*National Level Training Course on "Spring Rejuvenation" under National Hydrology Project (NHP), at Hotel Anand Portico, Kalimpong during March 11-15, 2019*

# *Geophysical Survey for Spring Water Investigation*

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# Exploration of Spring Water

## A. Surface exploration

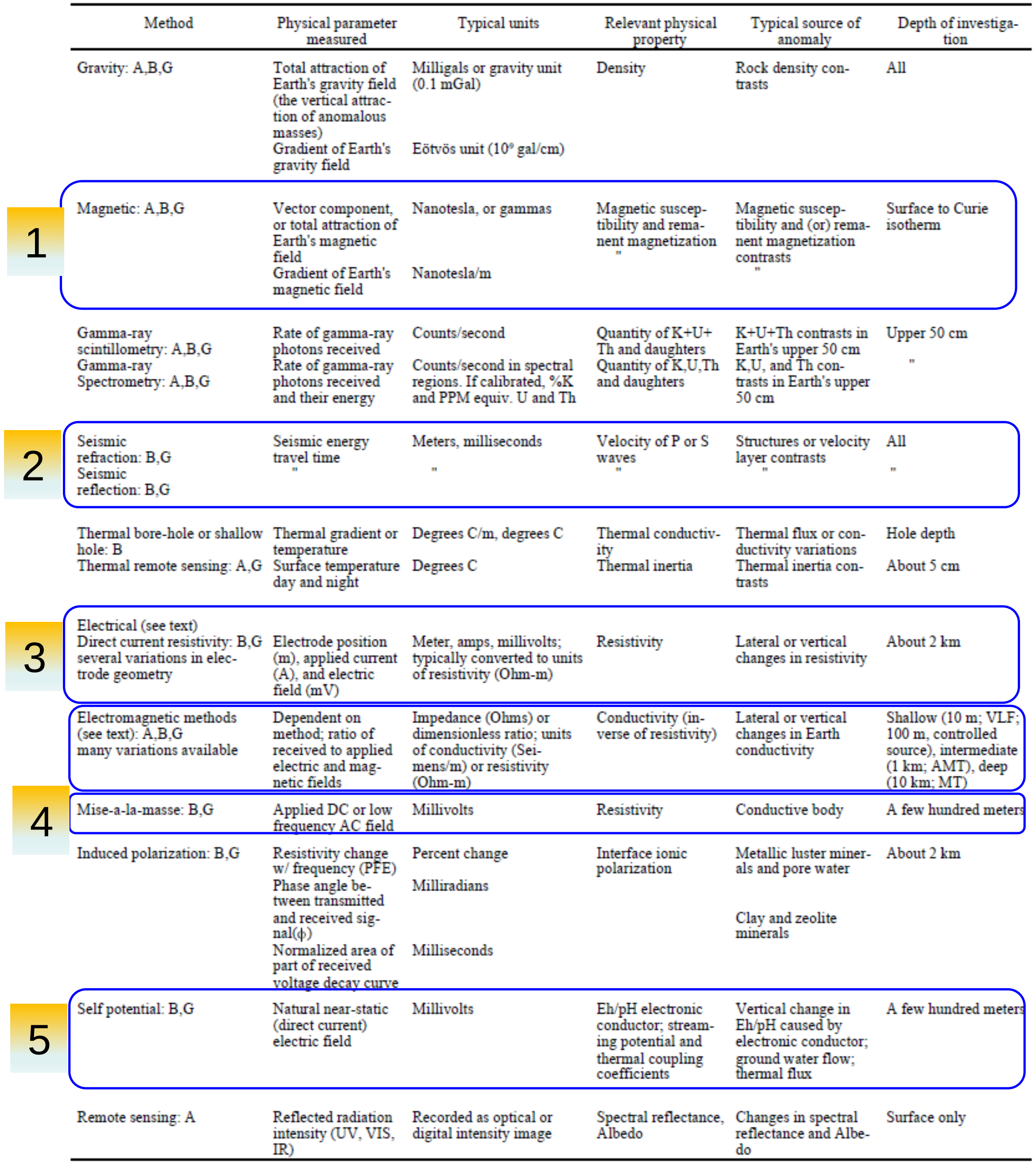
**- “Non-invasive" ways to map the subsurface.**
**-Less costly than subsurface investigations**

**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

## B. 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

**Table 1.** Summary of geophysical methods and their characteristics applicable to exploration and geo-environmental studies a certain extent to the Spring Water [In method column: A, airborne surveys; B, borehole surveys; and G, ground surveys]



| Method | Physical parameter measured | Typical units | Relevant physical property | Typical source of anomaly | Depth of investigation |
|---|---|---|---|---|---|
| Gravity: A,B,G | Total attraction of Earth's gravity field (the vertical attraction of anomalous masses)<br>Gradient of Earth's gravity field | Milligals or gravity unit (0.1 mGal)<br>Eötvös unit ($10^9$ gal/cm) | Density | Rock density contrasts | All |
| Magnetic: A,B,G | Vector component, or total attraction of Earth's magnetic field<br>Gradient of Earth's magnetic field | Nanotesla, or gammas<br>Nanotesla/m | Magnetic susceptibility and remanent magnetization<br>" | Magnetic susceptibility and (or) remanent magnetization contrasts<br>" | Surface to Curie isotherm |
| Gamma-ray scintillometry: A,B,G<br>Gamma-ray Spectrometry: A,B,G | Rate of gamma-ray photons received<br>Rate of gamma-ray photons received and their energy | Counts/second<br>Counts/second in spectral regions. If calibrated, %K and PPM equiv. U and Th | Quantity of K+U+Th and daughters<br>Quantity of K,U,Th and daughters | K+U+Th contrasts in Earth's upper 50 cm<br>K,U, and Th contrasts in Earth's upper 50 cm | Upper 50 cm<br>" |
| Seismic refraction: B,G<br>Seismic reflection: B,G | Seismic energy travel time<br>" | Meters, milliseconds<br>" | Velocity of P or S waves<br>" | Structures or velocity layer contrasts<br>" | All<br>" |
| Thermal bore-hole or shallow hole: B<br>Thermal remote sensing: A,G | Thermal gradient or temperature<br>Surface temperature day and night | Degrees C/m, degrees C<br>Degrees C | Thermal conductivity<br>Thermal inertia | Thermal flux or conductivity variations<br>Thermal inertia contrasts | Hole depth<br>About 5 cm |
| Electrical (see text)<br>Direct current resistivity: B,G several variations in electrode geometry | Electrode position (m), applied current (A), and electric field (mV) | Meter, amps, millivolts; typically converted to units of resistivity (Ohm-m) | Resistivity | Lateral or vertical changes in resistivity | About 2 km |
| Electromagnetic methods (see text): A,B,G many variations available | Dependent on method; ratio of received to applied electric and magnetic fields | Impedance (Ohms) or dimensionless ratio; units of conductivity (Seimens/m) or resistivity (Ohm-m) | Conductivity (inverse of resistivity) | Lateral or vertical changes in Earth conductivity | Shallow (10 m; VLF; 100 m, controlled source), intermediate (1 km; AMT), deep (10 km; MT) |
| Mise-a-la-masse: B,G | Applied DC or low frequency AC field | Millivolts | Resistivity | Conductive body | A few hundred meters |
| Induced polarization: B,G | Resistivity change w/ frequency (PFE)<br>Phase angle between transmitted and received signal(ϕ)<br>Normalized area of part of received voltage decay curve | Percent change<br>Milliradians<br>Milliseconds | Interface ionic polarization | Metallic luster minerals and pore water<br>Clay and zeolite minerals | About 2 km |
| Self potential: B,G | Natural near-static (direct current) electric field | Millivolts | Eh/pH electronic conductor; streaming potential and thermal coupling coefficients | Vertical change in Eh/pH caused by electronic conductor; ground water flow; thermal flux | A few hundred meters |
| Remote sensing: A | Reflected radiation intensity (UV, VIS, IR) | Recorded as optical or digital intensity image | Spectral reflectance, Albedo | Changes in spectral reflectance and Albedo | Surface only |

*[Hoover, et al.]*

# Geophysical methods are divided into two types : Active and Passive

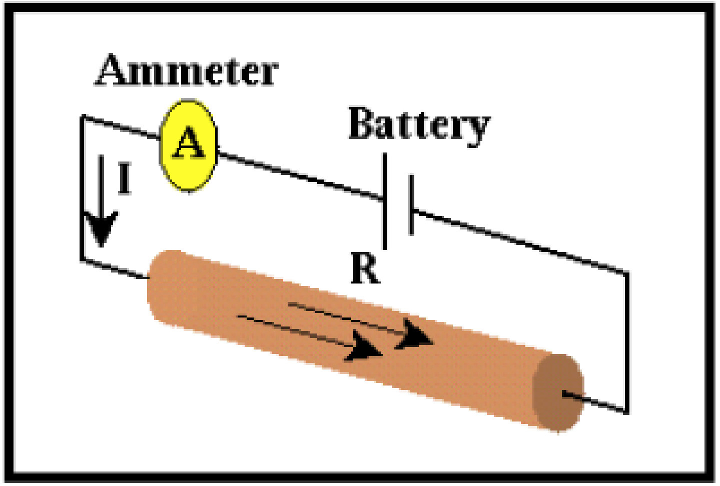
**Passive methods** (Natural Sources): Incorporate measurements of natural occurring fields or properties of the earth. Ex. SP, Magnetotelluric (MT), Telluric, Gravity, Magnetic, etc.

**Active Methods** (Induced Sources) : A signal is injected into the earth and then measure how the earth respond to the signal. Ex. DC. Resistivity, Seismic Refraction, IP, EM, Mise-A-LA-Masse, etc.

## But Spring Water Exploration

D C. Resistivity, Magnetic and EM have found broad use in Spring Water studies.

# Ohm’s Law (discovered in 1827)



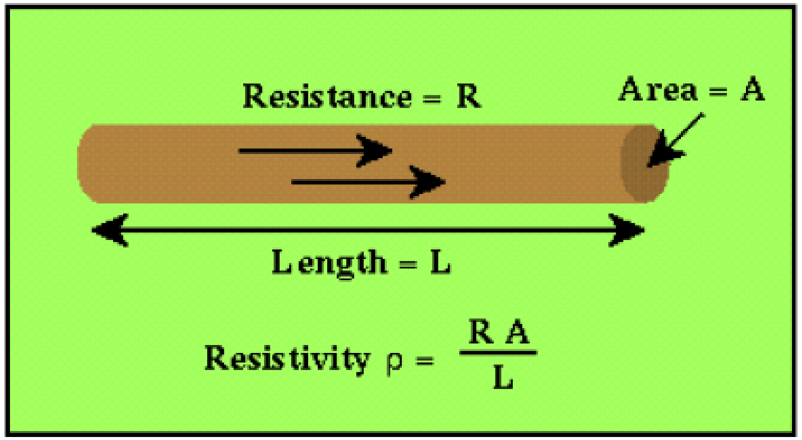
Georg Simon Ohm
(1787-1854)

$$V = IR$$

It relates the voltage of a circuit to the product of the current and the resistance. This relationship holds for earth materials as well as simple circuits.

**Resistance( R)**, however, is not a material constant. Instead, resistivity is an intrinsic property of the medium describing the resistance of the medium to the flow of electric current.

# It's Resistivity, NOT Resistance



$$R = \rho \frac{L}{A}$$

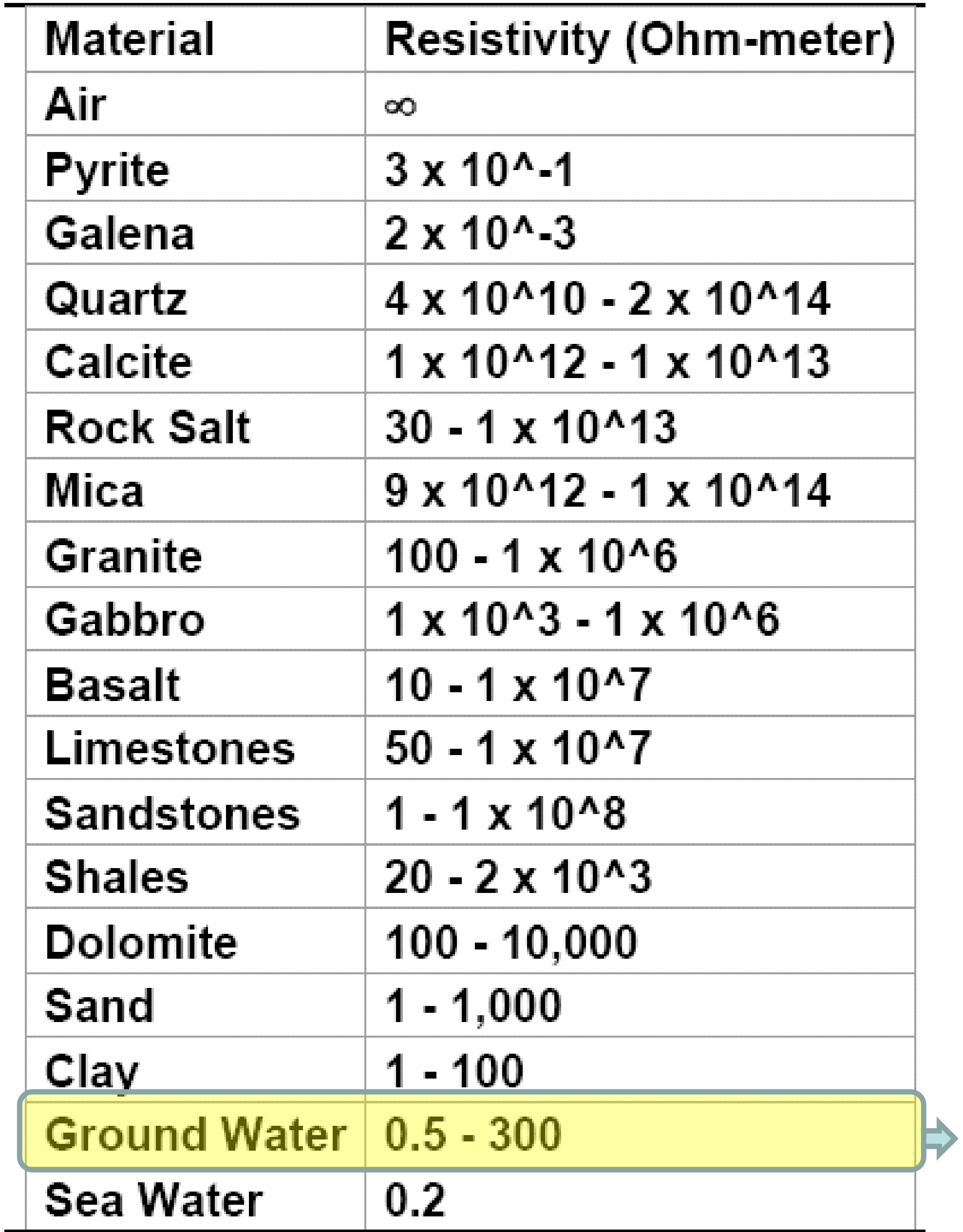
$$\rho = \frac{RA}{L}$$

**So the unit for resistivity is ohm-meter**

**Resistivity ρ** is defined as a unit change in resistance scaled by the ratio of a unit cross-sectional area and a unit length of the material through which the current is passing.

**Resistivity** is measured in Ohm-m or Ohm-ft, and is the reciprocal of the conductivity of the material.

# Resistivity of various earth materials are shown below



| Material | Resistivity (Ohm-meter) |
|---|---|
| Air | ∞ |
| Pyrite | 3 x 10^-1 |
| Galena | 2 x 10^-3 |
| Quartz | 4 x 10^10 - 2 x 10^14 |
| Calcite | 1 x 10^12 - 1 x 10^13 |
| Rock Salt | 30 - 1 x 10^13 |
| Mica | 9 x 10^12 - 1 x 10^14 |
| Granite | 100 - 1 x 10^6 |
| Gabbro | 1 x 10^3 - 1 x 10^6 |
| Basalt | 10 - 1 x 10^7 |
| Limestones | 50 - 1 x 10^7 |
| Sandstones | 1 - 1 x 10^8 |
| Shales | 20 - 2 x 10^3 |
| Dolomite | 100 - 10,000 |
| Sand | 1 - 1,000 |
| Clay | 1 - 100 |
| Ground Water | 0.5 - 300 |
| Sea Water | 0.2 |

Of Course, depending upon water quality

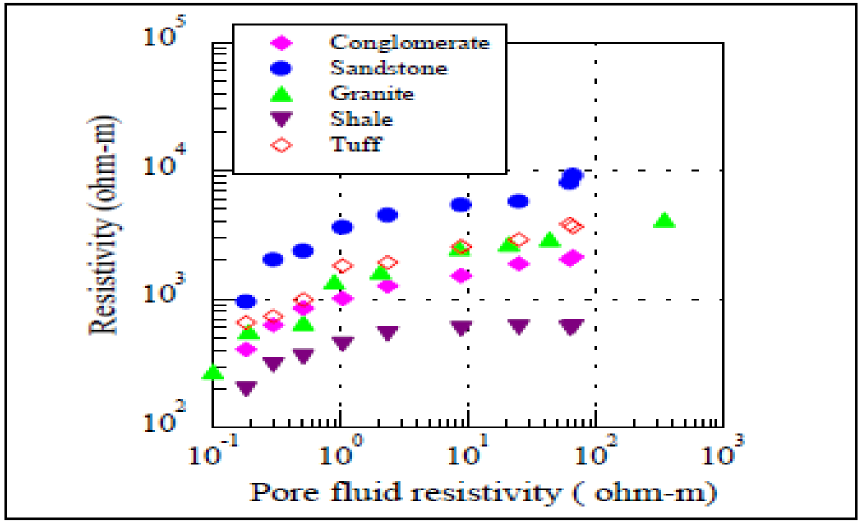
**Archie's law:** (1942; Barker and Worthington, 1973)

In the ground, and in low frequencies, electricity is essentially conducted through the interstitial water in pores by ionic transport

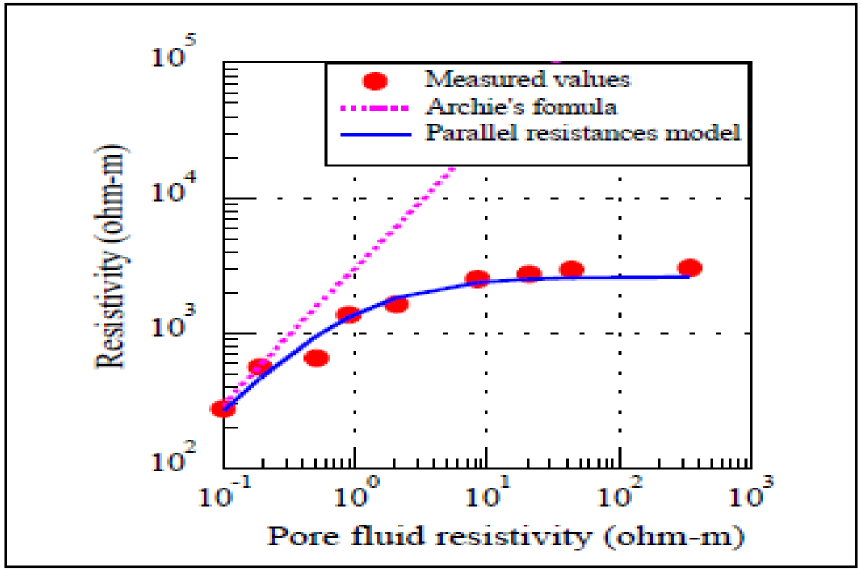
$$\rho = a\phi^{-m} S^{-n} \rho_w$$

$\rho$–effective formation resistivity;
$\rho_w$–pore water resistivity;
$\phi$ – porosity;
S – saturation;
a – 0.5-2.5;
m – 1.3-2.5;
n ~2.

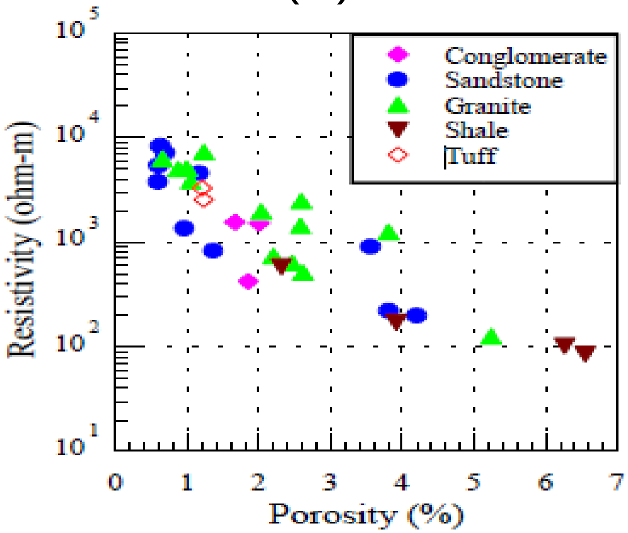
(a)



(b)



( c)



Pore fluid resistivity : 50 ohm.m

Relationship between formation and pore fluid resistivity and porosity: (a) resistivity of different rock specimens with Saturating fluid of NaCl concentration 20 to 32500 ppm and (b) comparison between measured and calculated resistivities ( c) variations with porosity

(Source :Matsui,T, S G Park, M K Park and s Matsuura, 2000, Relationship between electrical resistivity and physical properties of rocks, *GeoEng 2000 Intenational Conference on Geotechnical &Geological Engineering, Melbourne, Australia )*

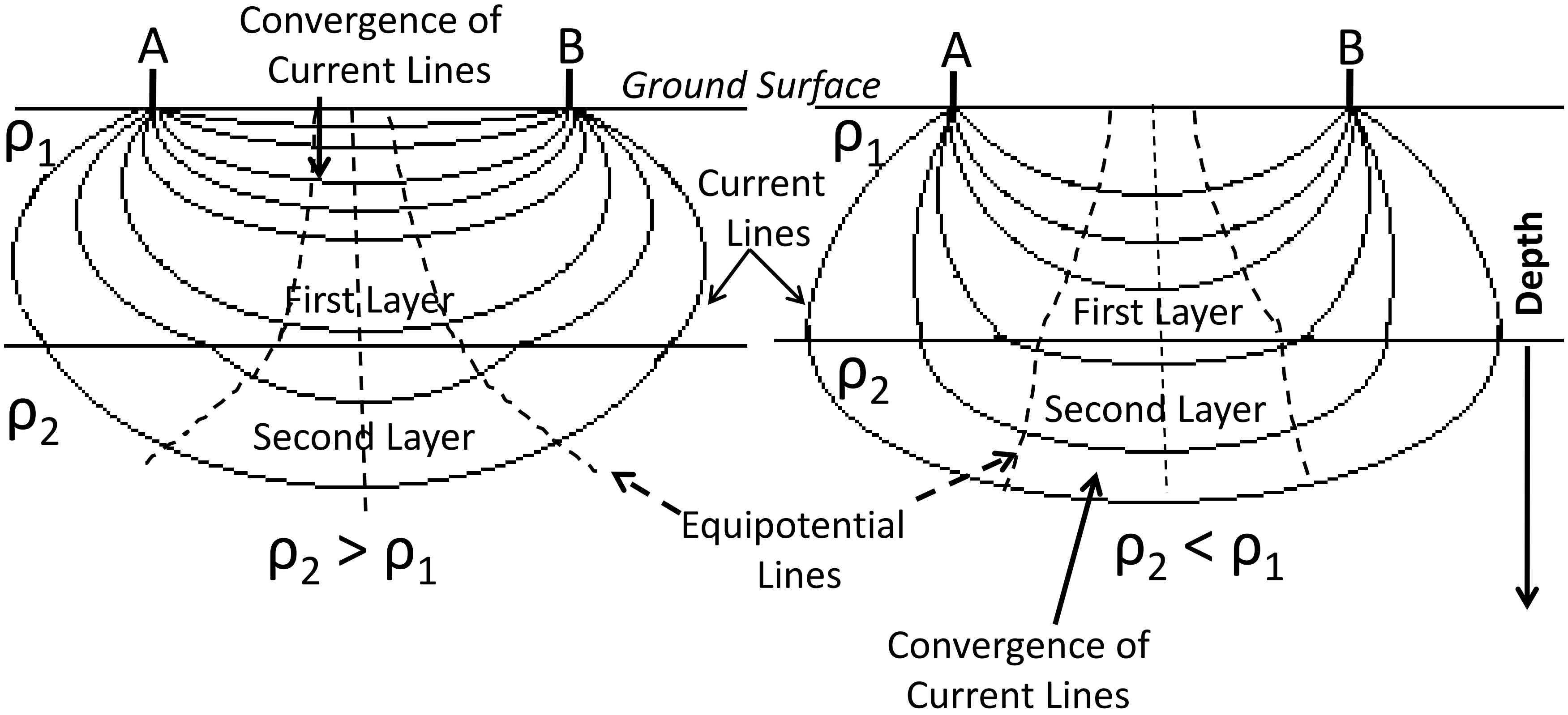
The resistivity of the order of $10^{10}$ ohm.m for dry granite sample reduces to $1.8 \times 10^{6}$ ohm.m with 0.19 % water content and to $4.4 \times 10^{3}$ ohm.m with 0.31% water content.

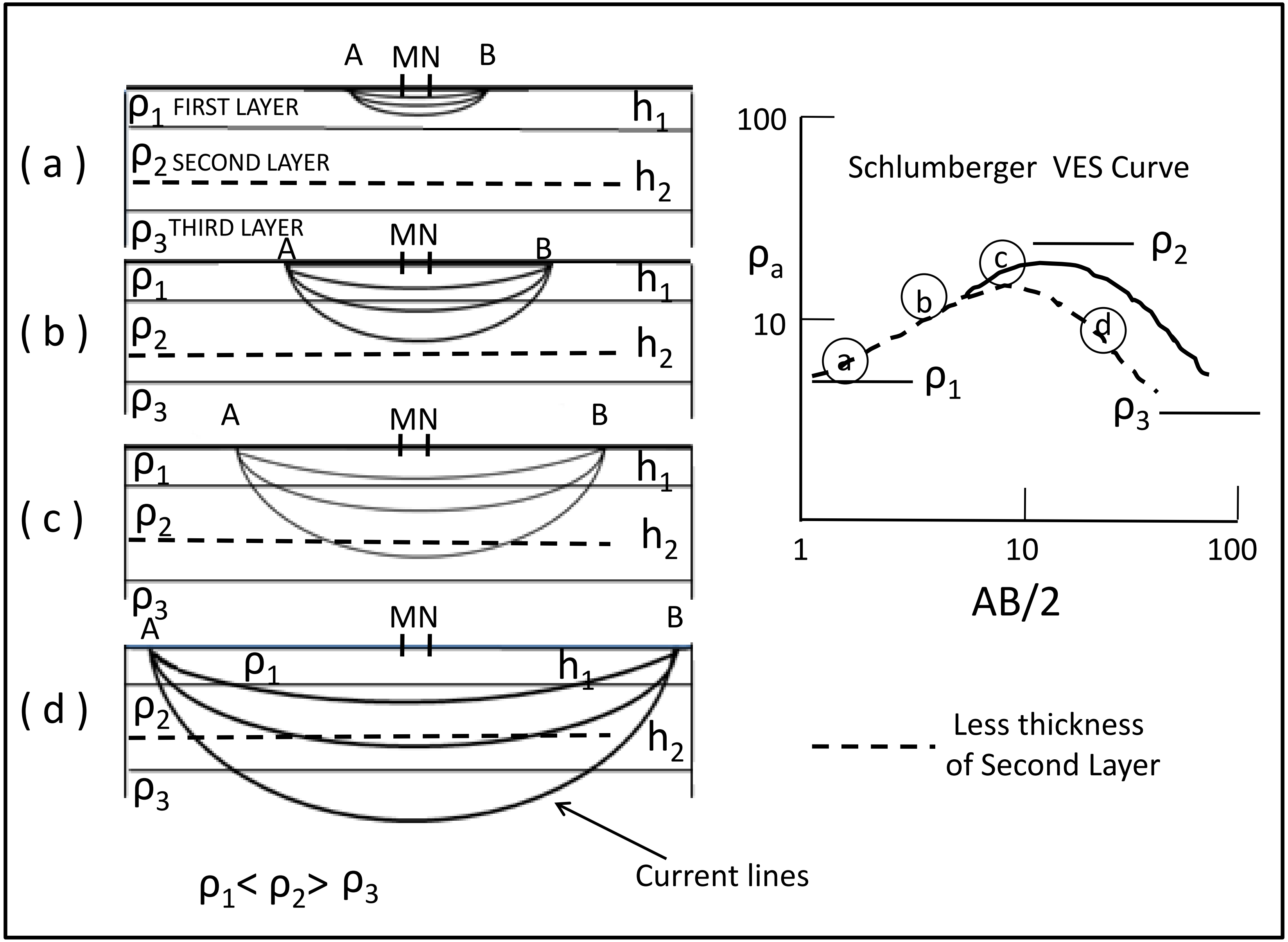
Whereas the resistivity of $1.3 \times 10^{8}$ ohm.m for dry basalt reduces to $4 \times 10^{4}$ohm.m with 0.95 % water content.

(Telford et al, 1990)

## Apparent Resistivity

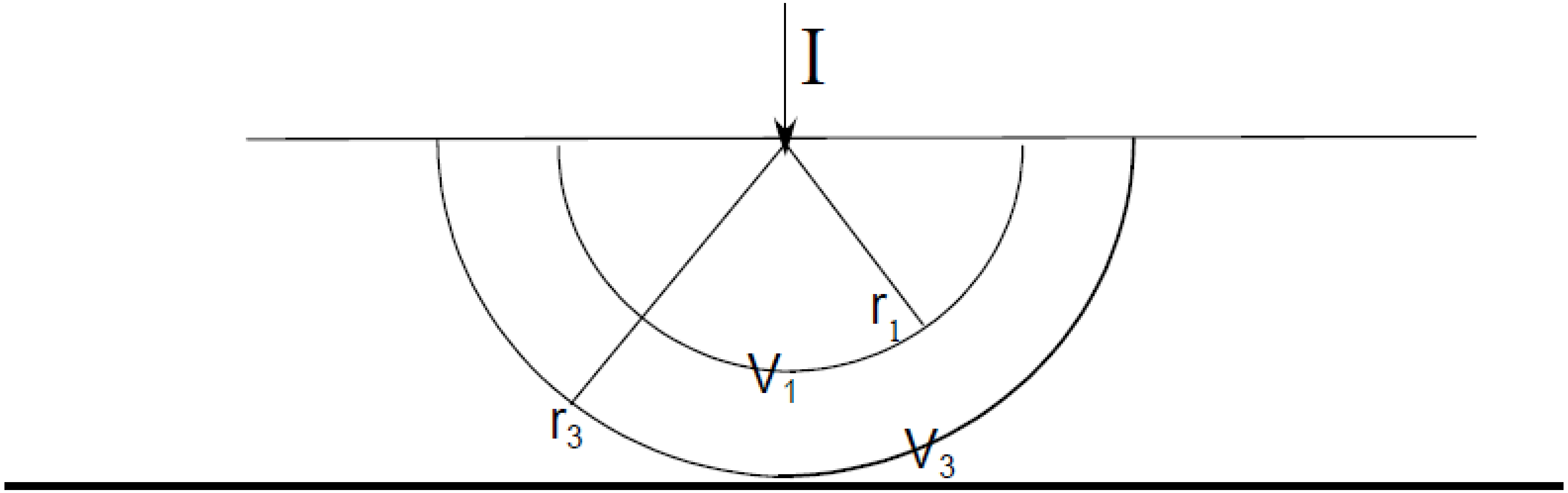
In case the subsurface is layered or inhomogeneous which is, in general observed, multiplication of the ratio of developed potential difference to current input with ‘geometric factor’ for the electrode geometry gives ‘apparent’ resistivity ( $\rho_a$ ) of the ‘inhomogeneous’ ground.


Convergence of Current Lines
A
B
Ground Surface
$\rho_1$
$\rho_2$
First Layer
Second Layer
Current Lines
$\rho_2 > \rho_1$
Equipotential Lines
A
B
$\rho_1$
$\rho_2$
First Layer
Second Layer
Depth
$\rho_2 < \rho_1$
Convergence of Current Lines


( a )
A
MN
B
ρ1 FIRST LAYER
h1
ρ2 SECOND LAYER
h2
ρ3 THIRD LAYER
( b )
A
MN
B
ρ1
h1
ρ2
h2
ρ3
( c )
A
MN
B
ρ1
h1
ρ2
h2
ρ3
( d )
A
MN
B
ρ1
h1
ρ2
h2
ρ3
Current lines
ρ1< ρ2> ρ3
Schlumberger VES Curve
100
10
ρa
a
b
c
d
ρ1
ρ2
ρ3
1
10
100
AB/2
Less thickness of Second Layer

**In practice, the field surveys usually measure the Voltage ΔV, other than the potential itself. This voltage ΔV is the difference of potential between 2 points. IN DC resistivity surveys the voltage is usually measured by two electrodes planted on the surface.**

$$\Delta V = V_1 - V_3 = \frac{\rho I}{2\pi r_1} - \frac{\rho I}{2\pi r_3}$$



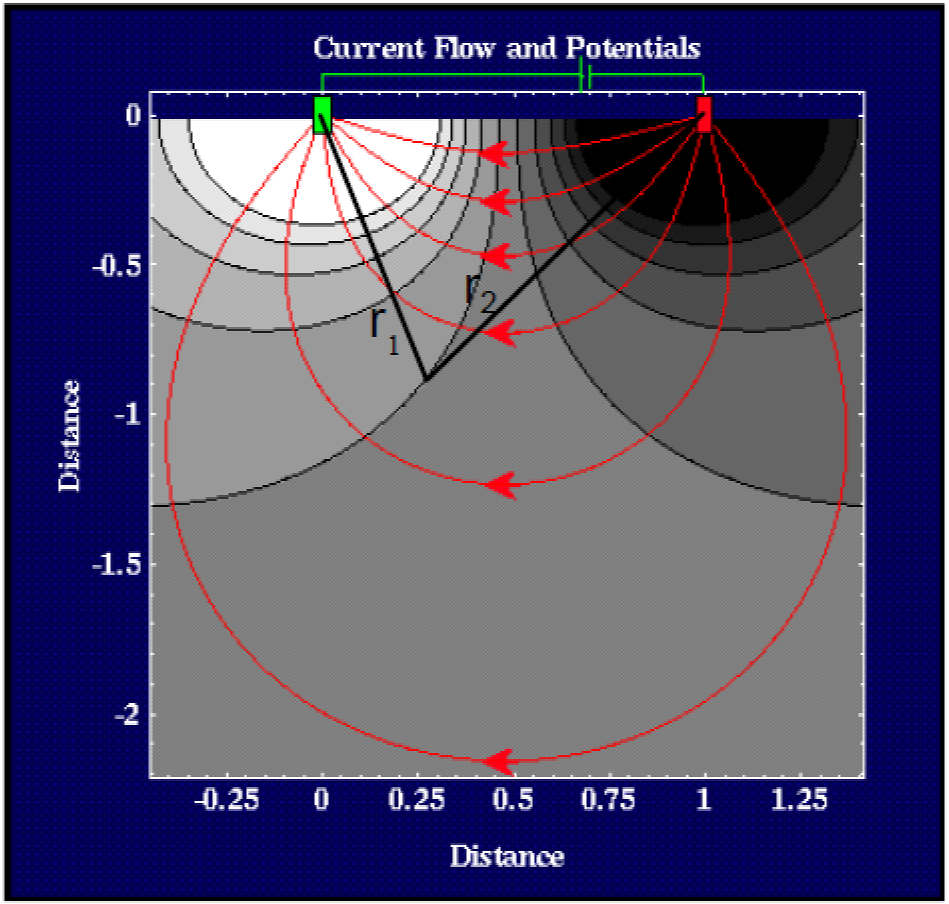
**For the current can be physically flowing through the ground, we have to have 2 poles: one for current injected in (source) and one for the current flow out (sink). Thus, both the source and sink will generate an electric potential, but with opposite polarity**

$$V_1 = \frac{\rho I}{2\pi r_1}$$

*and*

$$V_2 = -\frac{\rho I}{2\pi r_2}$$

**Dipole**

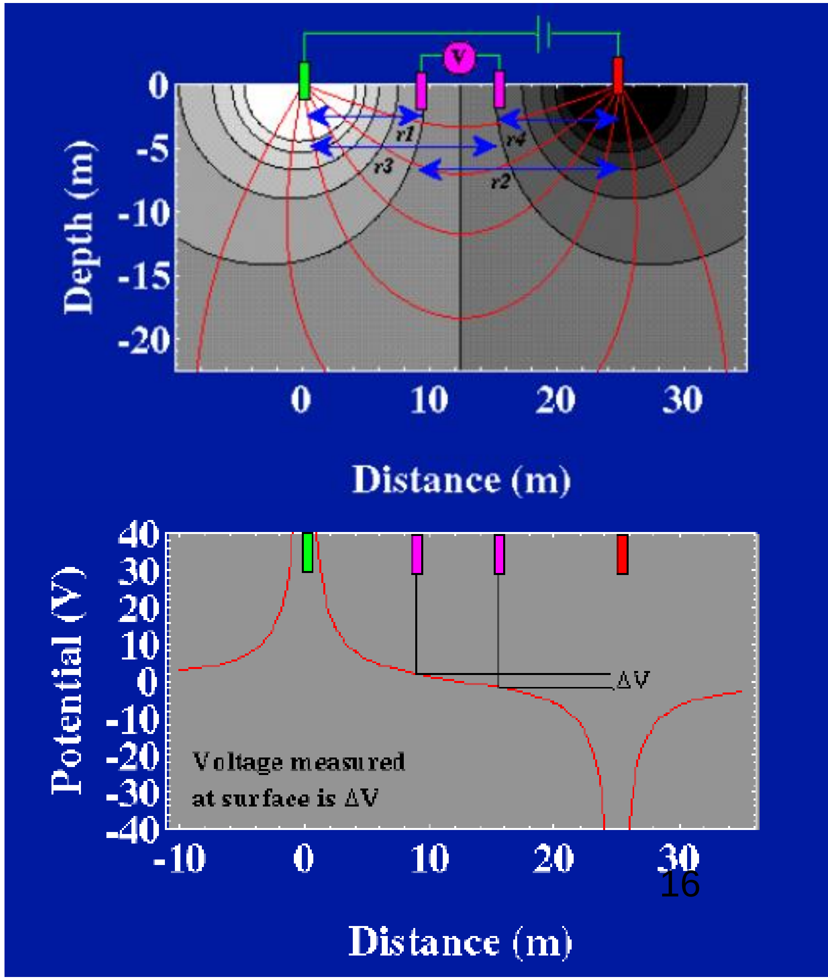


**And the total potential for the two poles is**

$$V = V_1 + V_2 = \frac{\rho I}{2\pi r_1} - \frac{\rho I}{2\pi r_2} = \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$

**And the total voltage between two points generated by the two poles is**

$$\begin{aligned}\Delta V &= \Delta V_1 + \Delta V_2 \\ &= \left(\frac{\rho I}{2\pi r_1} - \frac{\rho I}{2\pi r_3}\right) - \left(\frac{\rho I}{2\pi r_2} - \frac{\rho I}{2\pi r_4}\right) \\ &= \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)\end{aligned}$$



# APPARENT RESISTIVITY

because

$$\Delta V = \frac{\rho_a I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)$$

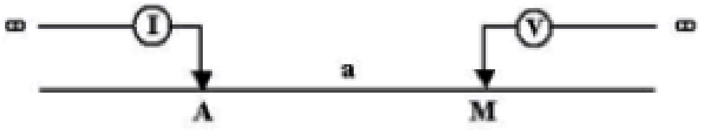
then

$$\rho_a = \boxed{2\pi\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)^{-1}} \frac{\Delta V}{I}$$

**K is Geometrical factor**

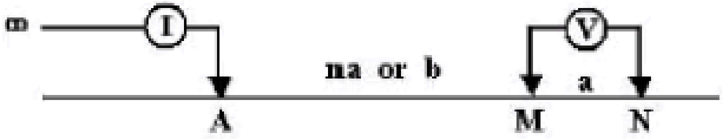
$$= k\frac{\Delta V}{I}$$

## Pole – pole



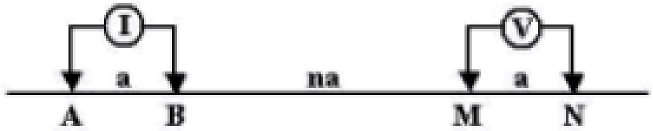
$$\rho_A = \frac{V}{I} 2\pi a$$

## Pole - dipole



$$\rho_A = 2\pi \frac{(a+b)}{b} \frac{V}{I}$$

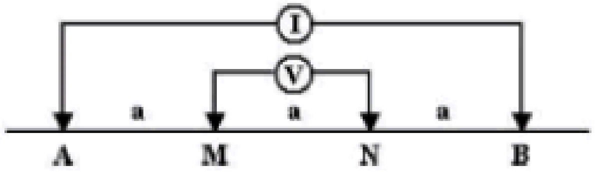
## Dipole - dipole



$$\rho_A = \frac{V}{I} \pi\, a\, n(n+1)(n+2)$$

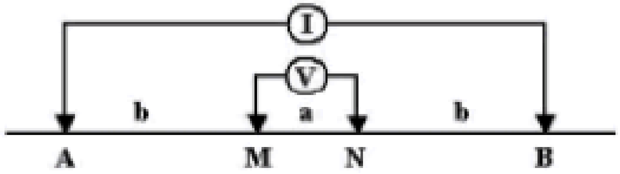
○ Geometrical factors

## Wenner



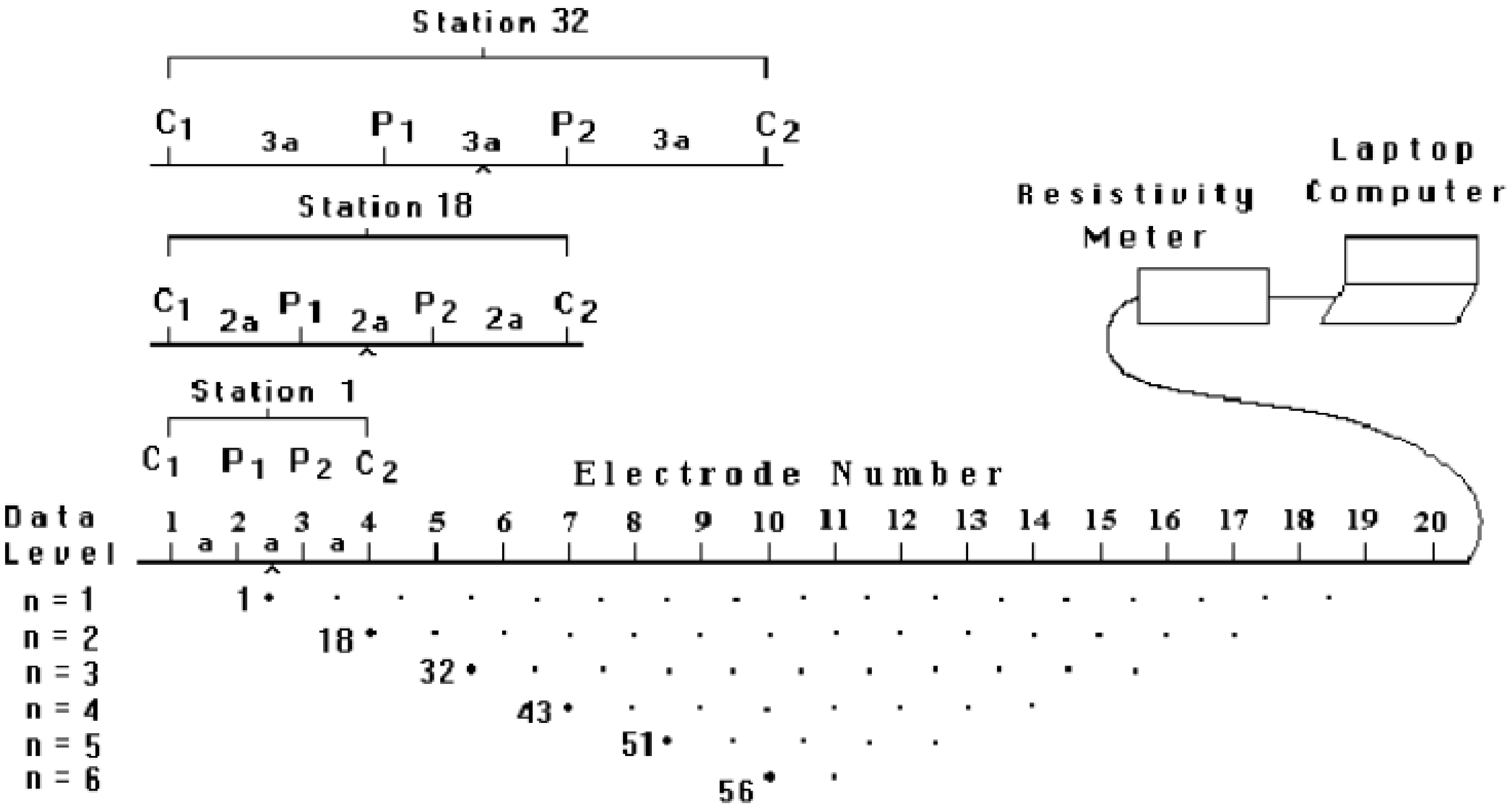
$$\rho_A = 2\pi a \frac{V}{I}$$

## Schlumberger



$$\rho_A = \frac{V}{I}\pi \frac{b\,(b+a)}{a} \approx \frac{V}{I}\pi\frac{b^2}{a} \quad \text{if } a \ll b$$

# ELECTRODE ARRAYS



Sequence of measurements to build up a pseudosection

## Data plotting

## Resistivity Methods

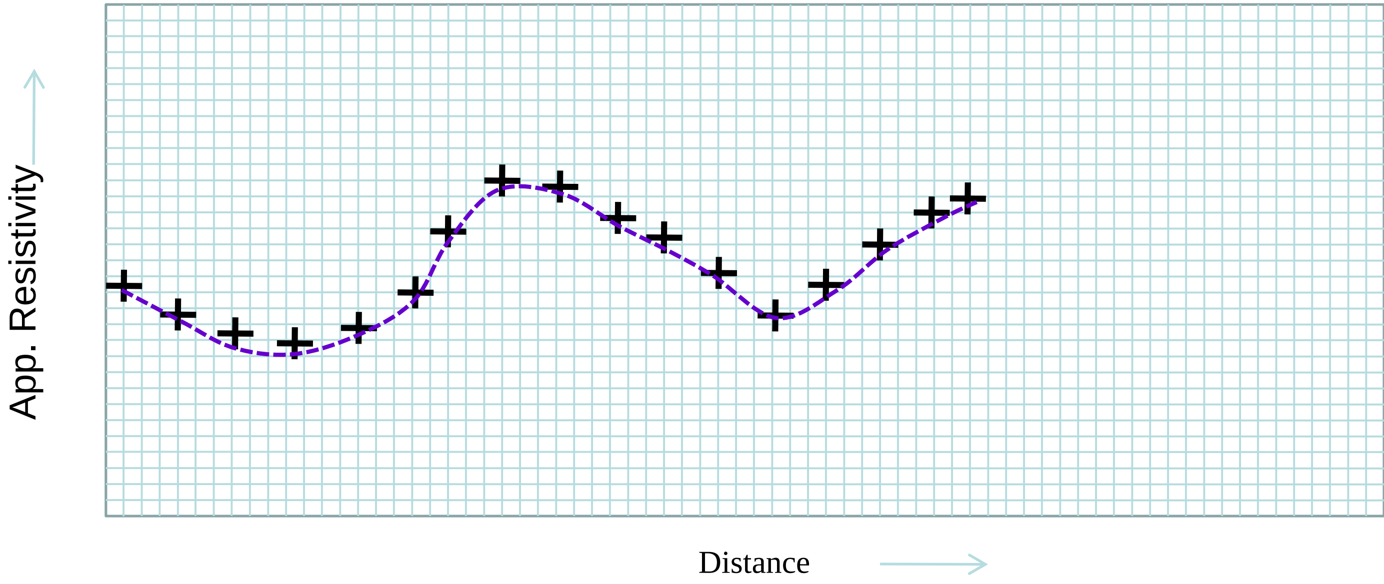
**Profiling:** to map lateral variations; electrode spacing is fixed for all readings

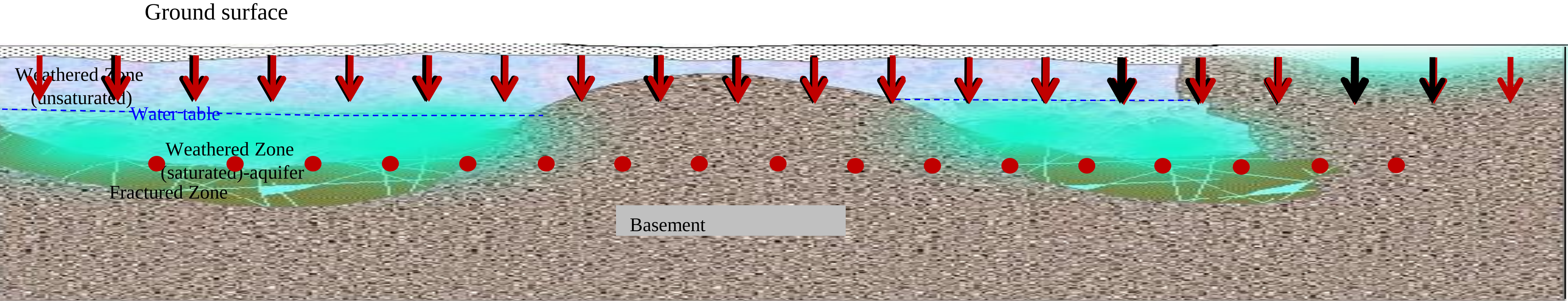
**Sounding:** to map vertical variations

# RESISTIVITY Profiling

# Resistivity: Profiling

Resistivity Plot

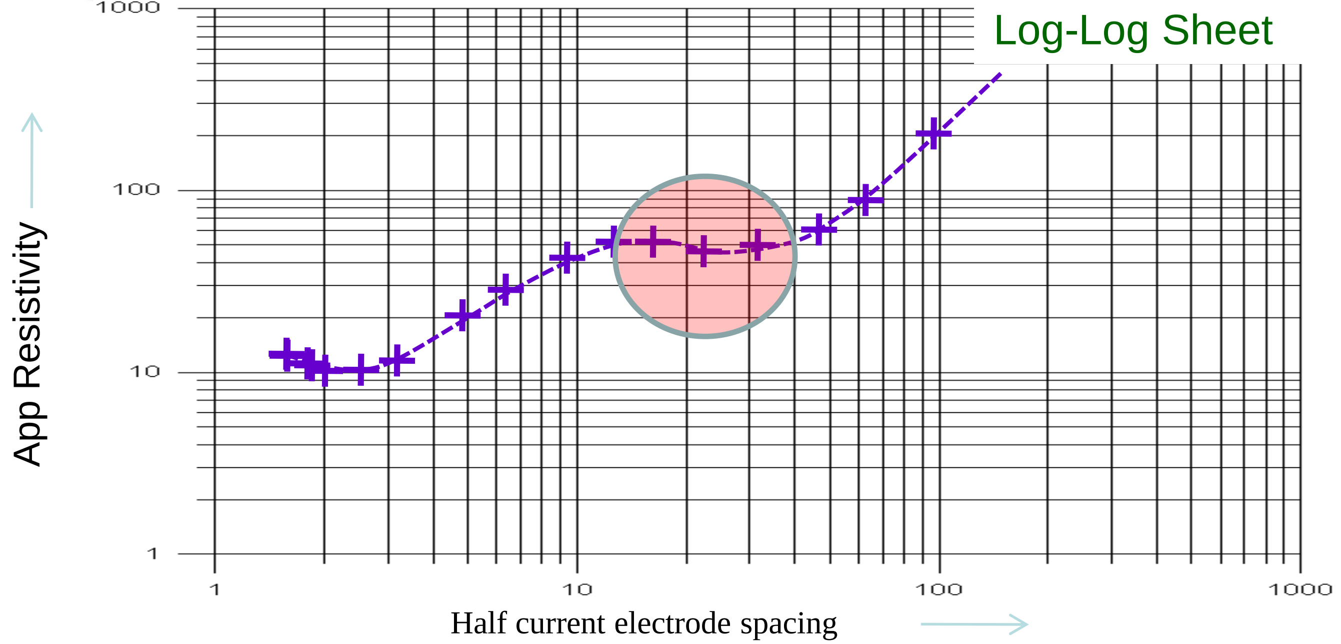


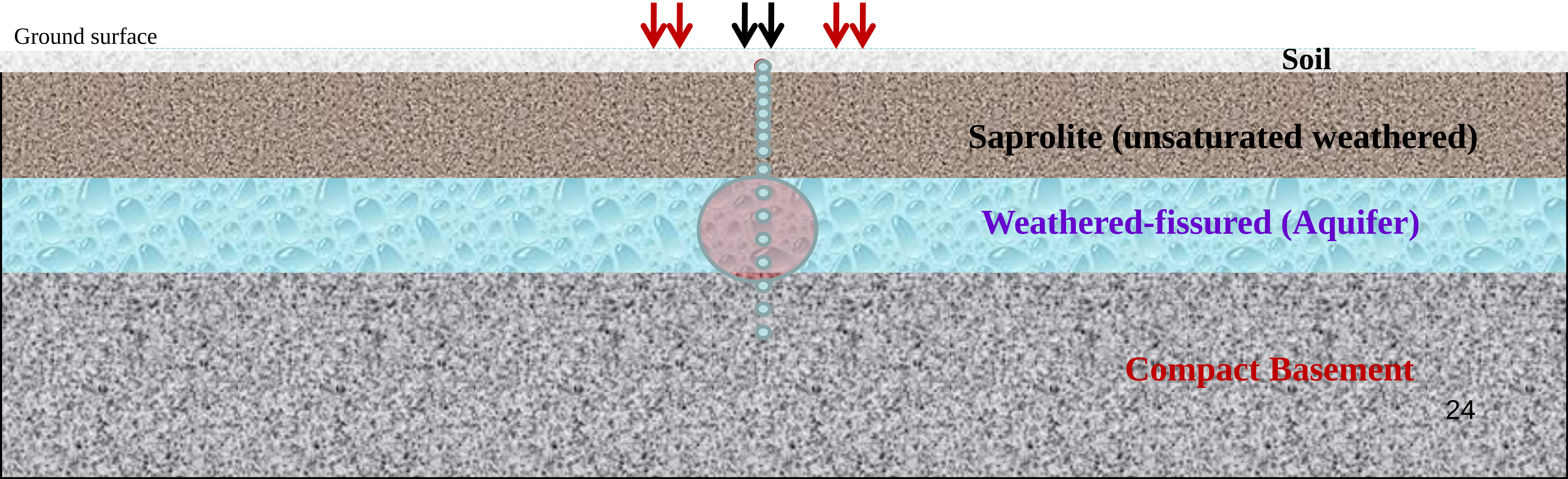


Schematic Subsurface model

# **RESISTIVITY** Sounding

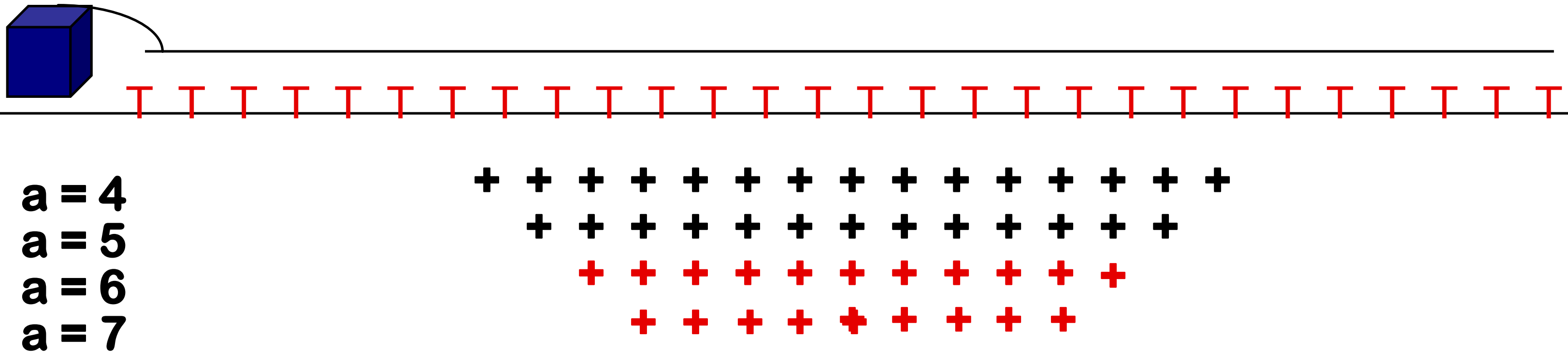
# Resistivity: Sounding





# <u>ERT</u> Surveying

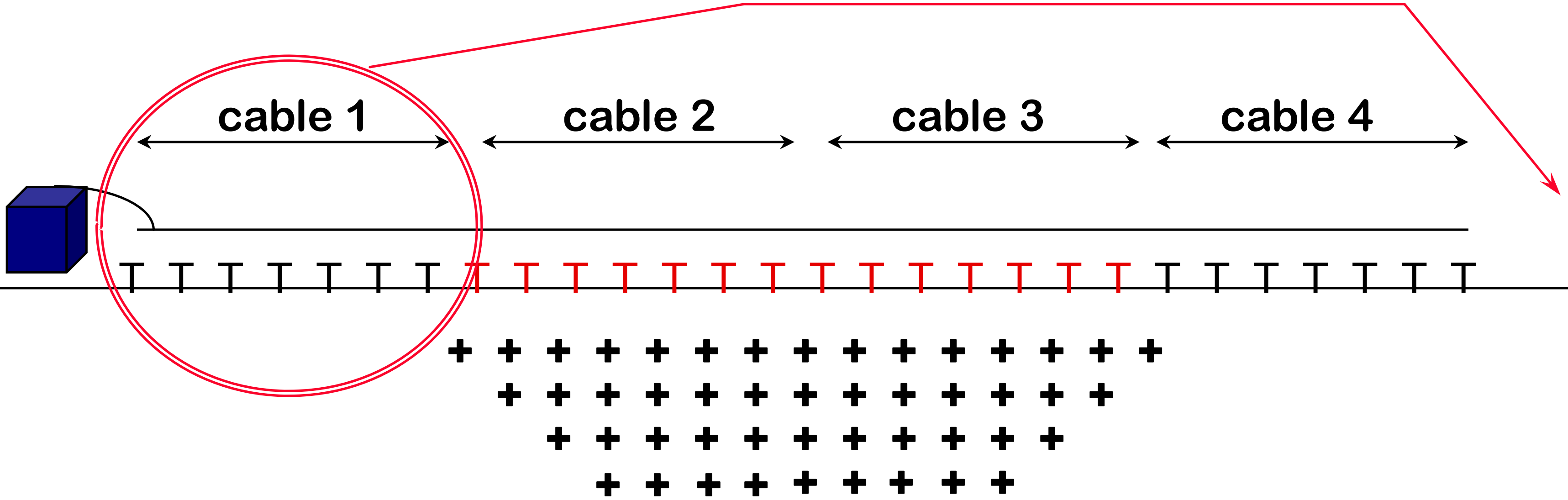
# Principle for multi-electrode systems



All measurements for a=4 to a=7

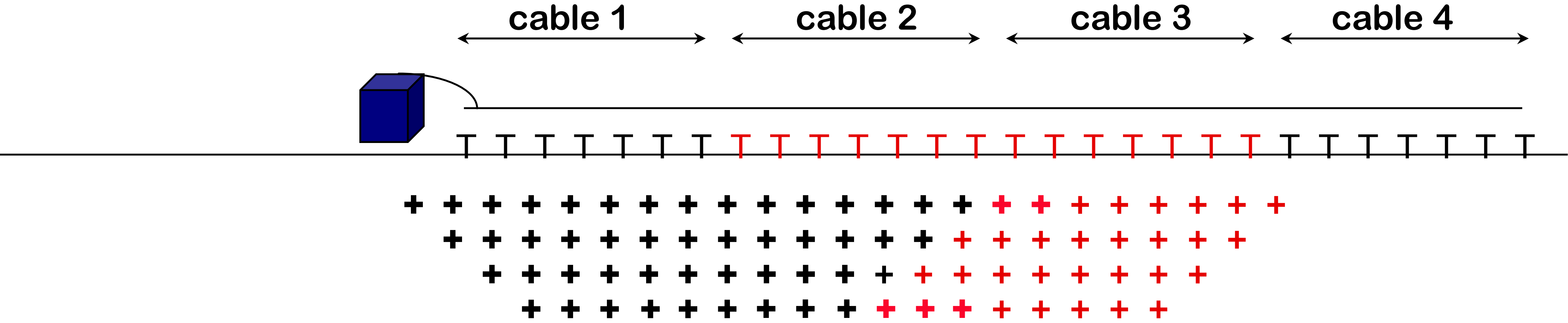
At least 10 different electrode separations are normally used. Different electrode arrays may be used (Wenner, Schlumberger, dipole-dipole, pole-dipole etc).

# Principle for multi-electrode systems



Multiple cables allow for roll-along surveying.

# Principle for multi-electrode systems



After moving former cable 1, new measurements are added.

A profile can be extended infinitely using roll-along technique.

A data set from a profile may contain a few hundred to many thousands of data points.

## Conducting the Survey

Profile or Sounding? - Decide

**Choose the electrode configuration:** Wenner, Schlumberger, Dipole-dipole etc.

**Profiling:** keep the electrode spacing constant, move the electrodes in a grid pattern, Wenner

**Used:** 1) Geological mapping
2) Mapping structures i.e., Faults, shear zones, joints, fractures etc.
3) Mapping of salt/fresh water boundary
4) Identification of paleo-river channels, Buried river valley, G/W pollution zones etc.
5) Determining direction & intensity of joints and fractures

**Sounding:** Increase the electrode spacing for each reading from a center point

**Used:** 1) Identification aquifer/ multi-aquifers system
2) Tracing groundwater quality and salt/fresh water boundary.
3) Identification potential zones in hard rock like saturated weathered zones, fractures shear zones etc.

# DEPTH OF INVESTIGATION

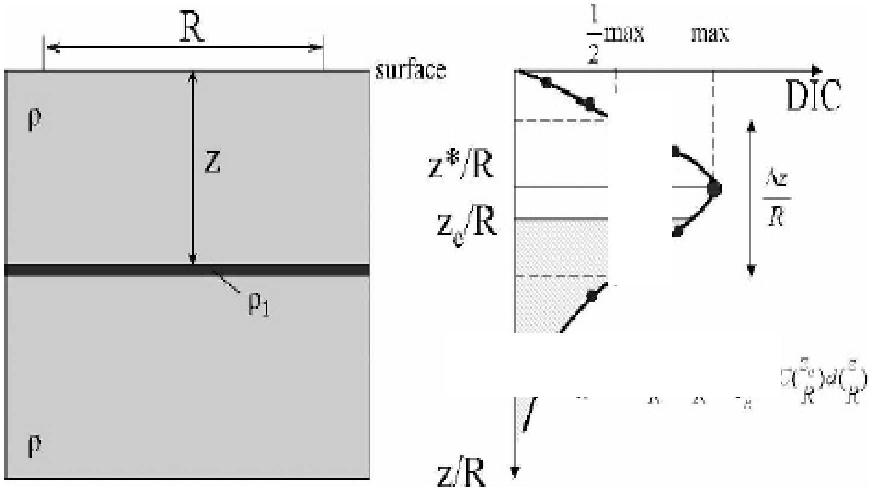
The terms '**depth of current penetration**' and '**depth of investigation**' are commonly used. When the electrical resistivity sounding is conducted a question is generally asked, up to what depth we get the information for a certain electrode array and electrode spacing.

That is, to relate the resistivity sounding measurement upto a particular electrode Spacing to a certain depth. Though there are rules of thumb for the depth of investigation as AB/4 for Schlumberger and 'a' for Wenner electrode array, the answer is quite complex.

The depth of current penetration is a function of spacing between the current electrodes. For homogeneous earth, Van Nostrand and Cook (1966) show that only 37% of the total current penetrates to a depth equal to 1/3 rd of the current electrode spacing, 50% penetrates to a depth equal to half the spacing and 70.5% penetrates to a depth equal to the current electrode spacing. Depth of current penetration depends on the current electrode separation only, whereas, the depth of investigation depends on the separation between current and potential electrodes.

In electrical resistivity surveys the potential difference measured between the potential electrodes is the sum of contributions from different depths, and the contributions from different depths are not the same.

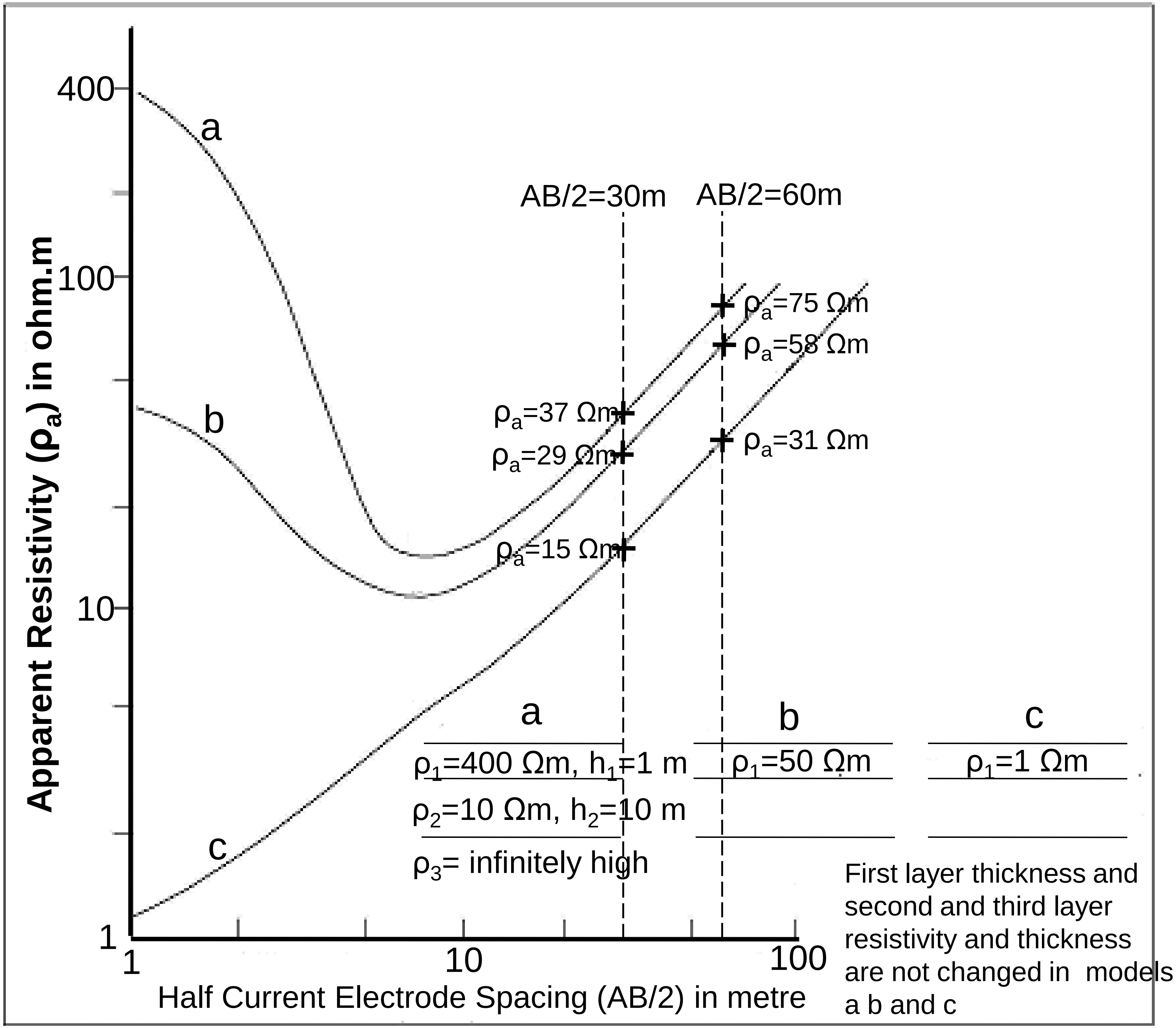
So, the depth of investigation could be defined as that depth at which a thin horizontal layer of the subsurface contributes maximum to the total signal measured at the ground surface.



gure 1. Principle of the depth of investigation characteristic (DIC) function. $R$: array length; $z$: variable depth of the thin sheet; $z^*$: depth of the maximum response (Roy and Apparao, 1971); and $z_e$: median of the DIC function (Edwards, 1977).

The depth of investigation has been computed from **depth of investigation characteristic (DIC)** function response to a certain array of electrodes for a homogeneous, isotropic horizontal thin layer placed at different depths in a homogeneous subsurface. The DIC curve is presented as a function of depth of the thin layer.

The depth of the thin layer at which DIC curve attains the maximum response is the depth of investigation for that electrode arrangement. For Wenner it is 0.11L and for Schlumberger it is 0.125L, where L is the distance between the current electrodes.



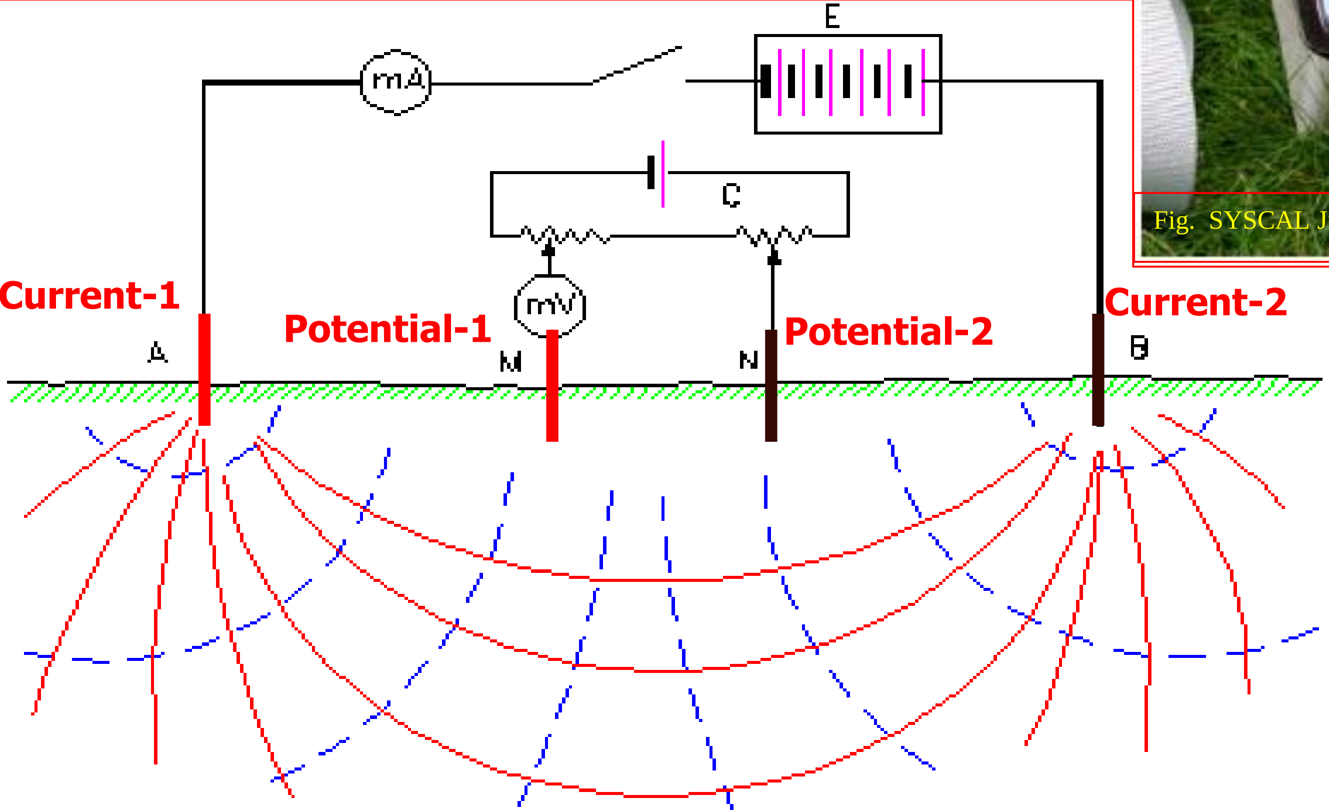
First layer thickness and second and third layer resistivity and thickness are not changed in models a b and c

**DC resistivity Techniques :** Resistivity measurements of the ground are normally made by injecting current through two current electrodes and measuring the resulting voltage difference at two potential electrodes. From the current (I) and voltage (V) values, an apparent resistivity (ρa) value is calculated,

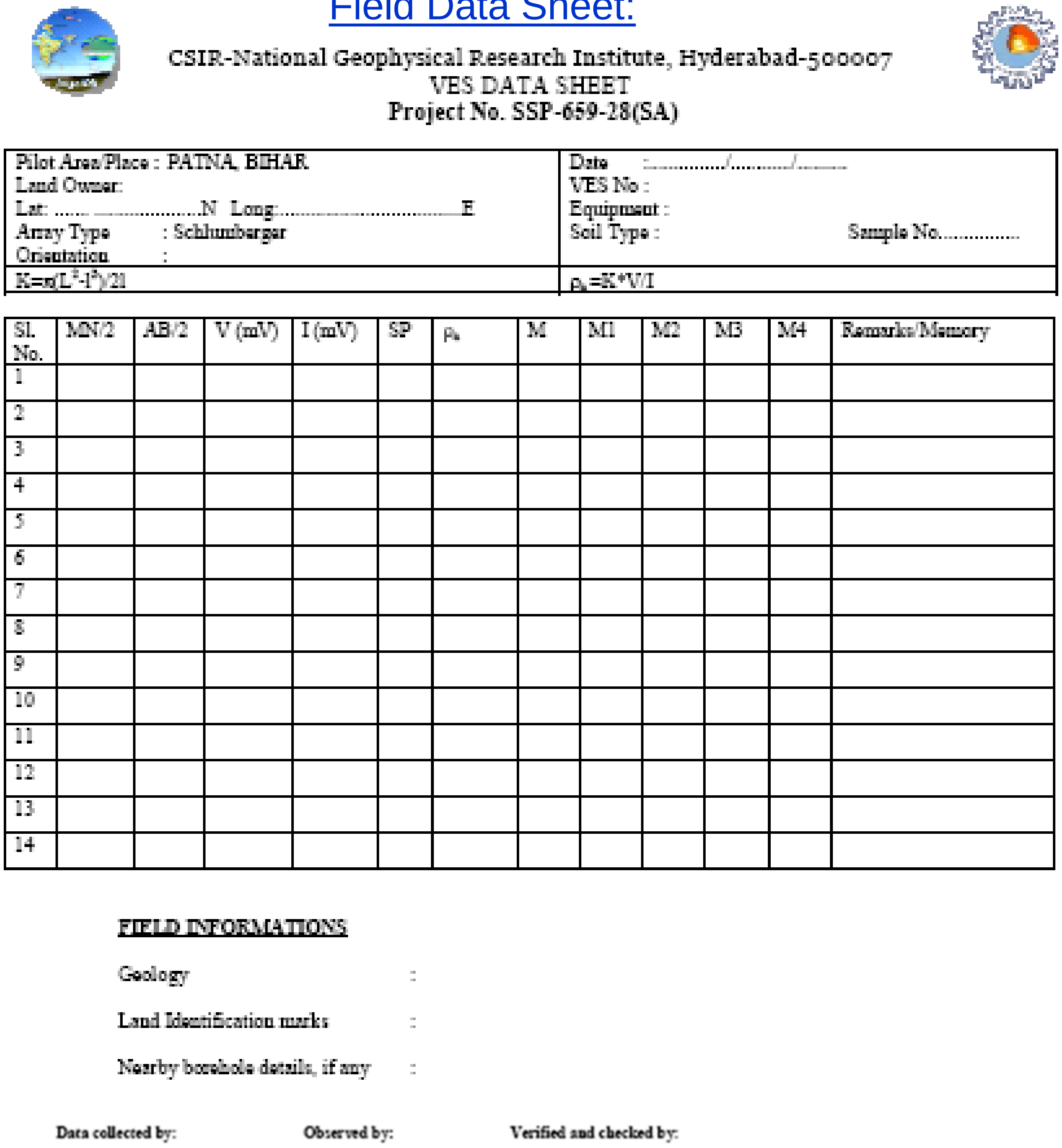
Consist of the following:

1- Energy source, (Battery).
2- Resistivity meter.
3- Two potential electrodes.
4- Two current electrodes.

Fig. SYSCAL Jr Switch-72 resistivity meter



# Field Data Sheet:



CSIR-National Geophysical Research Institute, Hyderabad-500007
VES DATA SHEET
Project No. SSP-659-28(SA)

| | |
|---|---|
| Pilot Area/Place : PATNA, BIHAR<br>Land Owner:<br>Lat: ...... ...................N Long:.................................E<br>Array Type : Schlumberger<br>Orientation : | Date :............../.........../.........<br>VES No :<br>Equipment :<br>Soil Type : Sample No............... |
| $K=\pi(L^2-l^2)/2l$ | $\rho_a=K*V/I$ |

| Sl. No. | MN/2 | AB/2 | V (mV) | I (mV) | SP | $\rho_a$ | M | M1 | M2 | M3 | M4 | Remarks/Memory |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | | | | | | | | | | |
| 2 | | | | | | | | | | | | |
| 3 | | | | | | | | | | | | |
| 4 | | | | | | | | | | | | |
| 5 | | | | | | | | | | | | |
| 6 | | | | | | | | | | | | |
| 7 | | | | | | | | | | | | |
| 8 | | | | | | | | | | | | |
| 9 | | | | | | | | | | | | |
| 10 | | | | | | | | | | | | |
| 11 | | | | | | | | | | | | |
| 12 | | | | | | | | | | | | |
| 13 | | | | | | | | | | | | |
| 14 | | | | | | | | | | | | |

**FIELD INFORMATIONS**

Geology :

Land Identification marks :

Nearby borehole details, if any :

Data collected by: Observed by: Verified and checked by:

# Field Data:

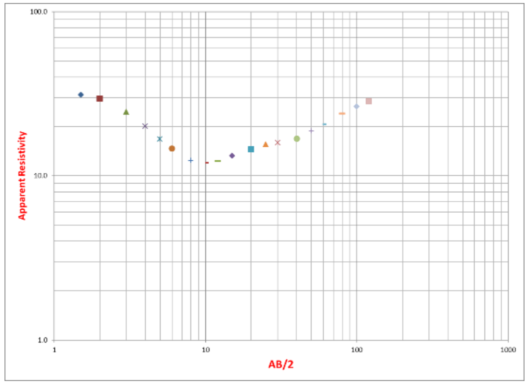
Site_B-1:H-Type curve

| AB/2 | MN/2 | Rho |
|---|---|---|
| 1.5 | 0.5 | 31.2 |
| 2 | 0.5 | 29.6 |
| 3 | 0.5 | 24.5 |
| 4 | 0.5 | 20.1 |
| 5 | 0.5 | 16.8 |
| 6 | 0.5 | 14.6 |
| 8 | 0.5 | 12.4 |
| 10 | 0.5 | 12.0 |
| 12 | 0.5 | 12.3 |
| 15 | 0.5 | 13.2 |
| 20 | 0.5 | 14.6 |
| 25 | 0.5 | 15.5 |
| 30 | 0.5 | 15.9 |
| 30 | 5 | 15.9 |
| 40 | 5 | 16.9 |
| 50 | 5 | 18.7 |
| 60 | 5 | 20.6 |
| 80 | 5 | 24.0 |
| 100 | 5 | 26.5 |
| 120 | 5 | 28.4 |

# Lithology nearby well

| Depth (m) | | Lithology |
|---|---|---|
| From (in m) | To(in m) | |
| 0 | 10.5 | Medium Sand |
| 10.5 | 13.8 | Clay |
| 13.8 | 29.4 | Sandy Clay |
| 29.4 | 42.3 | Medium Sand |
| 42.3 | 57.4 | Gravel & Medium Sand |
| 57.4 | 82.6 | Gravel |
| 82.6 | 98.5 | Clay |
| 98.5 | 107.8 | Gravel & Medium Sand |
| 107.8 | 123.7 | Clay |
| 123.7 | 189.7 | Medium Sand |
| 189.7 | 227 | Gravel & Medium Sand |
| 227 | 240 | Clay |
| 240 | 245 | Medium Sand |
| 245 | 252.54 | Clay |

# Graph:



# Interpretation

Apparent resistivity is calculated knowing the current, potential difference (voltage), and the electrode spacing (AB/2 & MN/2 provide ‘G’ geometrical factor),

**Then apparent resistivity Vs electrode spacing is plotted in log-log sheet.**

## Interpretation:

Analytical /Semi-analytical methods

- Layered Earth: Manual partial curve matching
- Curve Break
- Factor Method
- Inverse Slope

Inverse

- Computer based inversion (i.e., IX1-D Software)

# Ground Penetrating Radar (GPR)

**Ground Penetrating Radar (GPR)** works on the principle of reflection and refraction of electromagnetic waves. In Electromagnetic spectrum GPR uses the Radio waves and microwaves of frequency range from **10 MHz to 1000 MHz** The Transmitter of GPR emits the electromagnetic wave and after encountering some electromagnetic discontinuity, EM Wave get back reflected/total internally reflected/ or after multiple refraction to the surface and received by receiver part of the GPR

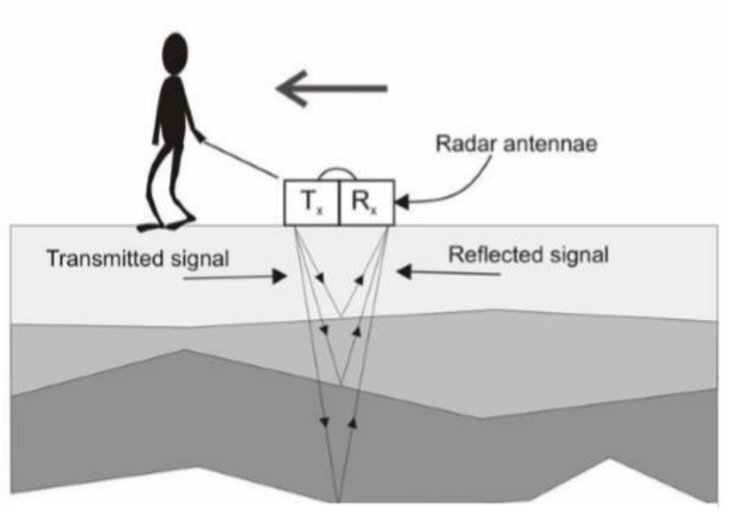
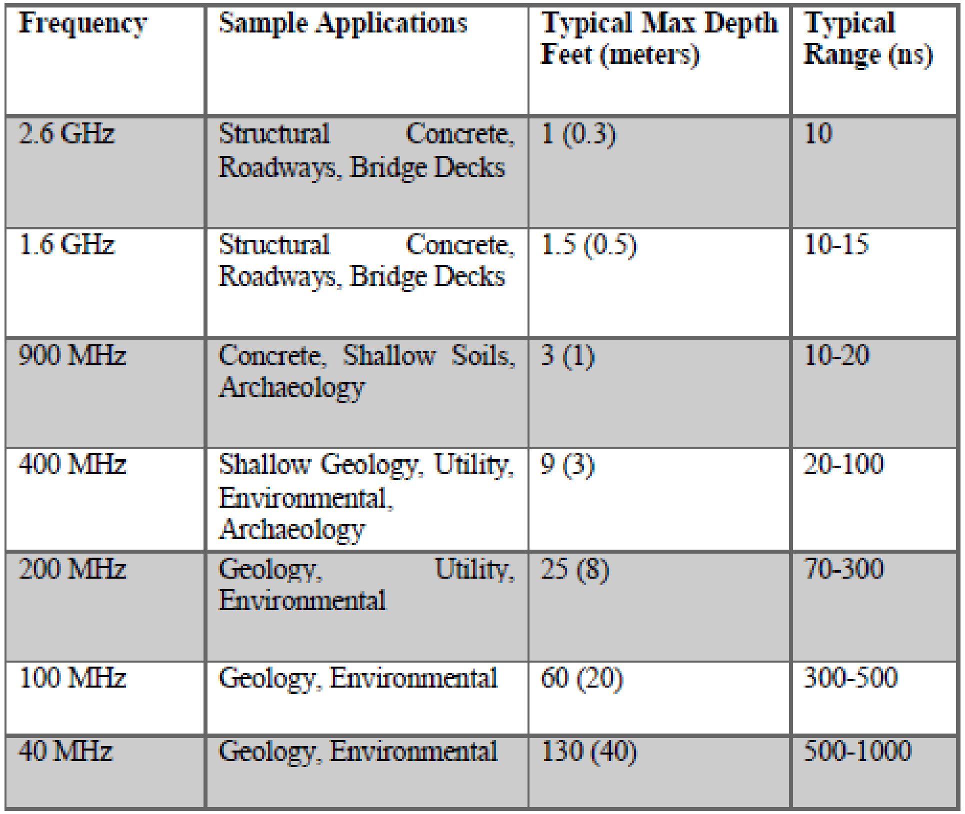


Fig 1: GPR components and transmitted and reflected signals illustration (environmental-geophysics.co.uk)

The Depth of Penetration is also controlled by the frequency of the antennae used. The depth range of different antennae along with their applications are given in the table below (GeoScan Subsurface surveys):

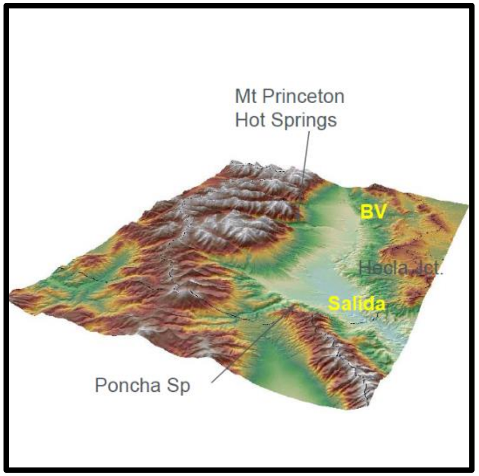


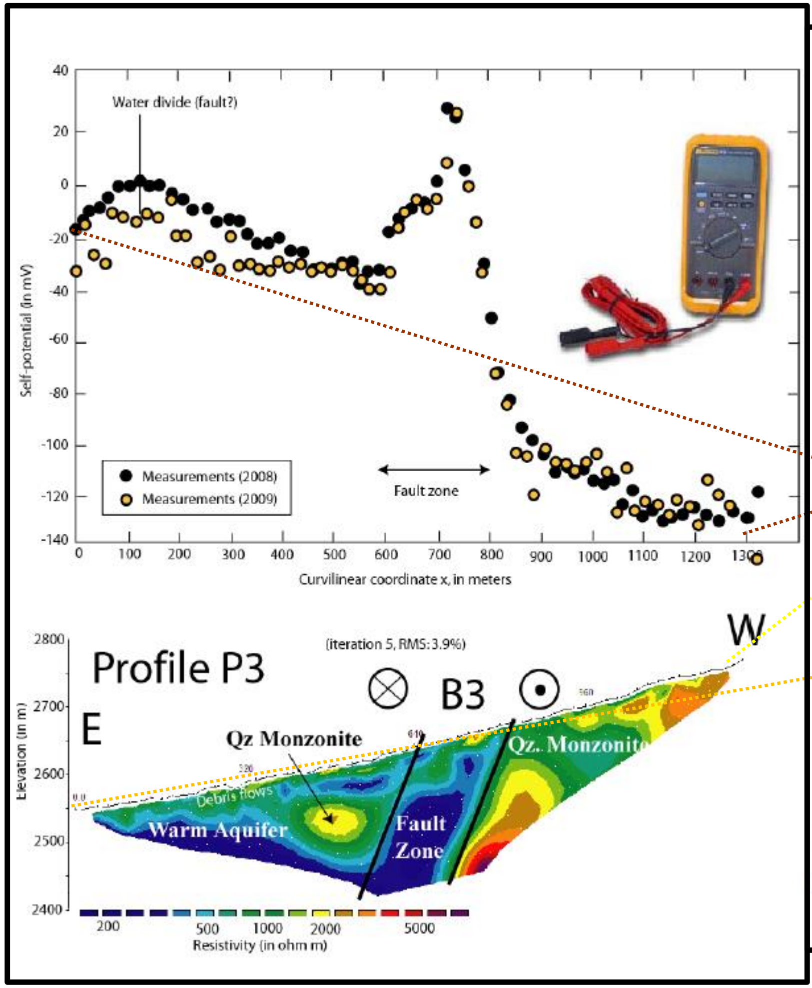
| Frequency | Sample Applications | Typical Max Depth Feet (meters) | Typical Range (ns) |
|---|---|---|---|
| 2.6 GHz | Structural Concrete, Roadways, Bridge Decks | 1 (0.3) | 10 |
| 1.6 GHz | Structural Concrete, Roadways, Bridge Decks | 1.5 (0.5) | 10-15 |
| 900 MHz | Concrete, Shallow Soils, Archaeology | 3 (1) | 10-20 |
| 400 MHz | Shallow Geology, Utility, Environmental, Archaeology | 9 (3) | 20-100 |
| 200 MHz | Geology, Utility, Environmental | 25 (8) | 70-300 |
| 100 MHz | Geology, Environmental | 60 (20) | 300-500 |
| 40 MHz | Geology, Environmental | 130 (40) | 500-1000 |

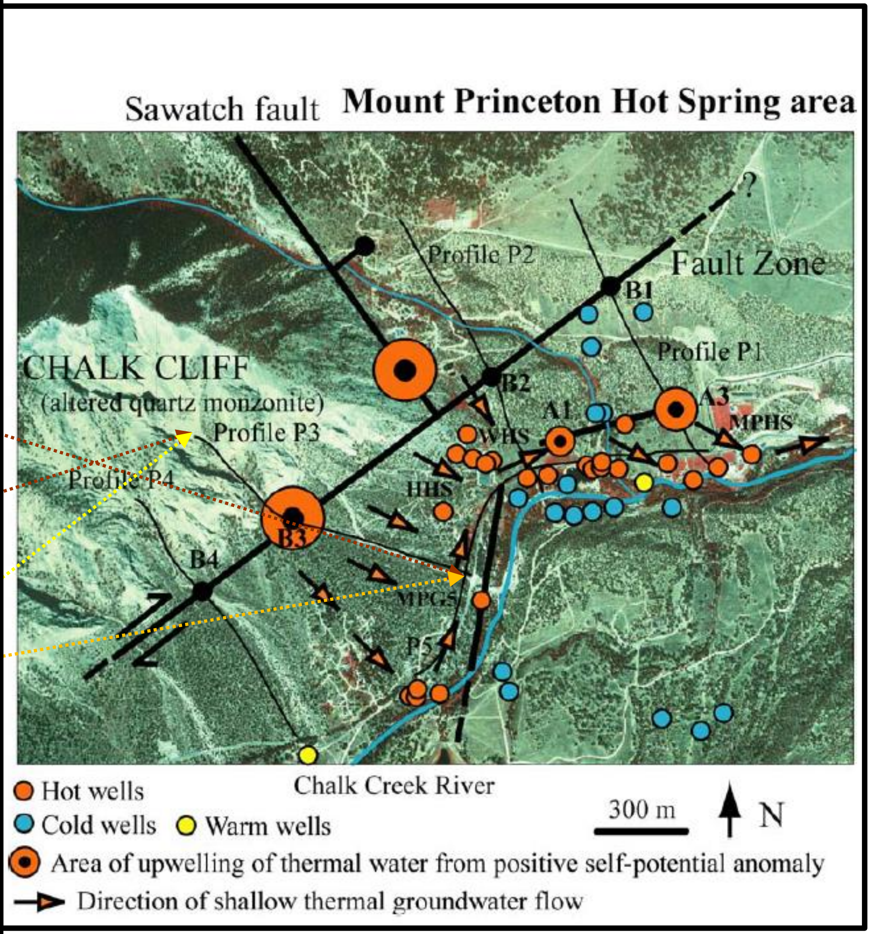
# Case Studies

Case Study: I

# Use of **DC Resistivity & Self-Potential (SP)** to Characterize a Geothermal Reservoir (at Mount Princeton Geothermal Field, Upper Arkansas Valley)







[Revil, Colorado School of Mines, 2010]

Case Study: II

# Self-Potential Measurements of a Hot Spring site in Rabulu, Fiji (South Pacific Ocean)

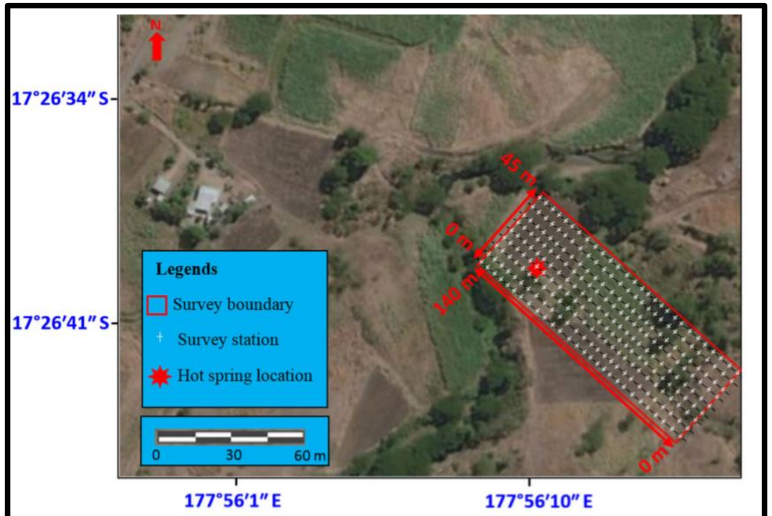
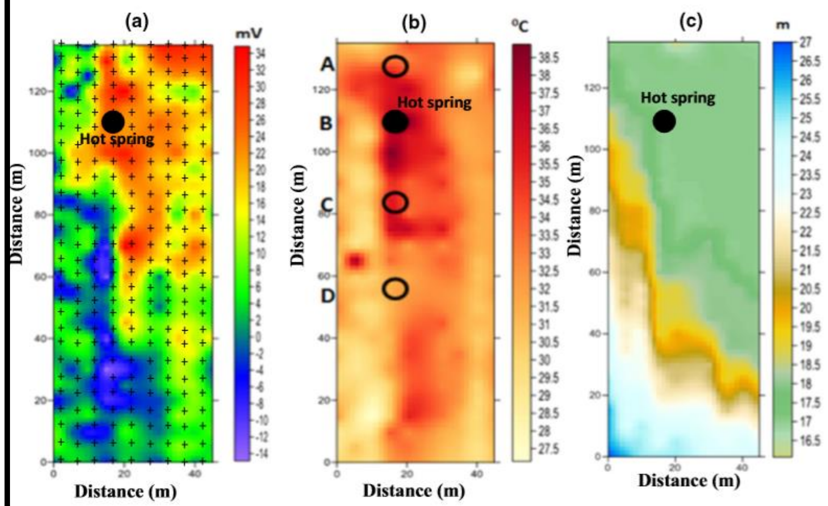


**Fig.:** Location of the study area with a schematic of the study area boundary and survey stations (Source: Google Earth)

**Fig.:** (a) SP distributions, (b) Gr.T at 0.3 m depth with locations of the four thermal probes denoted by circles and hot spring discharge zone denoted by square, and (c) elevation distribution at the hot spring site



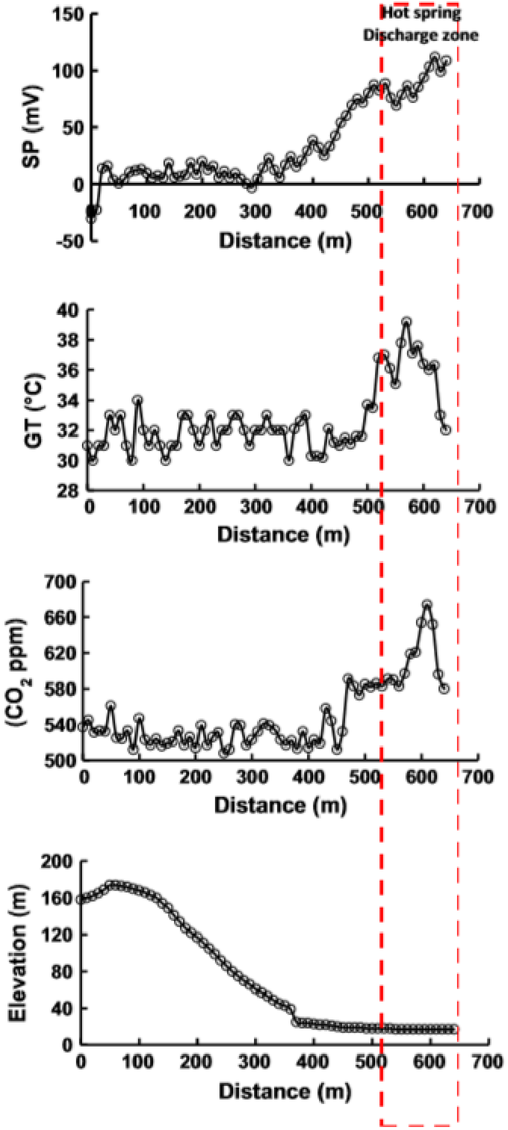


**Fig.:** SP, Gr. T, soil $CO_2$ concentration and elevation profiles at the hot spring site

## Results:

Self-potential (SP), ground temperature and soil carbon dioxide ($CO_2$) concentrations were measured and investigated for their distribution characteristics and inter-linkages. The results indicated obvious anomalous zone at the hot spring discharge site. The SP profile analysis highlighted thermal water upwelling zones and elevation-driven subsurface groundwater pathways.

*[Lal et al., 2018, Acta Geophysica]*

Case Study: III

# Geophysical Approaches (such as GRP & ERT) to Define Structural Implication of the Molinaccio Spring (Spello, Italy)

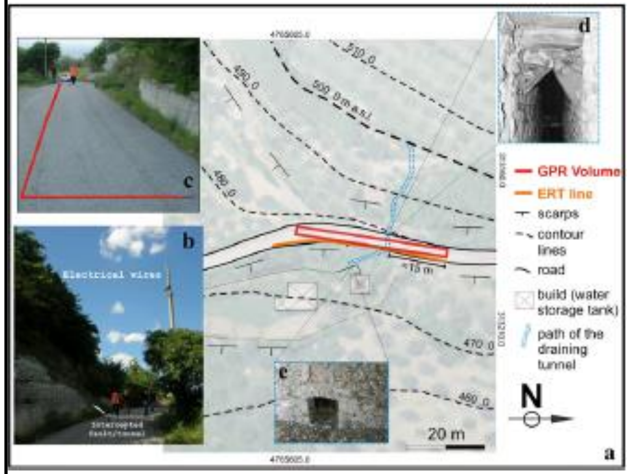


**Fig.:** *a) Schematic map of the survey site: it shows an approximated location of the water-supply tunnel plotted on a schematic topographic base overlapping an orthophoto. The 3D GPR grid is represented in dark gray, while the ERT profile is in light gray; while the ERT profile is in orange; b) a picture of the survey site illustrating features such as trees, walls, poles and electrical lines, that are the origin of out-of-plane-reflections. The white dashed lines indicate the attenuated area F, interpreted as a fault area; c) materialization of the 3D GPR survey grid over the road; d) detail of the tunnel from the inside (Bazzurri et al., 2003); e) detail of the small entrance (60 cm height) of the draining tunnel. The relief inside the tunnel operated by Bazzurri et al. (2003) has been done starting from this point.*

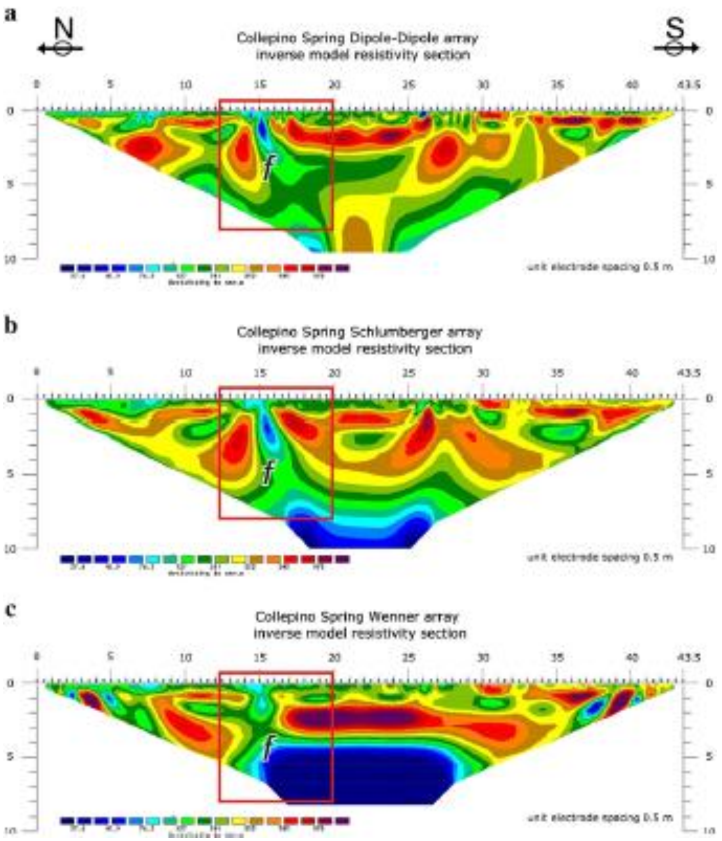


**Fig.:** Inverted real resistivity sections obtained for the three cases for a) Dipole–dipole; b) Schlumberger–Wenner; c) Wenner. The interpreted fault zone "f" and the tunnel "T" are highlighted by the red rectangle.

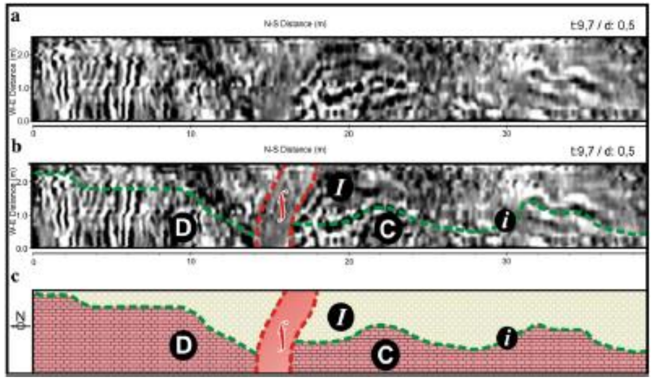


**Fig. :** a) A depth-slice extracted from the 3D GPR volume; b) interpretation of Fig. a. The winding line "i" marks the contact of two different lithologies: the Scaglia Rossa limestone labelled with D (high dip) and C (low dip), and the deposits I. "f" highlights the attenuated zone interpreted as the fault zone; c) schematic draw of the depth-slice interpretation of panel b.

**Results:**

The GPR data revealed, in the area of the water-caption tunnel, two main tectonic structures, both also confirmed by ERT data: the presence of a zone (maximum 2 m wide), interpreted as a normal fault area and an over thrust that puts in contact the permeable Scaglia Rossa limestone (Early Turonian–Middle Eocene), and the Scaglia Variegata–Cinerea marly limestones (Middle Eocene–Upper Oligocene) on the footwall, characterized by lower hydraulic permeability.

[Ercoli et al., 2012, JAG]

Case Study: IV

# Use of DC Resistivity Soundings and Profiles (Wenner) at Bakreswar Hot Spring

## >300 hot springs in India

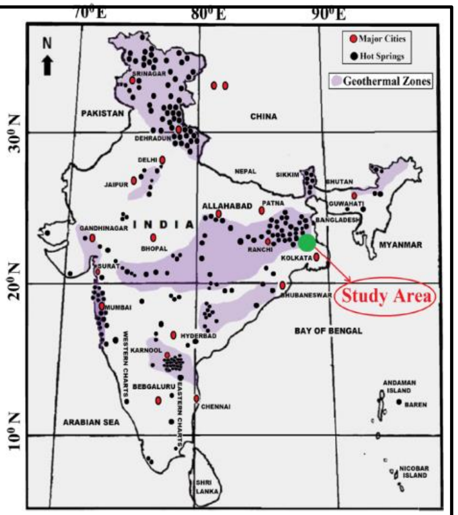


**Fig.:** Location of Bakreswar area (after Gupta et al., 2016)

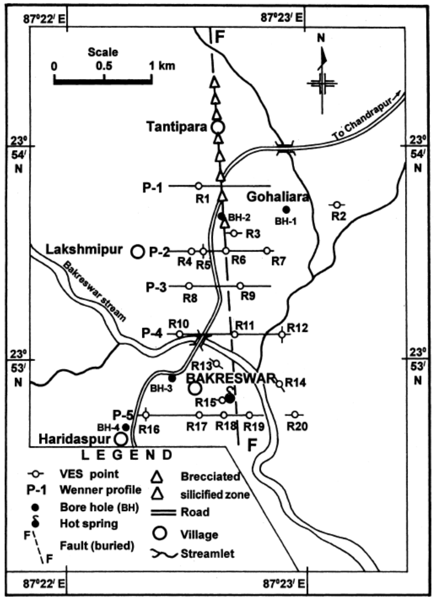


*Fig.: Locations of geoelectric resistivity investigations and bore holes: VES Schlumberger .and profiles Wenner.*

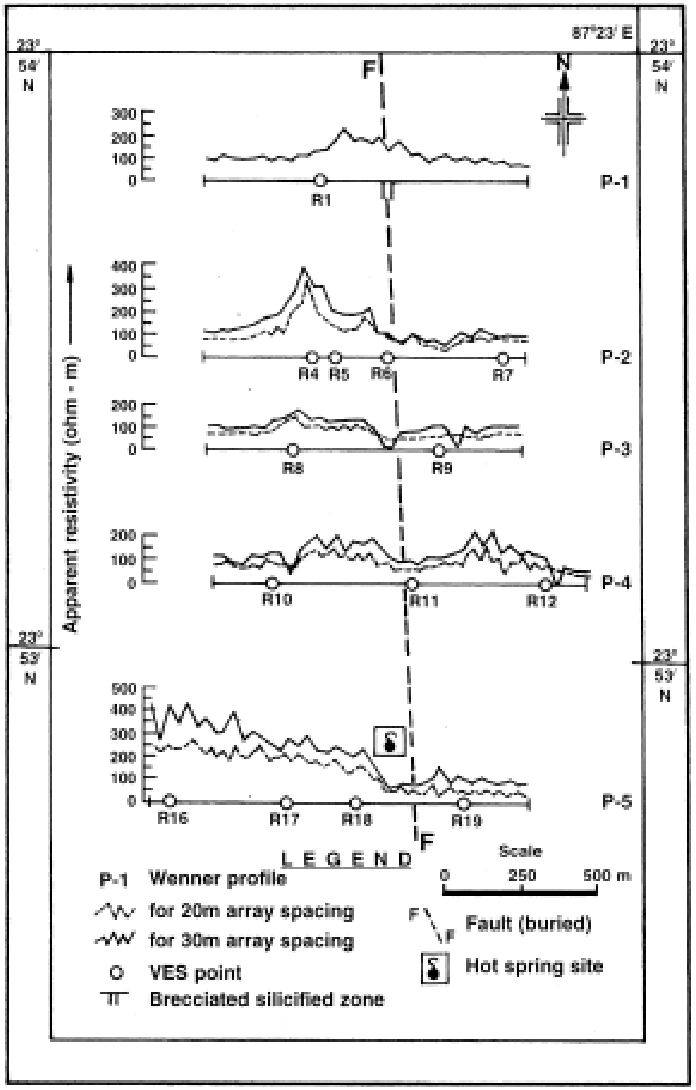


**Fig.:** Wenner apparent resistivity responses along five profiles for 20- and 30-m array spacings

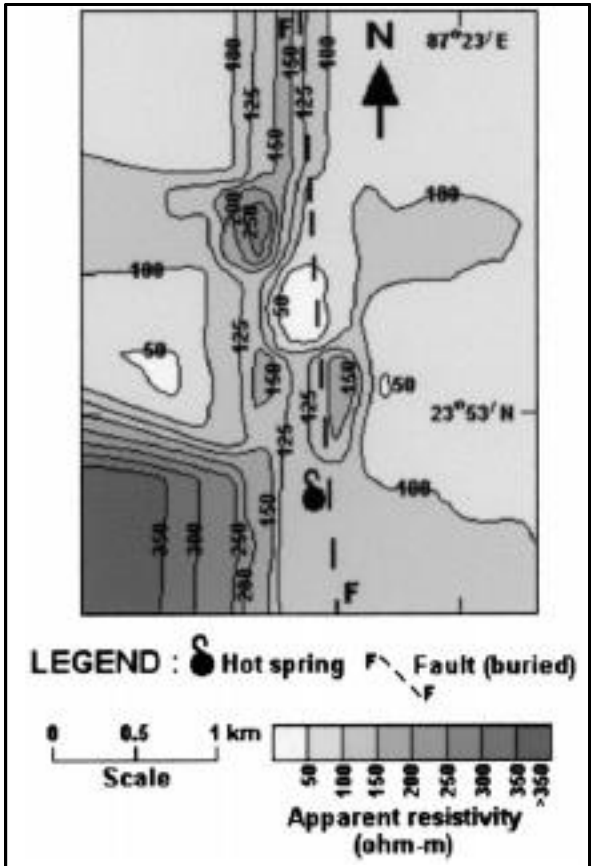


**Fig.:** Apparent resistivity contours for five Wenner profiles array spacings30 m. Contour values are in ohm-meter.

**Results:**

Vertical electrical sounding (VES) & profiling resistivity were carried out in and around Bakreswar by Majumdar et al. (2000), and the presence of a nearly N-S striking buried fault allowing passage for hot water to emerge in the form of springs (35-88$^0$C) was identified

[Majumdar et al, 200, JAG]

Case Study: V

# Integrated geophysical investigation to map shallow surface alteration/ fracture zones of Atri and Tarabalo hot springs, Odisha, India

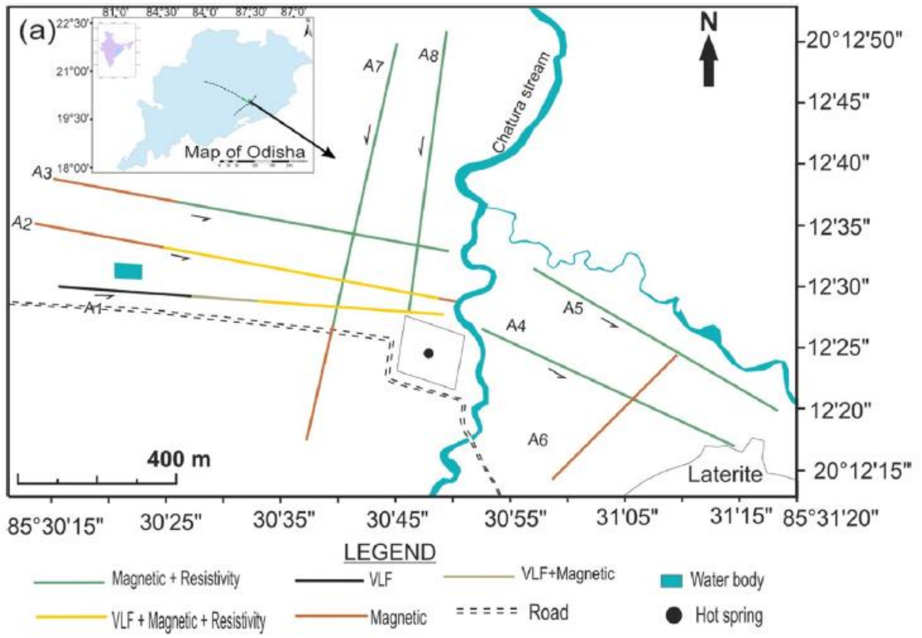


**Fig.:** Study area map showing the geophysical survey locations at **Atri hot spring**

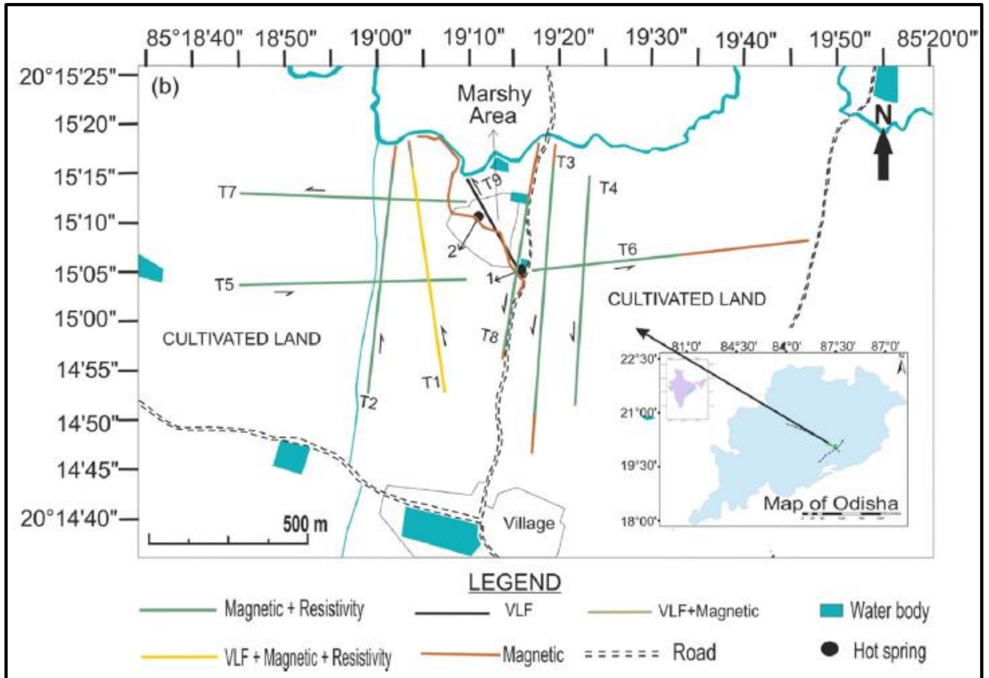


**Fig.:** Study area map showing the geophysical survey locations at **Tarabalo hot spring**

## Investigations:

An integrated geophysical study consisting of magnetic, very low frequency (VLF) electromagnetic and electrical resistivity tomography (ERT) surveys has been carried out in the vicinity of hot springs at Atri and Tarabalo in central Odisha, India.

## Objectives:

The study aims to delineate near-surface structural settings of these regions (e.g., faults, fracture network etc.) that controls the flow of geothermal fluids.

[Mandal et al. (2019), Geothermics]

Case Study: V

# Integrated geophysical investigation to map shallow surface alteration/ fracture zones of Atri and Tarabalo hot springs, Odisha, India

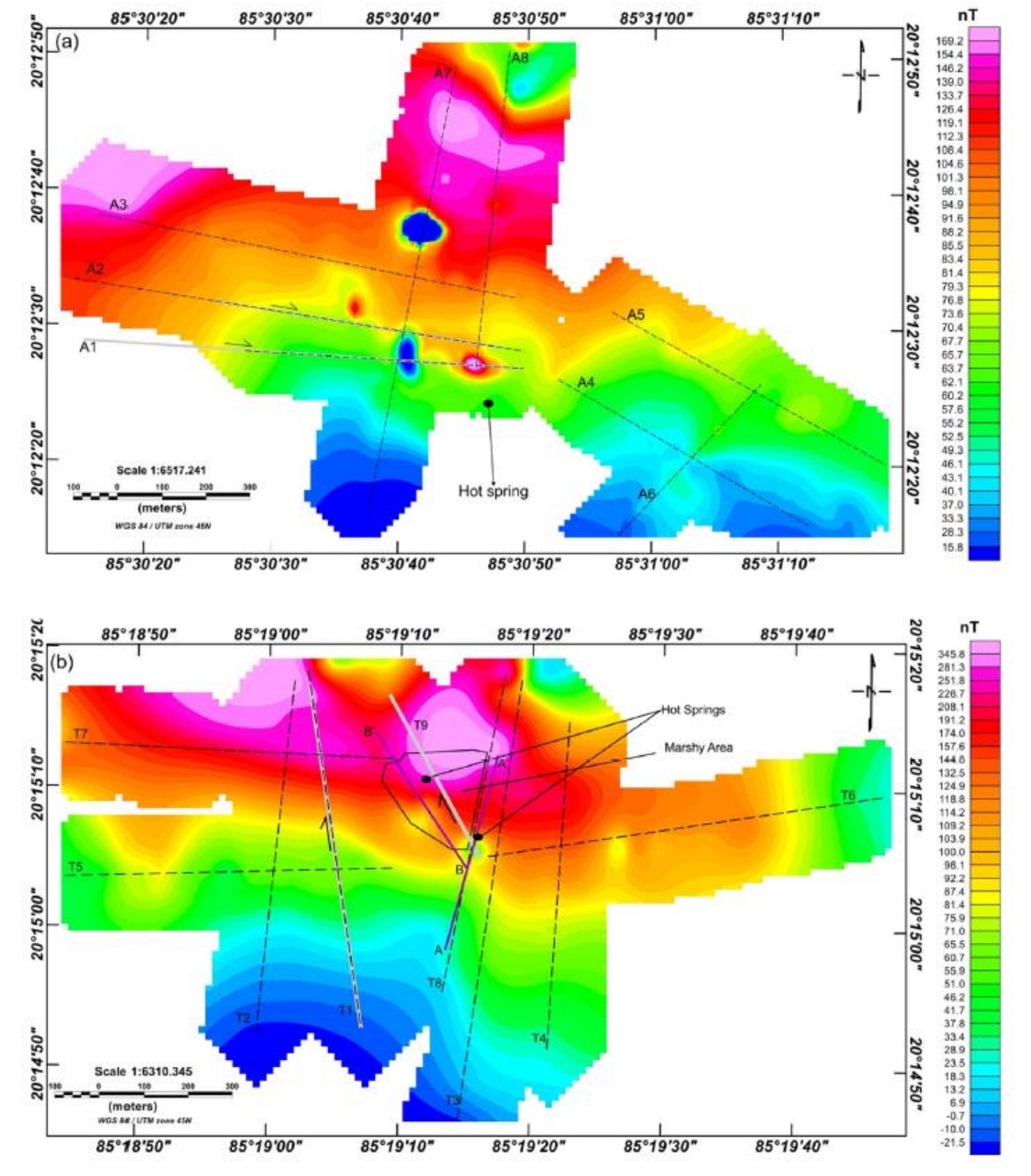


**Fig.:** Total field magnetic anomaly maps of the study area, (a) Atri, and (b) Tarabalo

**Results:**

Processed magnetic data shows distinct low anomaly as well as high-low transition zone near the hot springs and high anomaly away from the hot springs of both the regions.

*[Mandal et al. (2019), Geothermics]*

Case Study: V

# Integrated geophysical investigation to map shallow surface alteration/ fracture zones of Atri and Tarabalo hot springs, Odisha, India

Measurements along EW profiles were carried out at a frequency of 17.1kHz corresponding to the transmitter at Moscow (UMS) (T-VLF User's manual, 2006) located in a northerly direction (i.e., along the NS strike direction of Atri) from the study area.

Further, along NS profiles the data were acquired at a frequency of 22.3kHz using the transmitter in Australia (NWC) (T-VLF User's manual, 2006) located in an easterly direction (i.e., along the EW strike direction of Tarabalo) from the study area

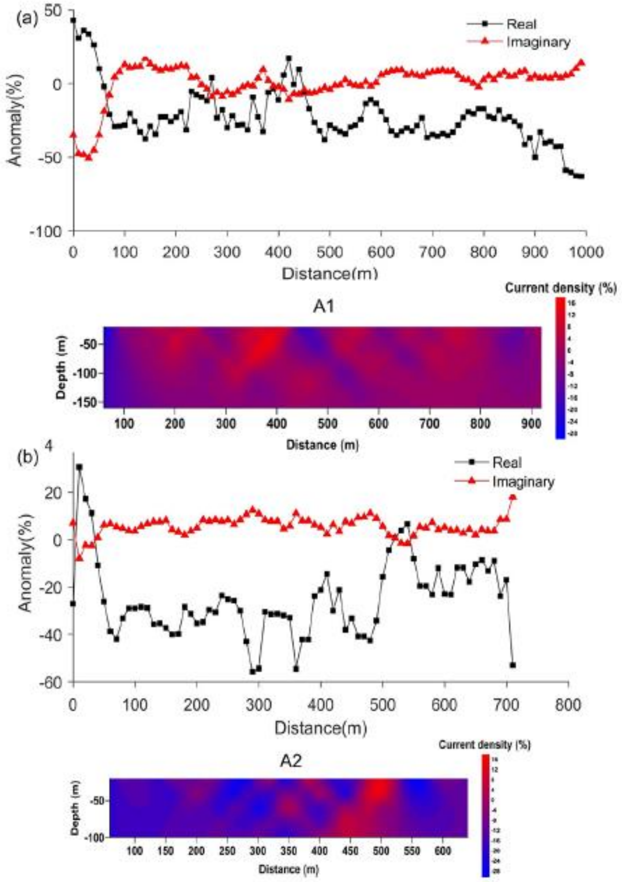


**Fig.:** Current density sections (lower panel) as computed from the VLF real anomaly (upper panel), (a) along profile A1, (b) along profile A2 of Atri region

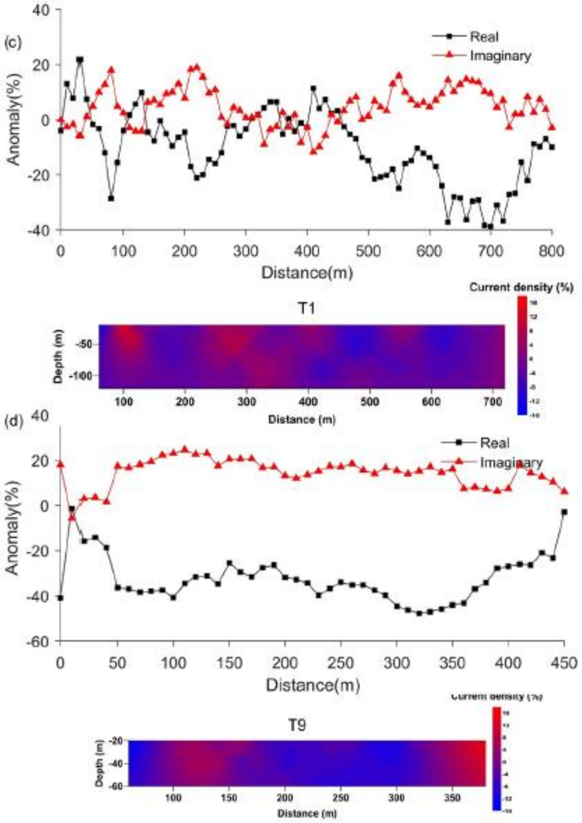


**Fig.:** Current density sections (lower panel) as computed from the VLF real anomaly (upper panel), (c) along profile T1, (d) along profile T9 of Tarabalo region

**Results:**
VLF current density sections along the selected profiles reveal existence of conductive fractures near to the hot springs of both the areas.

[Mandal et al. (2019), Geothermics]

Case Study: V

# Integrated geophysical investigation to map shallow surface alteration/ fracture zones of Atri and Tarabalo hot springs, Odisha, India

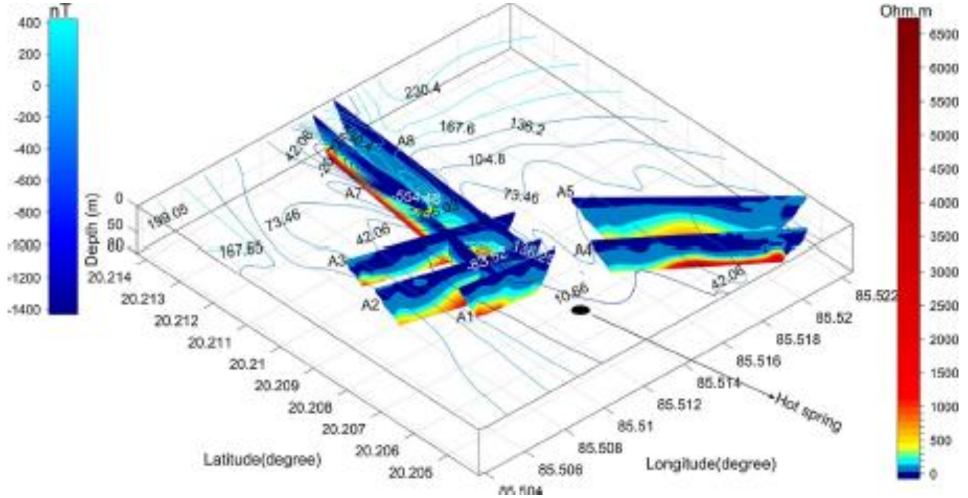


**Fig.:** 2-D resistivity inverse models along profiles A1 to A5, A7 and A8 of Atri region overlaid by magnetic contours. Depicted the gradual decreasing trend of subsurface resistivity and a magnetic low (15–30 nT) towards the Atri hot spring (region between profiles A4 and A1).

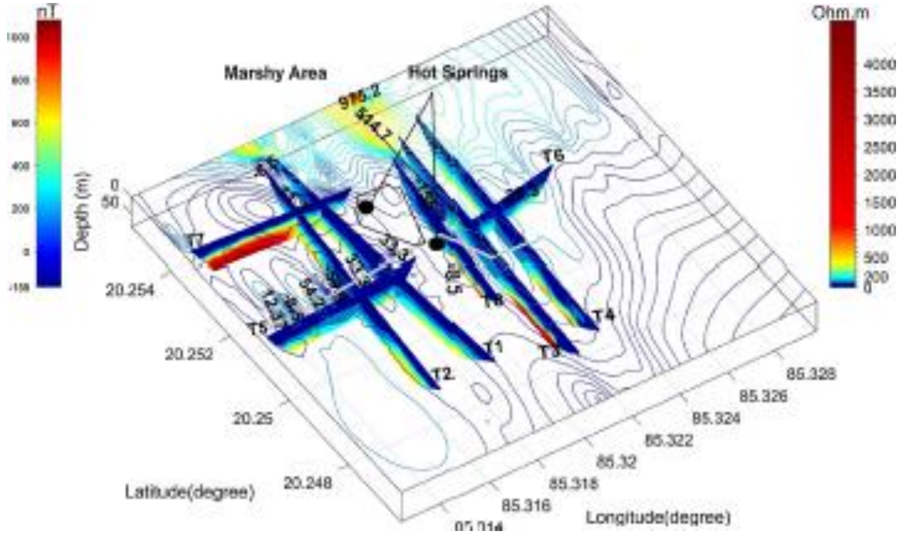


**Fig.:** 2-D resistivity inverse models along profiles T1 to T8 of Tarabalo region overlaid by magnetic contours. A low resistive EW channel passing through the marshy area with low magnetic zone is depicted in the subsurface of the region between profiles T2 -T4 and marked with a grey line

**Results:**

- Coincidence of low magnetic anomalies, and low resistivity (or high current density) values at same location indicate the existence of alteration/fracture zones.
- Resistivity models at Tarabalo depict a low resistive (~75-100 Ohm.m) dipping faulted/fractured zone extending beyond a depth of 80 m.
- VLF depth sections and reduced to pole magnetic anomaly maps also reveal high current density and low magnetic signatures, respectively in this zone.
- This fracture zone is extending about 600 m in EW direction with the marshy area at the center and may have acted as a conduit for the warm water movement from depth to surface.
- Indication of faulted/fractured zones around the Atri hot spring are also there but the inferences are not as conclusive as that of Tarabalo area due to the nearby power line hindrances.

Thus, the study provides a cost effective approach to delineate near surface fracture zones as well as helps to understand the thermal fluid flow mechanism of the hot springs.

*[Mandal et al. (2019), Geothermics]*

# Summary

It is summarised that a few geophysical methods could be used for the exploration of Spring Water Pathways. They are such as

- ☐ Magnetic
- ☐ Seismic
- ☐ Ground Penetration Radar (GPR)
- ☐ Self-Potential (SP)
- ☐ Vertical Electrical Sounding & Profiling
- ☐ Electrical Resistivity Tomography (ERT)
- ☐ Very Low Frequency (VLF), etc.

- ➢ But No competition
- ➢ Only cooperation
- ➢ No winner – no loser, and
- ➢ The ultimate judge is the driller of Spring Water!

Then only proceed for the Spring Water Flow Path-ways in India!

# THANKS
# FOR YOUR PATIENCE