na

GROUNDWATER EXPLORATION FOR DRINKING WATER SUPPLIES IN DEVELOPING COUNTRIES

Training Modules Series

February 1982.

GROUNDWATER EXPLORATION FOR
DRINKING WATER SUPPLIES
IN DEVELOPING COUNTRIES

Training Modules Series

February 1982.

NOTE

This Training Module has been prepared by Mr. Ebbo Hofkes, of the International Reference Centre, using material contributed by Mr. Leonard Terwey, of BKH Consulting Engineers, The Hague, Netherlands, and material from other expert sources.

TABLE OF CONTENTS

1. INTRODUCTION

There is much more to groundwater exploration than the mere location of subsurface water. To be reliable, groundwater exploration must combine knowledge with experience and common sense. It cannot be achieved by the mere waving of a magic forked stick as may be claimed by those who practise what is often referred to as water witching, water dowsing, or water divining. Methods of exploration include simple hydrogeological tools based upon the application of common sense, intelligence and good judgement, but also sophisticated techniques.

The approach to be used in groundwater prospection may cover any or all of the following steps:

- study of relevant geological maps and reports (if any)
- study of topographical maps (e.g. 1 : 25,000 scale)
- examination of existing wells
- sinking of test holes
- hydraulic methods of exploration
- geophysical investigations (seismic refraction, electric resistivity, magnetic field measurement etc.)

The first step is to define an approximate area of study and to gather information on that area. A frequent reason for the failure of an exploration study is that the study area is too small and may exclude the best or perhaps the only suitable groundwater source. If, after a preliminary investigation, the area appears to be too large, then the study can be narrowed to more specific areas.

Succesful groundwater exploration requires a basic knowledge of the manner in which water exists in the aquifers (water-bearing ground formations). Without this knowledge, effective and efficient water prospection is impossible, and well drilling would become something like a game of roulette.

Sometimes, a thorough search for information will yield a previous study that can form a suitable basis for the exploration study. Assuming that no prior study is found, one of the cheapest methods for locating suitable

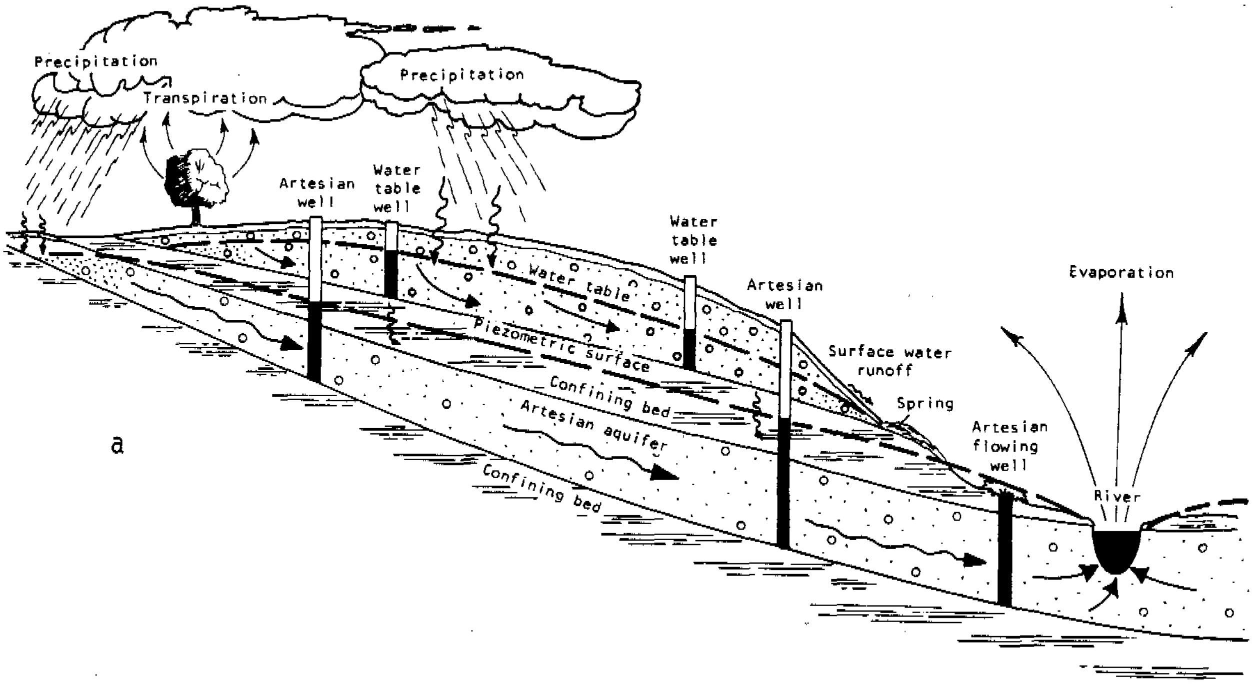


Fig. 1. Groundwater Movement (Schematic)

aquifers is to develop geological cross sections of the area. This is done by plotting the existing wells on a map of the area. The well logs and any available pumps tests of these wells are listed on this map. From this information cross sections then can be developed. For each cross section line, the topography (surface) is plotted from the map contours. The development of geological cross sections using information from existing wells and geological maps of the study area is a powerful instrument in locating suitable aquifers (Fig.2).

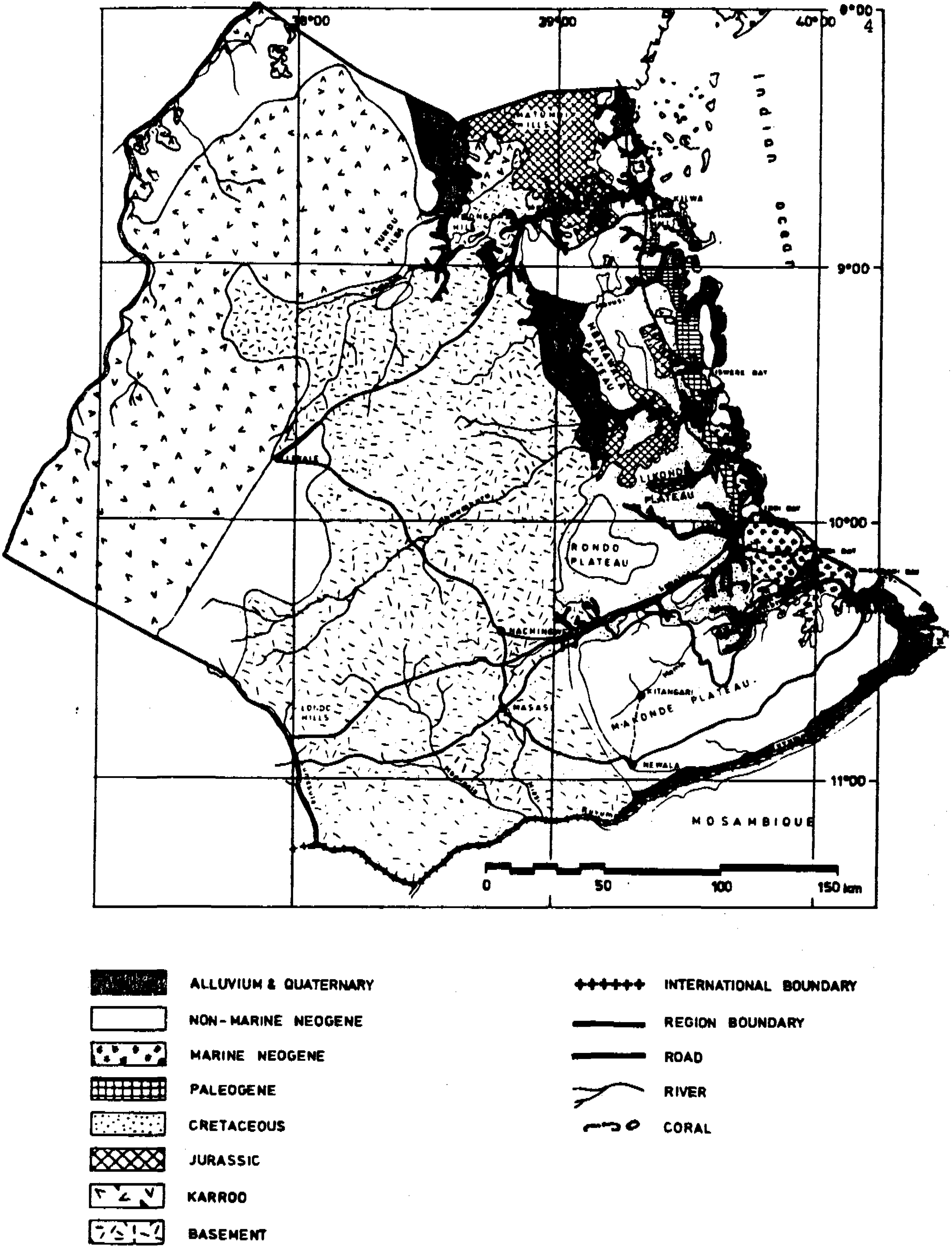


Fig.2. Geological map of Mtwara and Lindi regions (Tanzania).

As part of the information collection effort, a survey of the study area should be made, preferably towards the end of the dry season when groundwater levels will probably be at their lowest. In some cases this may be all that is needed for an experienced hydrogeologist to define groundwater sources for small community supplies, and no further investigation would be required. If essential data are lacking, some field work would be necessary to obtain them. The survey should provide sufficient data to form a basis for the drawing up of a hydrogeological map showing the distribution of aquifers; depth of the groundwater table and the piezometric levels. (Fig.3 gives an example).
The most likely locations for groundwater in alluvial formations are in the valleys near watercourses.

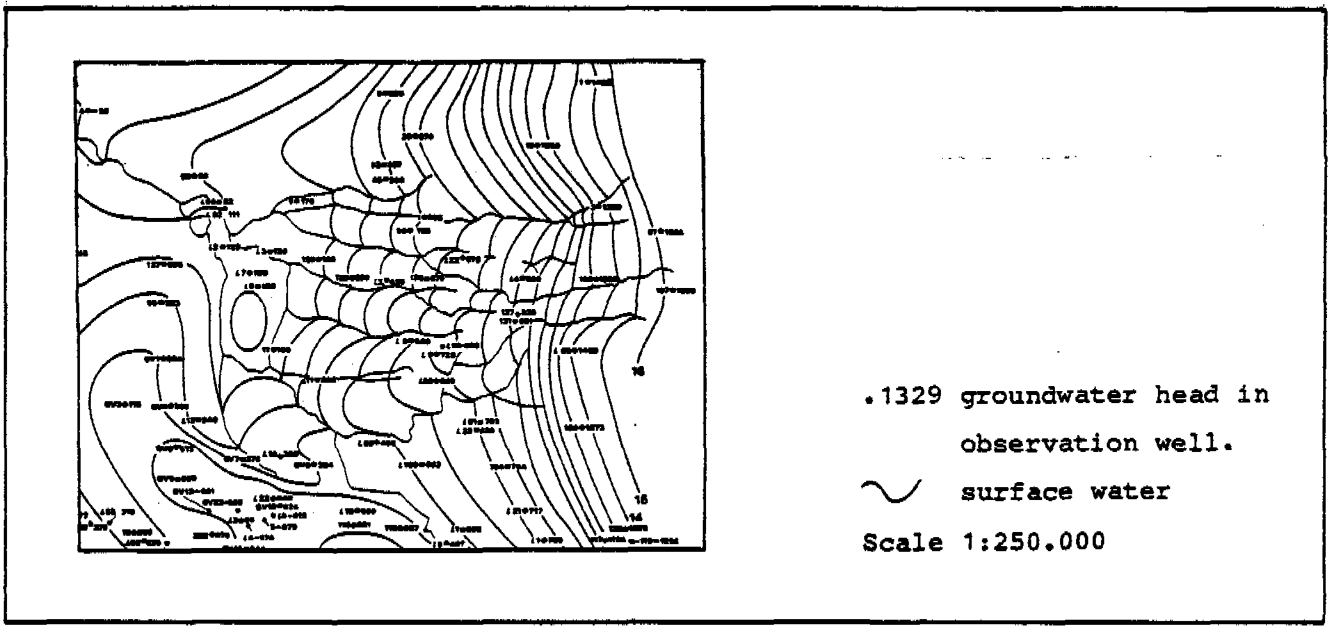


Fig.3. Example of a groundwater contour map.

The preparation of such a groundwater map may involve the use of specially drilled boreholes and geophysical exploration methods. However, the drilling of boreholes will only be required when an aquifer is to be fully exploited, for which a knowledge of the hydraulic permeability and water storage capacity of the ground formation is needed.

Geophysical methods are important tools in groundwater exploration. With these methods, it is possible to obtain subsurface information about a proposed well site as effectively and at less cost than through the drilling of boreholes. However, the role of traditional hydrogeological investigations for cost-effective groundwater exploration should not be overlooked. These should be supplemented, not replaced, by geophysical exploration techniques such as electrical resistivity, seismic refraction and well logging. The modern methods are capable of yielding more accurate information about the subsurface conditions and aquifer characteristics, and so complement the groundwater data obtained by traditional investigations. This is summarized in Fig.4.

Several surface exploration techniques may provide useful information without requiring costly borings. For instance, stream monitoring can identify areas where streams are gaining flow from groundwater that might be intercepted by wells, or where streams are losing water into permeable stream beds from which water may be withdrawn water directly with wells.

It may be said that groundwater as yet has not played the important role in the supplying the world's water needs, which its relatively abundant availablility would indicate. Its out-of-sight location and the associated lack of knowledge with respect to its occurrence, have no doubt contributed to this situation.

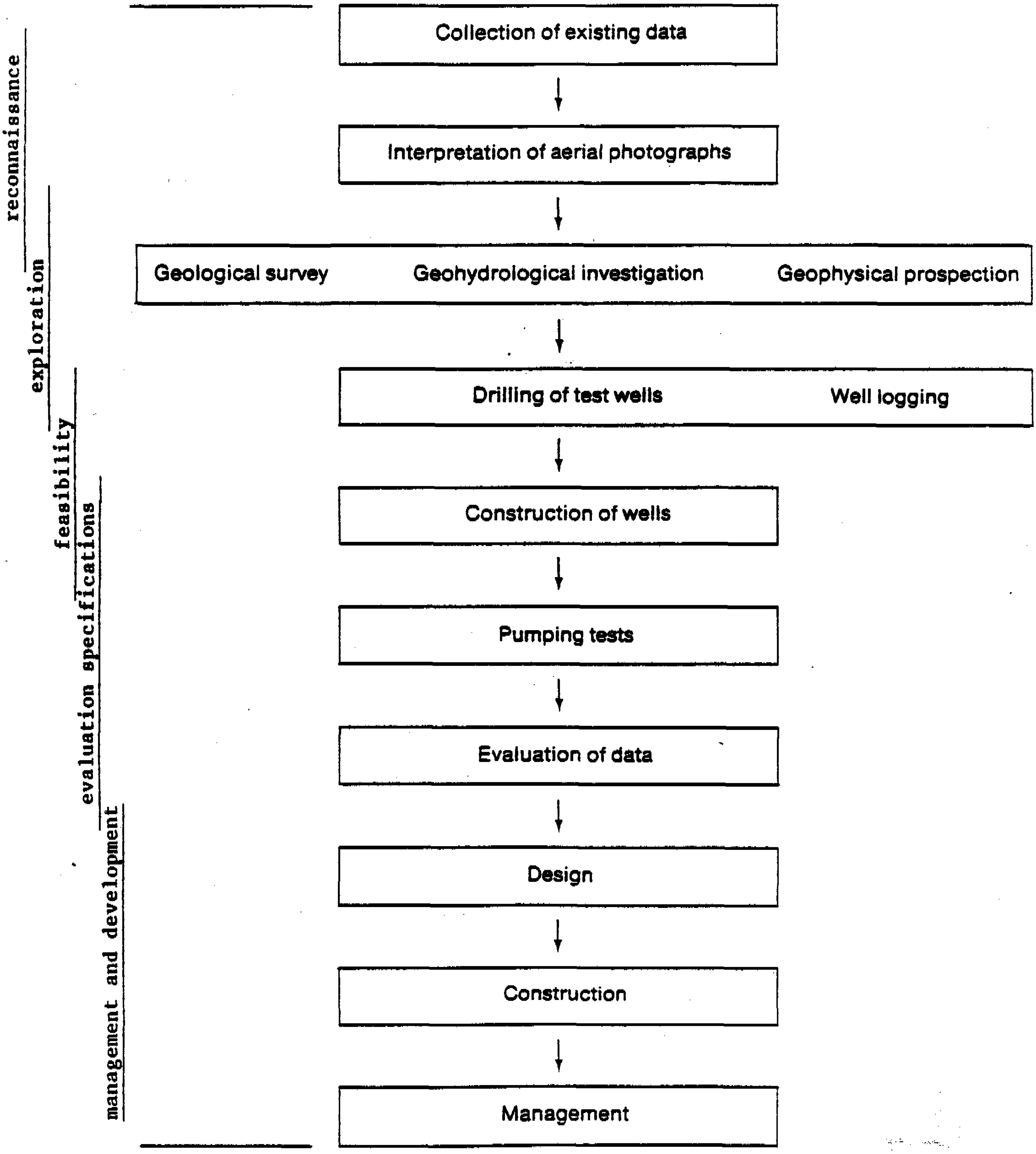


Fig.4. Stages of Groundwater Exploration and Development.

2. SURFACE GEOPHYSICAL METHODS

Of all surface geophysical methods only electrical resistivity and seismic refraction have more than limited application in the exploration of shallow geological formations. Experience and research have made possible that geophysical data are interpreted in terms of geological structure, type of formation, porosity, water content and salinity of the water.

2.1 Electrical Resistivity Method

Electrical resistivity measurements are very useful in understanding the distribution and quality of groundwater. To interpret the results of an electrical resistivity survey is specialist work, but is not difficult to learn how to do the measurements in the field.

Differences in resistivity can indicate the location of permeable strata because materials with a low permeability such as clay, have low resistivities, and highly permeable strata such as sands and gravels tend to have much higher resistivities. Surface resistivity measurements do not eliminate the need for subsurface borings completely, but they may considerably reduce the number of borings required.

Resistivity measurements are made by passing an electric current through the ground between two electrodes and measuring the voltage drop between two other electrodes. The electrodes are placed in a straight line, at points symmetrical to a central point. The depth of penetration of the current is controlled by the spacing of the electrodes. By increasing the electrode spacing the current can be made to penetrate deeper, and so a complete resistivity depth probe can be carried out.

The electric resistivity method is particularly useful in cases where there are marked differences in the resistivity of the ground formations, e.g. alluvial sediments alternating with clay or sand layers. Resistivity probes can, under suitable conditions, go as deep as 300m or more. The larger the depth of the ground formations to be investigated, the larger is the power required to produce sufficiently large potentials that can be measured accurately.

There exists a wide range of equipment, from small and portable to big and heavy which need to be mounted on a truck. Low-cost surface electrical resistivity equipment has recently been developed in Thailand.

Different electrode arrangements are in use depending on the type of subsurface information required. In all configurations, the electrodes are placed in a straight line.

In practice, the Schlumberger electrode spacing arrangement is the most common. This arrangement has the potential electrodes (P) close together; the current electrodes (C) are placed at a distance symmetrical to a central point (the sounding point), which is increased in steps (Fig.5). A series of resistivity readings are taken at different electrode spacings. As the electrode spacing increases, a deeper penetration of the electrical field occurs so that more underground strata will influence the measurements.

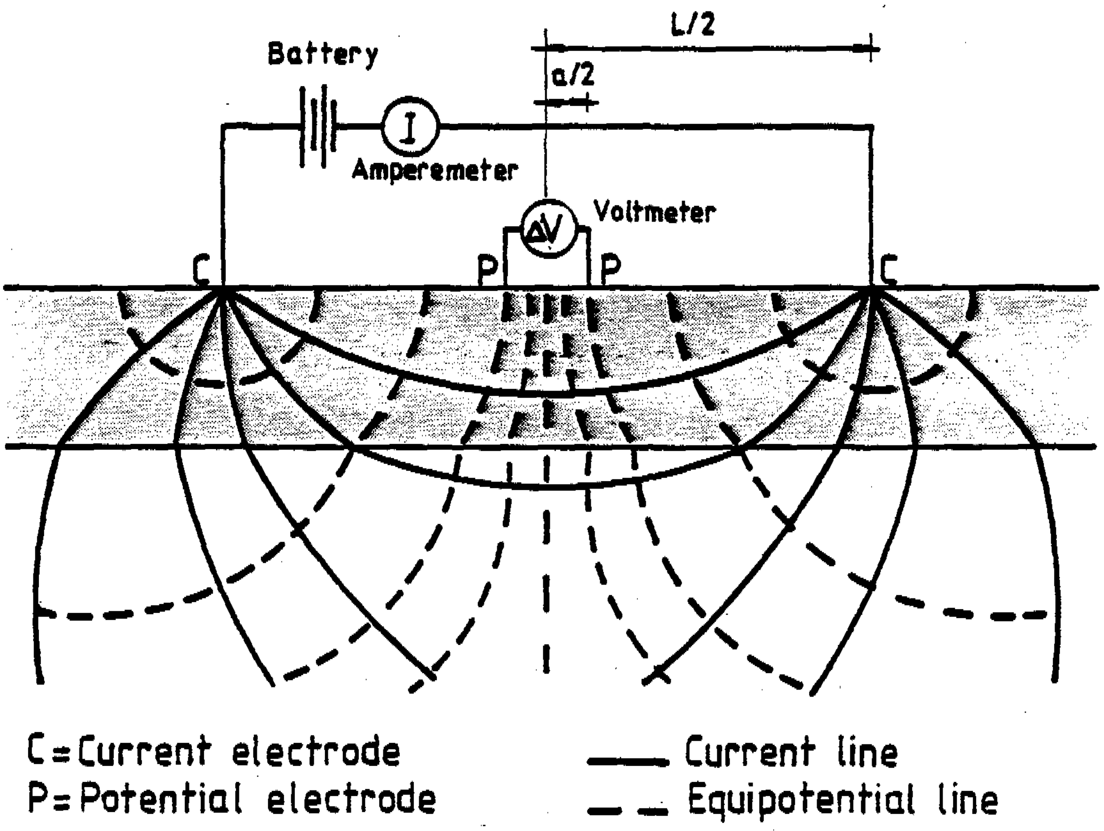


Fig.5. Electrical resistivity equipment (Schlumberger arrangement)

The resistivity probe is started with a short electrode spacing, e.g. 3m. The current then mainly traverses the upper ~~larger~~ layers. The apparent resistivity is computed as:

$$\rho_a = \frac{\pi}{4} \frac{(AB^2 - MN^2)}{MN} \frac{\Delta V}{I}$$

P_a = apparent resistivity
AB = outer electrodes spacing
MN = inner electrodes spacing
AV = voltage drop
I = electrical current

Note:

The ability of a material to resist the electrical current flow is expressed as electrical resistivity (p). The resiprocal of it is electric conductivity (σ) which is often used when water is concerned. The electrical resistance of a homogenius medium is defined as a ratio of the voltage gradient (E) across a small surface element within it to the current density (I) flowing across the element at right angles to it (Parasnis, 1973). This is called Ohm's law and can be written as follows:

$$\frac{\bar{E}}{\bar{I}} = \rho = \frac{1}{\sigma} \qquad (1)$$

The unit of resistivity is ohmm and the unit of conductivity is 1/(ohmm) or mho/m. In this context uS/cm is used as a unit of conductivity. The inverse relationship with the units is:

1 ohmm corresponds to 10 000 µS/cm
10 ohmm corresponds to 1 000 µS/cm

In general, the soil consists of a solid, a liquid and a gaseous component which contributes to the electrical formation resistivity (ρ). The solid and gaseous components can be regarded as insulators. On the other hand, the liquid component acts as a conductor (electrolyte) by means of the salts dissolved in it.

In electrical resistivity measurement using direct current (DC), the current is used to energise the formations. The measured potentials are also DC potentials. The current is meassured separately.

In some electrical resistivity measuring equipment the current is kept constant at 10 milli-ampere by compensating for the varying load conditions i.e. for the changes in the resistance of the formations. In such equipment, only the potentials need to be measured. Potentials can be measured directly with millivolt-meters or microvolt-meters, or they can be measured by the null method making use of potentiometric circuits.

Most of the boreholes drilled for rural water supply programmes are shallow, or medium-depth i.e. less than 30-40 m. Hydrogeological information up to such shallow depths can be obtained easily by equipment using a small amount of power for energising the formations. The voltages developed will be of the order of milli-volts. Thus, the equipment used for such ground investigations can be simple, compact and portable.

Very low resistivity (<10 ohm) seldom indicates good aquifers; the water may be saline or the ground layer is impermeable due to high clay content. Very high resistivity (> 500 ohm) indicates dry formations or impermeable formations with low porosity. Good aquifers usually have resistivity values ~~higher than 200 ohm~~ in the range of 100-300 ohm, if the formation material is coarse and the water fresh (EC < 400 µS/cm). Young sediments providing a good aquifer often have a resistivity between 30 and 100 ohm.

When apparent resistivity is plotted against electrode spacing for various spacings at one location, a smooth curve can be drawn through the points. Often quite a lot of information about the underground can be deduced even from qualitative inspection of these curves (Fig.6).

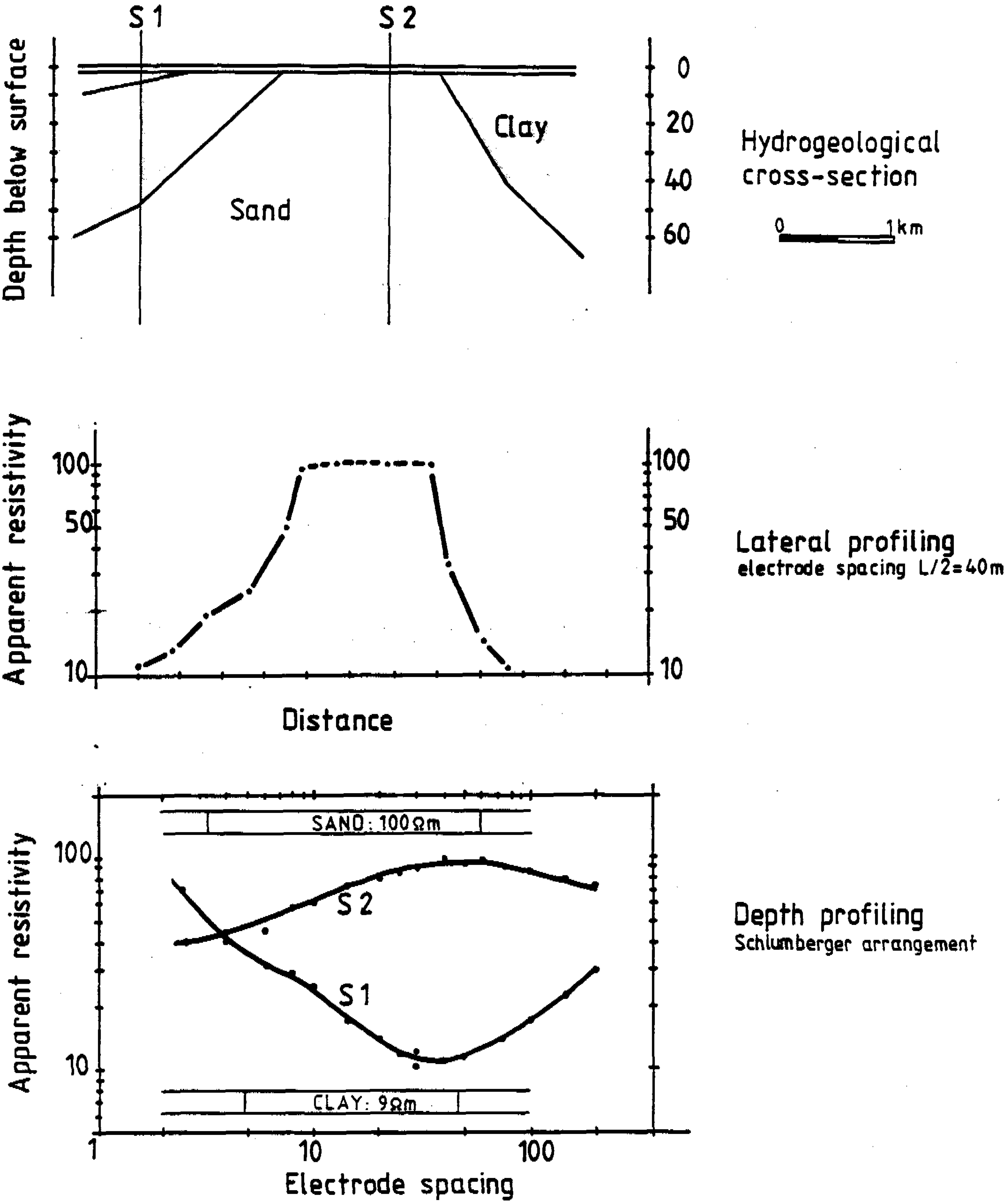


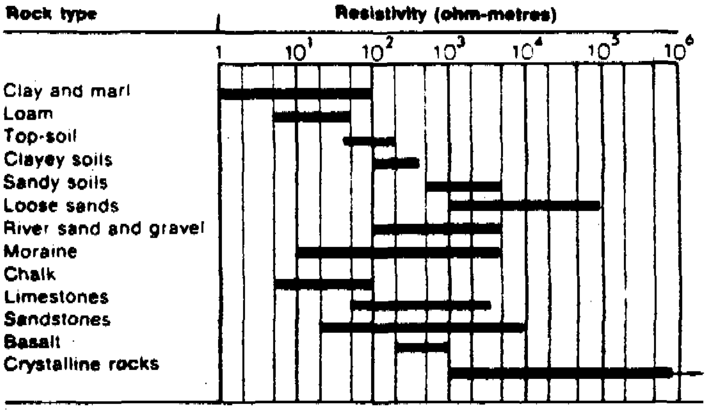
Fig.6. Electrical Resistivity Curves and Interpretation.

The quantitative interpretation of the resistivity curves in terms of subsurface conditions for a multi-layer situation is often a more complex problem. Additional data may then be necessary for an effective evaluation of the curves. Formation resistivities vary over a wide range depending upon the rock type, rock porosity, water content and water composition (Table 1). For aquifers composed of unconsolidated materials, the resistivity is more dependent on the content and composition of the water contained in the formation than on the resistivity of the ground materials themselves.

Table 1

Approximate Range of Electrical Resistivities

(Kollert, 1969)



If a resistivity depth probe is done near to an existing well or borehole of which the water level, water quality and aquifer thickness are known, then a correlation between the resistivity values and the hydrogeological conditions may be established. This would provide a basis for the interpretation of resistivity depth probes carried out in other areas with much the same geology.

Conducting the resistivity measurements in a grid pattern over an area, allows the readings to be plotted on a grid map to form patterns of high and low resistivity for each electrode spacing used. Lines of equal resistivity can then be drawn on the map for identification of areas of low resistivity, which are more likely to be permeable and water-bearing ground formations, than are high-resistivity areas (Fig.7).

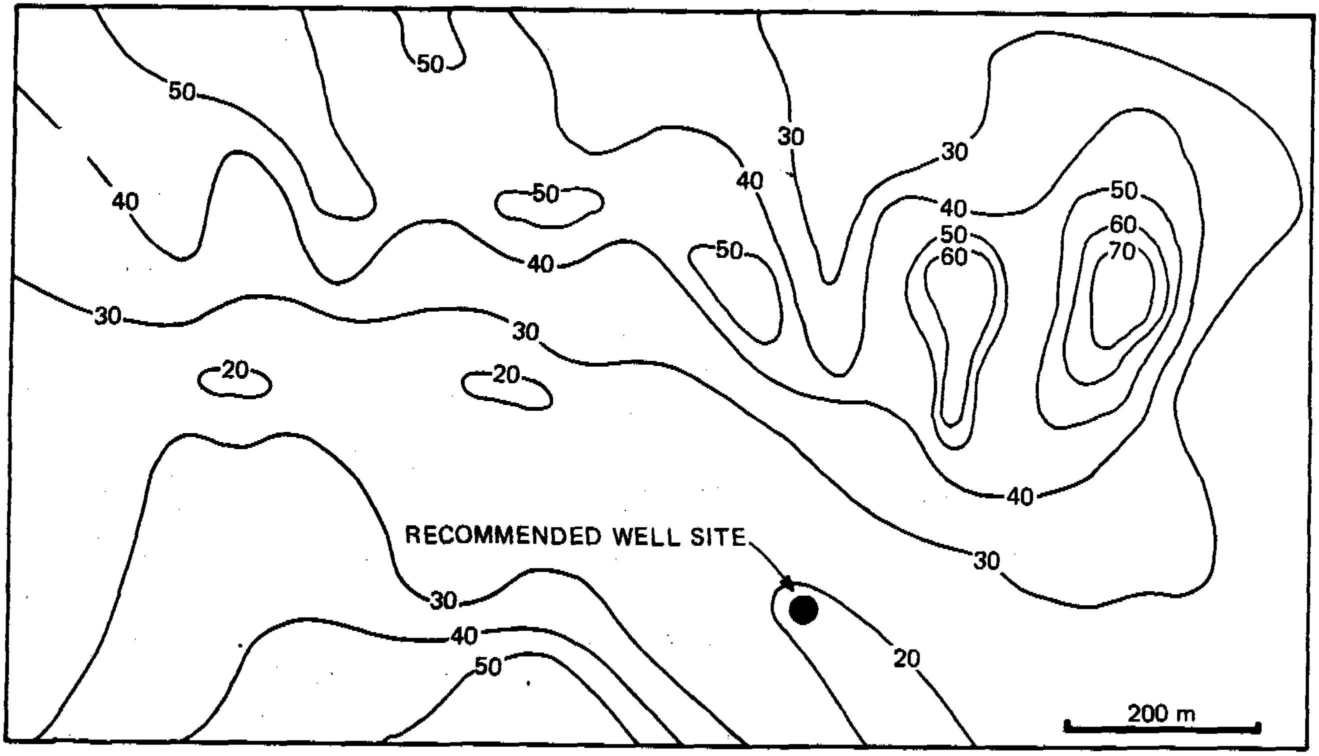


Fig.7 Apparent Resistivity Contour map

(Contour interval: 10 ohm-meter)

Jallapally Area, District Nizamabad, Andhra Pradesh

~~Source: National Geophysical Research Institute,~~

~~Hyderabad,~~

~~Andra Pradesh, Indi~~a

In Tanzania, a project with Finnish assistance for installation of wells, found electrical resistivity sounding particularly useful in the location of aquifers (spec. resistivity $>$30 ohm) in sedimentary areas. Clayey ground layers and layers containing saline water showed low resistivity (less than 10 ohm).

With electrical resistivity measurements alone it is not possible to differentiate sand or gravel layers containing saline water from clays or marl containing fresh water.

2.2 Test Pumping Method

Test wells are by far the most common type of exploration borings made. These wells usually are used to test-pump aquifers located by earlier surface investigations, and to obtain water samples. Keeping the diameter of the screened portions of the well at 15 cm (6 in.), the overall cost of the well can be kept reasonable.

Test pumping is somewhat difficult if the aquifer to be tested is very permeable or has a close source of recharge. Even at a pumping rate of 4,000-7,500 m^3/day possible from such 6-inch dia wells, no sufficient drawdown may be created to enable the aquifer's potential to be determined with sufficient accuracy.

In view of the costs of test borehole drilling, by far the best means to carry out a pumping test is to use an existing well, if one is available. For a test at the necessary flow rate this usually entails removing an existing pump and installating a temporary pump that has a higher capacity. However, pumping an old well at a higher than normal rate can cause problems such as the collapse of its casing and the loosening of ground materials opposite the well screen openings which may lead to sand entering the well.

2.3 Seismic Refraction Method

The seismic refraction method is based on measuring the velocity of elastic waves transmitted through the underground formations. Changes in seismic velocity are governed by variations in elastic properties of the formations.

The field technique involves creating the seismic waves by striking the ground surface with a hammer or by firing an explosive charge, and measuring the time required for the resulting shock wave to travel known distances. Geophones (detectors) are placed at equal intervals along a straight line and a seismograph records the time elapsed between the firing and the arrivel of the resulting wave at each geophone. These waves may either travel directly from the shot point, or will arrive along a refracted path to the geophone (Fig.8). The greater the contrast in the various velocities of the shock wave, the more clearly the formations and their boundaries can be identified.

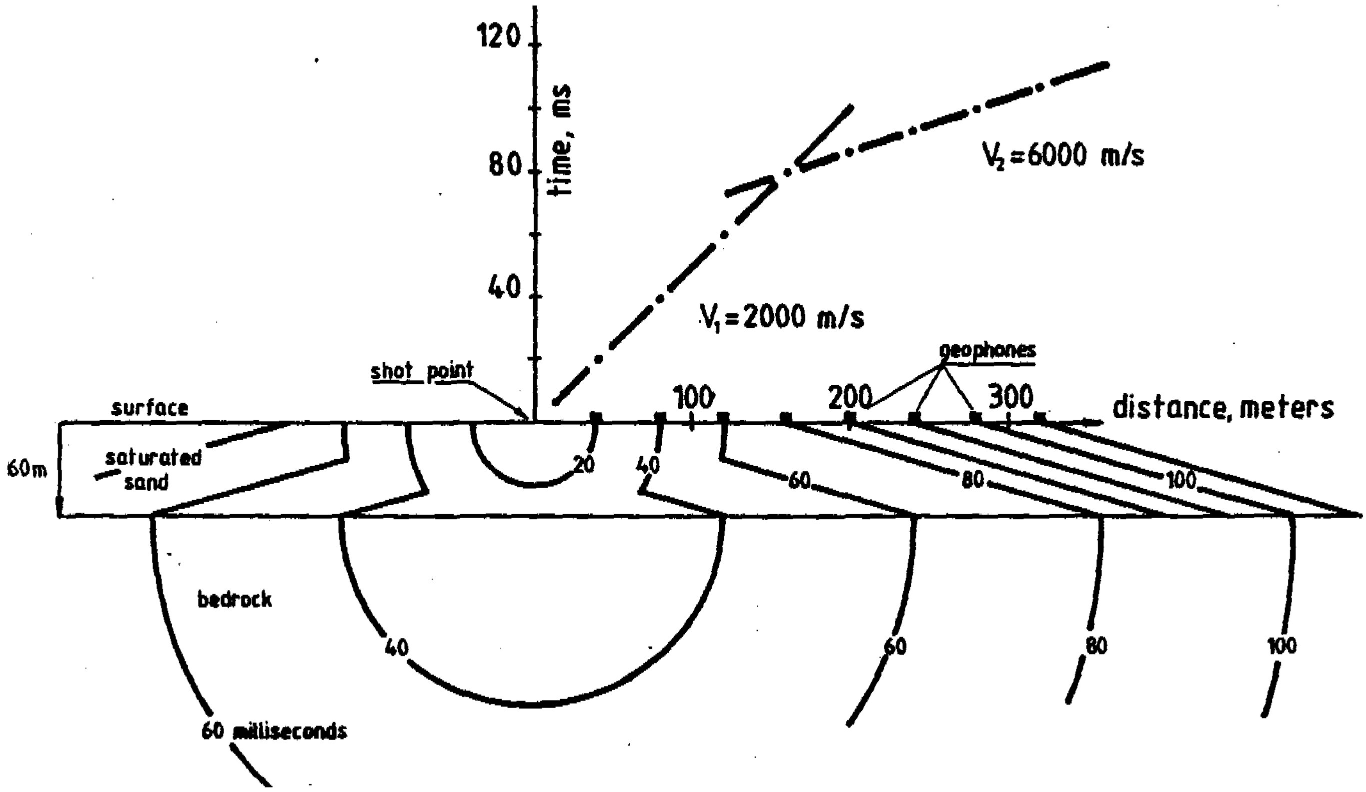


Fig.8 Seismic Refraction

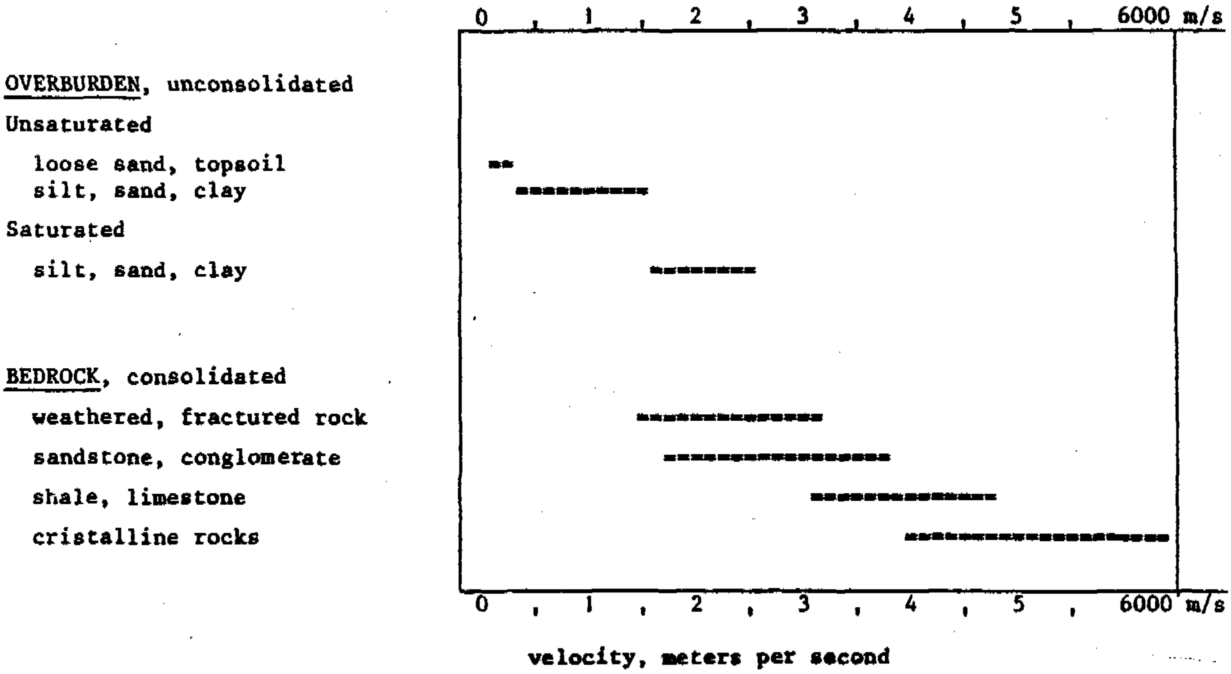
A time distance graph representing the arrival time of the first shock wave at each geophone against geophone distances from the shot point determines the seismic wave velocities in formations. The greater the contrast in velocities, the more clearly the formations and their boundaries can be identified.

Velocities are lowest in unsaturated, unconsolidated sediments; they increase markedly for saturated zones. The more consolidated the material, the higher the velocity; the highest values are recorded insolid igneous rocks. The depth range of seismic refraction surveys is usually in the order of 100-200m.

Characteristic seismic velocities for various geological materials are shown in Table 2.

Table 2

Approximate Range of Seismic Velocities



In seismic refraction surveys a combination of low-velocity contrast and deep bedrock leads to difficulty, and the depth range is restricted to the layer with the highest sound velocity. Moreover, quiet surroundings without noise or interference from traffic or aircraft will be an advantage.

Explosives may only be applied with legal restrictions and regulations. For shallow exploration, less expensive portable seismographs may be used, and in quiet surroundings shock waves may be initiated by using hammers.

Where two adjacent subsurface formations have an equal electrical resistivity, their different seismic refraction velocities may be distinguished with the seismograph. The seismograph on the other hand cannot notice a layer of low velocity under a layer of high velocity, but in this case a difference in electrical resistivity may be detected.

An example of a seismic survey is shown in Figure 9.

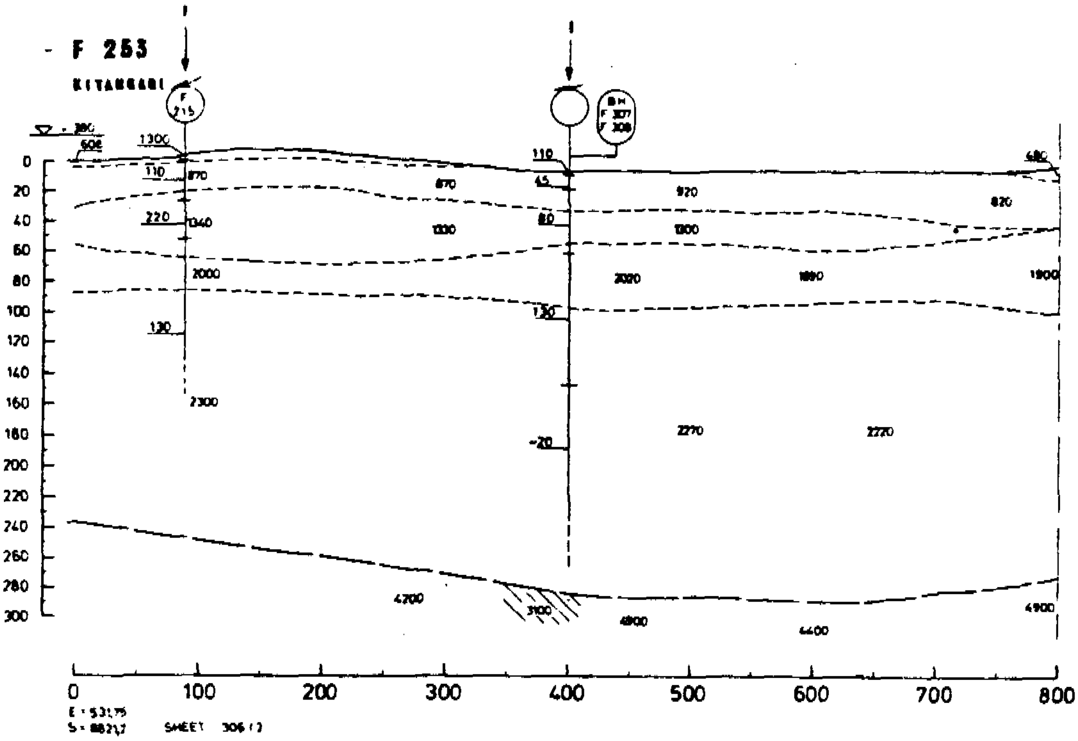


Fig. 9 Seismic Survey

Most seismic equipment is relatively expensive multi-channel equipment. However, less expensive single-channel equipment ~~useful~~ suitable for shallow exploration, has become available.

2.4 Photogrammetry and Remote Sensing

Photographs taken from aeroplanes or satellites can provide useful information regarding groundwater resources and conditions.

In addition to conventional black and white and color photographs, the technology and applications to water resources of remote sensing techniques such as infrared photography, multispectral and thermal infrared scanning, and side-looking radar have expanded rapidly in recent years (Table 3). In general, these techniques sense only those properties and characteristics associated with the ground surface, from which indirectly subsurface information may be derived. However, geophysical devices, both airborne and ground-based have the capacity of greater depth penetration, so that they can directly indicate subsurface characteristics.

Table 3

Application of Photogrammetry and Remote Sensing

TECHNIQUES		SOME MAJOR APPLICATIONS
AERIAL PHOTOGRAPHS	black and white color infrared	Topographic mapping, differences in geology soils-vegetation, land use, general flow pattern, fracture patterns in rock, natural resources inventory
MSS-LANDSAT	multispectral scanning	Dynamic natural processes, flooding areas, geological structures, mineral exploration, land use patterns
THERMAL IR	thermal infrared scanning imagery	Geological structures, soil moisture, groundwater circulation, coastal submarine springs, fresh water flow into sea, salt water intrusion, water pollution, detection, source identification
RADAR	side-looking radar imagery	Topographic mapping in forest areas, land use patterns, soil moisture, reconnaissance geological surveys, oil spilling

Airborne geophysics such as magnetic, radiometric and electric-magnetic measurements are used for mapping and inventories of relatively large areas. These methods are rapid, relatively inexpensive (per unit of area covered), and very useful in locating mineral deposits. Also for identifying geological structures, tectonic and structural trends, faults and other discontinuities in geological formations.

The results of aerial geophysical investigations are increasingly recorded on magnetic tape and computer-processed. They are usually presented in the form of maps.

2.5 Gravity and Magnetic Surveys

Gravity surveys are made by recording the extremely small variations in the earth's gravitational field caused by changes in the density of the subsurface geology. By mapping variations or anomalies in an otherwise uniform area, gravity surveys can indicate the location of buried valleys or river channels that might contain sand and gravel aquifer suitable for development as groundwater sources.

These methods of geophysical prospecting can be useful in determining the stratigraphy of consolidated rock and in locating major fault and fracture zones. Analysis of the results may indicate qualitatively the depth to bedrock and the presence of buried valleys. These methods have little application to groundwater prospection and, ingeneral, are less suitable than the seismic refraction or electrical resistivity methods. Subsurface conditions such as type, dimensions and physical characteristics of the geological formations can may be determined with these techniques.

3. SUBSURFACE GEOPHYSICAL METHODS

Quantitative data about groundwater and conditions under which it occurs can only be made by subsurface investigations. Test and production well drilling furnish information on the thickness and composition of perforated geological formations.

3.1 Well Logging

Well logging provides data on the physical properties and characteristics of the formations, water composition, and the quality of well construction. Geophysical measurements made inside a borehole are called geophysical well logging.

Borehole geophysics such as well logging are used to determine the lithography and stratigraphy of the borehole. This information is used to locate the aquifers (where well screens should be placed) and impervious layers (where plain pipes are to be placed) of measurements obtained with it.

The well logging technique and the interpretation of measurements obtained with it, have mainly been developed in oil prospecting. Well logging is mostly used in connection with fast drilling methods when samples are difficult to take, e.g. with rotary drilling. Used in groundwater investigations, well logging can provide information on the lithology and stratigraphy of the ground formations, and the porosity, resistivity and salinity of the water in it.

Fig.10 shows a typical electric log of a borehole.

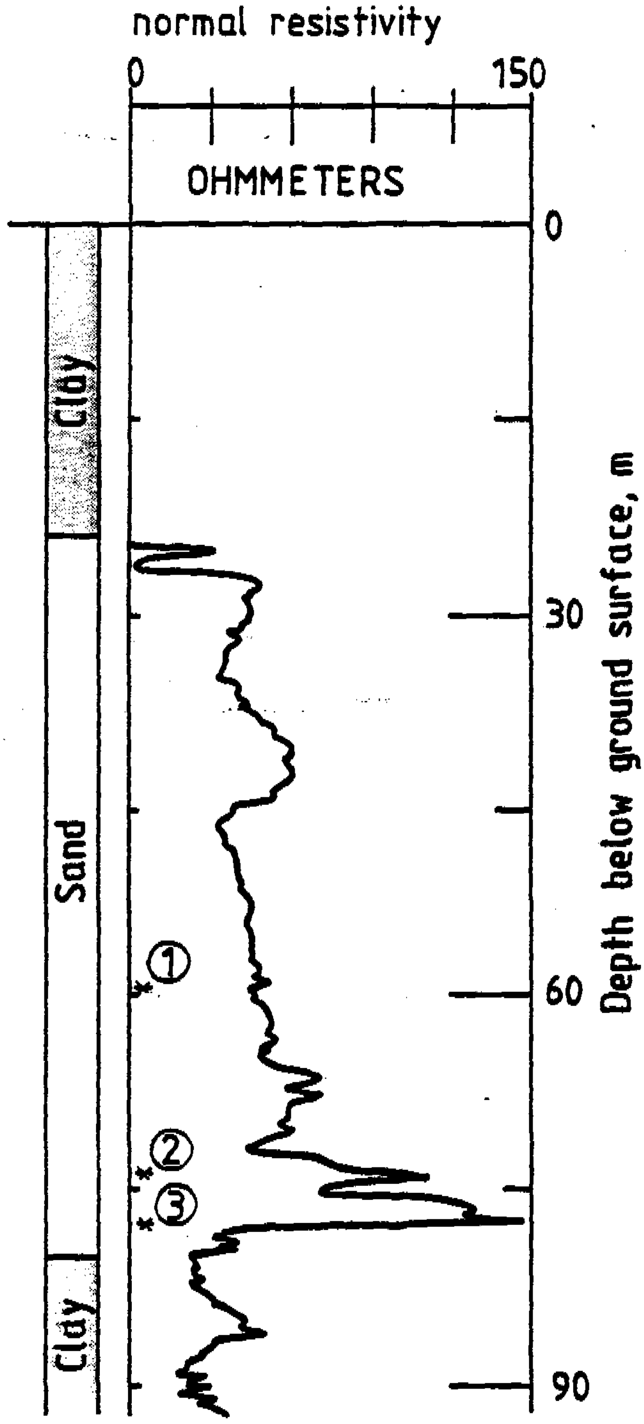


Fig.10 Geophysical Well Log

There are various applications of geophysical well logging. (Table 4).

Table 4

Application of Geophysical Well Logging

SUBSURFACE PROPERTIES to be investigated	TYPE OF LOG single point resistivity	normal resistivity	spontaneous potential	natural gamma
Lithological changes	x	x	x	x
Thickness, boundaries	x	x	x	x
Formation resistivity		x		
Groundwater resistivity		x		
Stratigraphical correlation				x

A wide variety of well logging techniques is available, but the most important in groundwater exploration are: electric resistivity, spontaneous potential and natural gamma radiation.

An electric log consists of a record of the apparent resistivity of the subsurface formations and the spontaneous potential in the borehole, both plotted against depth below ground surface. These two geophysical properties are related to the character of the subsurface formations and to the quality of water contained in them. Gamma ray logging is based on measuring the natural radiation of gamma rays from certain radioactive elements that occur in varying amounts in subsurface formations. The gamma ray log is a diagram showing the relative emission of gamma rays, plotted against depth below surface.

Changes in radiation are commonly associated with differences between types of materials. In unconsolidated sediments, for instance, the log indicates principally clay beds at those depths where the gamma ray intensity is high and sand strata where the intensity is low. Results from these logs may give welcome additional information to be combined with the available subsurface data. This will eventually allow a more detailed interpretation of the geophysical surface survey results.

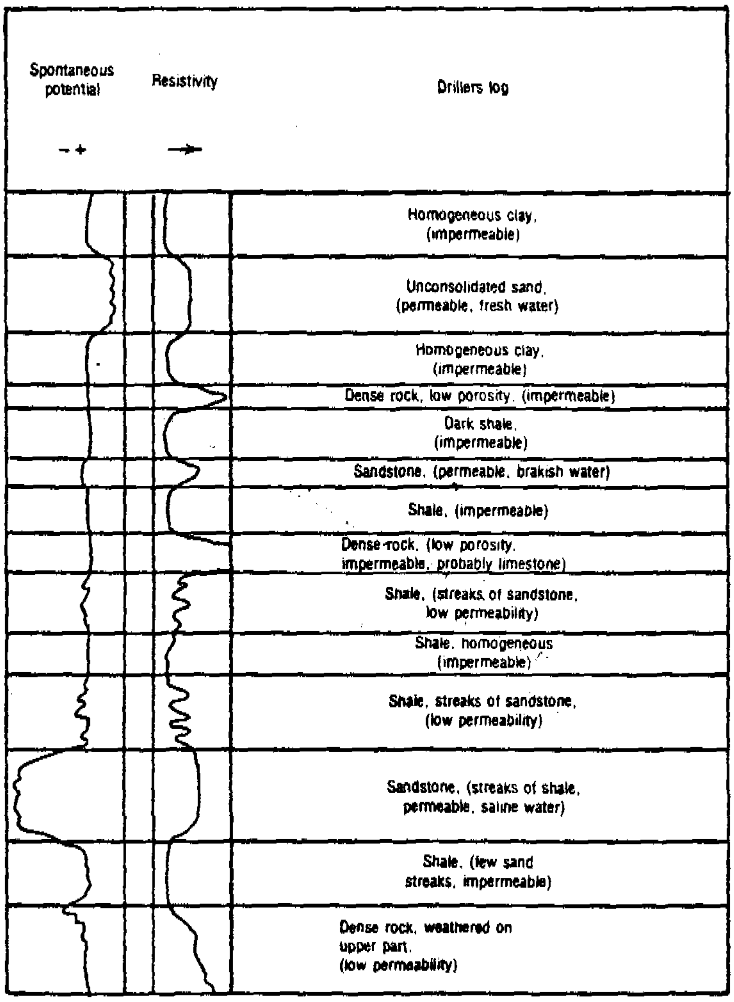


Fig. 11 Electrical Resistivity Log (Schematic)

Let us consider how to use the Spontaneous Potential (SP) and Resistivity curves to distinguish changes in rock formations and water quality. SP curves are most descriptive in unconsolidated formations. Clay formations usually are represented by a straight, uniform line. This line is called the clay-base line and variations from this line to either the right (+) or the left (-) side are useful in analyzing formation properties.

1) A shift to the right or positive potential usually is indicative of a permeable fresh water formation.
2) A minor shift to the left or negative potential may also represent a fresh water aquifer, but with a greater concentration of dissolved solids.
3) A large shift to the left generally signifies penetration of a saline aquifer.

Resistivity increases toward the right and changes in formation characteristics affect the resistivity curve in the following ways:

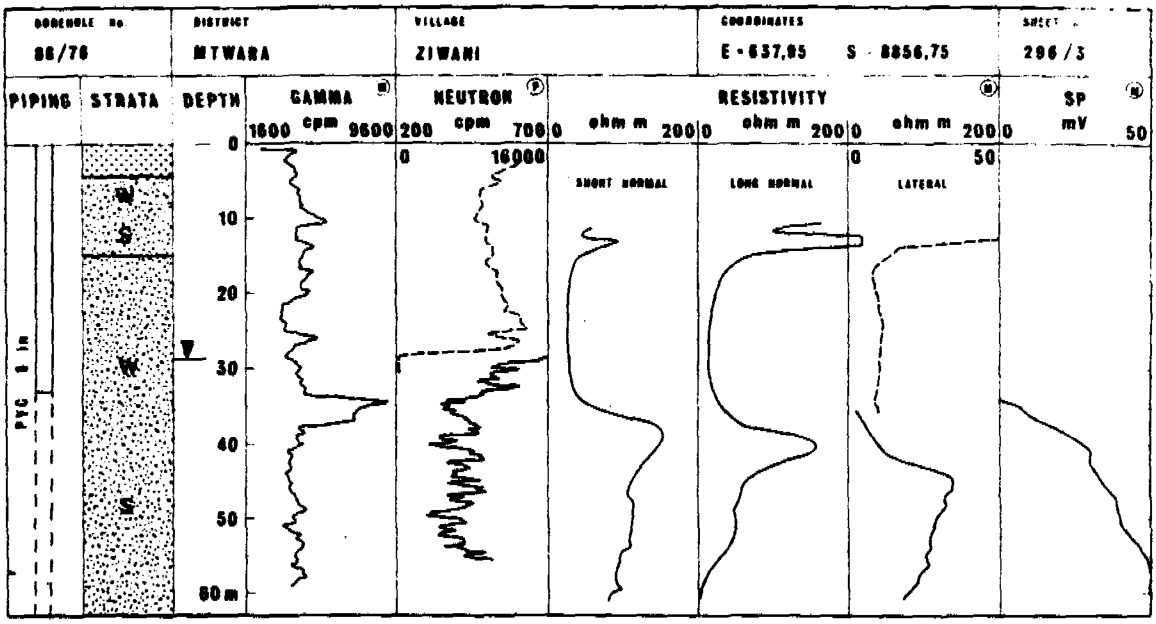
1) Fresh water aquifers and dense rocks have high resistivities and are denoted by movement of the curve to the right.
2) Clays have low resistivities and are depicted by movement of the curve to the left side of the log.
3) Aquifers containing highly saline water have resistivities similar to that of clays.

If you the driller's log is covered up, you can see that it is possible to determine where the changes in rock type occur, and the thickness of the major rock units. It may also be possible to delineate the clay or shale beds. However, when the driller's log is also considered, you are in better position to evaluate the rock type of your aquifers, to determine whether changes in porosity are due to variations in lithology or the result of fractures or solution cavities, and to determine qualitative changes in water quality.
Figures 12 and 13 show typical examples of well logging results.

The spontaneous potential and the resistivity log are made with a single instrument, and are commonly known as electrical logs. The down-hole resistivity instrument is essentially the same as that used for surface resistivity measurements, except that its probes are hung down in the well.

Readings are taken between probes placed at set distances apart. An increase in the distance between probes increases the total surface area and the vertical distance for which the instrument averages the resistivity. Down-hole resistivities tend to be more precise than surface resistivities, so that the differing strata in the bore-hole normally can be recognized. As a rule, soils containing portions of such electrically active materials as clay will have a very low resistivity. Sands and gravels will have a moderate resistivity.

Four logs are plotted from the four down-hole logging techniques used: the drillers'log, the spontaneous potential log, the resistivity log and the gamma log.



GAMMA = NATURAL GAMMA RAY LOG

NEUTRON = NEUTRON - NEUTRON LOG (- - - - 0 - 16000 cpm, —— 200 - 700 cpm)

RESISTIVITY = ELECTRICAL RESISTIVITY LOG

SHORT NORMAL = POTENTIAL ARRAY AM = 0,40m

LONG NORMAL = POTENTIAL ARRAY AM = 1,60m

LATERAL = GRADIENT ARRAY ~~AM~~ = 5,60 m

(- - - - 0 - 50 ohm m , —— 0 - 200 ohm m)

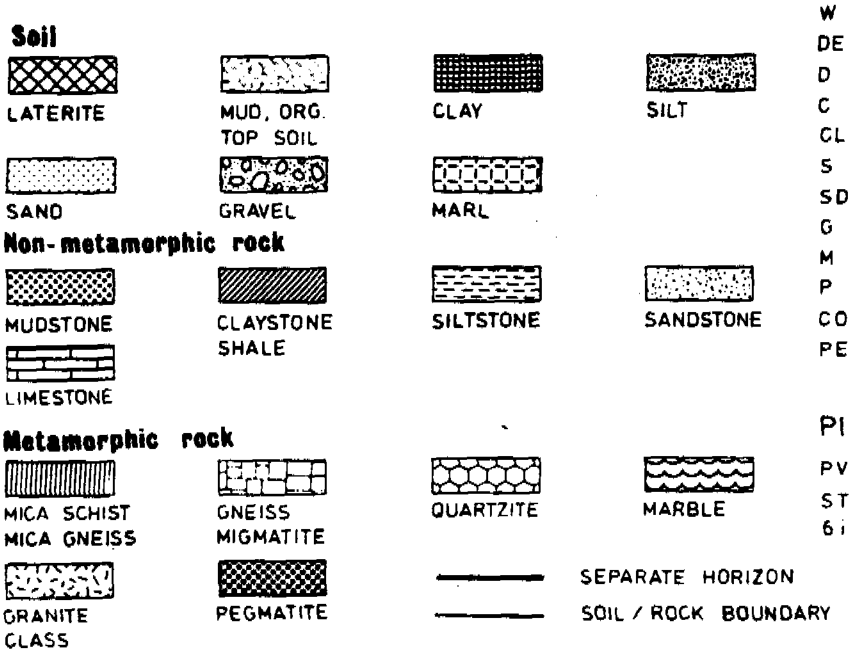
SP = SPONTANEOUS POTENTIAL LOG

Ⓜ = LOGGED BEFORE PIPING (IN MUDHOLE)

Ⓟ = LOGGED AFTER PIPING (IN PIPED HOLE)

▼ = STATIC GROUND WATER LEVEL

GEOLOGICAL SYMBOLS



LETTER SYMBOLS

W = WEATHERED
DE = DECOMPOSED
D = DISINTEGRATED
C = CALCAREOUS
CL = CLAYEY
S = SILTY
SD = SANDY
G = GRAVELLY
M = MARLY
P = PEGMATITIC
CO = CONGLOMERATIC
PE = PEBBLY

PIPING

PVC = PLASTIC
ST = STEEL
6 in = PIPE DIAMETER

Fig.12 Well Logging Profile

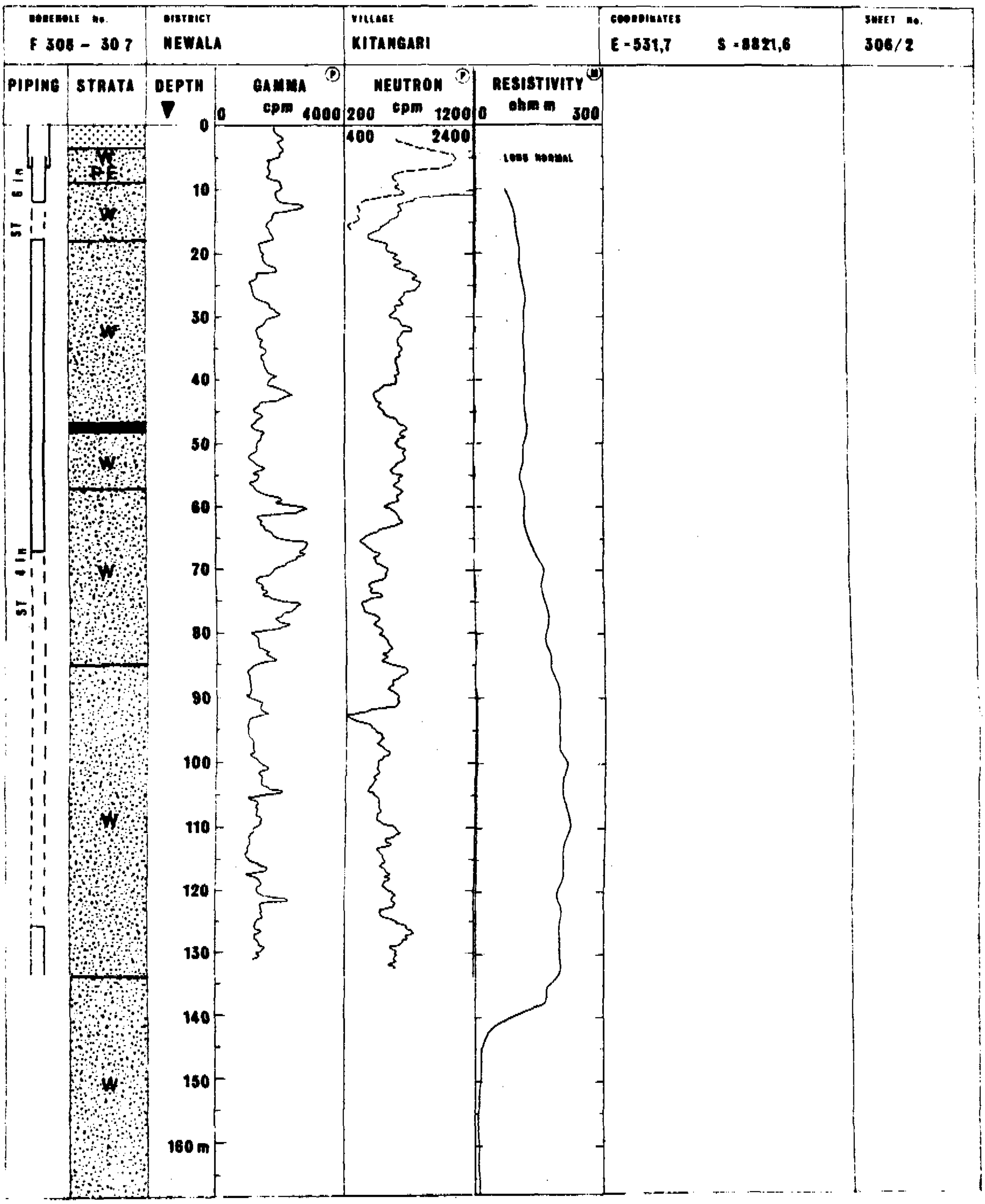


Fig.13 Well Logging Profile

3.2 Radiation Logging

Radio isotopes as groundwater tracers give a direct insight into the movement and distribution of groundwater within the aquifer . Groundwater in its natural state contains numerous istopes, and conclusions may be drawn from the varying levels at which they are present.

The isotopes commonly employed in groundwater investigations are the heavy stable isotopes of the water molecule, Deuterium (^{2}H) and Oxygen-18 (^{18}O), and the radio-active isotopes, Tritium (^{3}H) and Carbon-14 (^{14}C). The stable isotopes are excellent indicators of the movement of water while the radio-active isotopes are of special value in detecting the residence time, assuming no contamination of the water has occurred.

In nature, most groundwater is renewed by direct infiltration of precipitation, by infiltration from surface water or by subsurface inflow. Owing to the evaporation and exchange processes, the isotope content and its distribution in time and space can change during the transition from precipitation to groundwater, and sometimes in the groundwater itself.

There is a global network established jointly by WHO and the International Atomic Energy Agency, sampling precipitation on a monthly basis, the samples being analysed for Deuterium, Oxygen-18 and Tritium.

The average precipitation data showing the distribution of stable isotopes correlated with the groundwater isotope composition, define the origin and movement of subsurface waters. The short half-life of Tritium provides valuable information on recent recharge whereas the long half-life of Carbon-14 dates slow-moving groundwater.

Natural gamma logging means continuous records of gamma radiation produced by radioisotopes naturally occuring in all rocks. Radioactivity of rocks is primarily due to the content of radioactive potassium.

Potassium 40 is the most common radio isotope and occurs in several minerals, including a variety of feldspars, micas and clays. Radioactivity in sedimentary rocks is highest in finegrained, clayey or shaly rocks, it is lowest in clean quartz sand, sandstones and limestones. The acid types of igeneous rocks (granites) have the highest, and the ultrabasic rocks the lowest gamma activity.

Neutron-neutron logging gives information of the total hydrogen content. A neutron source, used in the measurements, emits fast neutrons which are moderated (slowed) in the fluid colomn, casing and rock by collisions with automic nuclei. The element most effective in moderating neutrons is hydrogen because the nucleus of hydrogen atom has about the same mass as a neutron. Above the zone of saturation the calibrated and corrected neutron log provides a continuous measurement of the moisture content, and in the zone of saturation it provides a record of porosity.

When calibrated, gamma-gamma logging measures the density of rock. The logging tool concists of a gamma-ray source and a detector shielded in such a way that it records back-scattered gamma rays from the formation. This secondary radiation depends on the density of electrones which can roughly be said to be proportional to the rock density.

Radiation logging can be madeboth in cased and in uncased boreholes. The intensity of radiation can be measured as the number of radiation pulses reaching the detector per time unit. The radius of investigation is small; the order of magnitude is some ten centimetres.

Table 5

Application of Radio Isotopes in Groundwater Exploration

	RADIO - ISOTOPES			
CHARACTERISTICS	**Hydrogen**		**Oxygen**	**Carbon**
isotope **name** **half-life**	^{2}H(D) **Deuterium** **stable**	^{3}H(T) **Tritium** **13,3 yr**	^{18}O **Oxygen-18** **stable**	^{14}C **Carbon-14** **5730 yr**
APPLICATION				
recent recharge		x		
dating, residence time				x
origin	x		x	
movement	x		x	x
precipitation 1)	o	o	o	

REFERENCES

- A. Bernardi - J. Mouton POSSIBILITÉS ET LIMITES DE LA GÉOPHYSIQUE AVEC LES MÉTHODES DES PROFILS DE RÉSISTIVITÉ, DES SONDAGES ÉLECTRIQUES ET DE LASISMIQUE RÉFRACTION. Recherche d'Eaux Souterraines dans les formation cristallines et métamorphiques du socle africain.
  International Congress of Hydrology, 1975.

- Davis, S.N.; De Wiest, R.
  HYDROGEOLOGY
  John Wiley & Sons, New York/London, 1970.

- Johnson, E.E.
  GROUND WATER AND WELLS
  St.Paul, Minnesota, 1972
  Universal Oil Products Co.
  Keller, G.V., Frischknecht, F.C.
  ELECTRICAL METHODS IN GEOPHYSICAL PROSPECTING
  McMillan, Oxford, 1970.

- Kollert, P
  GROUND WATER EXPLORATION BY ELECTRICAL RESISTIVITY METHOD
  Geophysical Memorandum No.3
  ABEM (Atlas Copco), Bromma, Sweden, 1969.

- P. Lasfargues
  CASTES DE POTENTIEL - RÈSISTIVITÉ - POLARISATION SPONTANÉE - POLARISATION PROVOQUÉE.
  Chez MASSON & Cie; 1957 - MANUELS DE PROSPECTION GÉOPHYSIQUE

- J.C. Lachaud
  PROSPECTION ELECTRIQUE - APPLICATION PRACTIQUE DE GÉOPHYSIQUE.
  OUAGADOUGOU Haute-Volta - EIER - CIEH; 1978.

- J.P. Mathiez - G. Huot
  PROSPECTION GÉOPHYSIQUE ET RECHERCHES d'EAUX SOUTERRAINES
  Examples d'Application en Afrique Occidentale.
  Comité interafricain d'etudes Hydrauliques, 1966.

- L. Simler - E. Caneiro Feitosa
  PROSPECTION ÉLECTRIQUE - APPLICATION DE LA MÉTHODE ET NOITON PRATIQUE d'EXPLOITATION ET DE PRÉSENTATION DES RÉSULTATS.
  Bulletin du B.R.G.M. Section III N° 4, 1968.

- Terwey, J.L.
  GEOPHYSICAL INVESTIGATIONS
  Engineering Geology, 1974, No.10

- Tornquist, B.
  MODERN WATER EXPLORATION
  Atlas Copco, Stockholm, 1977

- Willis, R.F.
  GROUNDWATER EXPLORATION AND DEVELOPMENT TECHNIQUES
  Journal AWWA, October 1979.

GLOSSARY

Airborne geophysical survey

Use of geophysical instruments in aircraft to enable electric, magnetic, radiometric or other measurements to be carried out more rapidly and over greater areas.

Anomaly

A deviation of physical and chemical properties from normal (as caused by the presence of subsurface deposits when these are searched for by geophysical and geochemical methods).

Apparent resistivity

The ground resistivity calculated from measurements and a geometric factor depending on the electrode configuration. It is an ohms law ratio of measured voltage V to applied current I, with geometric constant K, such that

$$\rho_a = \frac{K.V.}{I}$$

is expressed in ohm-meters.

Apparent resistivity curve

A graph of apparent resistivity against electrode separation. Usually plotted on logarithmic paper and compared with type or master curves to determine resistivity, thickness, and depths of subsurface layers.

Aquifer

Geologic formation having structures that permit appreciable quantities of water to move through it under ordinary field conditions. Literally meaning: water-bearing.

Array

Arrangement of a group geophones or shotpoints in seismic studies. The arrangement of electrodes in resistivity surveying also called "configuration". Resistivity arrays include: Wenner, Schlumberger, Dipole-Dipole, Gradient, Pole-Dipole, Pole-Pole.

Arrival time

The time from shot or other energy release to the time picked out for an event, measured in milliseconds.

Basement

Electrical basement in the surface below which resistivity is very high and hence variations below this surface do not affect electrical survey results significantly. Geologic basement is the surface beneath which sedimentary rocks are not found.

Bedrock

Any solid rock underlying the overburden.

Compressional wave

The type of seismic wave assumed in conventional seismic surveys. Also known as P-wave, longtudial wave, and dilatational wave.

Conductivity

The ability of a ground material to conduct electricity. The reciprocal of resistivity. Measured in "mho per meter".

Current electrode

The A and B electrodes in resistivity surveying. Low electrical resistance at these electrodes is desirable to maximise current flow into the ground.

Drawdown

When a well is pumped, water is removed from the aquifer surrounding the well whereby the water table will be lowered. The drawdown at a given point is the distance the water is lowered.

Electrical profiling

An electrical resistivity method utilising fixed electrode spacings in which the array is moved progressively along the profile to detect resistivity changes. Also known as electrical trenching.

Electrical sounding

An electrical resistivity methid in which electrode spacing is increased in orde to detect changes of resistivity with depth. Also known as electrical drilling.

Formation (geological)

A large and persistent stratum of some kind of rock. Set of strata possessing a common suite of lithological and/or faunal characteristics. Also loosely employed for any local, more or less related group of rocks.

Gamma ray log

A well log that records the natural radioactivity.

Geometric factor

A numerical factor used to multiply the V/I ratio from measurements between electrodes to give the apparent resistivity.

Geophone

A moving coil device used to transform seismic energy into an electrical voltage. Also known as seismometer.

Geophysics

The science that uses application of physical properties such as electricity, magnetism, gravity, etc. in a detailed study of the composition of the earth's crust.

Ground water

Without further specification; water occupying all voids within a geologic formation. In practice; water of appreciable quantities infiltrating into, travelling through and being stored in the ground.

Ground water level

Same as ground water table. The level below which all voids of the rock or soil, down to unknown depth, are full of water.

Hydrogeology

The science which deals with the occurrence, distribution and movement of water below the surface of the earth.

Magnetic field

The field of force that surrounds a magnet. The earth has its own magnetic field which can be measured in terms of total, vertical or horizontal intensity at any given point.

Master curve

One of a set of theoretical curves calculated from models against which an observed curve is matched in an effort to find a fit so close that the model data is applicable to the actual situation.

Neutron log

A porosity well log that mainly measures hydrogen density. A low hydrogen density indicates low liquid filled porosity.

Ohm

Unit of electrical resistance or impendance. One ohm means a potential drop of one volt per ampere of current. V/I=R.

Ohm-meter

Unit of resistivity, being the resitivity of a meter cube that offers a resistivity of one ohm to the flow of current between opposite faces. Reciprocal is mho per meter (conductivity).

Overburden

Clay, sand, boulders and other unconsolidated material overlying bedrock.

Photo interpretation

Examination of aerial photographs or mosaics by stereoscopic or other methods in orde to detect and analyze geological features not easily obsevable from the ground.

Radioactivity log

A well log of natural or induced radiation.

Refraction survey

A programme to map geologic structures by using seismic waves that enter and leave the high velocity medium at the critical angle. The waves are identified in terms of time after and distance from the shot.

Resistivity method

Observation of electric fields caused by current introduced into the ground as a means for studying earth resistivity.

Resistivity log

A borehole measurement of an electrical resistivity. Normal, lateral, focussed potential or induction log. Most resistivity logs derive their readings from 10-100 ft^3 material around the probe.

Sediment

In the singular the word is usually applied to material in suspension in water or recently deposited from suspension. In the plural, the word is applied to all kinds of deposits from the water of streams, lakes or seas, and in a more general sense also the material deposited by the action of wind and ice. Such deposits that have been consolidated are generally referred to as sedimentary rocks.

Self potential

The natural voltage differences of ground currents which are caused by chemical reactions in or between subsurface structures. These voltages are seldom larger than ± 1 volt.

Spacing

Separation (distance) of electrodes.

Time distance curve

A plot of the arrival time against shotpoint- to geophone distance. The slopes of the segments of the curves give the reciprocals of the apparent velocities of the various layers.

Timing lines

Lines at precise intervals of time, usually 0.002 sec, on seismograms, used to measure arrival times as accurately as possible.

Traveltime

The time between time break and the recording of a seismic event.

Well log

A record of one or more physical measurements as a function of depth in a borehole. Also known as borehole log.