# Geophysical Techniques for Groundwater Mapping

**V. C. GOYAL**
*National Institute of Hydrology, Roorkee*

## WHAT IS GEOPHYSICS?

Geophysics uses physical theories and measurements to determine the earth's properties.

### What Geophysics Does?

- 'Sees through ground'
- Used to deduce some aspect of the earth's internal structure on the basis of measurements taken at (or near to) the earth's surface
- Exploration geophysics uses surface methods to measure physical properties of the subsurface earth
- Useful in exploration of hydrocarbons, minerals, groundwater, engineering/archealogical structures, subsurface contamination, soil mapping, etc.

## GROUNDWATER EXPLORATION & MAPPING

- Geological mapping
- Geophysical mapping

### What to look for?

- Aquifer location & extent
- Quantity estimation
- Quality estimation

**Exploration of Groundwater**

**1.1.1 Surface exploration**

- "non-invasive" ways to map the subsurface.
-less costly than subsurface investigations

1. Geologic methods
2. Remote Sensing
3. Surface Geophysical Methods
   (a) Electric Resistivity Method
   (b) Seismic Refraction Method
   (c) Seismic Reflection Method
   (d) Gravimetric Method
   (e) Magnetic Method
   (f) Electromagnetic Method
   (g) Ground Penetrating Radar
   and others

**1.1.2 Subsurface exploration**

1. Test drilling
   geologic log
   drilling time log
   Water level measurement
2. Geophysical logging/borehole geophysics
   Resistivity logging
   Spontaneous potential logging
   Radiation logging
   Temperature logging
   Caliper Logging
   Fluid Conductivity logging
   Fluid velocity logging
3. Tracer tests
   and others

## GEOPHYSICAL TECHNIQUES

### In terms of their source of energy

- **Active**- which require input into earth of artificially generated energy/signal and the earth's response to the signal is measured
  - seismic, electrical resistivity, EM methods, ground-probing radar, induced polarization
- **Passive**- which make use of the naturally occurring fields, thereby measuring the earth's response to the signal
  - gravity, magnetic, radiometric decay method, self potential methods, and telluric methods
  - provide information on earth's properties to significantly greater depths

### In terms of their operational procedure

- Ground- resistivity and seismic methods, radar
- Airborne- magnetic and EM methods, Airborne AFMAG (Audio Frequency Magnetics) and Radioactivity
- Borehole methods- acoustic (sonic), nuclear

| Method | Measured parameter | Main uses |
|---|---|---|
| Seismic | Travel times of reflected/refracted seismic waves | Hydrocarbon prospecting |
| Gravity | Spatial variations in the strength of the gravitational field of earth | Mineral, coal prospecting |
| Magnetic | Spatial variations in the strength of the geomagnetic field | Mineral, coal prospecting |
| Electrical Resistivity | Earth resistance | Groundwater |
| Induced polarization | Polarization voltages or frequency-dependent ground resistance | Aquifer mapping, contamination |
| Self-potential | Electrical potentials | Groundwater |
| Electromagnetic | Response to EM radiation | Groundwater, mineral |
| Well logging | | Hydrocarbon, minerals, groundwater |
| Radar | Travel times of reflected radar pulses | Civil engg. structural mapping |

## Limitations of geophysical techniques

- Geophysical interpretation is normally an *inverse* problem (infer some property of the underground on the basis of measurements taken at (or near to) the earth's surface)

- Inverse problems do not provide unambiguous solution, & suffer from an inherent ambiguity, or non-uniqueness, in the conclusions that can be drawn

- Best results when used in combination with other techniques (e.g. geol., remote sensing)

## Electrical Methods

- Groundwater, through the various dissolved salts it contains, is ionically conductive and enables electric currents to flow into the ground. Consequently, measuring the **ground resistivity** gives the possibility to identify the presence of water, taking in consideration the following properties:

- **a hard rock** without pores or fracture and a **dry sand** without water or clay are very resistive: several tens thousands ohm-m
- **a porous or fractured rock** bearing free water has a resistivity which depends on the resistivity of the water and on the porosity of the rock (see below): several tens to several thousands ohm-m
- **an impermeable clay layer**, which has bound water, has a low resistivity: several units to several tens ohm-m
- **mineral orebodies** (iron, sulphides, ...) have very low resistivities due to their electronic conduction: usually lower or much lower than 1 ohm-m

**ELECTRICAL PROPERTIES OF ROCKS**

→ THE ELECTRIC CURRENT FLOWS INTO THE GROUND THANKS TO THE IONS OF SALTS DISSOLVED IN THE WATER

Salt ions (+) →  ← (−)

Current →

+ ions: Na, Ca, K, ...
- ions: Cl, $SO_4$, $NO_3$, ...

| TYPE OF POROSITY | TYPE OF WATER | TYPE OF ROCK | |
|---|---|---|---|
| matrix | free | | sand, gravel |
| fracture | free | | limestone, sandstone |
| adherence | bound | | clay |

→ THE RESISTIVITY OF ROCKS DEPEND ON:

- THE WATER CONTENT (Porosity)
- THE RESISTIVITY OF THE WATER
- THE CLAY CONTENT
- THE CONTENT IN METALLIC MINERALS

→ VALUES OF RESISTIVITY OF ROCKS:

| | | |
|---|---|---|
| 0.1 | ohm.m | SALTED WATER |
| 1 | ohm.m | MASSIVE SULPHIDE |
| 10 | ohm.m | CLAY |
| 100 | ohm.m | SAND, MARL |
| 1 000 | ohm.m | DRY SAND, LIMESTONE |
| 10 000 | ohm.m | HARD GRANITE, BASALT |

## ARCHIE LAW

- Resistivity of a porous non-clayey material can be estimated by the Archie law formula:

  **rock resistivity = a x (water resistivity) / (porosity)$^n$**,

  where "a" and "n" are constants which depend on the nature of the rock. In a very rough approximation, "a" can be taken equal to 1 and "n" to 2. For example, a 10 ohm-m water and a 20% porosity give a rock resistivity of the order of 250 ohm-m.

- This formula means that a low value of a non-clayey rock resistivity means either a high porosity or a low water resistivity, hence an **uncertainty** in the interpretation of resistivity anomalies.

- Clay formations also give low resistivity values.

## GROUNDWATER DETECTION

- To identify the presence of groundwater from **res. measurements**, look to the value of the ground resistivity, through the Archie law: a usual target for aquifer resistivity can be between 50 and 2000 ohm-m
- It is the **relative value** of the ground resistivity which is considered for detecting groundwater: in a hard rock (resistant) environment, a **low resistivity** anomaly will be the target, while in a clayey or salty (conductive) environment, it is a **high resistivity** anomaly which will most probably correspond to (fresh) water
- **In sedimentary layers**, the product of the aquifer resistivity by its thickness can be considered as representative of the interest of the aquifer. Electrical methods cannot give an estimation of the permeability but only of the porosity.
- The contrast of resistivity between **a fresh water** and **a saline water** (e.g. from a sea intrusion) is high and the depth of the water wedge is usually well determined with electrical methods

| Rock type | Approx. resistivity range (ohm-m) |
|---|---|
| Clay | 1- 10 |
| Alluvium | 10-1,000 |
| Shale | 10-10,000 |
| Sandstone | $1\text{-}10^{9}$ |
| Quartzite | $10\text{-}10^{8}$ |
| Schist | 10-10,000 |
| Gabbro | $1{,}000\text{-}10^{6}$ |
| Granite | $100\text{-}10^{6}$ |

## AQUIFER PARAMETER ESTIMATION

- Since ions flow thru the same paths as water, the EC and hydraulic conductivity of aquifer are expected to be affected by similar variables.
- Flow rate of GW depends on hydraulic conductivity/permeability (K), and electric current depends on EC ($\sigma$) of the formation.
- Based on the analogy between Darcy's law of groundwater flow and ohm's law of current flow, a relationship has been established:

  $K = a\,\sigma$ or $K = a\,1/\rho$
- Permeability (K) is inversely proportional to the aquifer resistivity ($\rho$).
- Low resistive formation is an indication of highly weathered-fractured water saturated material. In such conditions, permeability of the material is expected to be high.
- By multiplying a factor 't' (i.e. aquifer thickness) on both sides

  $Kt = a\,t\,1/\rho$ or $T = a\,C$

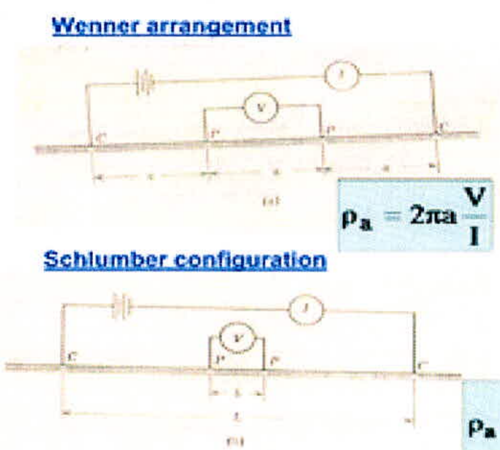
  where T and C are transmissivity ($m^2/d$) and longitudinal conductance (mho) of the formation.

In field, C is obtained using resistivity measurements, and permeability is estimated via T

## RESISTIVITY METHOD

- For measuring the ground resistivity, **a current i**s transmitted with two electrodes, while **the potential** created on the surface by the circulation of this current into the ground is measured with two other electrodes. This involves deploying long lengths of wire on the ground and injecting a DC current into the earth through a widely spaced pair of electrodes. The distance between current electrodes must be three or more times the intended depth of exploration.

- Increasing progressively the distance between the transmitting and the receiving electrodes permits increasing the depth of investigation (**sounding array** for aquifer depth and thickness determination); translating the four electrodes together permits to detect lateral change of resistivity (**profiling array**, for fault or fracture localization).




$$\rho_a = 2\pi a \frac{V}{I}$$

$$\rho_a = \pi \frac{(L/2)^2 - (b/2)^2}{b} \frac{\Delta V}{I}$$

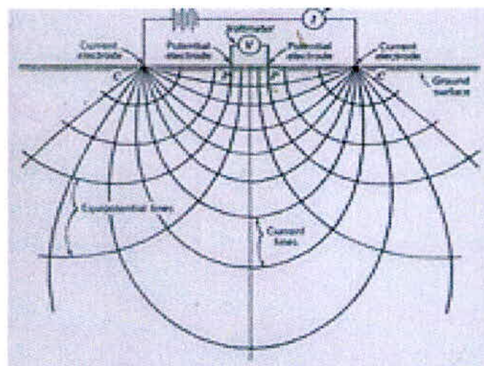



Fig. 11.4 Electrical circuit for resistivity determination and electrical field for a homogeneous subsurface stratum

## APPLICATIONS

- Mapping buried stream channels
- Mapping clay layers
- Mapping water table
- Aquifer parameters
- Mapping freshwater-saline water interface
- Ground water contamination
- Ground water flow direction

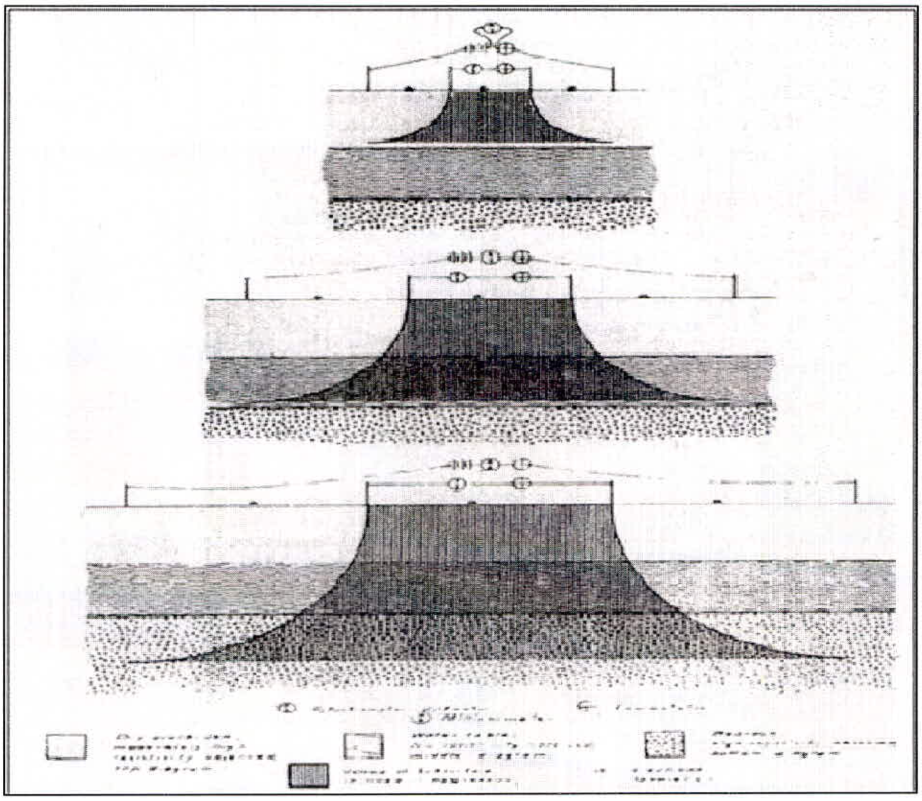
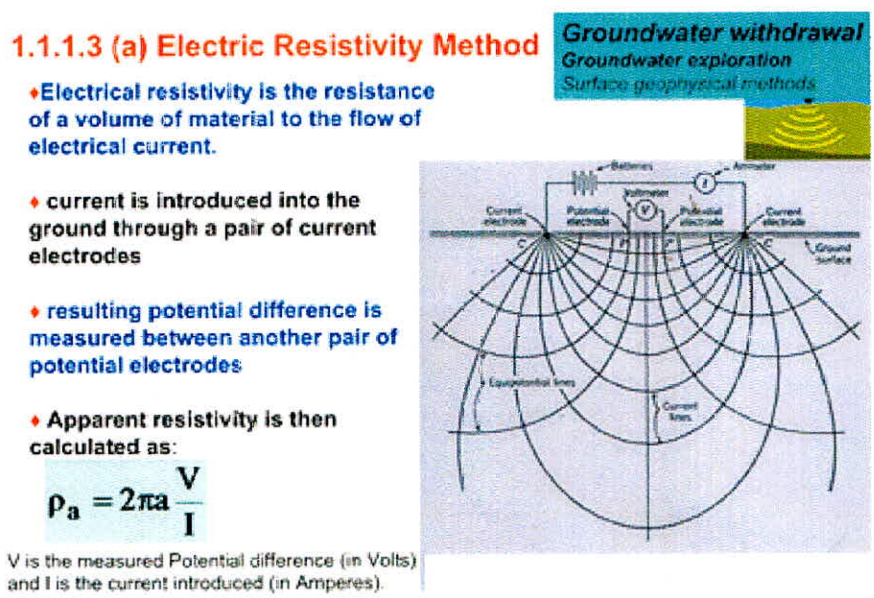


**Fig. 1 Principles of resistivity observations**




## Data Interpretation

- From field, data is recorded as current injected (I) and potential measured ($\Delta V$)
- Resistance ($R = \Delta V/I$) is converted into apparent resistivity ($\rho_a$), after multiplication with a configuration factor
- Resistivity curve is plotted with $\rho_a$ on Y-axis and electrode spacing on X-axis

- Traditionally, this was interpreted manually by a curve matching technique using 'Master Curves'
- Now interpretation is done by computer software, in terms of resistivity and thickness of different layers
- Modern μP-based instruments have capability of automated data collection from multiple points, and generating depth sections showing potential aquifer zones

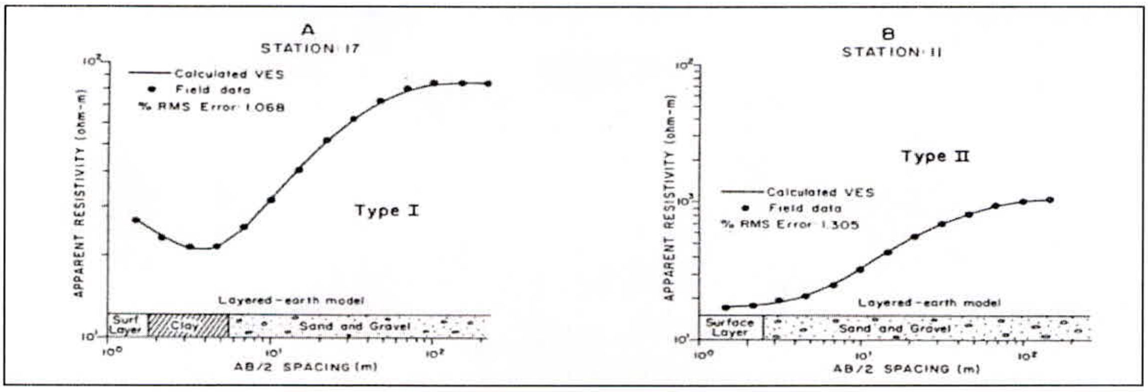



**Fig. 2 Field examples of Type I and Type II VES curves**

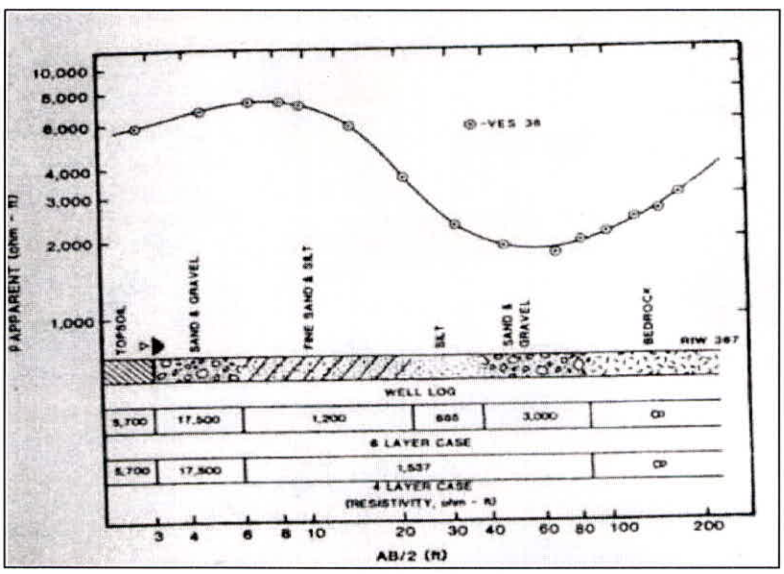


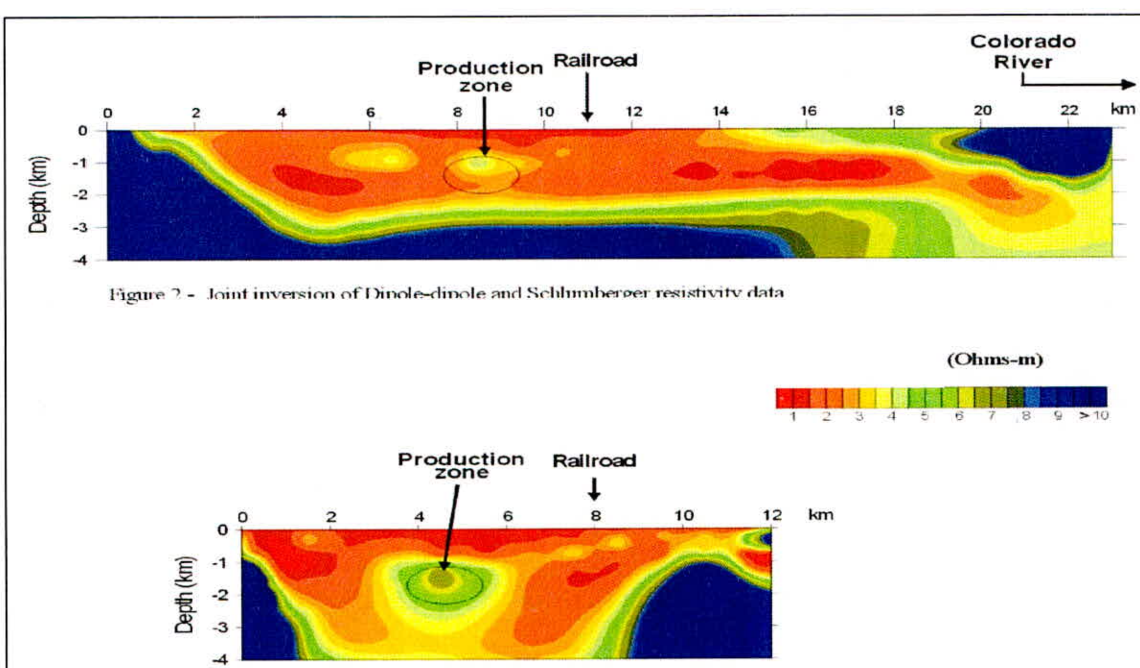

**Fig. 3 Vertical electric sounding curve near test boring**

## EM METHODS

- EM methods induce small electrical currents in the ground. These currents flow more readily in conductive earth materials than in resistive strata. Sand or gravel aquifers tend to be much more resistive than silts and clays. By studying the behavior of the electrical currents in the ground we can deduce the location of resistive strata (aquifers).
- **Frequency-domain (FDEM)**
- often used in a profiling mode- to search for lateral changes in soil conditions (e.g., mapping the geometry of a gravel paleo-channel)- provide limited depth information.
- **Time-domain (TDEM)**

- Useful in sounding mode- to measure depth to an interface, or interfaces. They can be used to measure the thickness of a gravel unit, depth and thickness of a clay aquitard, or depth to bedrock.
- TDEM soundings are made by laying out a loop of wire 20 to 200' on a side and pulsing it with a controlled current. Measurements are made in the center of the loop, with an antenna coil about 3' across. Equipment is portable; easily six to ten soundings can be made in a day, depending on field conditions.

**VES and Dipole-dipole Resistivity** (Source: Charre-Meza et al, 2000)



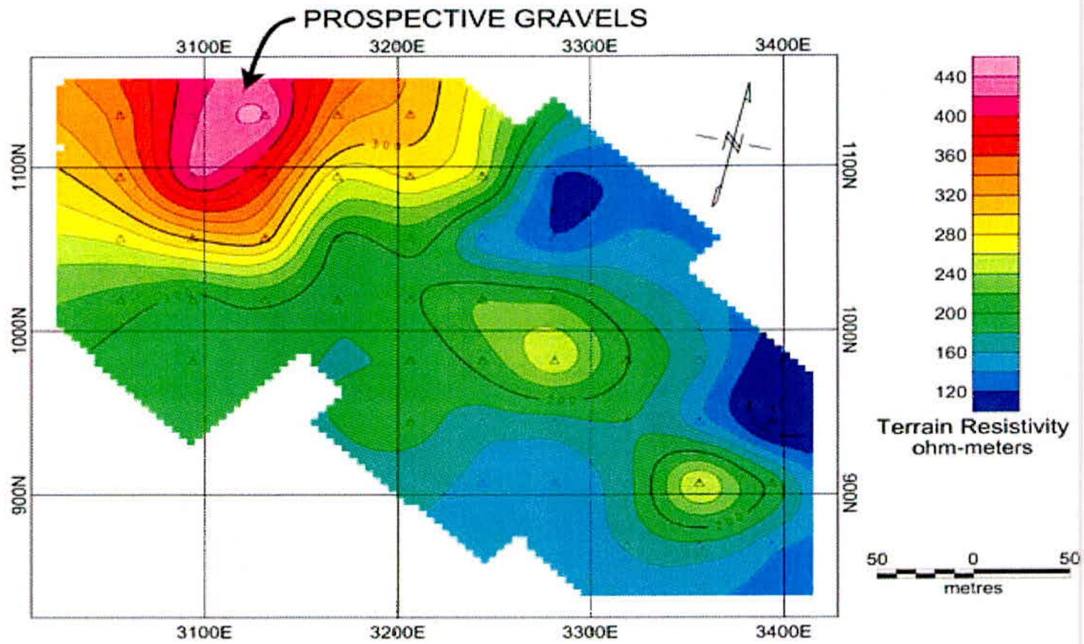
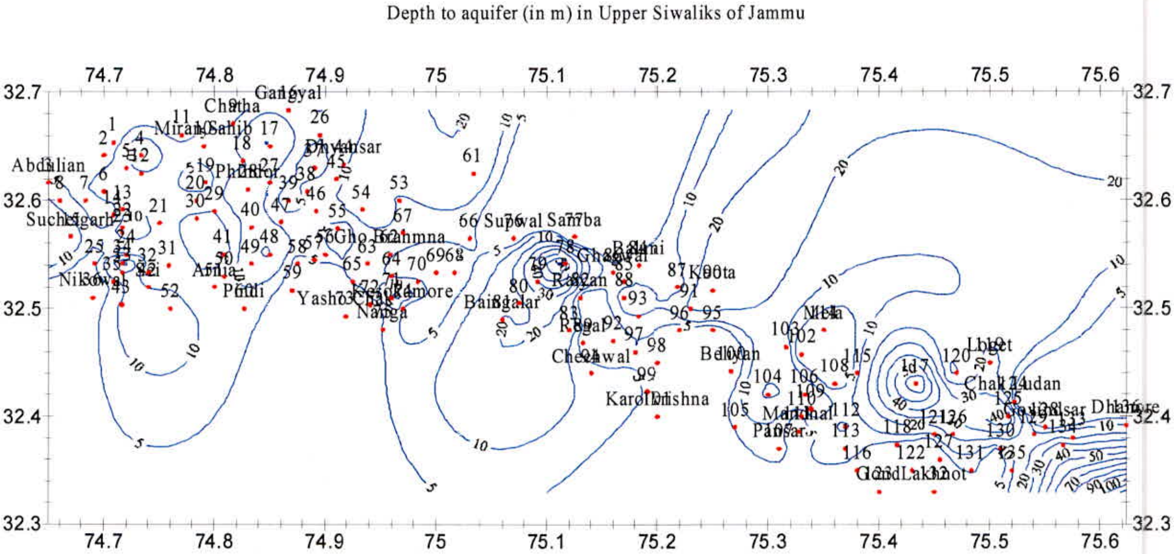



**Fig. 4 Resistivity Soundings for Hydrogeologic Evaluation in Piedmont Region of Jammu Siwaliks**

- Delineation of the thickness and water-bearing characteristics of the major geologic units, and determining the groundwater potential in the area.
- Data of geoelectrical soundings in Sirowal and Kandi belts were used to explore the groundwater potential. Total 136 geoelectrical soundings were used to cover an area of 1,440$km^2$ approx., with maximum spread length (AB) of 840m.
- Transverse resistance was estimated from the sounding curves, and good correlation with aquifer transmissivity was observed.
- Transverse resistance values were used to classify the area into three groundwater development classes, which corroborated well with the known groundwater potential at selected sites.



Variation of Top Layer Thickness (in m) in Upper Siwaliks of Jammu

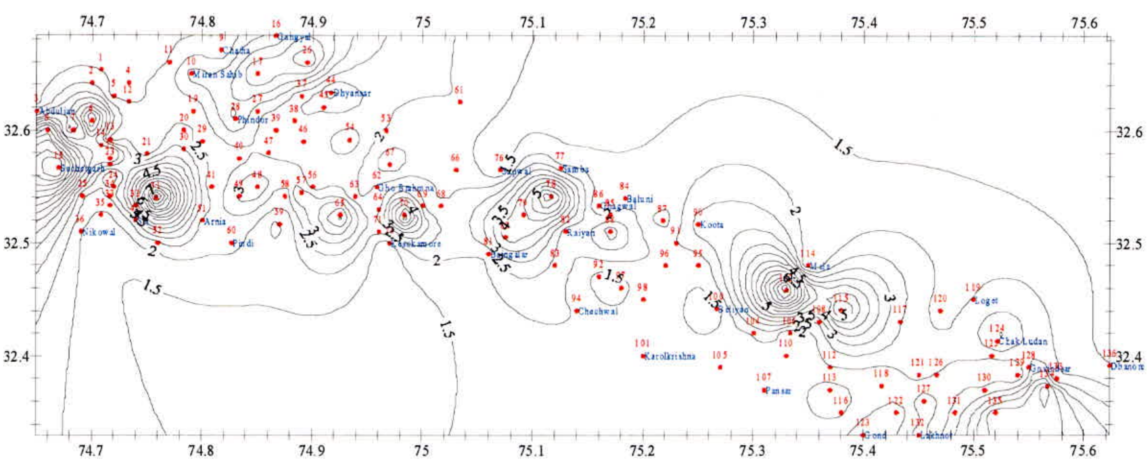
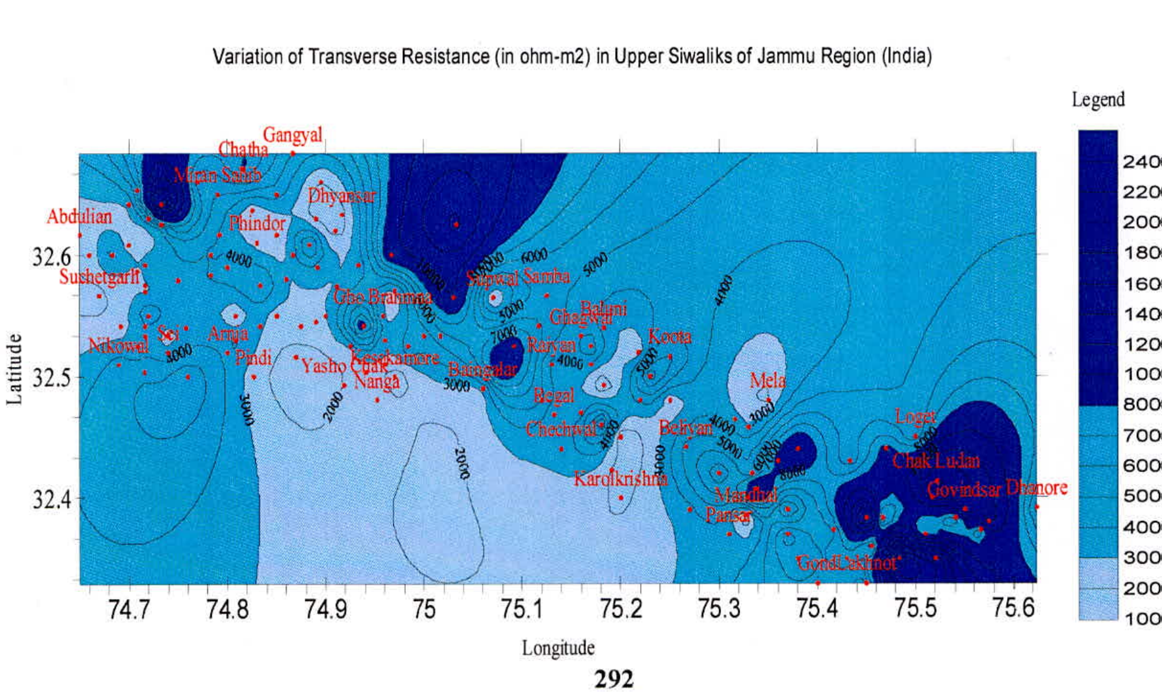


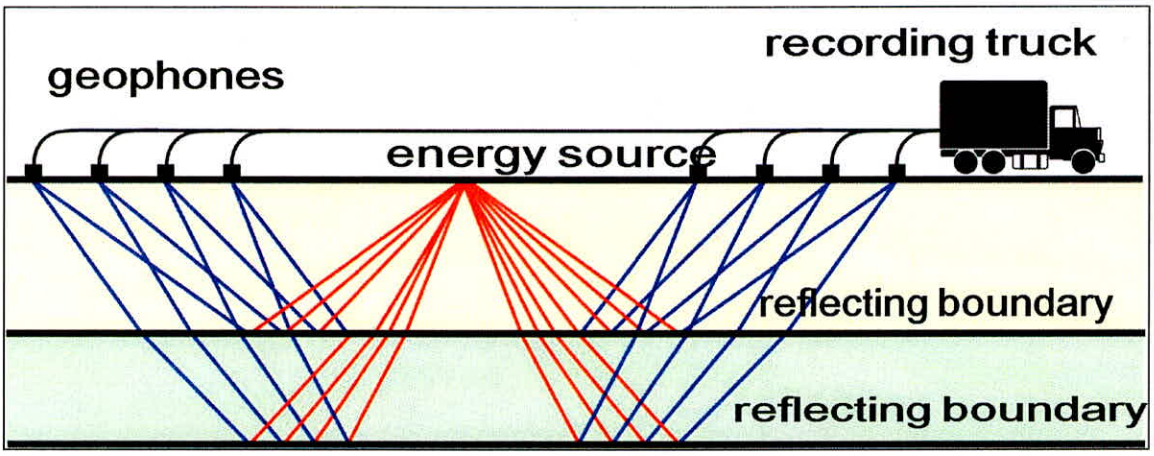

**Table: Groundwater development classes based on transverse resistance**

| Transverse Resistance (R) (ohm-m$^2$) | Groundwater Development Zone | Number of VES sites | Percentage Coverage |
|---|---|---|---|
| *R<3000* | *Low* | *42* | *31* |
| 3000<R<8000 | Moderate | 72 | 53 |
| R>8000 | High | 22 | 16 |

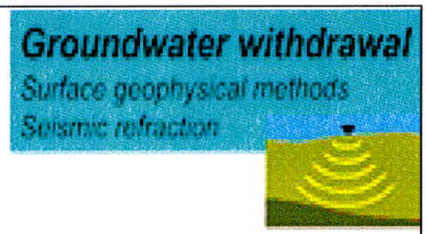
Variation of Transverse Resistance (in ohm-m2) in Upper Siwaliks of Jammu Region (India)



**Seismic Surveys**



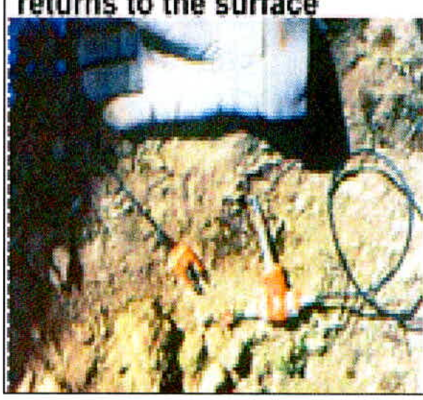

♦ The seismic waves travel through the subsurface at a velocity dependent on the density of the soil/rock.

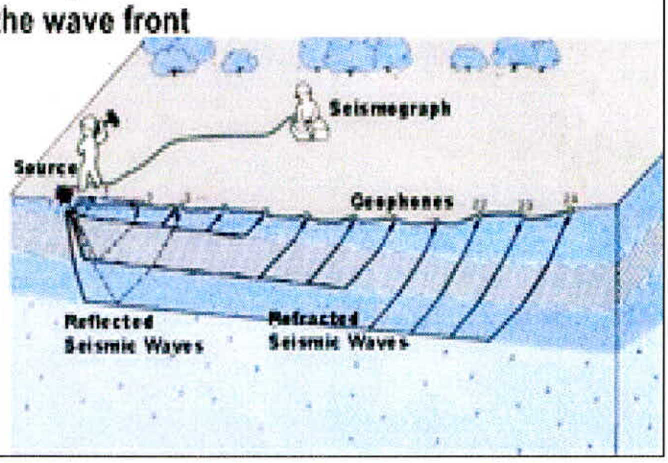



♦ When the seismic wave front encounters an interface where seismic velocity drastically increases, a portion of the wave critically refracts at the interface, traveling laterally along higher velocity layers.

♦ A series of seismic receivers, geophones *(right)* are laid out along the survey line at regular intervals and receive the reflected wave energy.

♦ Due to compressional stresses along the interface boundary, a portion of the wave front returns to the surface



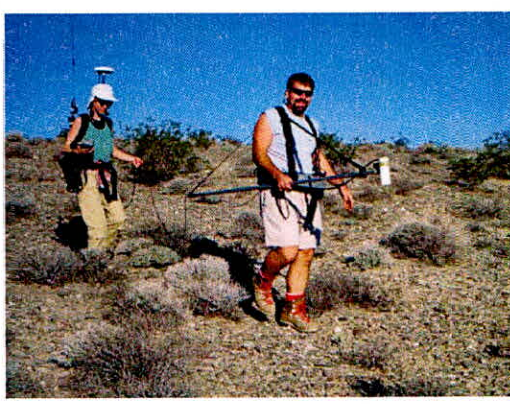


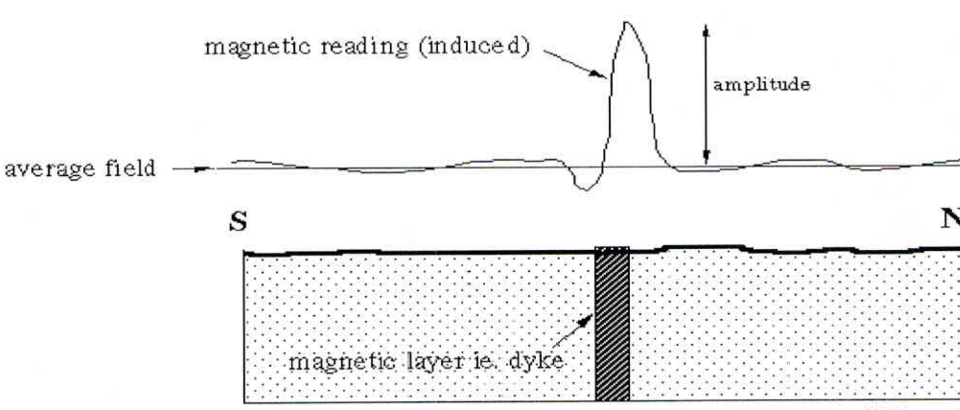
## Airborne EM Survey

Collects aeromagnetic and gravity data

## Magnetic survey using a proton magnetometer

- Aeromagnetic surveys are taken from a moving plane.
- A magnetometer is the instrument used to measure the intensity of the magnetic field at a particular place





## 1.1.2.2 Geophysical logging/ Borehole geophysics

**Groundwater exploration**
*Subsurface geophysical methods*
*Borhole geophysics*

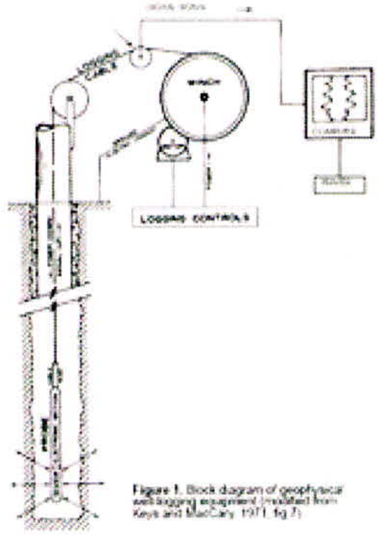



Figure 1. Block diagram of geophysical well-logging equipment (modified from Keys and MacCary, 1971, fig.7)

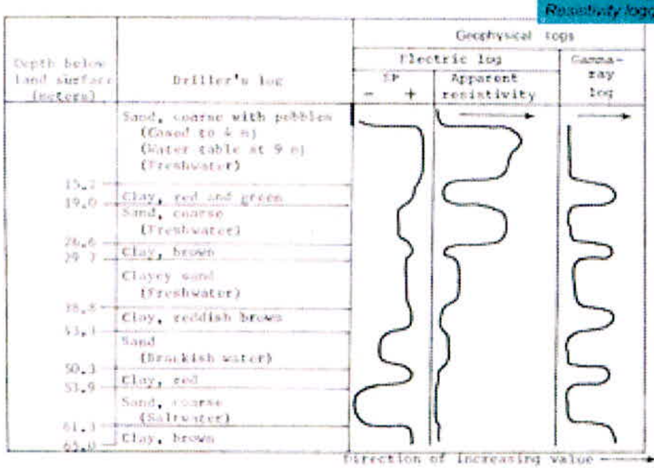
**What is Borehole Geophysical Logging?**

➢Borehole geophysical logging is a procedure to collect and transmit specific information about the geologic formations penetrated by a well by raising and lowering a set of probes or sondes that contain water-tight instruments in the well

➢The data collected can be used to determine general formation geology, fracture distribution, vertical borehole flow, and water-yielding capabilities.

### 1.1.2.2(a) Resistivity log

**Groundwater exploration**
*Subsurface geophysical methods*
*Resistivity logging*




**Uses of Resistivity Logs**

interpretation and identification of rock types

- identification of the position of the water table
- determination of bed contacts and bed thickness
- determination of aquifer parameters
- evaluation of quality of formation water
- determination of depth of casing

## 1.1.2.2(b) Spontaneous potential (SP) logging

*Subsurface geophysical methods*
*Spontaneous potential logging*

- measures differences in the voltages of an electrode at the land surface and an electrode in the borehole
- potentials are primarily produced by electrochemical cells formed by the electric conductivity differences of drilling mud and groundwater where boundaries of permeable zones intersect a borehole.