**
  - ✓ Spontaneous potential
  - ✓ Caliper
  - ✓ Fluid velocity
  - ✓ Temperature

1. Introduction to Borehole Geophysics techniques

➢ **Dynamic techniques**

- ✓ Formation resistivity
- ✓ Fluid resistivity
- ✓ Point resistivity
- ✓ Gamma-Gamma
- ✓ Fluid velocity
- ✓ Neutron Gamma

1. Introduction to Borehole Geophysics techniques

The importance for ground water exploration is to:

- Assist in the hydrogeological assessment of an investigation area. Logging in exploration wells is undertaken to collect the information on physical parameters of individual subsurface rock layers which can be interpreted in terms of layer thickness, rock types, rock water contents, ... etc.
- Calibrate the formation resistivities interpreted from geo-electrical surveys carried out at land surface. Exploration drilling is usually planned in combination with geo-electrical surveying programs. Formation resistivities of individual rock layer which have been interpreted from geo-electrical measurements carried out following the variable electrode distance technique can be calibrated using information from long normal resistivity logs.

1. Introduction to Borehole Geophysics techniques

- Assist in well design. Geophysical logs may prove to be vital for the determination of the design details for exploration or production wells. Details include well depth, position of screens and casing, pump housing, ..etc.

2. Working Principles

- Sensitive equipment is lowered down a well to measure a range of physical parameters at various depths.

- As opposed to surface geophysical techniques, the geophysical logging techniques record for each individual layer the value of the physical parameter concerned.

2. Working Principles

- Geophysical well logging equipment consists of basic elements such as a power supply, the recording unit annex display charts, the winch cable combination, and the metal cable head which holds a sensor. By changing the sensor on the cable head another physical parameter can be measured in the well. By lowering the sensor in the hole a geophysical well log showing values of a physical parameter against depth is obtained. To correlate various logs with each other, most modern recorder equipment plots the parameter values on the display chart along the same depth axes.

3. Spontaneous Potential (SP) Logging

3.1 Instrumentation

- SP logging means that a single measuring sensor (electrode) is lowered into the uncased well filled with drilling fluid. A second measuring electrode is grounded in the pit with drilling fluid or in a wetted area not too far from the well. Between the two electrodes a spontaneous potential which is generated inside the well is measured with a sensitive voltmeter. This meter is coupled with the revolving chart of the recording unit for a graphyical display of the spontaneous potential log. A schematical layout of the spontaneous potential logging technique is presented in **Figure 3.1**.

3. Spontaneous Potential (SP) Logging

3.2 Uses of (SP) logs

- Identify porous and permeable beds.
- Locate certain impermeable zones .
- Calculate the percentage of clay contained in the rock :
- Calculate the resistivity of the formation water which enables determination of resistivity and thereby the chemical quality of the water.

3. Spontaneous Potential (SP) Logging

3.3 Principle and Interpretation

- SP logs are records of natural potential between the borehole fluid and the surrounding rocks. SP circle closes only in the presence of fluid.
- Drilling fluid and formation water seldom have the same ion concentration. Since the migration velocities of positive and negative ions are not the same, charge differences will develop between that part of the permeable formation invaded with drilling fluid and the not invaded part of the formation.
- From the above point, we will notice a sharp deflection, **usually to left**, **opposite permeable formation** with pore water resistivities much **smaller** then the resistivity of the drilling fluid (see **Figure 3.1**).

3. Spontaneous Potential (SP) Logging

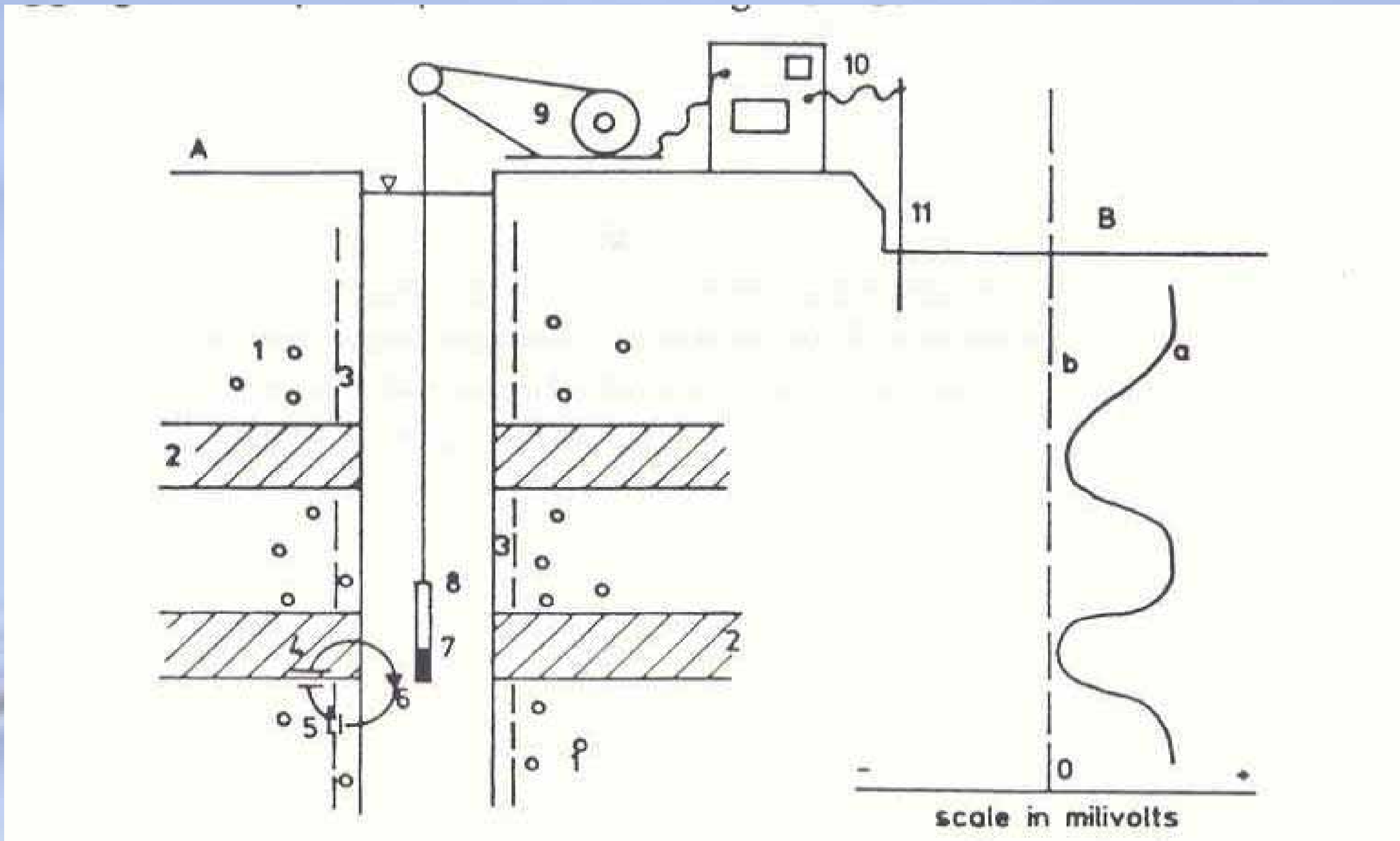


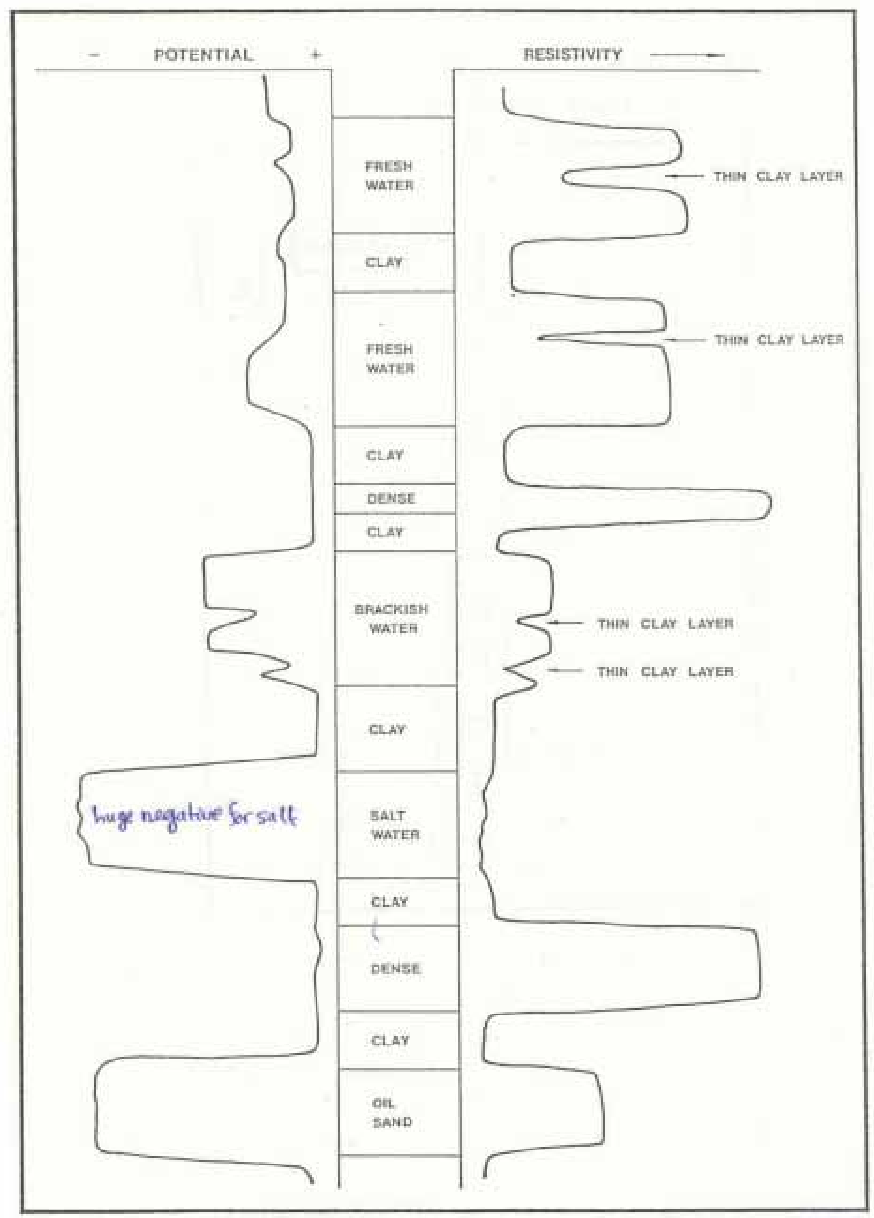
Figure 3.1 Layout (A) and associated log (B) for SP logging

3. Spontaneous Potential (SP) Logging

- The above observation reveals in case the permeable formation contains brackish or saline water. When the porewater resistivities of the permeable formations and the resistivity of the drilling fluid are about the same, then there are hardly any deflections on the log. This is often the case when we work in an environment where the formations contain freshwater and the drilling fluid is made up of water with about the same amount of total dissolved solid (see **Figure 3.2**).

3. Spontaneous Potential (SP) Logging

Figure 3.2 Idealised Electric log



3. Spontaneous Potential (SP) Logging

- When (in permeable formations) we have much higher porewater resistivities than the resistivity of the drilling fluid, then the sign of the measured potential is reversed and deflections **usually to the right** are shown on the log.

- The above observation is valid in the case when we log permeable formations containing water with very low dissolved solid contents or when we have used drilling fluid with a high content of TDS (brackish to saline water)

3. Spontaneous Potential (SP) Logging

- The deflections for the measured potential on the logs are **in reference** to the so called **shale (or clay) line**. This is the line which indicates the measured potential opposite the impermeable formations such as clays and shales in the well. Usually the value for the potential at impermeable formations is neutral or slightly negative.

- It is often difficult to distinguish the signal at impermeable formations from the signal that is produced opposite a permeable layer with fresh formation water whereby the drilling fluid contains about the same TDS. The problem is illustrated in **Figure 3.3** which shows that SP log for the two permeable sandy layers is in about the sample position as the log opposite the clay layers.

3. Spontaneous Potential (SP) Logging

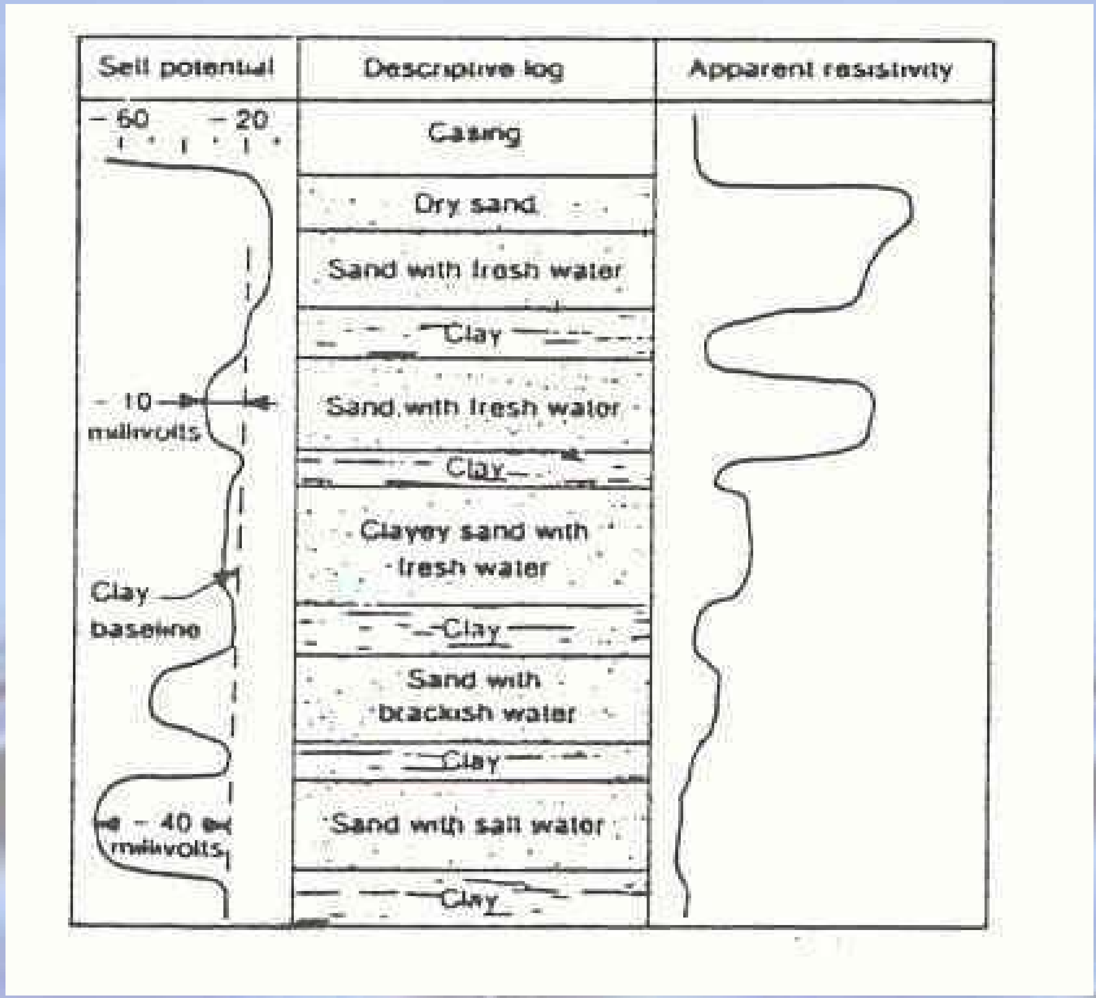


Figure 3.3 Shale (clay) line on a SP log

3. Spontaneous Potential (SP) Logging

- The logs can be used to determine the water levels when the SP circle is closed. This is useful in layered aquifers.

3. Spontaneous Potential (SP) Logging

3.4 Factors Affecting the Shape of SP Deflection

- **Salinity**
- When $\mathbf{R_{mf}}$ (resistivity of drilling fluid) **>** $\mathbf{R_w}$ (resistivity of formation fluid), **then:**

✓ The formation water is more saline than the drilling fluid.

✓ The positive is opposite the clay (to the right) and deflection towards the negative signifies the presence of a porous and permeable formation (see **Figure 3.4 A**)

✓ The deflection increases as contrast salinities increases.

3. Spontaneous Potential (SP) Logging

- $R_{mf} \approx R_{w,}$ then SP is flat because of no clear difference between clays and porous and permeable beds (see Figure 3.4 B).

- $R_{mf} < R_w$, then:
  - ✓ The formation water is less saline than the drilling fluid.
  - ✓ The positive is opposite to the right (permeable formations) and deflection towards the negative signifies the presence of the clay (Figure 3.4 B)

3. Spontaneous Potential (SP) Logging

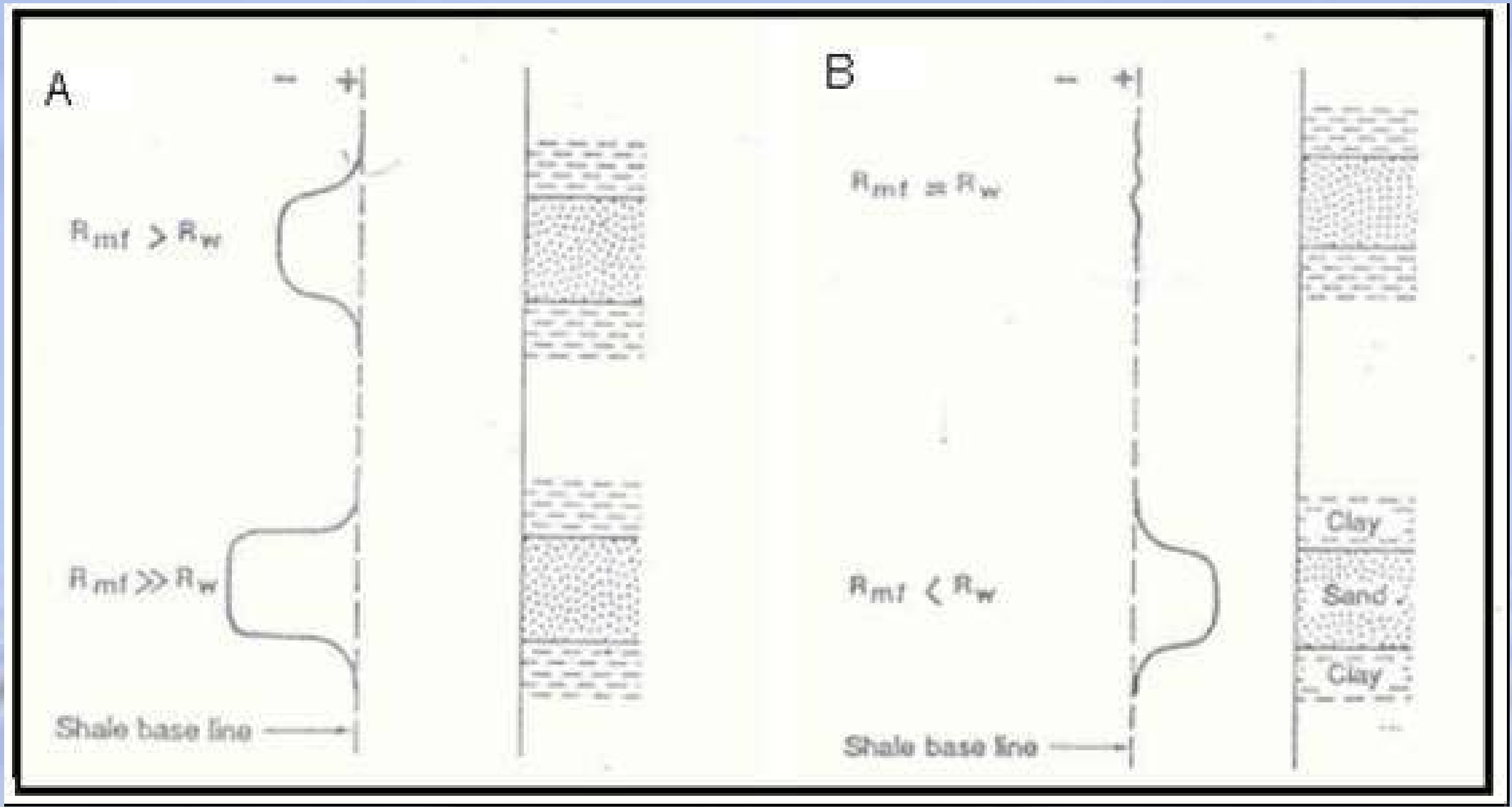


Figure 3.4: Influence of Salinity

3. Spontaneous Potential (SP) Logging

2. Thickness of Permeable Bed

- Generally, the boundaries between the clay and the permeable formation correspond to the point of inflection of the SP curve.
- If the layer is thick, the deflection is maximum.
- If the layer is thin, the curve is recorded as narrow peak.
- Figure 3.5 illustrates the influence of thickness of permeable bed on SP logs

3. Spontaneous Potential (SP) Logging

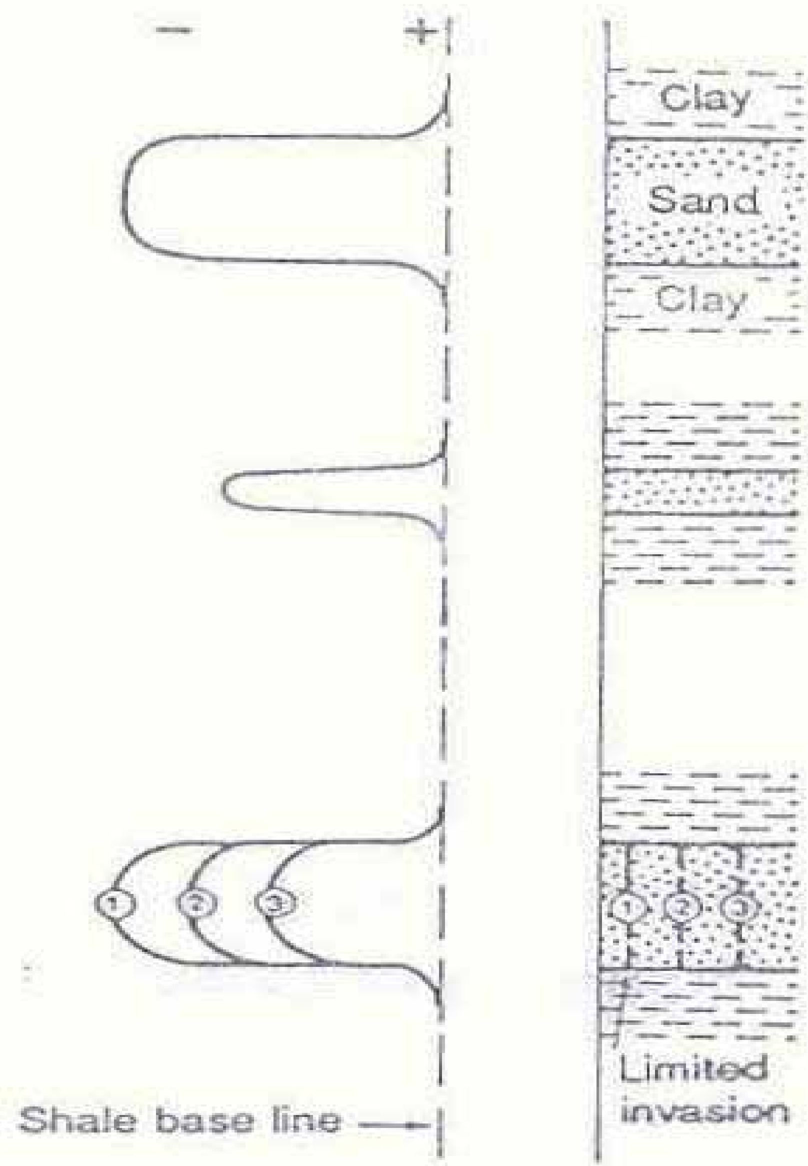


Figure 3.5: Influence of bed thickness and invasion

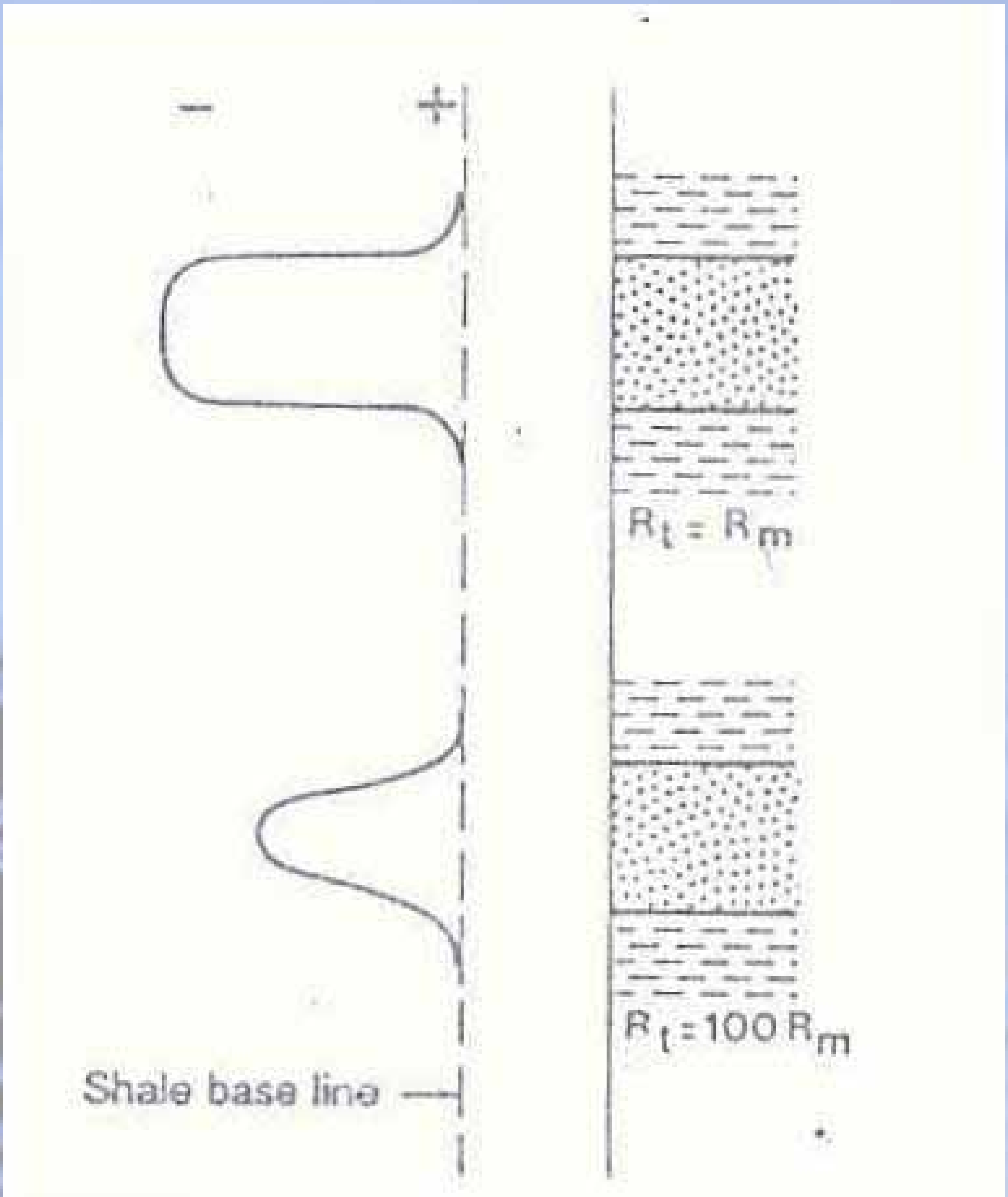
3. Spontaneous Potential (SP) Logging

3. Resistivity

If the permeable bed has a high resistivity, SP currents do not develop readily. The SP deflection and boundaries are less clearly indicated **(see Figure 3.6)**

3. Spontaneous Potential (SP) Logging

Figure 3.6: Influence of resistivity



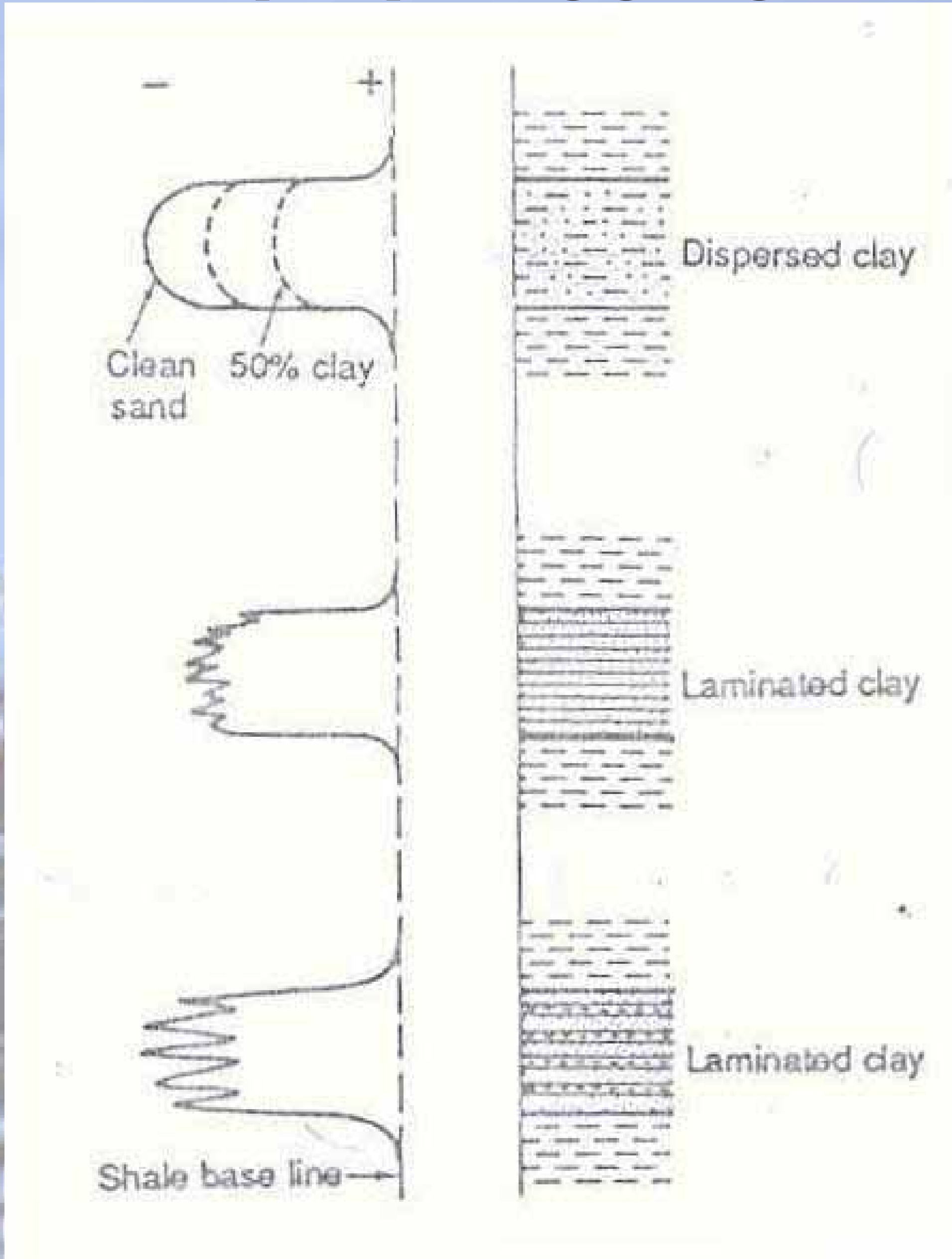
3. Spontaneous Potential (SP) Logging

4. Influence of Clay

- The presence of clay reduces the amplitude of SP deflection (see Figure 3.7).
- When the probe passes through a zone containing thin band of clay and sand beds, the SP deflection varies according to the relative amounts of these two types of formation and the contrast in their respective resistivities.

3. Spontaneous Potential (SP) Logging

Figure 3.7: Influence of presence of clay



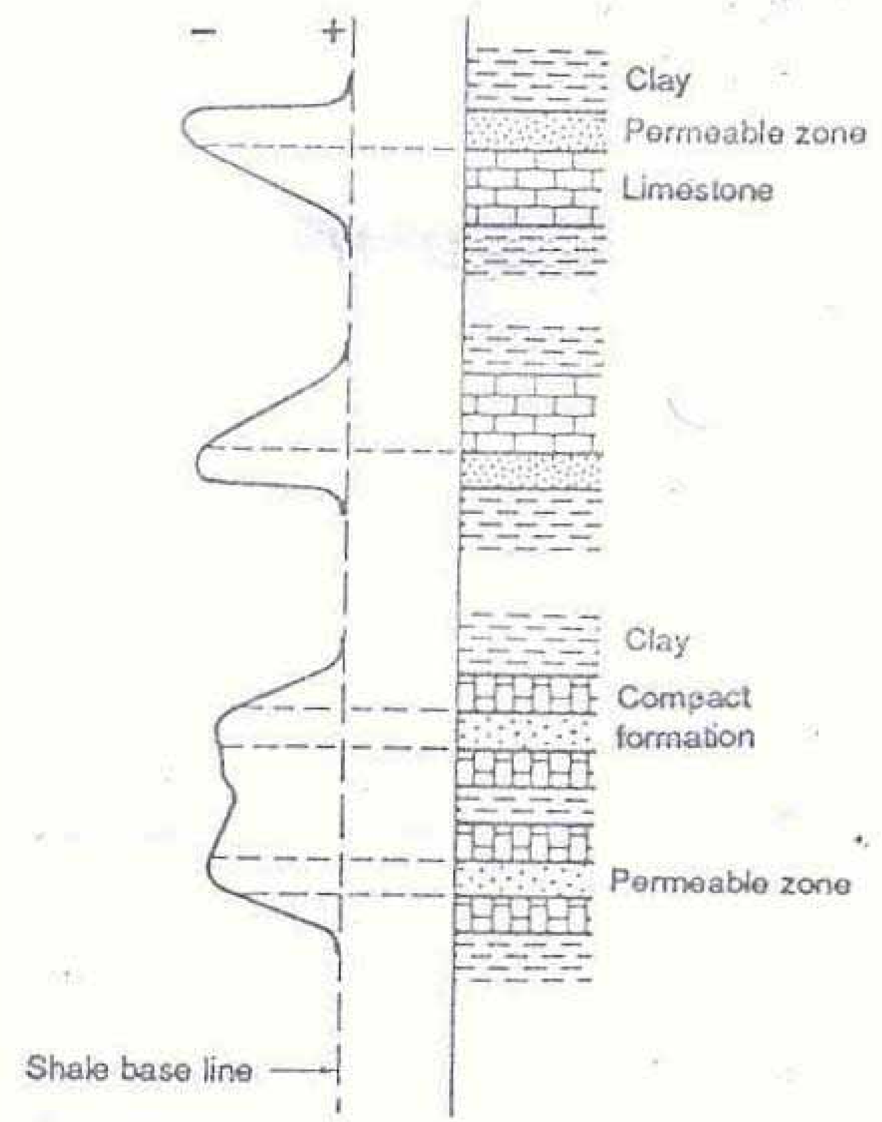
3. Spontaneous Potential (SP) Logging

5. Effect of Compact Formations

Permeable zones are often identified by a curvature which is concave towards the shale line (**see Figure 3.8**).

3. Spontaneous Potential (SP) Logging

Figure 3.8 Effect of a compact formation



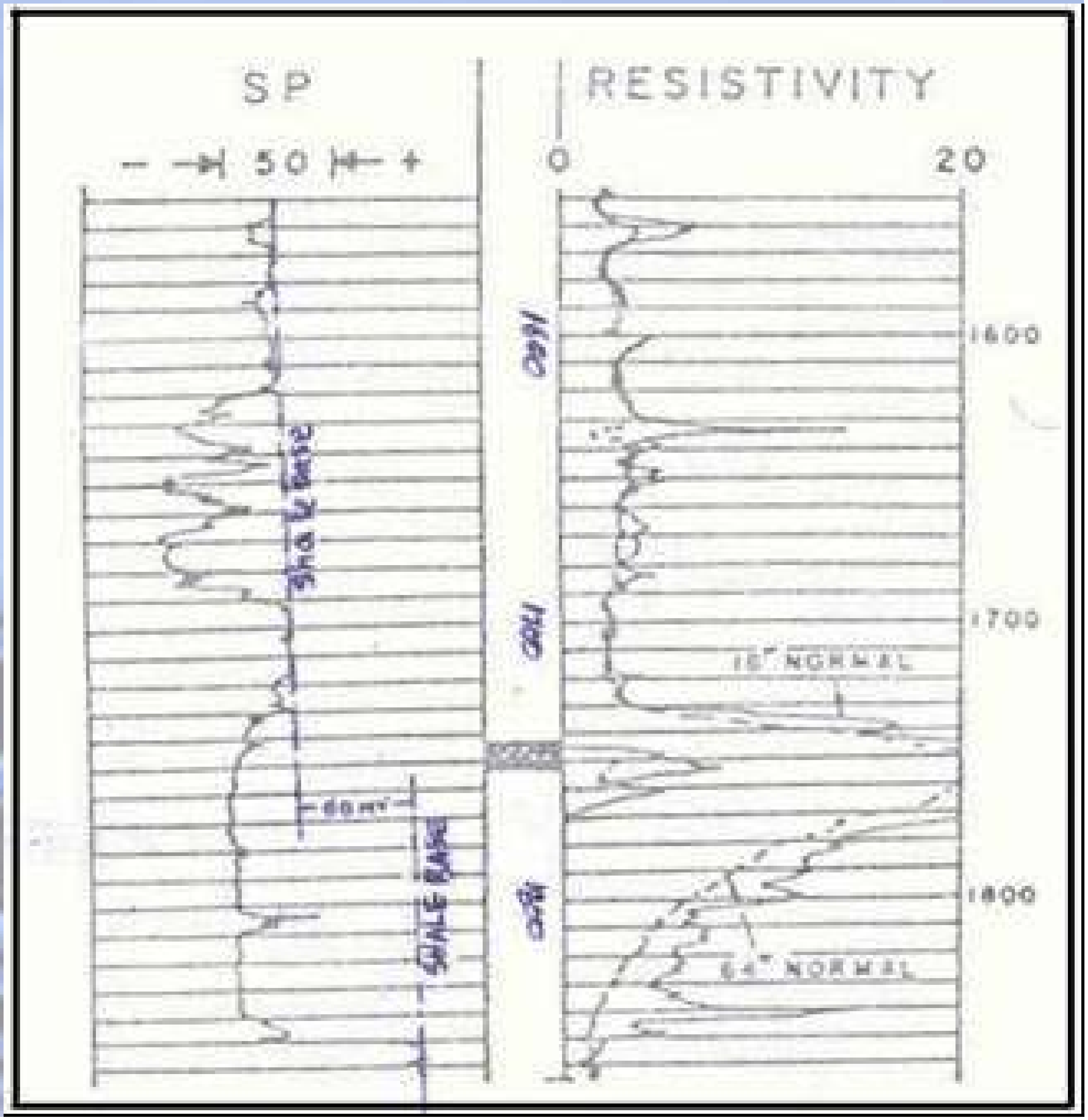
3. Spontaneous Potential (SP) Logging

6. Shift in Shale Line (see Figure 3.9)

- Change in geological formations.
- Variation in salinity saturating the rocks.
- Change in the properties of the clay.

3. Spontaneous Potential (SP) Logging

Figure 3.9 Shift in the shale base line



4. Resistivity Logging

4.1 Principle

- Resistivity logging has to be carried out in uncased wells.

- During resistivity logging a combination of current and measuring sensors (electrodes) is lowered into the well. Potential differences, which result from the currents injected at the current electrodes, are measured at the measuring or potential electrodes. Various resistivity logging techniques have been developed over the years (long and short normal resistivity logging techniques).

4. Resistivity Logging

- The layout for long and short normal resistivity logging are presented in Figure 4.1 and Figure 4.2. For both, the long and short normal setups, the same current electrode arrangement is used: one electrode C_2 at the bottom of the cable head and another electrode C_1 at land surface. The electrode at land surface consists of a metal stake which is grounded at a considerable distance from the recording instrument. Both C_1 and C_2 are connected with the current input unit powered by batteries or a generator set.

4. Resistivity Logging

- The difference in arrangement between long and short normal resistivity logging is reflected in the position of the measuring electrodes on the cable head. In the long normal technique, we have one measuring electrode P_1 on the cable head at a distance of about 1.5 meter from C_2. In the short normal technique, the distance between C_2 and the measuring electrode P_2 on the cable head is in the order of 0.4m. each of the measuring electrodes works in combination with a reference electrode P_n at land surface.

4. Resistivity Logging

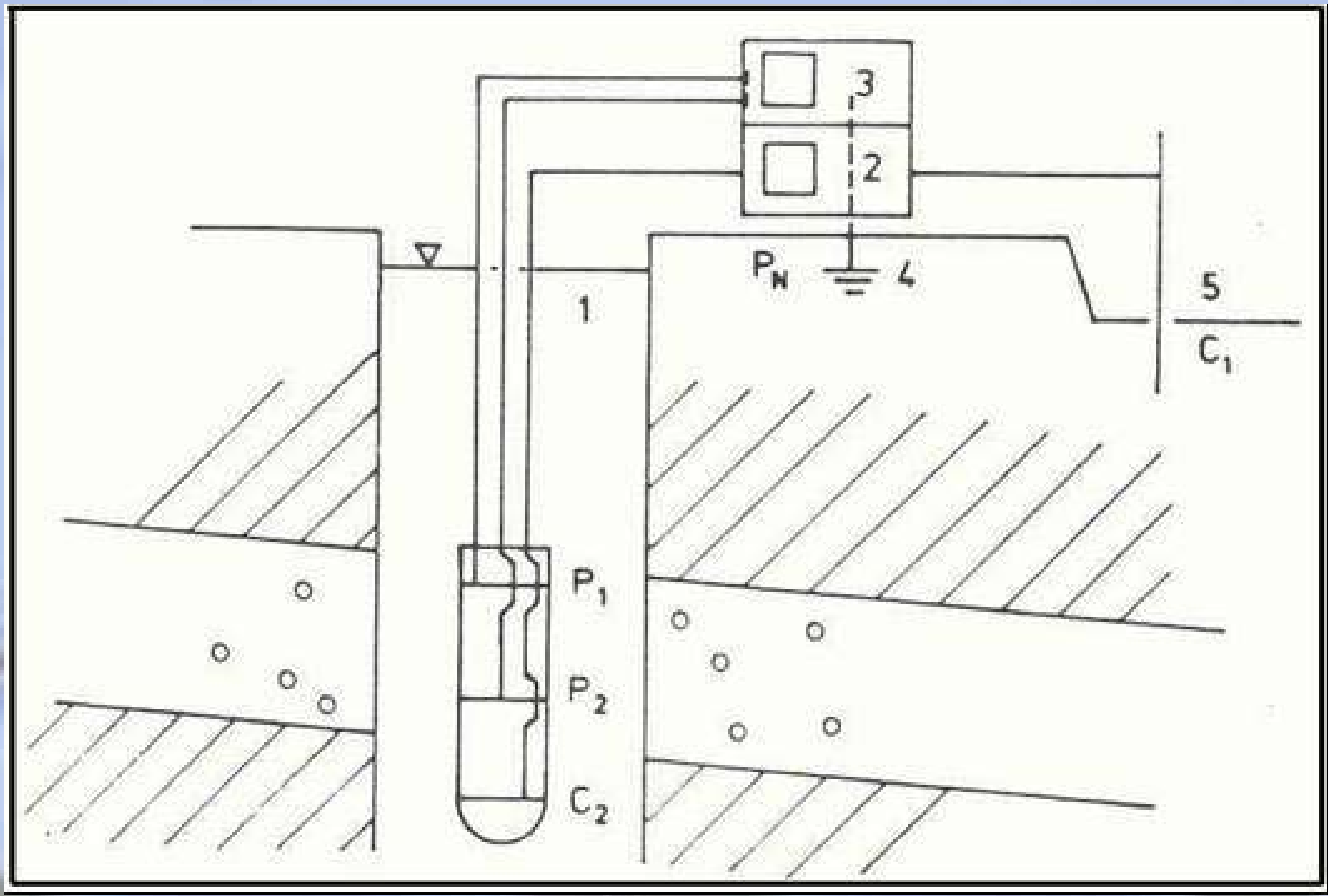


Figure 4.1 The layout for resistivity logging

4. Resistivity Logging

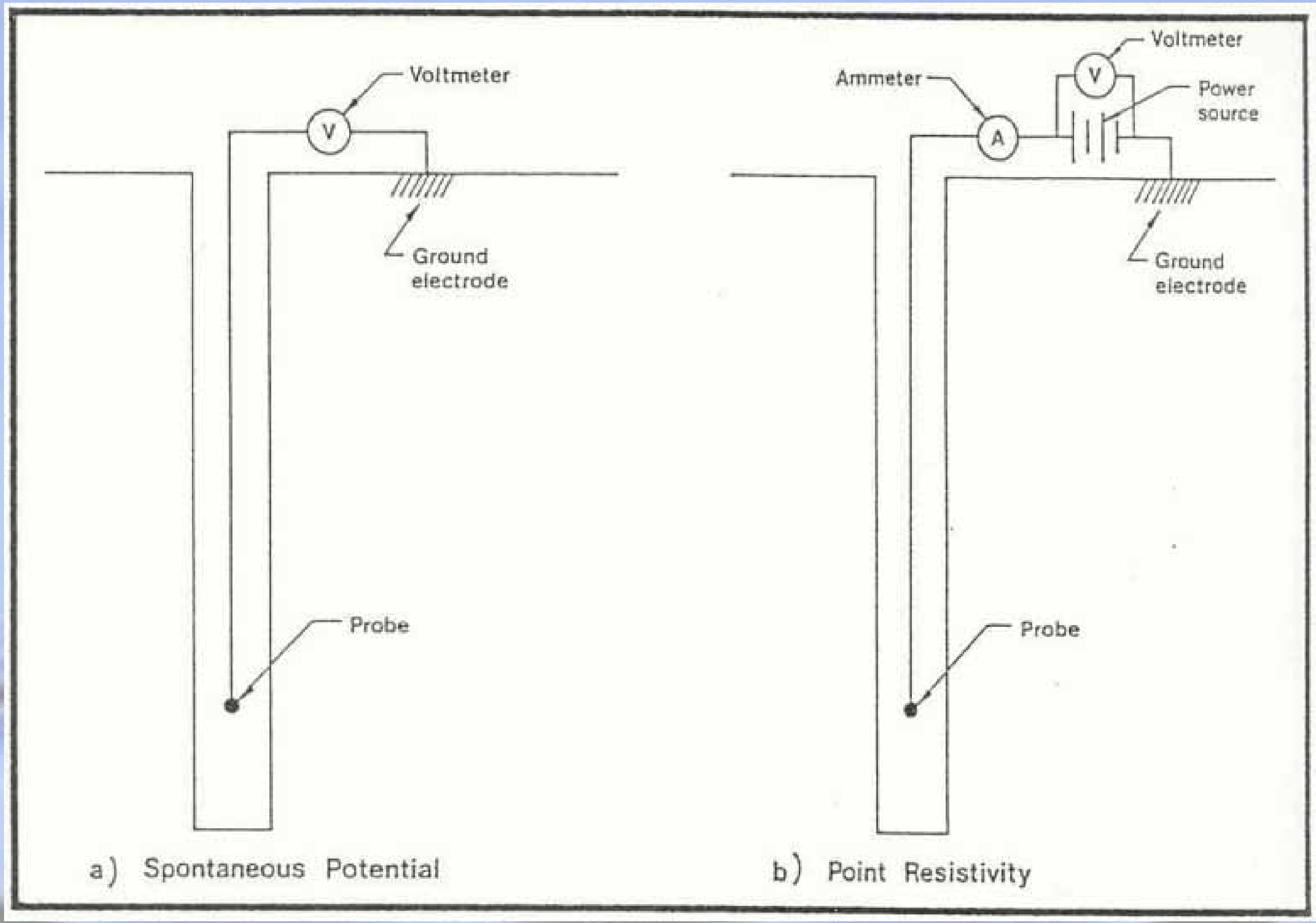


Figure 4.2: Schematic circuits for measuring Spontaneous Potential and Point Resistivity

4. Resistivity Logging

4.2 Theoretical Aspects

- Physical parameters measured during resistivity logging are potential differences and current strengths. These can be used for the computation of the formation resistivities of the individual subsurface formations in the well (well resistivities).

- The well resistivity of the short normal logging:

$$\varphi_c = \frac{\Delta V}{I} 4\pi C_2 P_2$$

4. Resistivity Logging

- The well resistivity of the long normal logging:

$$\varphi_c = \frac{\Delta V}{I} 4\pi C_2 P_1$$

- Modern resistivity logging equipment carries out resistivity computations automatically.

- The calculated well resistivities computed with short normal resistivity logging may deviate considerably from the formation resistivities: the influence of drilling fluid is large. It is usually considered that the well resistivities found in long normal logging to be representative for the formation resistivities.

4. Resistivity Logging

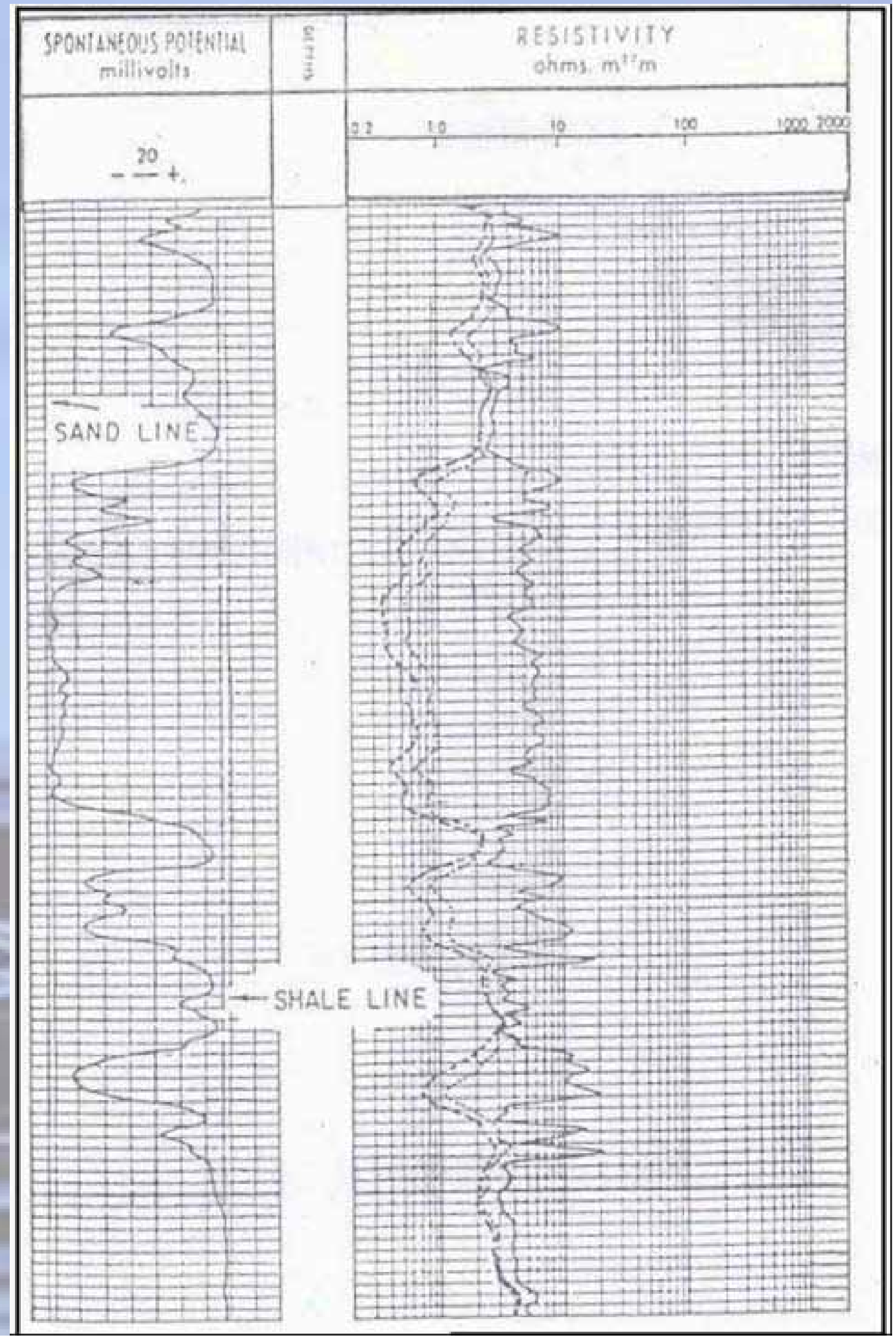
4.3 Interpretation

- Lithologies with high resistivities include sand and gravel while clay and shale have the lowest resistivity.

- Resistivity logs assist in determining the rock zones of highest water yield. This enables well's designers to locate the screens or perforated casing in the most desirable position with more accuracy than relying on the cutting log (see **Figure 4.3, 4.4**).

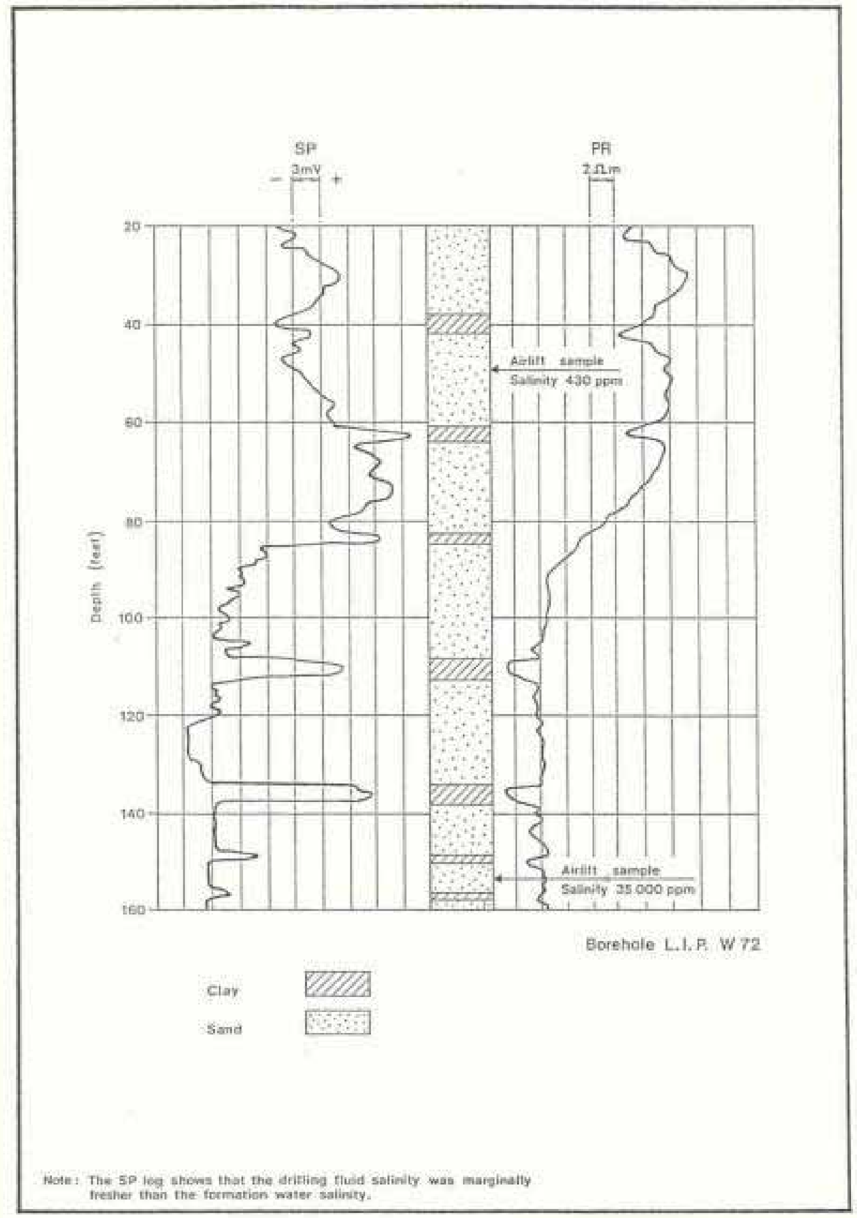
4. Resistivity Logging

Figure 4.3 Example of S.P and Resistivity in a series of sands and clays



4. Resistivity Logging

Figure 4.4 SP-PR log showing a change in groundwater salinity between 70 and 90 feet



SESSION 20

BOREHOLE GEOPHYSICS

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5. Natural Gamma Logging

5.1 Principle

- In natural gamma logging a specially designed sensor is lowered down a well to record the gamma radiation produced by radioactive materials in subsurface formations.

5.2 Scale and Units

- The measurement method is as follows. Natural gamma radiation which strikes the scintillation crystals (the sensor) causes light flashes which are trapped by a photomultiplier. The resulting electric pulse in the photomultiplier are in counts per minute. The unit is either API (American Petroleum Institute) or CPM (Counts Per Minute) or CPS (Counts Per Seconds) (see **Figure 5.1**).

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5. Natural Gamma Logging

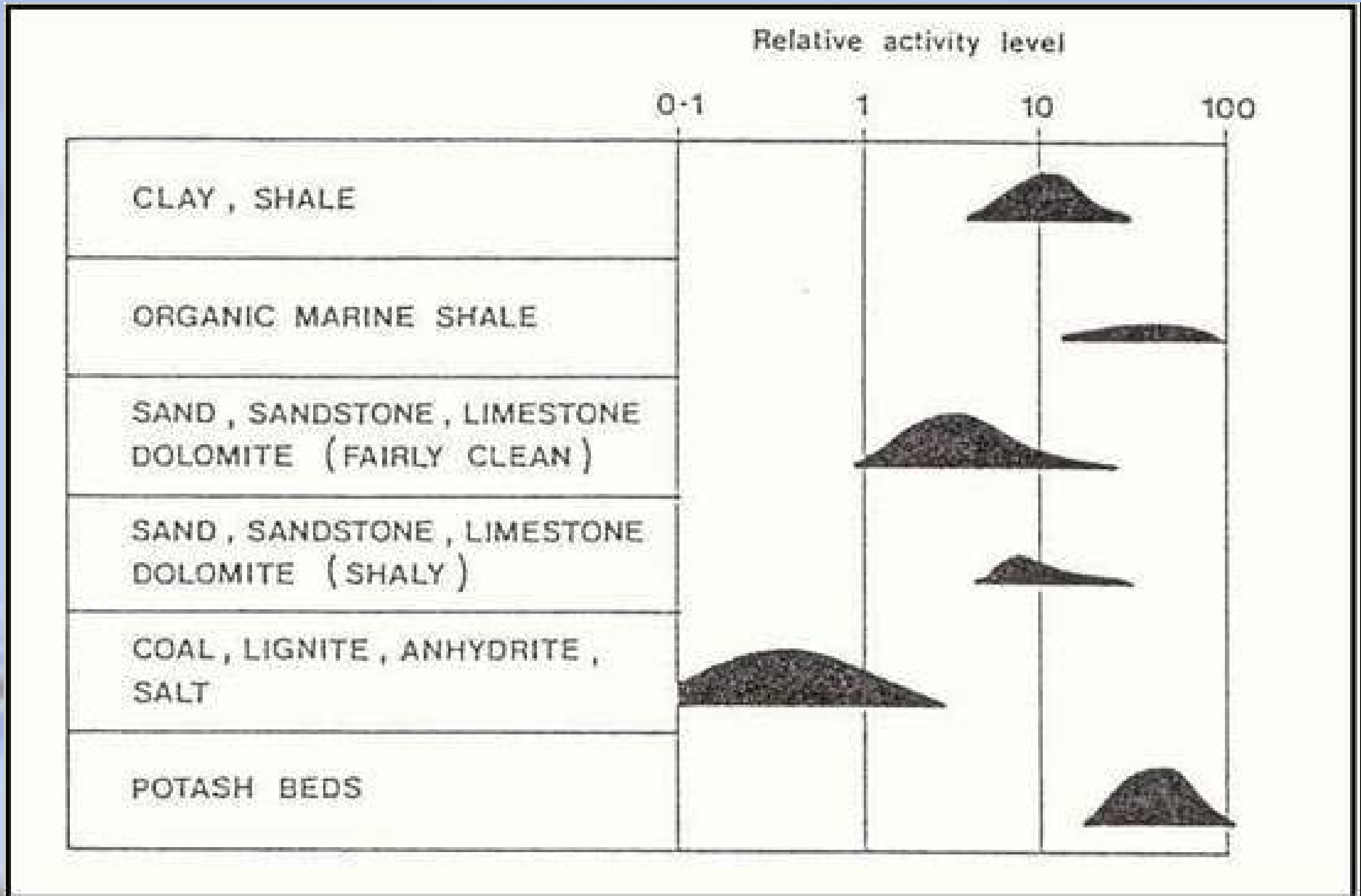


Figure 5.1: Radioactivity levels of various rock types

5. Natural Gamma Logging

5.3 Interpretation

Isotopes of Uranium, Thorium and also Potassium are responsible for radio-activity and gamma radiation in the subsurface rock layers. The radio active mineral contents of the three main rock types can be described as follows:

- **Clay and Shale:** Clay is unconsolidated rock consisting of the weathering products of feldspars and micas. Shale is consolidated clay. Both rocks may contain appreciable concentration pf the K^{40} isotope. This isotope may even be enriched by cation exchanged during the original deposition of the rock. Also, the radioactive U^{238} isotope, may be trapped in clays when deposited under marine conditions. Clays and shales usually have high levels of gamma radiation (see **Figure 5.2**).

5. Natural Gamma Logging

- **Sands and Sandstones:** As quartz is usually the dominant nonradioactive mineral, most unconsolidated sands and consolidated sandstones have low levels of gamma radiation. Nevertheless some gamma radiation may be recorded as minor amounts of clays or shales may be included in these rocks (see **Figure 5.3**).

5. Natural Gamma Logging

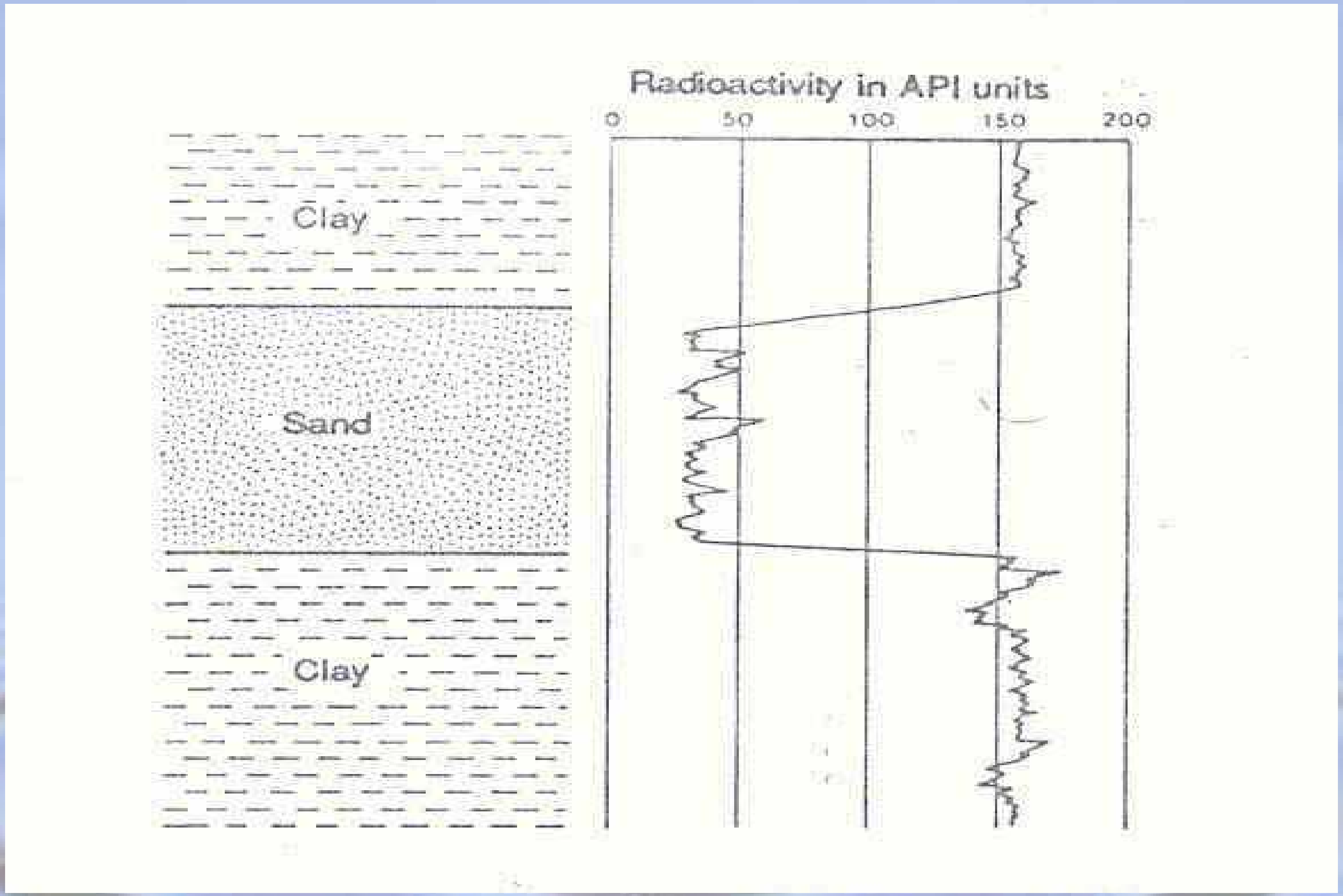


Figure 5.2: Natural radioactivity of clays

5. Natural Gamma Logging

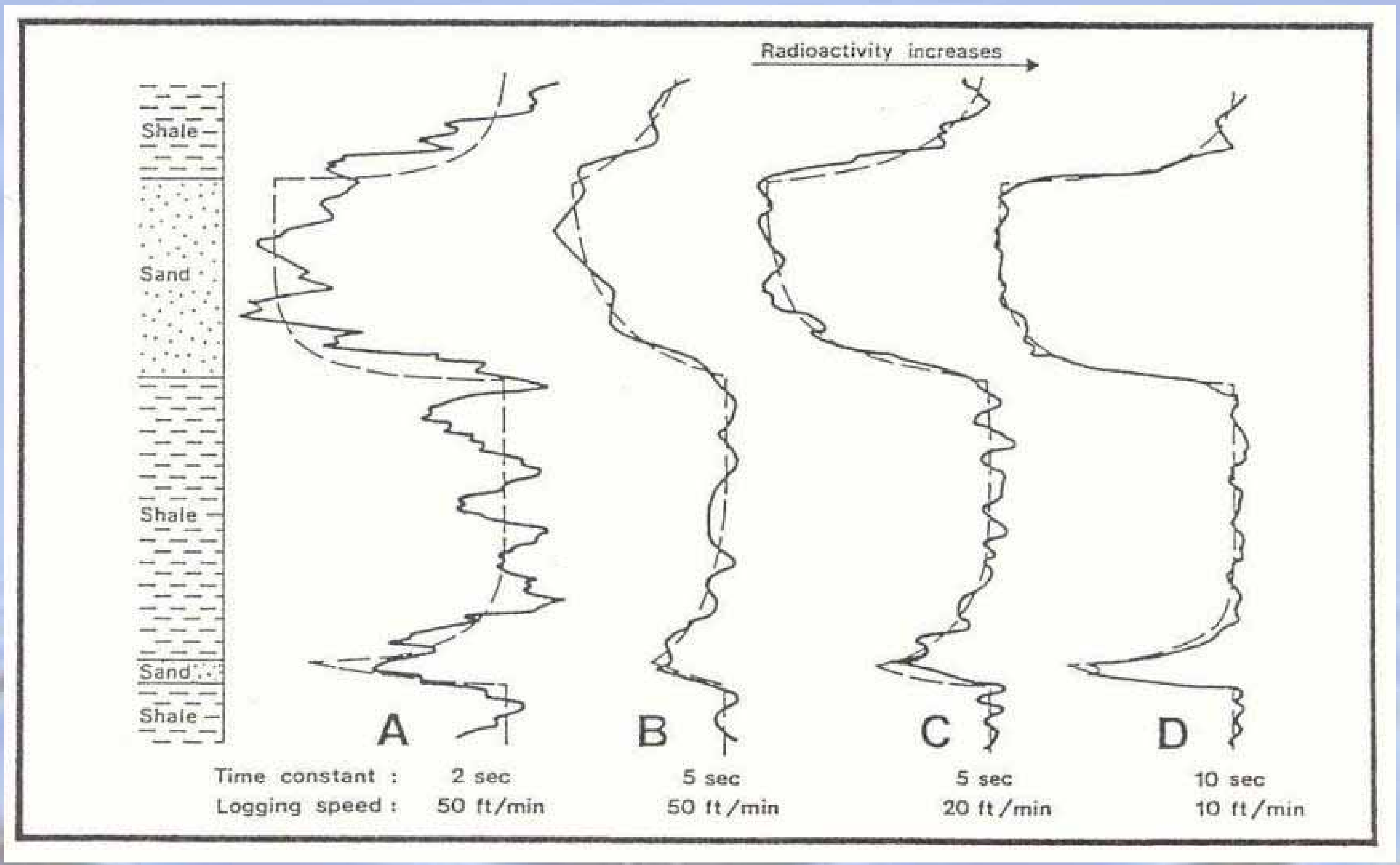


Figure 5.3: Gamma ray logs run at different speeds and with different time constants

5. Natural Gamma Logging

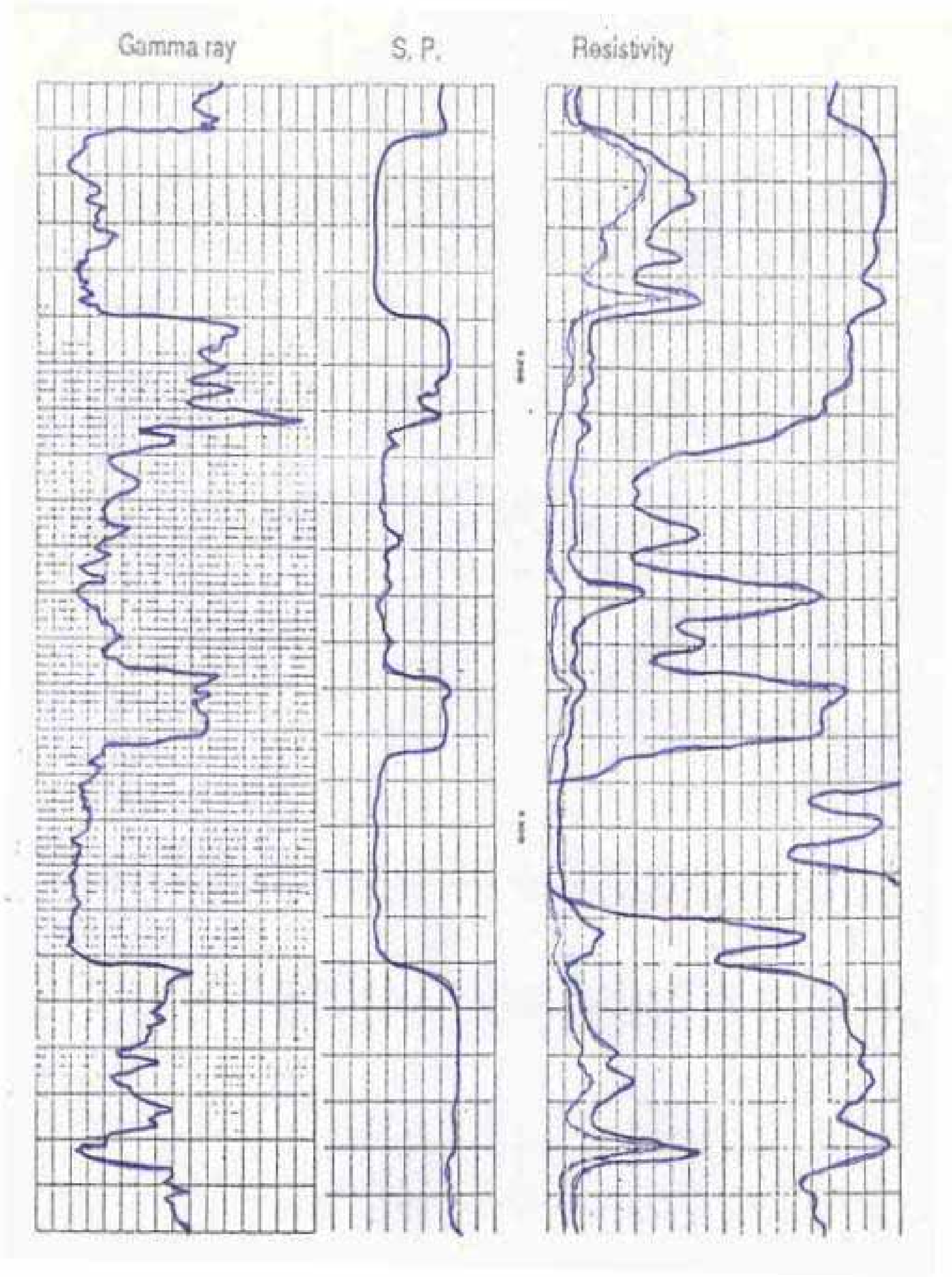
- **Chalk and Limestone:** Due to the absorption of the U^{238} isotope, deposits of chalk and consolidated limestone formations may have intermediate levels of gamma radiation.

- **Metamorphic and Igneous Rocks:** Due to the large variation in rock composition, the type and content of radioactive minerals in metamorphic and igneous rocks may vary considerably. Field and laboratory tests have indicated radio-activity and gamma radiation levels for individual metamorphic or igneous rock units. Slate and phyllites were found to have moderate gamma radiation levels; basalts and bedded tuffs may have a fairly high gamma radiation, while pegmatites (and some granites) usually have low radiation levels.

Figure 5.4 illustrates the differences between gamma ray, S.P, and P.R

5. Natural Gamma Logging

Figure 5.4 Comparison of gamma ray and S.P logs and Resistivity logs



5. Natural Gamma Logging

5.4 Determination of Clay Content

For the elevation of the clay content in an aquifer, the section in the well should contain an actual clay bed (see **Figure 5.5**) zone **A** (clay) and a zone of clean sand **(B)** which can be used as refernce. The volume of clay **(V_{clay})** at point **x** is then calculated as follows:

$$V_{clay} = \frac{\gamma_x - \gamma_{sand}}{\gamma_{clay} - \gamma_{sand}}$$

where,

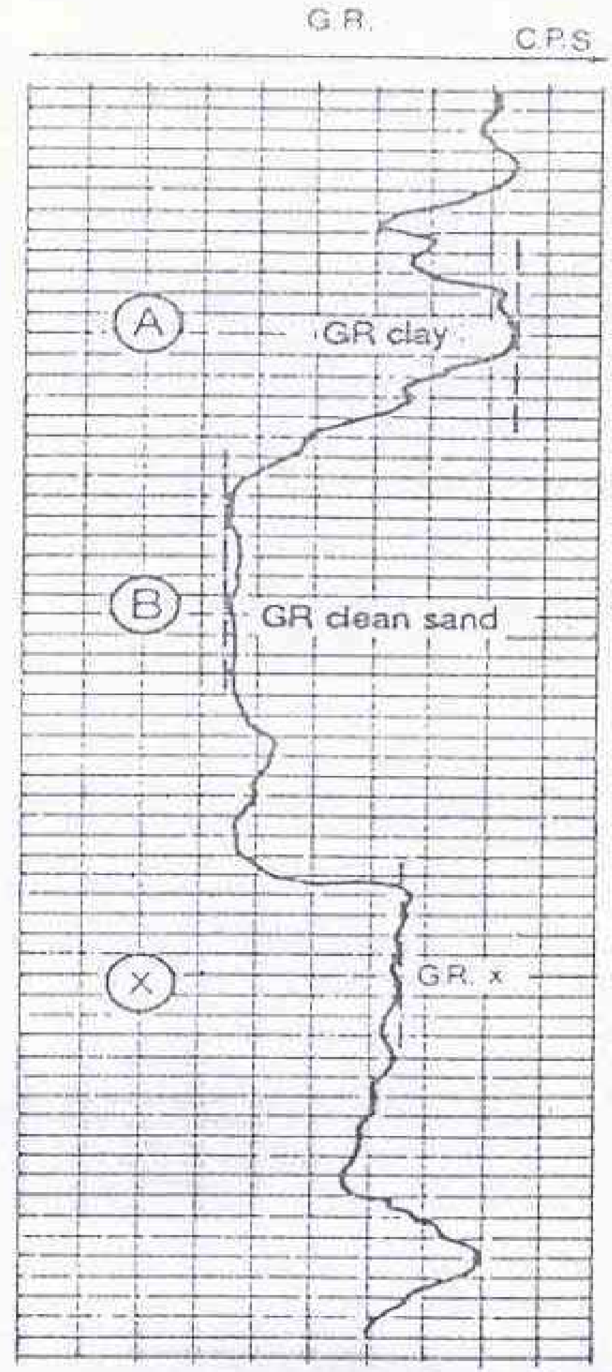
is the value of the gamma log opposite clay.

is the value of the gamma log opposite sand.

is the value of the gamma log opposite x.

5. Natural Gamma Logging

Figure 5.5 Determination of clay contents

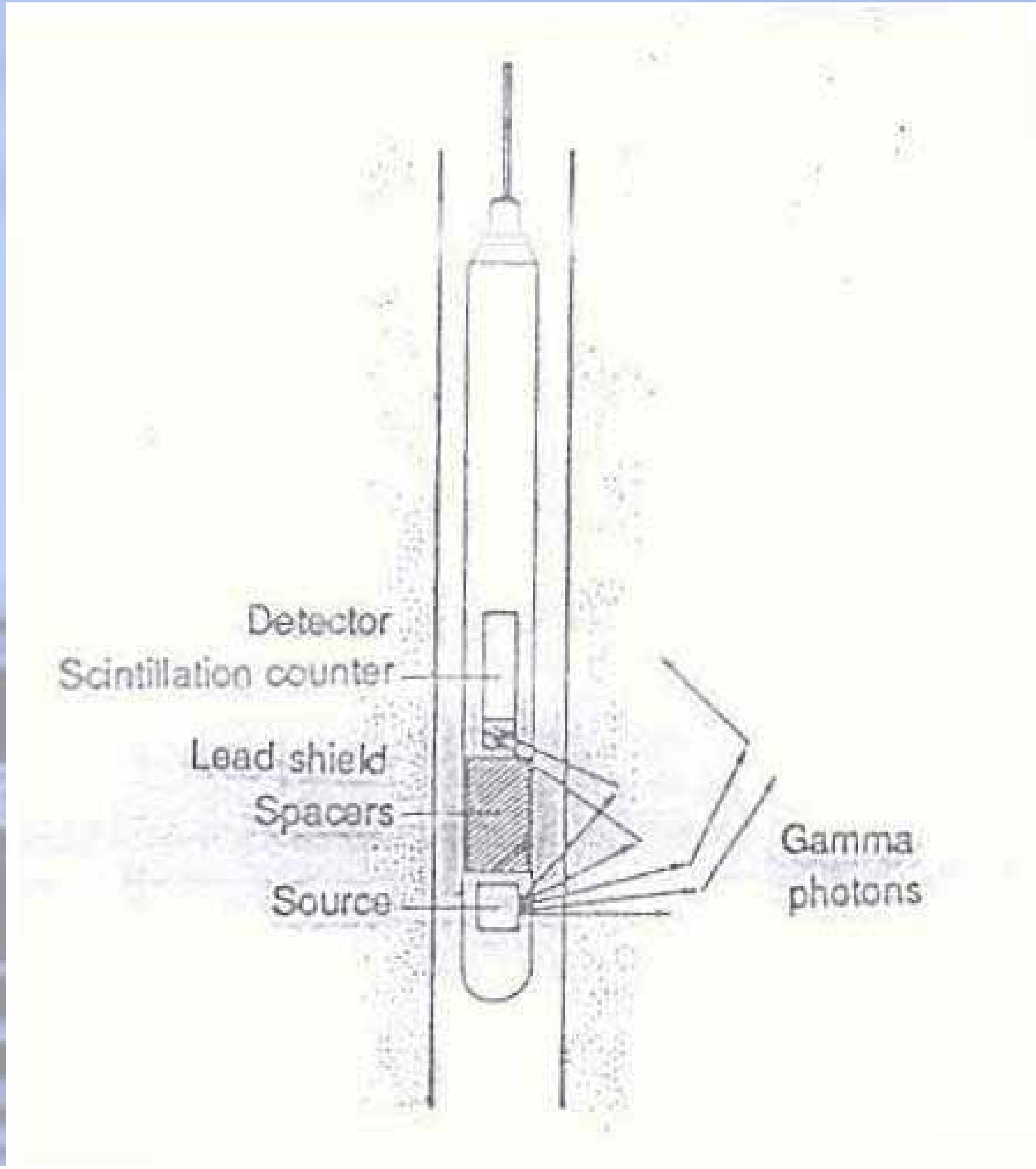


6. Gamma-Gamma or Density Logging

- The main purpose of this log is to measure the **density** of various formations encountered in the borehole. This measurement, in turn, facilitates the determination of different porosities.
- Gamma-gamma logs are records of the radiation received at a detector from a gamma source in a probe, after it is attenuated and scattered in the borehole and surrounding rocks (see **Figure 6.1**)
- Gamma-gamma logs are extensively used in the petroleum industry, but they are used much less for groundwater applications.

6. Gamma-Gamma or Density Logging

Figure 6.1 Working principle of a density probe



7. Neutron Logging

- The probe contains a source of neutrons, and detectors provide a record of the neutron interactions that occur in the vicinity of the borehole. Most of these neutron interactions are related to the quantity of hydrogen present in groundwater environments. In porous and saturated rocks, the hydrogen involved in neutron attenuation is generally from water and hence an increase in hydrogen content indicates an increase in porosity. These logs are used mainly to **measure porosity**.

8. Acoustic (Sonic) Logging

- An acoustic log is a record of the transmit time of an acoustic pulse between transmitters and receivers in probe. The main use of this log is to determine the degree of porosity (MATSADA chart) and fracture characteristics of a formation (see **Figure 8.1**).

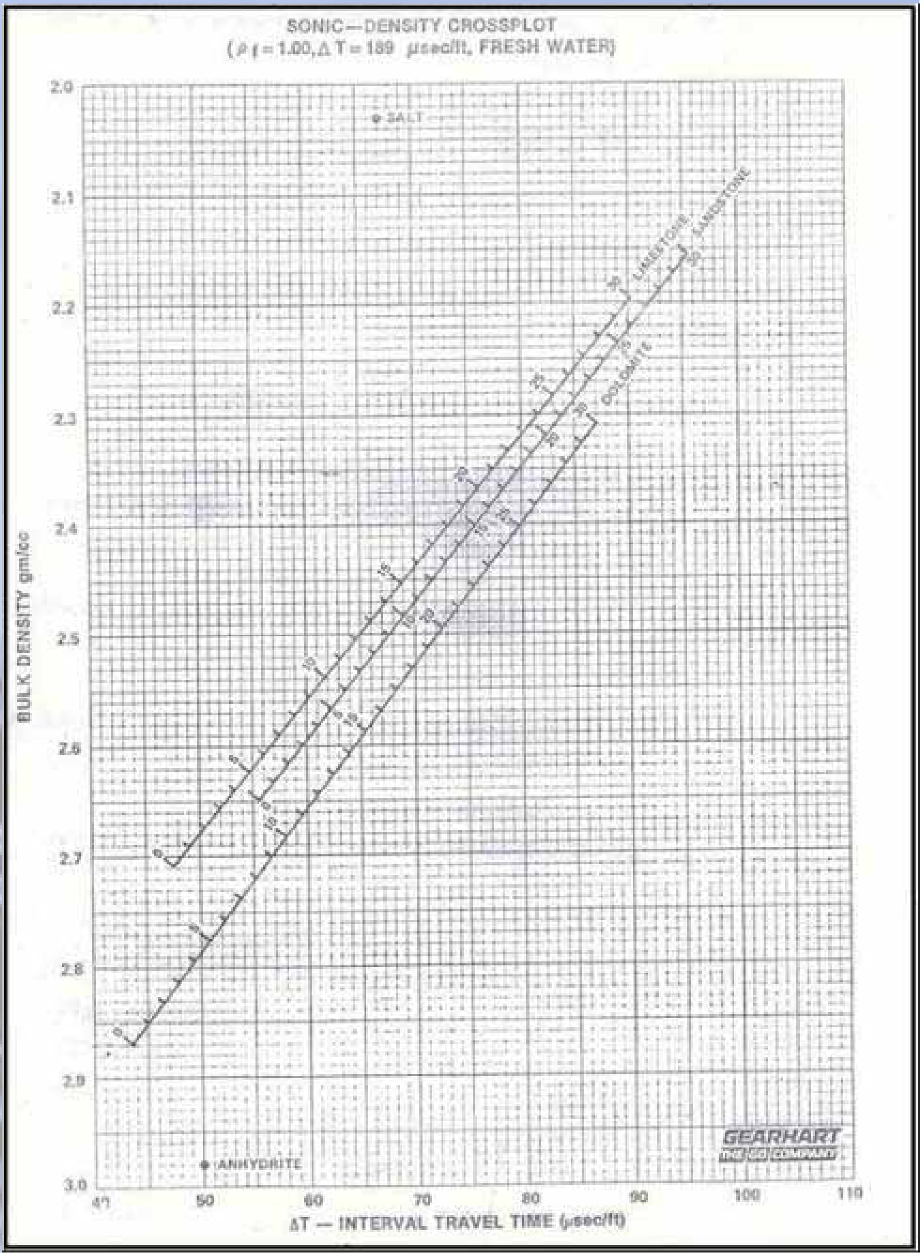
- Normally, the parameter measured by sonic log is the velocity of propagation of waves. This generally refers to the velocity of longitudinal or compression waves **(P waves).** It is observed that the velocity of seismic waves varies with the elastic properties of rocks.

8. Acoustic (Sonic) Logging

- Seismic velocities decrease with an increase in porosity. The velocity of **P waves** is greatly reduced in fractured zones to the extend that a study of velocities reveals those zones that could be of interest as sources of water. Generally, when transmit time Δt increases, velocity decreases, porosity increases (see **Figure 8.2**)

8. Acoustic (Sonic) Logging

Figure 8.1: Sonic-density crossplot



8. Acoustic (Sonic) Logging

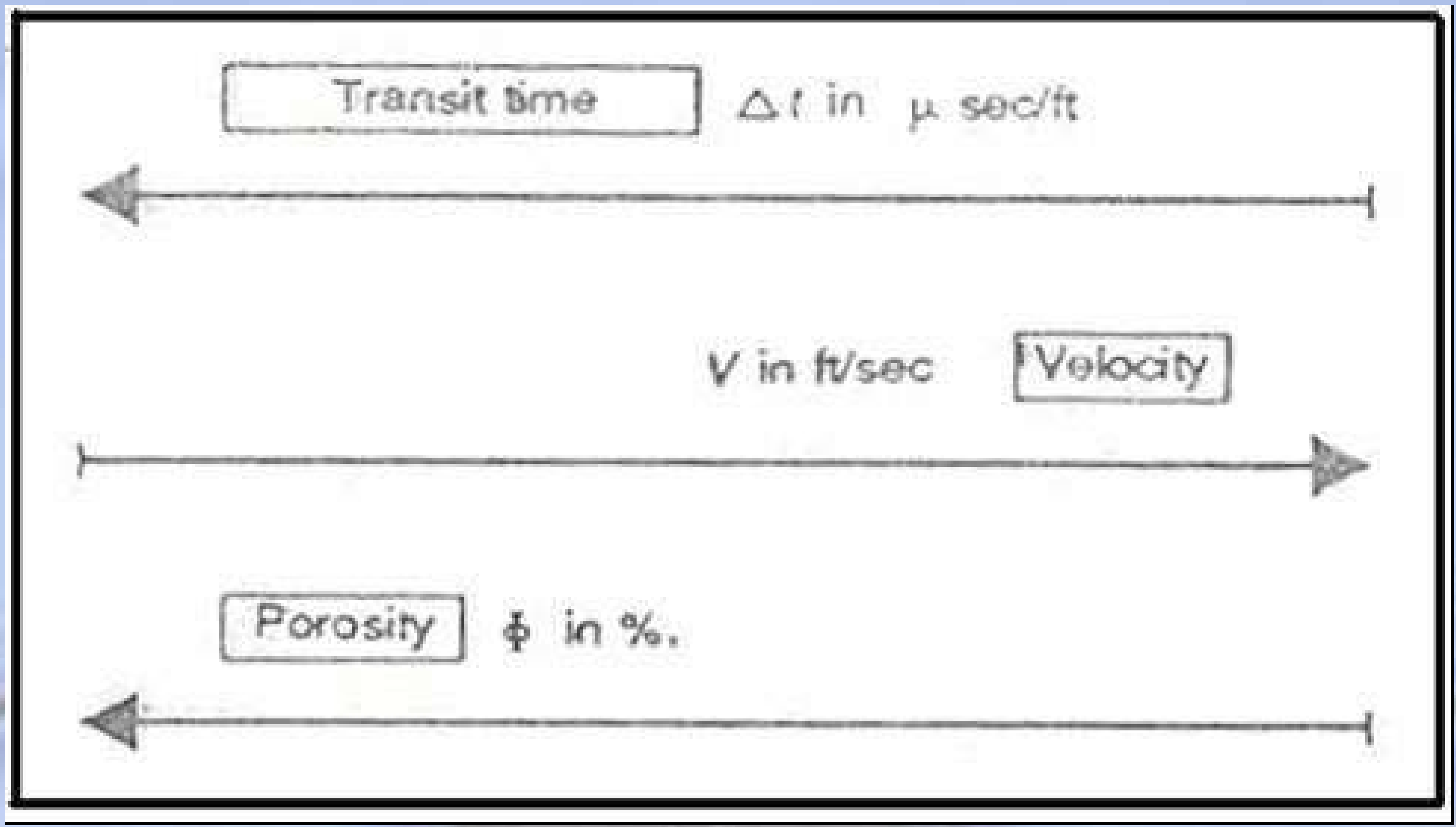
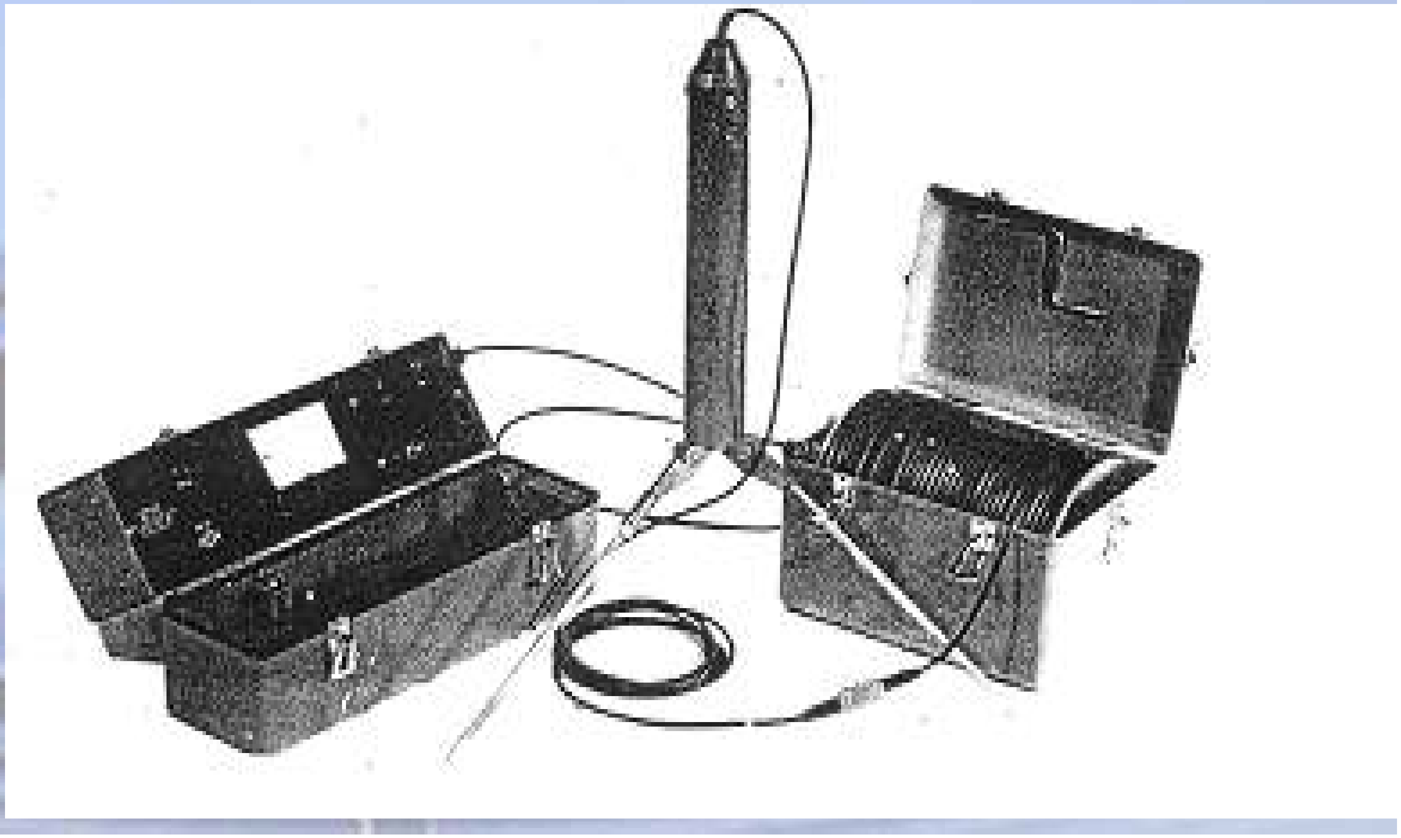


Figure 8.2 Scales for acoustic logs

9. Caliper logging

- Caliper logs are very useful in determining the exact borehole diameter and the fracture pattern in limestones (see **Figures 9.1 & 9.2**).

Figure 9.1
Calipers raised from the bottom of the borehole can provide information on the position of washouts, swelling clays, and casing separations.



9. Caliper logging

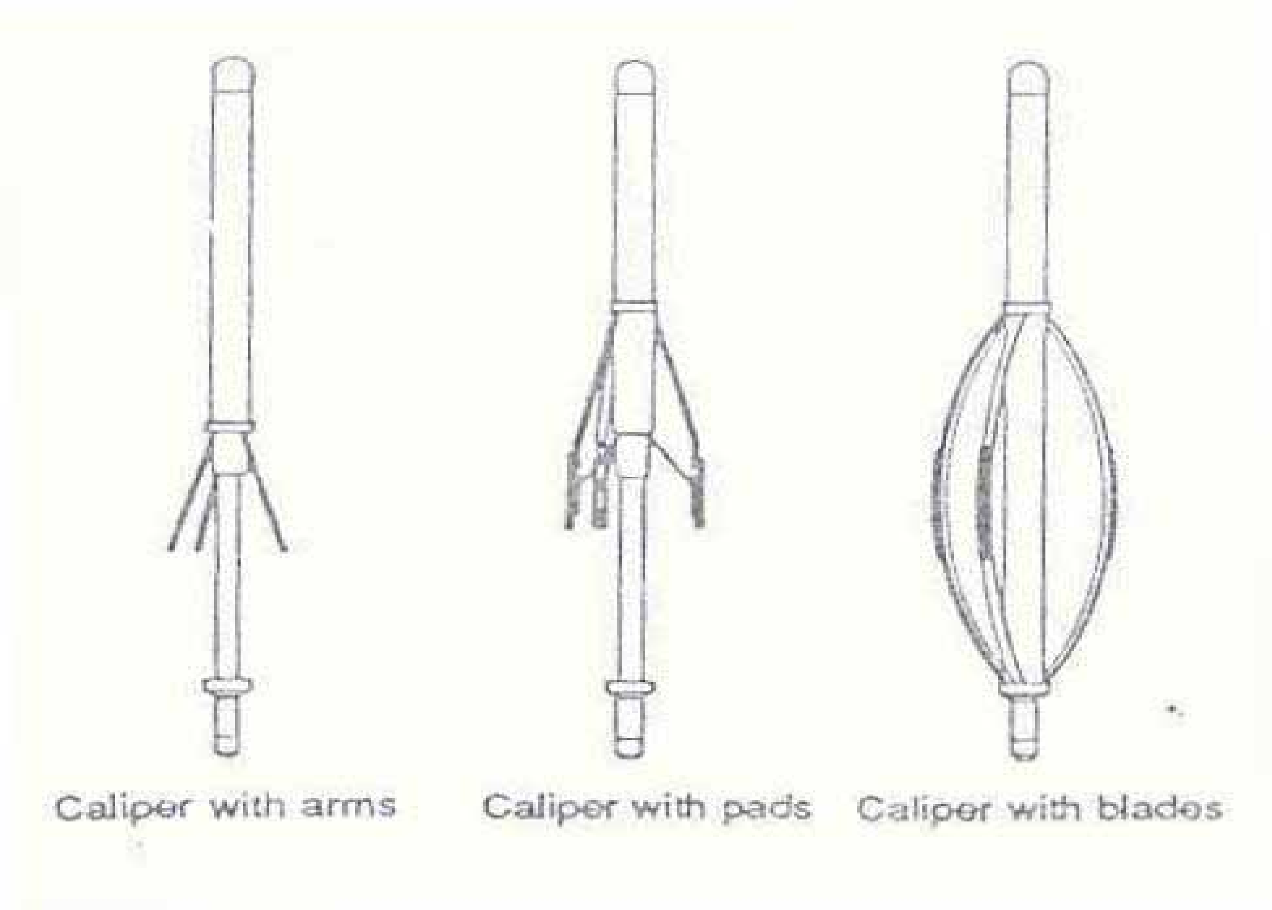


Figure 9.2: Various types of calipers

9. Caliper logging

- The diameter of a borehole (see **Figure 9.3**) may vary for many reasons; the important ones are:

  - ✓Changes in drilling procedure
  - ✓Caving
  - ✓Swelling of clays
  - ✓Presence of mud cake against porous and permeable formations

9. Caliper logging

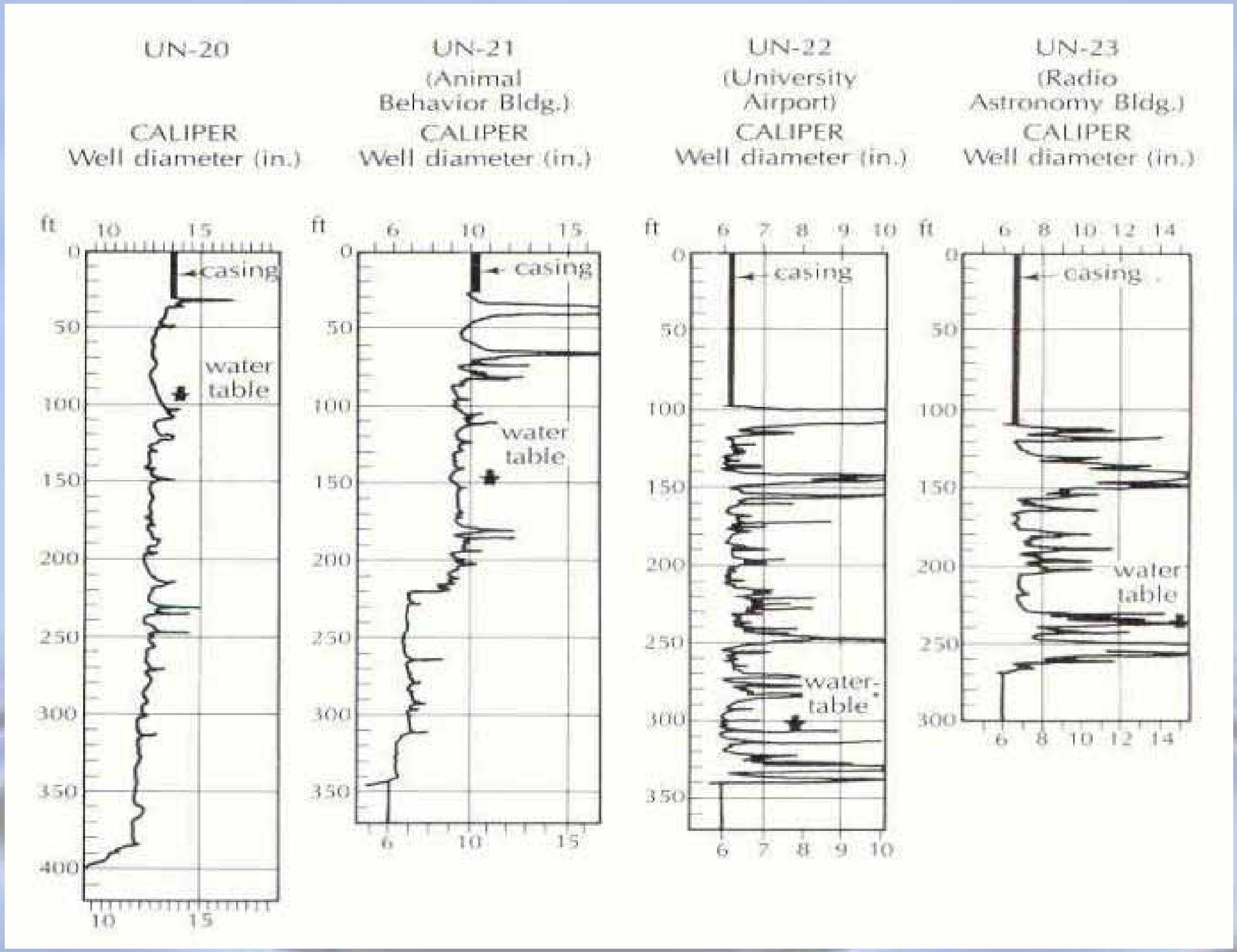


Figure 9.3: Caliper logs of wells in an area of carbonate rocks in central Pennsylvania. Wells UN-20 and UN-21 were drilled in interfracture area, Wells UN-22 and UN-23 were located on fracture traces.

10. Temperature Logging

The types of measurements are: continuous recording of temperature using a sensor lowered into the borehole and measurement of the temperature gradient using two sensors.

Interpretation

- ✓**Measurement of geothermal gradient**: on average, temperature increases one degree C for every 30 meters. This is known as **geothermal degree**. The geothermal degree varies with change of rock types (because rock types have different thermal conductivities); thus the temperature log can provide information on lithology.

10. Temperature Logging

✓Location of mud losses and water inflows (see **Figure 10.1**)

✓**Verification of cementation**: Temperature logs are often recoded in cased holes after cementation in order to determine the level to which the cement has risen. When cement sets, heat is released; the top of the cement column is registered on the log by a considerable increment in temperature (see **Figure 10.2**)

10. Temperature Logging

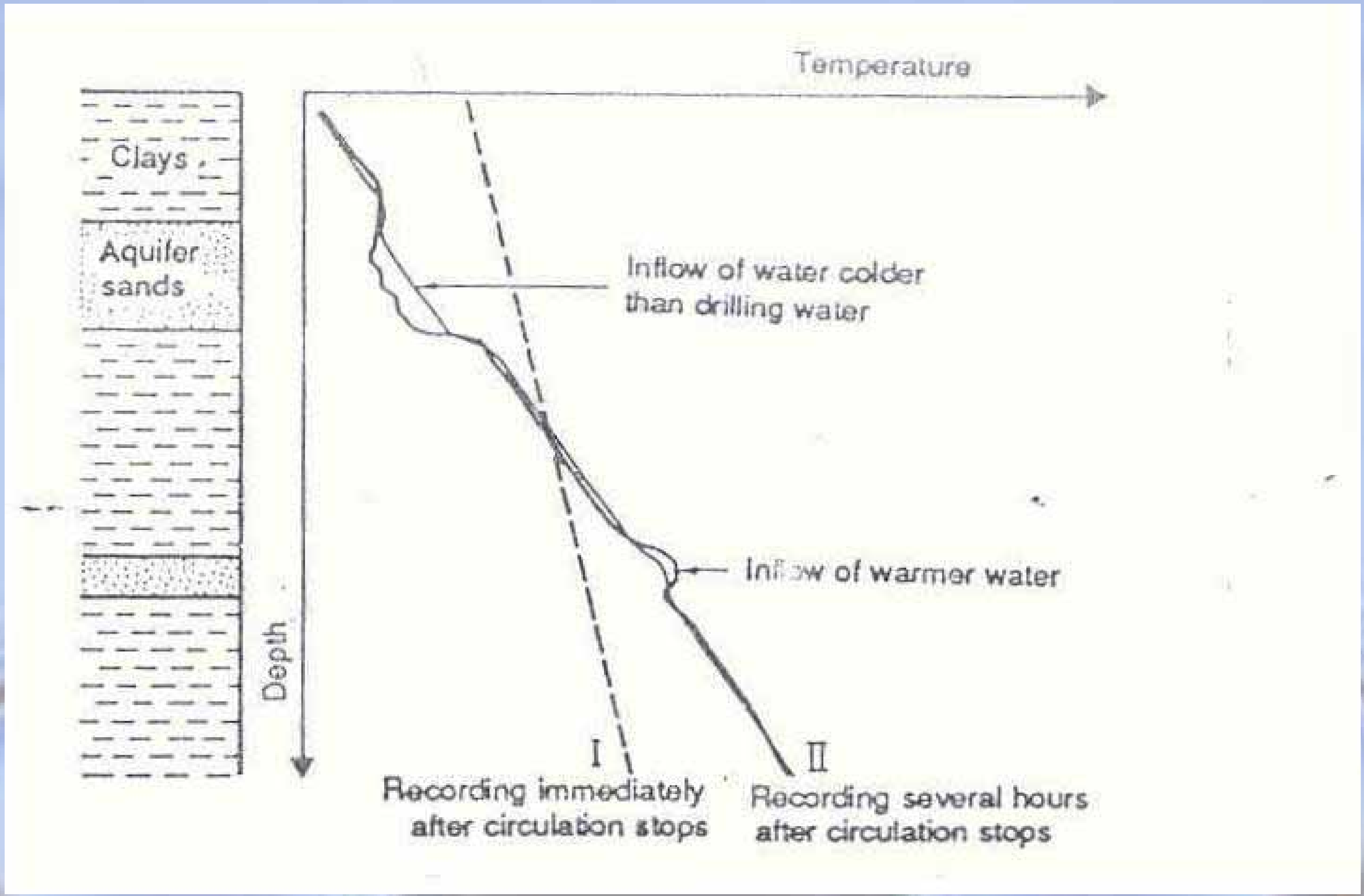


Figure 10.1 Example of a temperature log

10. Temperature Logging

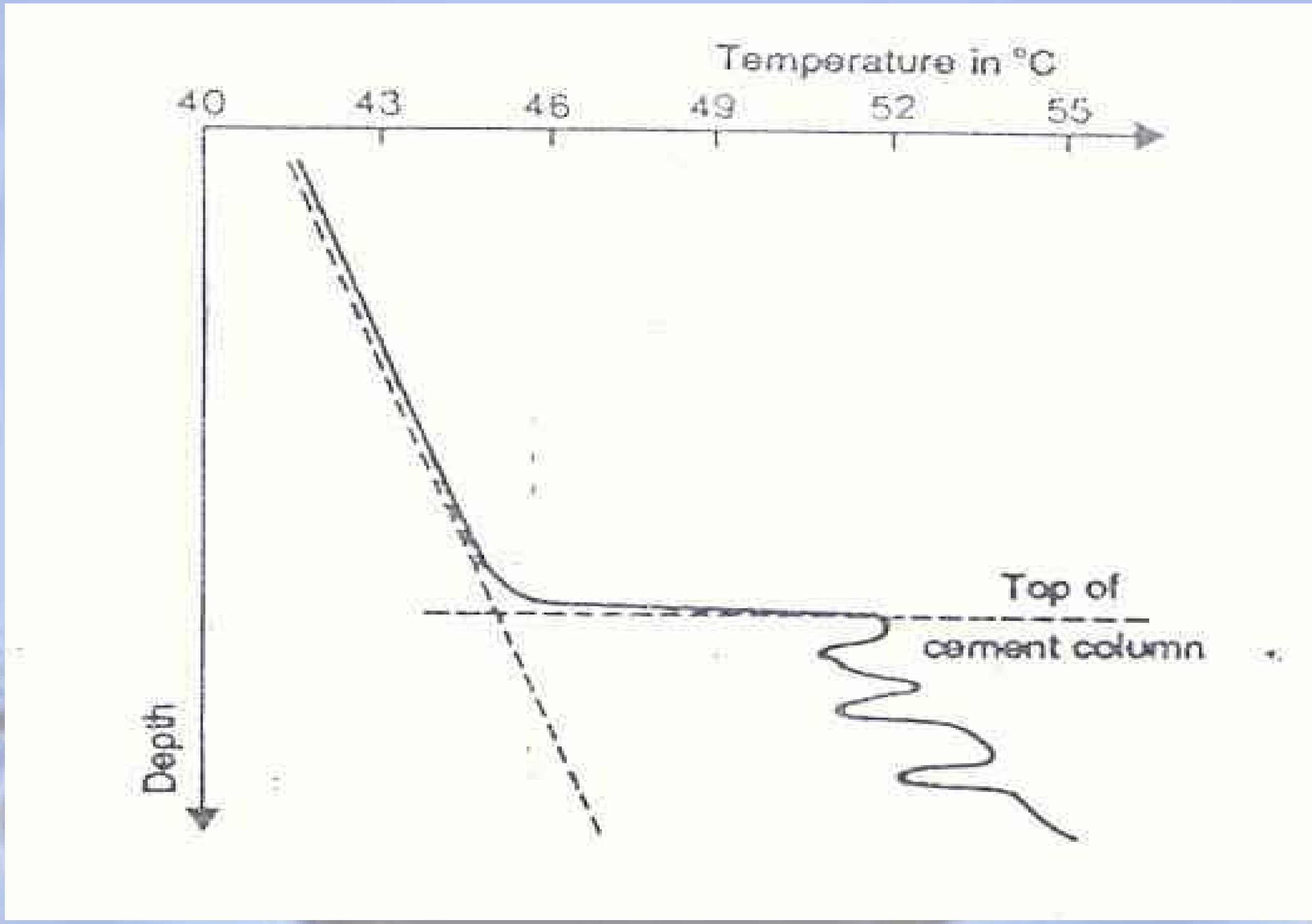


Figure 10.2 Determination of cement level

11. Fluid Resistivity Logging

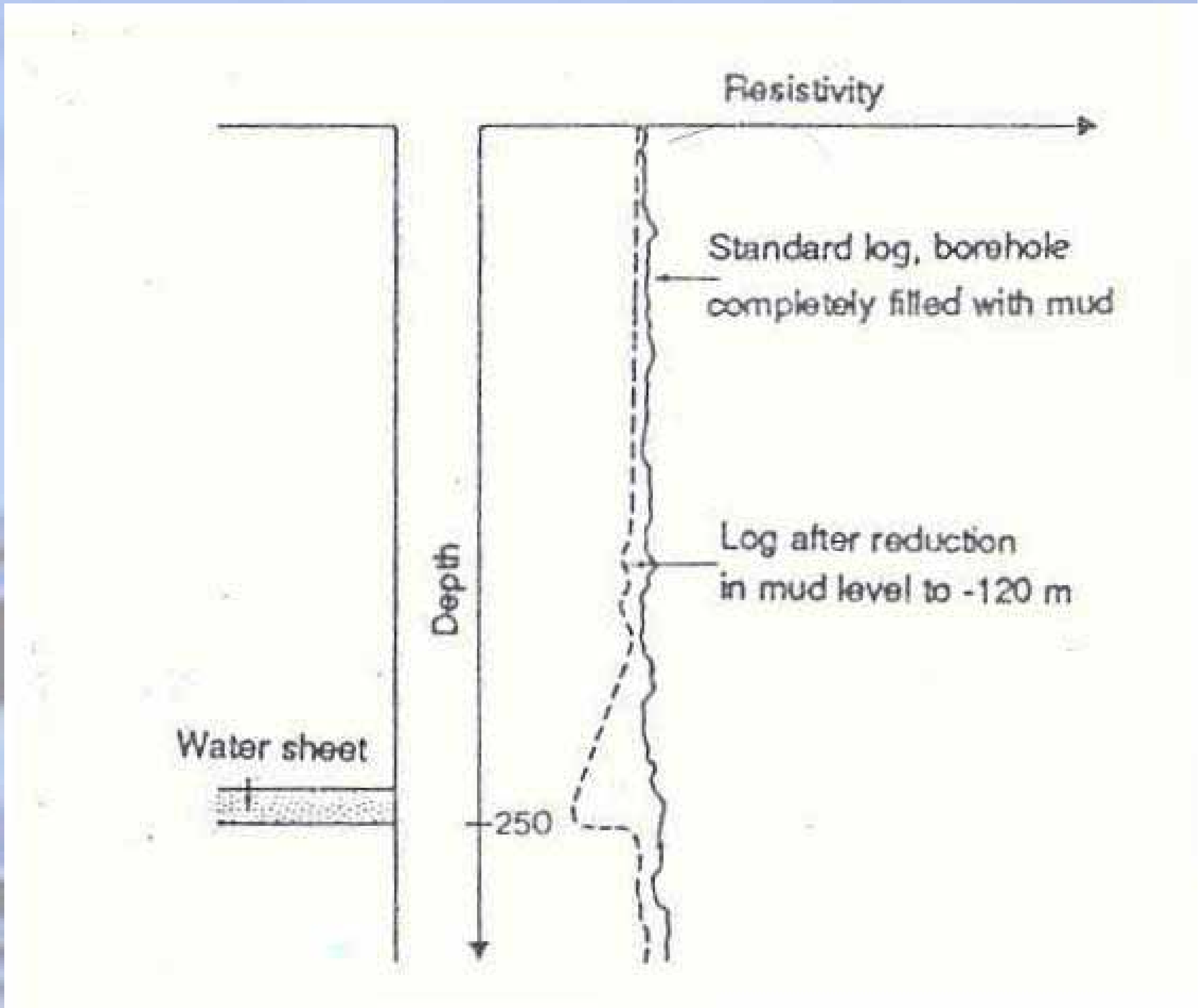
- The fluid resistivity logs is a measurement of resistivity of the fluid column in the borehole.

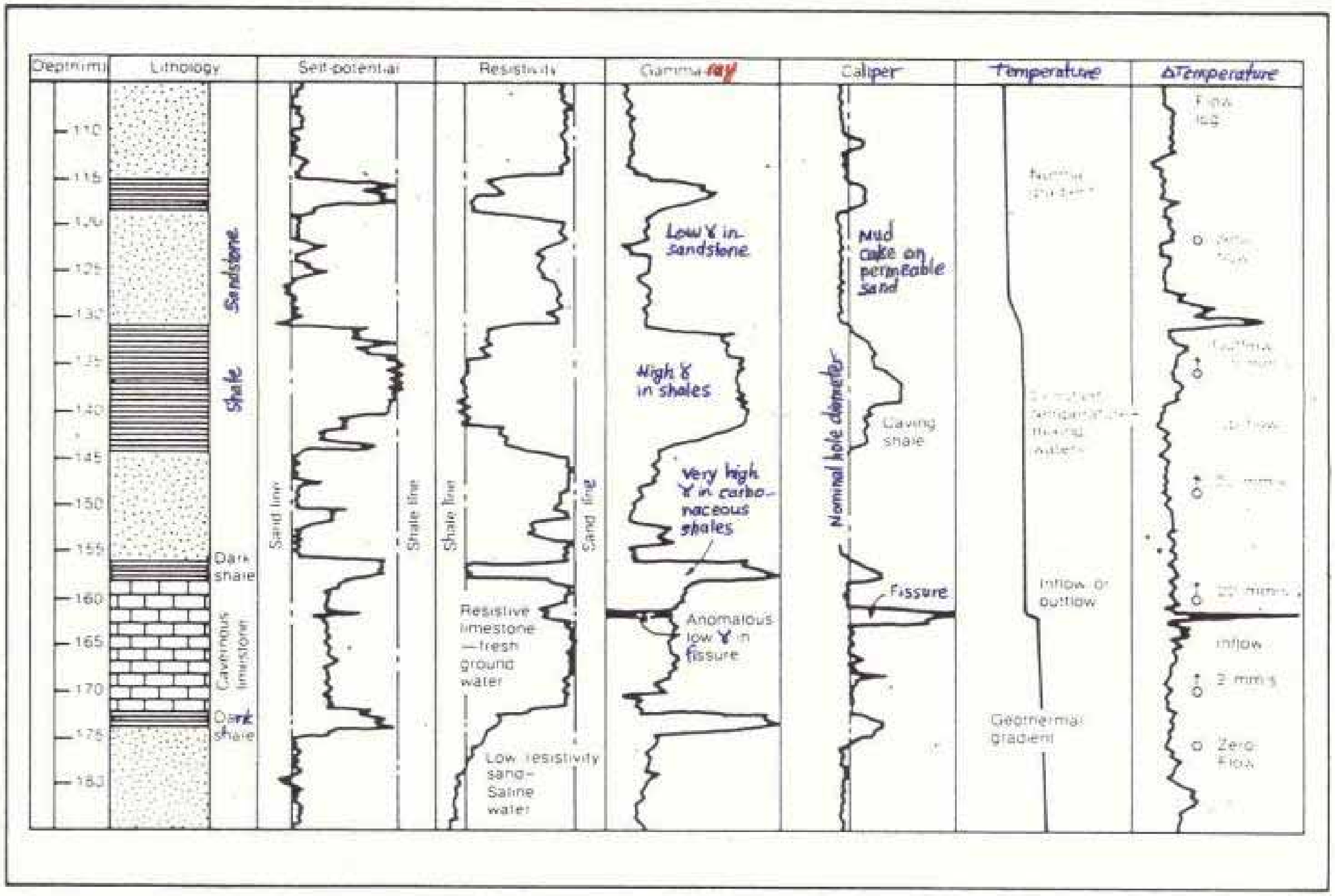
- The main purpose of this log is to correct the electrical and SP logs which are affected by differences in mud resistivity. Further, this type measurement helps identify water entry points especially in fractured media **(see Figure 11.1).**

11. Fluid Resistivity Logging

Figure: 11.1

Example of a fluid resistivity log





Depth (m)
Lithology
Self-potential
Resistivity
Gamma ray
Caliper
Temperature
ΔTemperature
110
115
120
125
130
135
140
145
150
155
160
165
170
175
180
Sandstone
Shale
Dark shale
Cavernous limestone
Dark shale
Sand line
Shale line
Shale line
Sand line
Resistive limestone —fresh ground water
Low resistivity sand— Saline water
Low γ in sandstone
High γ in shales
Very high γ in carbonaceous shales
Anomalous low γ in fissure
Mud cake on permeable sand
Nominal hole diameter
Caving shale
Fissure
Inflow or outflow
Geothermal gradient
Flow log
Zero flow
Inflow
2 mm/s
Zero Flow