Geophysical Techniques in Ground Water Exploration

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What is geophysics?

- Geophysics is the measurement of physical properties at or above the ground surface to reveal hidden subsurface structure.

- There are two broad divisions:
  - Exploration geophysics
  - Global geophysics

- **Advantages of geophysics**
  - Rapid and cheap survey tool
  - Easily integrated with other forms of ground survey
  - Non-destructive (archaeology, habitats, urban areas generally)
  - Modern processing methods give a visual image of the subsurface

- **Disadvantages of geophysics**
  - Can be ambiguous without controls
  - Poor discrimination in some cases
  - Can suffer from noise or artefacts

- Exploration geophysics involves collecting data according to a defined survey pattern. This may be along a line, around a polygon or over an area.
- The type of data is determined by the purpose of the survey and by the expected underground structure.

- Typical data are:
  - Arrival times of seismic waves
  - Arrival times of high-frequency electrical signals
  - Variations in the local magnetic field
  - Variations in local ground resistance

physical properties

– Elastic wave velocity (elasticity, density) = Seismic methods
– Electric pulse velocity (dielectric constant) = Georadar (GPR)
– Electrical DC resistance (resistivity) = DC resistivity methods
– Electrical AC conductivity = EM conductivity methods
– Magnetic field strength (susceptibility) = Magnetic methods
– Gravity field strength (density) = Gravity methods

Choice of method

- Factors
  - What type and shape of feature is being imaged?
  - Is an area or line survey the better?
  - What physical properties will show the best contrast?
  - Are there any strong but irrelevant contrasts that will mask the results?
  - To what depth must the survey penetrate?
  - What spatial resolution is needed?
  - What are the time or cost constraints?
  - Are there any special restrictions eg on access or damage?

Active and passive methods

- Geophysical methods are subdivided into **active** or **passive** methods, depending on whether or not the instrument puts energy into the ground.

- **Active methods:**
  - Seismic
  - Electrical resistivity
  - Ground penetrating radar

- **Passive methods**
  - Gravity
  - Magnetics

Active and passive methods

- **Active methods have the advantage of potentially greater penetration or resolution.**

- **In an active method the user can control the penetration vs resolution by adjusting the power input.**

Active and passive methods

- Passive methods have the advantage of being totally non-destructive and requiring less equipment.

- Passive methods are often based on anomalies in the strength of a potential field (eg magnetics). The results are always inherently ambiguous.

Contacting and non-contacting methods

- **Geophysical methods are further subdivided into contacting or non-contacting methods, depending on whether or not the source or receiver is actually in contact with the ground.**

- **Contacting methods:**
  - **Seismic**
  - **Electrical resistivity**

- Non-contacting methods
  - Gravity
  - Magnetics
  - Ground penetrating radar
  - EM conductance methods

Electrical methods divide into the following:

1- Passive Techniques.
2- Active Techniques.

1- DC Resistivity - This is an active method that employs measurements of electrical potential associated with subsurface electrical current flow generated by a DC.

2-**Induced Polarization (IP)** - This is an active method that is commonly done in conjunction with DC Resistivity.

3- **Self Potential (SP)** - This is a passive method that employs measurements of naturally occurring electrical potentials commonly associated with the weathering of sulfide ore bodies.

4- **Electromagnetic (EM)** - This is an active method that employs measurements of a time-varying magnetic field generated by induction through current flow within the earth.

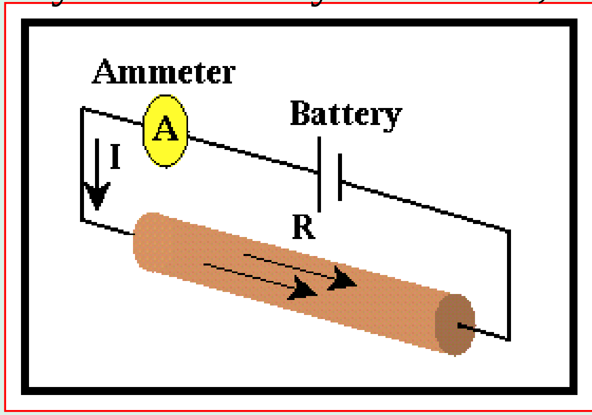
5- **Magnetotelluric (MT)** - This is a passive method that employs measurements of naturally occurring electrical currents, or telluric currents, generated by magnetic induction of electrical currents in the ionosphere.

It's Resistivity, not Resistance

The problem with using resistance as a measurement is that it depends not only on the material out of which the wire is made, but also the geometry of the wire. If we were to increase the length of wire, for example, the measured resistance would increase. Also, if we were to decrease the diameter of the wire, the measured resistance would increase. We want to define a property that describes a material's ability to transmit electrical current that is independent of the geometrical factors.

The quantity that is used is called *resistivity* and is usually indicated by the Greek symbol rho*,**.

ρ



In the case of the wire, resistivity is defined as the resistance in the wire, multiplied by the cross-sectional area of the wire, divided by the length of the wire.

The units associated with resistivity are thus **ohm.m**

Resistivity is a fundamental parameter of the material making up the wire that describes how easily the wire can transmit an electrical current. High values of resistivity imply that the material making up the wire is very resistant to the flow of electricity. Low values of resistivity imply that the material making up the wire transmits electrical current very easily.

Electrical Resistivity

1- Fundamentals

The electrical resistivity method is used to map the subsurface electrical resistivity structure, which is interpreted by the geophysicist to determine geologic structure and/or physical properties of the geologic materials. The electrical resistivity of a geologic unit or target is measured in ohmmeters, and is a function of porosity, permeability, water saturation and the concentration of dissolved solids in pore fluids within the subsurface.

The purpose of a DC electrical survey is to determine the subsurface resistivity distribution of the ground, which can then be related to physical conditions of interest such as lithology, porosity, the degree of water saturation, and the presence or absence of voids in the rock. The basic parameter of a DC electrical measurement is resistivity. Resistivity is not to be confused with resistance.

2- Advantages

A principal advantage of the electrical resistivity method is that quantitative modeling is possible using either computer software or published master curves. The resulting models can provide accurate estimates of depth, thickness and electrical resistivity of subsurface layers.

The layered electrical resistivities can then be used to estimate the electrical resistivity of the saturating fluid, which is related to the total concentration of dissolved solids in the fluid.

3- Limitations

Limitations of using the electrical resistivity method in ground water pollution investigations are largely due to site characteristics, rather than in any inherent limitations of the method. Typically, sites are located in industrial areas that contain an abundance of broad-spectrum electrical noise.

In conducting an electrical resistivity survey, the voltages are relayed to the receiver over long wires that are grounded at each end. These wires act as an antenna receiving the radiated electrical noise that in turn degrades the quality of the measured voltages.

Electrical resistivity surveys require a fairly large area, far removed from power lines and grounded metallic structures such as metal fences, pipelines and railroad tracks. This requirement precludes using this technique at many ground water pollution sites. However, the electrical resistivity method can often be used successfully off-site to map the stratigraphy of the area surrounding the site. A general “rule of thumb” for electrical resistivity surveying is that grounded structures be at least half of the maximum electrode spacing away from the axis of the electrode array. Electrode spacing and geometry or arrays (Schlumberger, Wenner, and Dipole-dipole) are discussed in detail in the section below entitled, *Survey Design*, *Procedure*, *and Quality Assurance*.

Another consideration in the electrical resistivity method is that the fieldwork tends to be more labor intensive than some other geophysical techniques. A minimum of three crewmembers is required for the fieldwork.

4- Instrumentation

Electrical resistivity instrumentation systems basically consist of a transmitter and receiver. The transmitter supplies a low frequency (typically 0.125 to 1 cycles/second or “Hertz”) current waveform that is applied across the current electrodes. Either batteries or an external generator, depending on power requirements can supply power for the transmitter. In most cases, the power requirements for most commonly used electrode arrays, such as Schlumberger (pronounced “schlum-bur-zhay”) and Wenner arrays are minimal and power supplied by a battery pack is sufficient. Other electrode configurations, such as Dipole-dipole arrays, generally require more power, often necessitating the use of a power generator. The sophistication of receivers range from simple analog voltmeters to microcomputer-controlled systems that provide signal enhancement, stacking, and digital data storage capabilities. Most systems have digital storage of data. Some systems may require the field parameters to be input via PC (personal computer) prior to collection of the data. The trend in manufacturers of resistivity equipment is to have the entire system controlled form a PC or preprogrammed software built into the instrument.

Fig (1) SYSCAL Jr Switch-72 resistivity meter

Electrical resistivity methods:

•Resistivity measurements are made by passing an electrical current into the ground using a pair of electrodes and measuring the resulting potential gradient within the subsurface using a second electrode pair (normally located between the current electrodes). Resistivity sounding involves gradually increasing the spacing between the current/potential electrodes (or both) in order to increase the depth of investigation. The data collected in this way are converted to apparent resistivity readings that can then be modelled in order to provide information on the thickness of individual resistivity units within the subsurface.

•The electrical resistivity method is one of the most useful techniques in groundwater hydrology exploration because the resistivity of a rock is very sensitive to its water content. In turn, the resistivity of water is very sensitive to its ionic content.

• In general, it is able to map different stratigraphic units in a geologic section as long as the units have a resistivity contrast. Often this is connected to rock porosity and fraction of water saturation of the pore spaces.

Applications:

1. Water table depth.
2. Groundwater quality
3. Brine plumes.
4. Seawater intrusion
5. Well sitting.
6. Aquifer exploration
7. General stratigraphic mapping

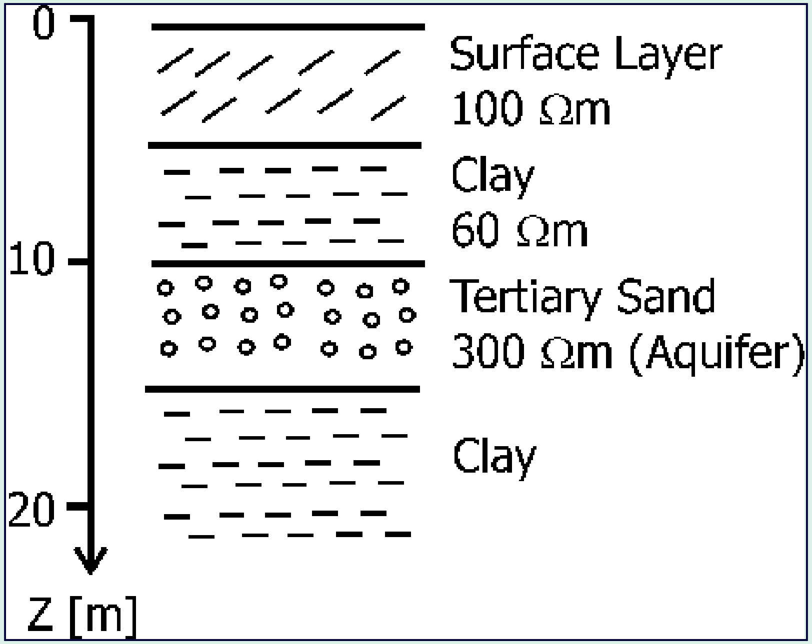
Advantages:

1. Less costly than drilling.
2. Non disturbing.

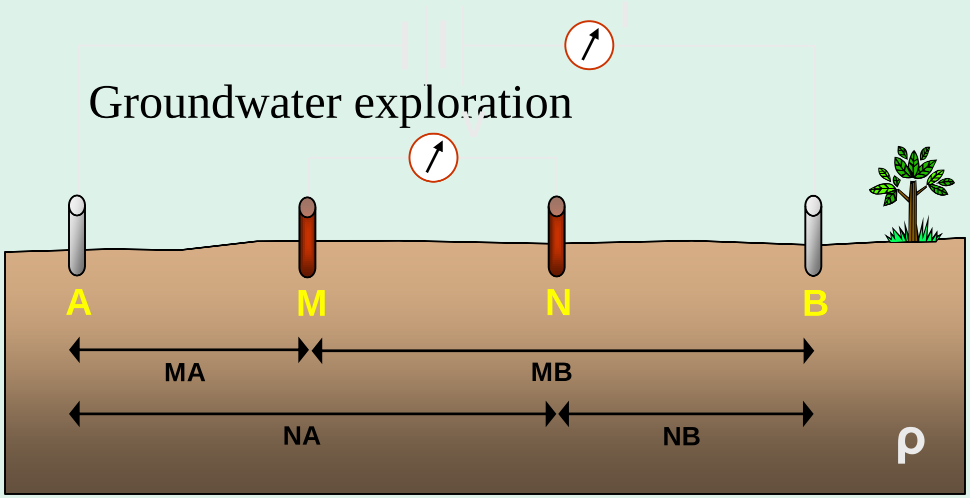
Disadvantages:

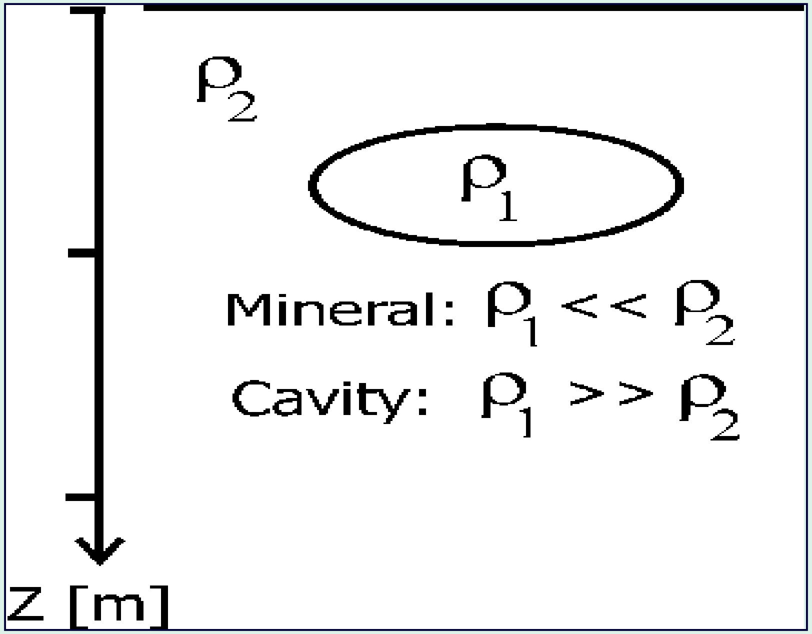
1. Cultural problems cause interference, e.g., power lines, pipelines, buried casings, fences .
2. Resolution.

Possible applications of resistivity surveying

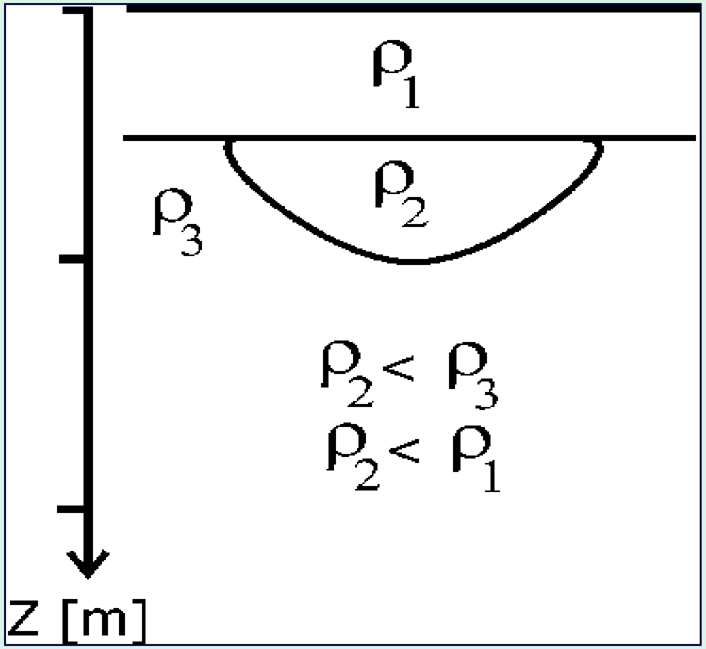


Groundwater exploration

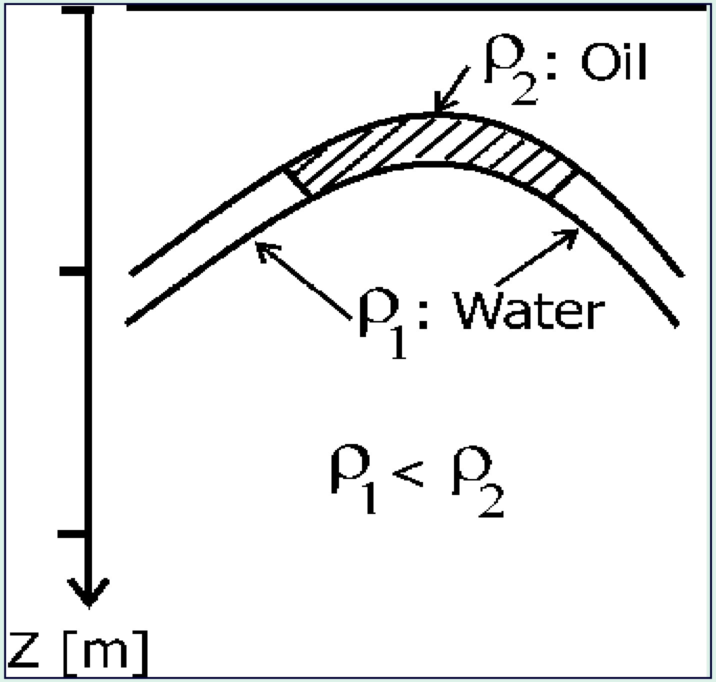




Mineral exploration, detection of cavities



Waste site exploration



Oil exploration

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:

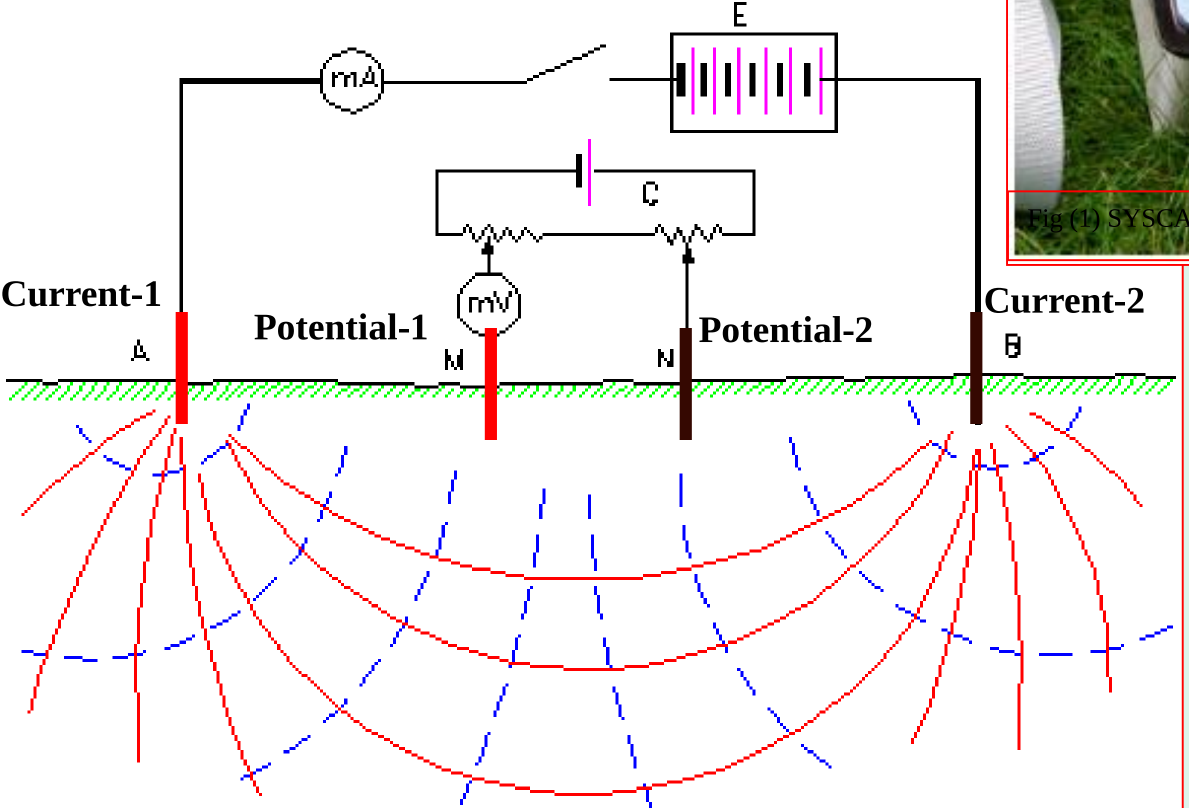
1- Energy source, (Battery).

2- Resistivity meter.

3- Two potential electrodes.

4- Two current electrodes.

Fig (1) SYSCAL Jr Switch-72 resistivity meter

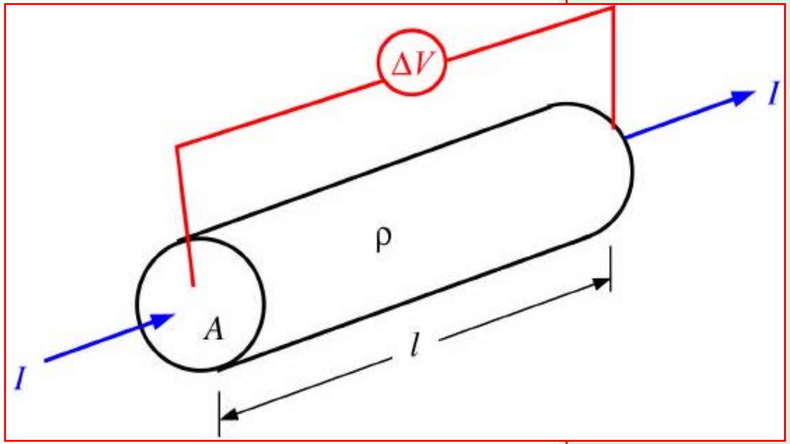


Electrical Resistivity - Conductivity

Ohm's Law

Empirical relationship between the current (*I*) flowing through a wire, of resistance R and the voltage potential (*V*) required to propagate the current.

$$V \alpha I \rightarrow V = IR$$



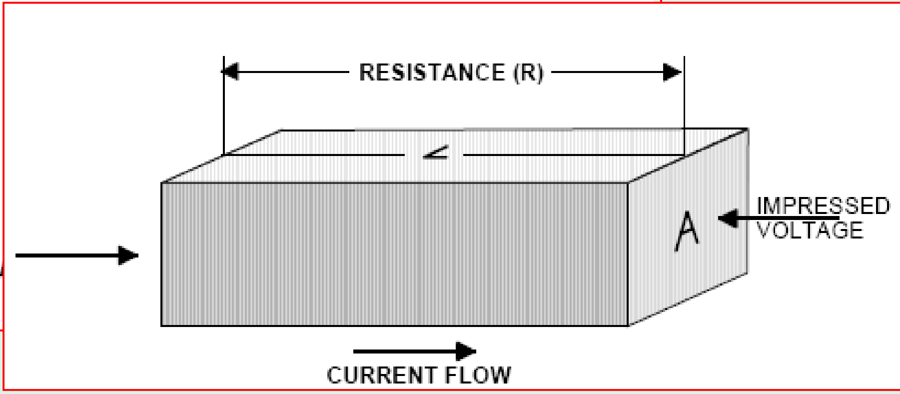
Further

$$R \propto \frac{L}{A}$$

where *L* is the length and *A* the cross sectional area of wire.

However, as we are not concerned with wires in the Earth, and electrical current is not constrained, the *resistivity, ρ* of a material is a more useful concept where.

$$\rho = \frac{RA}{L} \quad \text{or} \quad \rho = \frac{VA}{IL}$$



Theory

In a homogeneous earth, current flows radially outward from the source to dfine a hemispherical surface. The current distribution is equal everywhere on this surface which is also called an equipotential surface. Starting with Ohm's law (*V* = *IR*) and defining the resistance *R* in terms of the resistivity and the area of the shell (equipotential surface), the potential difference across the shell is

$$dV = i(R) = I\left(\rho\,\frac{L}{A}\right) = I\left(\rho\,\frac{dr}{2\pi r^2}\right)$$

where *V* is the voltage (or electrical potential), *I* is the current, is the resistivity, and *r* is the radius of the equipotential surface. Integrating the above equation and setting the potential at infinity to zero, the electric potential at a distance *R* from the source is given by:

$$V = \frac{\rho\, I}{2\pi\, R}$$

Resistivity has units of *ohm m* and is not to be confused with *resistance* which has units of *ohms*. The *resistivity* of a material is defined as = *RA L* where *R* is the resistance of the material, *A* is the cross-sectional area through which current flows and $\rho = \frac{RA}{L}$ length on the material.

The potential has been derived due to a single current source. The goal in resistivity surveying is to measure the potential different between two points due to the current from two current electrodes. The potential at each electrode is determined due to the current sources:

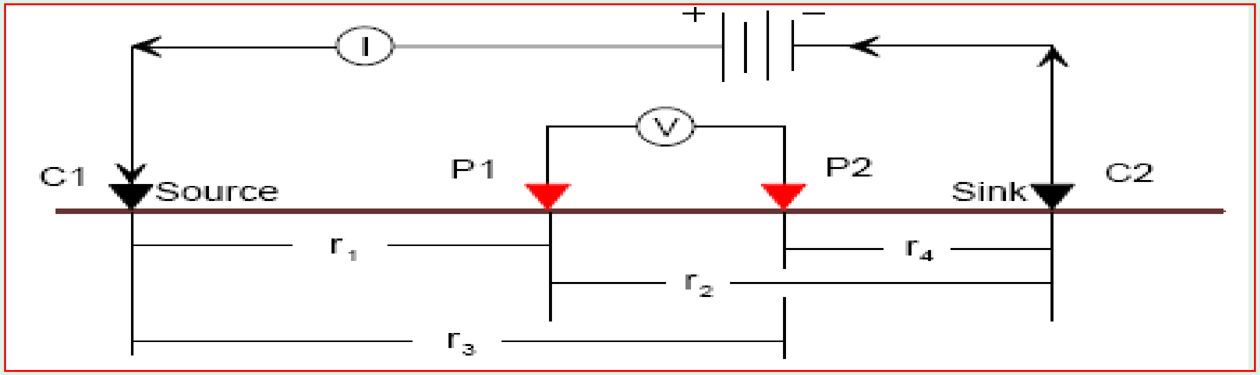
$$V_{P1} = \frac{I\rho}{2\pi r_1} - \frac{I\rho}{2\pi r_2}$$

$$V_{P2} = \frac{I\rho}{2\pi r_3} - \frac{I\rho}{2\pi r_4}$$

The potential difference $\Delta V = VP1 - VP2$ which simplifies to :

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

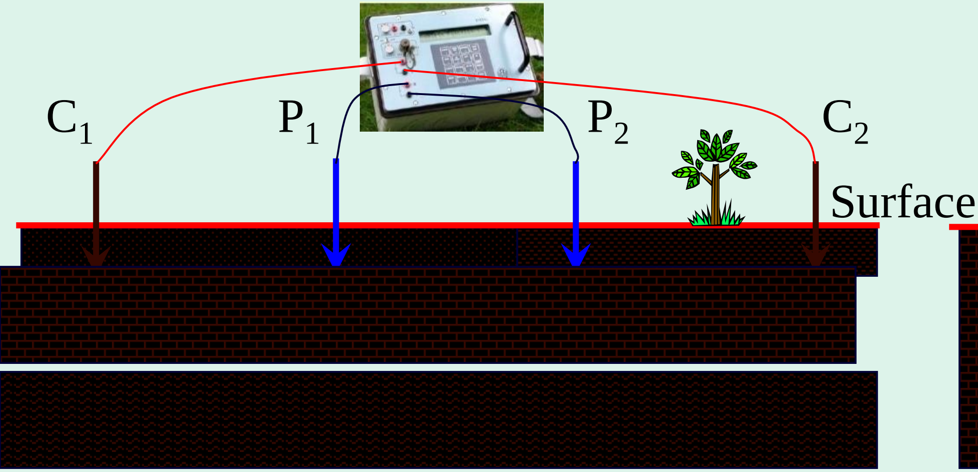
The above equation can then be solved for the resistivity . In a nonhomogeneous earth, the resistivity which is measured is not actually the true resistivity of the subsurface. For an earth with more than one layer, the *apparent resistivity* measured will be an average of the resistivities of the additional layers. The apparent resistivity data needs to be interpreted in terms of a subsurface model in order to determine the actual resistivities of the layers.



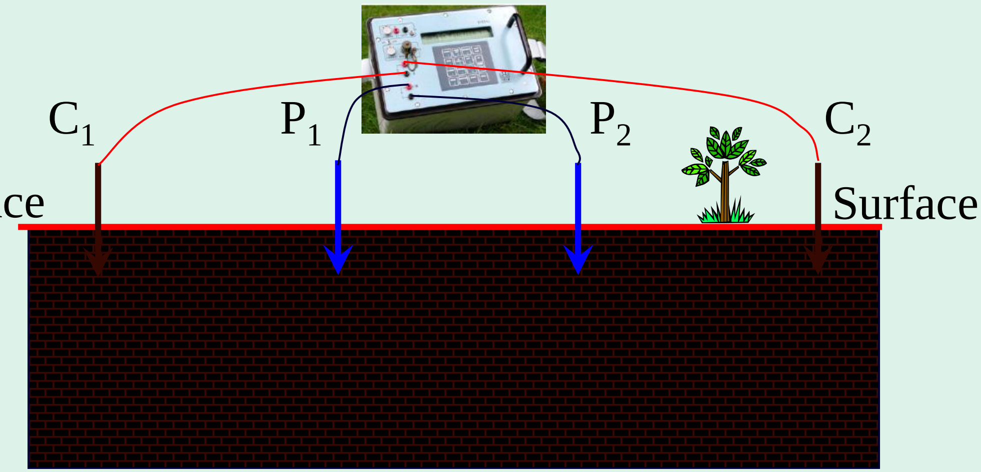
Apparent Resistivity

If the resistivity in the ground is uniform, then the measured resistivity will be constant and independent of electrode spacing and surface location. If the resistivity in the ground is inhomogeneous, then the measured resistivity will vary with relative and absolute location of the electrodes. In this case, the measured resistivity is an ***apparent resistivity***, ρa, which depends on the shape and size of anomalous regions, layering and relative values of resistivities in these regions.

The apparent resistivity is similar to the equivalent resistivity of a circuit with resistors in parallel and series. In order to figure out how many resistors there are in the circuit and their individual resistivity, you would need to interrupt the circuit at various locations and measure the voltage. With several measurements you may be able to isolate the particular circuitry. Similarly, in the earth, by changing the relative spacing and location of the potential electrodes you can unravel where the resistors are below the surface.

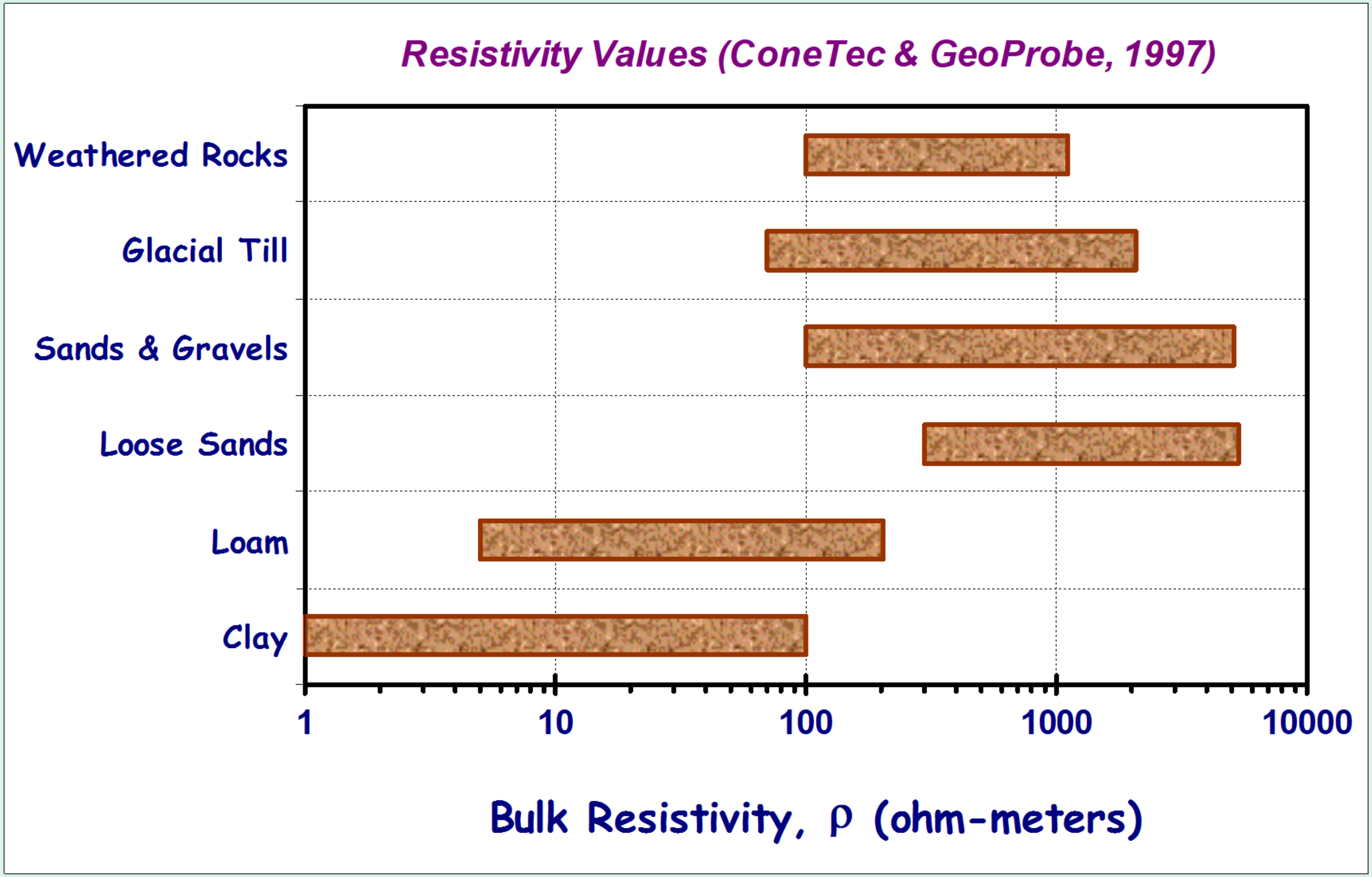


The reading represent apparent resistivity



The reading represent True resistivity

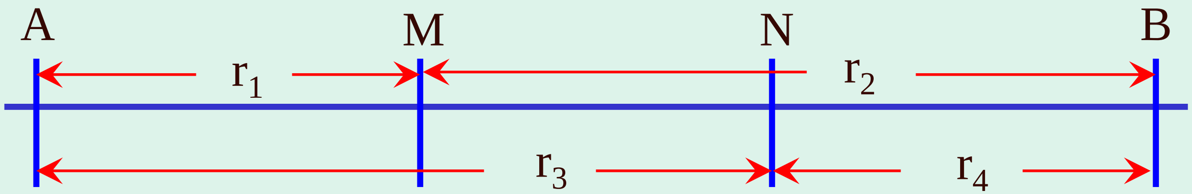
Electrical Resisitivity Measurements



Calculation of Apparent Resistivity :The most common problem encountered in resistivity sounding work is high contact resistances at the current electrodes. Whilst this does not directly affect the measured value of resistance, high contact resistances (>2kOhms) will reduce the maximum current that can be applied with the output voltage available from the meter (typically 300-400V). In order to overcome high resistances electrodes can be watered with a saturated salt solution or placed in hole filled with bentonite or clay slurry.

A, B : Are current electrodes

A, B : Are potential electrodes



After introducing current , the potential calculate by:

$$v = \frac{I\rho}{2\pi x}$$

The total potential at M and N are V_M and V_N

The potential at M calculate by:

$$v_M = v_{r1} - v_{r2}$$

$$v_{r1} = \frac{I\rho}{2\pi r_1}, v_{r2} = \frac{I\rho}{2\pi r_2}$$

$$\therefore v_M = \frac{I\rho}{2\pi r_1} - \frac{I\rho}{2\pi r_2} = \frac{I\rho}{2\pi}(\frac{1}{r_1} - \frac{1}{r_2})$$

By the same way the potential at N calculate by:

$$v_N = v_{r3} - v_{r4}$$

$$v_{r3} = \frac{I\rho}{2\pi r_3}, v_{r4} = \frac{I\rho}{2\pi r_4}$$

$$\therefore v_N = \frac{I\rho}{2\pi r_3} - \frac{I\rho}{2\pi r_4} = \frac{I\rho}{2\pi}\left(\frac{1}{r_3} - \frac{1}{r_4}\right)$$

Then the potential difference between M and N calculate by:

$$v = v_M - v_N$$

$$\therefore v = \frac{I\rho}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\right)$$

$$\rho_a = \frac{2\pi v}{I}\left\{\frac{1}{\frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}}\right\}$$

$$\rho_a : is\ \ apparent\ \ resistivity$$

In homogenous area

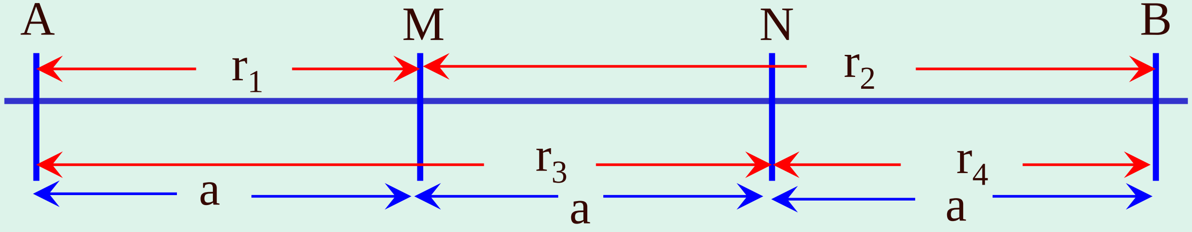
$$\rho_a = \rho_{true}$$

$$The\, quantity \frac{1}{r_1} - \frac{1}{r_2} - \frac{1}{r_3} + \frac{1}{r_4}\ \ is\, called\ Geometrical\ Factor\, (G)$$

$$\therefore \rho_a = 2\pi\ \ .\frac{V}{I}.G$$

<u>Apparent resistivity for Wenner spread:</u>

The distances between electrodes are constant , equal to (a)



$$AM = MN = BN$$

$$r_1 = r_4 = a$$

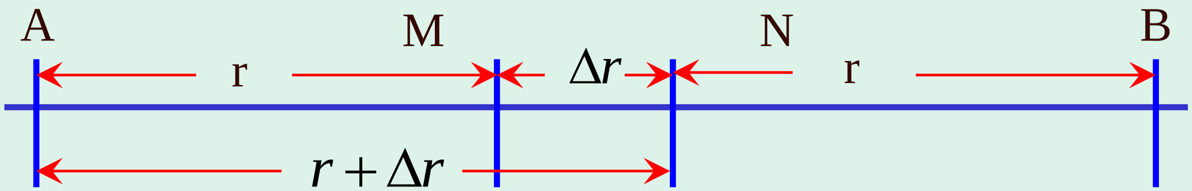
$$r_2 = r_3 = 2a$$

$$\therefore \rho_a = 2\pi \frac{v}{I}\left\{\frac{1}{\frac{1}{a}-\frac{1}{2a}-\frac{1}{2a}+\frac{1}{a}}\right\}$$

$$\rho_a = 2\pi \frac{v}{I} \,.\, a \quad or \; \rho_a = 2\pi R \,.\, a$$

<u>Apparent resistivity for Schlumberger spread:</u>

The distances between potential electrodes are too small compared to the current electrodes.



$$r_1 = r_4 = r$$

$$r_2 = r_3 = r + \Delta r$$

$$\rho_a = 2\pi.\frac{v}{I}\left\{\frac{1}{\frac{1}{r} - \frac{1}{r+\Delta r} - \frac{1}{r+\Delta r} + \frac{1}{r}}\right\}$$

$$\rho_a = 2\pi.\frac{v}{I}\left\{\frac{1}{\frac{2}{r} - \frac{2}{r+\Delta r}}\right\}$$

$$\rho_a = 2\pi.\frac{v}{I}.2\left\{\frac{1}{\frac{r+\Delta r - r}{2r(r+\Delta r)}}\right\} \quad \ldots.\Delta r \approx zero \quad so$$

$$\rho_a = \pi.\frac{v}{I}.\left\{\frac{1}{\frac{\Delta r}{r^2}}\right\} = \pi.\frac{v}{I}.\left\{\frac{r^2}{\Delta r}\right\}$$

$$\rho_a = \pi.R.\frac{AM^2}{MN}$$

Exploration of groundwater

Objective:

to locate aquifers capable of yielding water of **suitable quality**, in economic **quantities**, for *drinking*, *irrigation*, *agricultural and industrial purposes*, by employing, as required, geological, geophysical, drilling and other techniques.

Assessments of ground water resources range in scope and complexity from simple, qualitative, and relatively inexpensive approaches to rigorous, quantitative, and costly assessments.

Tradeoffs must be carefully considered among the competing influences of the cost of an assessment, the scientific defensibility, and the amount of acceptable uncertainty in meeting the objectives of the water-resource decision maker.

Exploration of Groundwater

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

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 4: Suitability of geophysical methods in different hydrogeological environments

Hydrogeological environment	*Electrical resistivity*		*Seismic refraction*	*Electro-magnetics*
	Sounding	*Profiling*		
Major Alluvial Formations	++	+	+	o
Consolidated Sedimentary Aquifers	+	+	+	o
Volcanic Formations	+	+	o	+
Weathered Crystalline Basement (regolith)	++	+	++	+
Weathered Crystalline Basement (fractured bedrock)	+	++	++	++
Fresh/Salt Water Interfaces	++	+	o	+

++ very suitable
+ suitable
o not suitable
Note: This gives a general overview of the more commonly used techniques.
Source: Van Dongen and Woodhouse, 1994.

Geologic Methods

- an important first step in any groundwater investigation

- involves collection, analysis and hydrogeologic interpretation of existing geologic data/maps, topographic maps, aerial photographs and other pertinent records.

- should be supplemented, when possible, by geologic field reconnaissance and by evaluation of available hydrologic data on stream flow and springs, well yields, groundwater recharge and discharge, groundwater levels and quality.

- nature and thickness of overlying beds as well as the dip of water bearing formations will enable estimates of drilling depths to be made.

Relationship between geology and groundwater

- **The type of rock formation will suggest the magnitude of water yield to be expected.**

- **it is the perviousness or permeability and not porosity which is significant in water yielding capacity of rocks.**

- **Igneous rocks have a porosity of 1% and may yield all water while some clays have a pososity as high as 50% but are practically impervious.**

- **Porosity = f (grainsize, shape, grading, sorting, amount and distribution of cementing materials)**

- **Permeability = f (interconnectedness, fissures, joints, bedding planes, faults, shear zones and cleavages, vesicles)**

alluvial aquifers : 90% of all developed Aquifers are alluvial aquifers, consisting of unconsolidated alluvial deposits, chiefly gravels and sands.

Limestone aquifer varies in density, porosity and permeability depending on degree of consolidation and development of permeable zones after deposition. Original rock materials offer important aquifers.

Volcanic rock can form highly permeable aquifers. Basalts form a good source of water; easily susceptible to weathering.

Sandstones are cemented forms of sands and gravels; yields are reduced by the cements. Some may form good aquifers depending on shape and arrangement of constituent particles and cementation and compaction.

Igneous and metamorphic rocks, in solid state, are relatively impermeable and hence serve as poor aquifers. Under weathered conditions, however, the presence of joints, fractures, cleavages and faults form good water bearing zones, and small wells may be developed in these zones for domestic water supply.

Selection of site for a well

Factors to be considered are:

(i) Topography: Valley regions are more favorable than the slopes and the top of the hillocks.

(ii) Climate (annual rainfall, sunlight intensity, max. temperature, humidity):

heavy to moderate rainfall -- more deep percolation – good aquifer.
Intense summer weather -- evaporates and depletes GW through direct evaporation from shallow depths and evapotranspiration through plants.

Selection of site for a well

(iii) Vegetation: **can flourish where GW is available at shallow depths.**

Phreatophytes, **plants that draw the required water directly from the zone of saturation indicate large storage of groundwater at shallow depths.**

Xerophytes, **plants that exist under arid conditions by absorbing the soil moisture (intermediate or vadose water), indicate the scarcity of groundwater at shallow depths.**

Selection of site for a well

(iv) Geology of the area: **thick soil or alluvium cover, highly weathered, fractured, jointed or sheared and porous rocks indicate good storage of groundwater, whereas massive igneous and metamorphic rocks or impermeable shales indicate paucity of groundwater.**

(v) Porosity, permeability: **highly porous, permeable zones of dense rocks encourage storage of groundwater. Massive rocks do not permit the water to sink.**

(vi) Joints and faults in rocks: **Wells sunk into rocks with interconnected joints, fractures, fissures and cracks yield copious supply of water.**

(vii) Proximity of rivers: **Streams and rivers serve as sources of recharge and water is stored in the pervious layers.**

Geophysical Methods

- Mechanical Wave Measurements
  - Crosshole Tests (CHT)
  - Downhole Tests (DHT)
  - Spectral Analysis of Surface Waves
  - Seismic Refraction
  - Suspension Logging
- Electromagnetic Wave Techniques
  - Ground Penetrating Radar (GPR)
  - Electromagnetic Conductivity (EM)
  - Surface Resistivity (SR)
  - Magnetometer Surveys (MT)

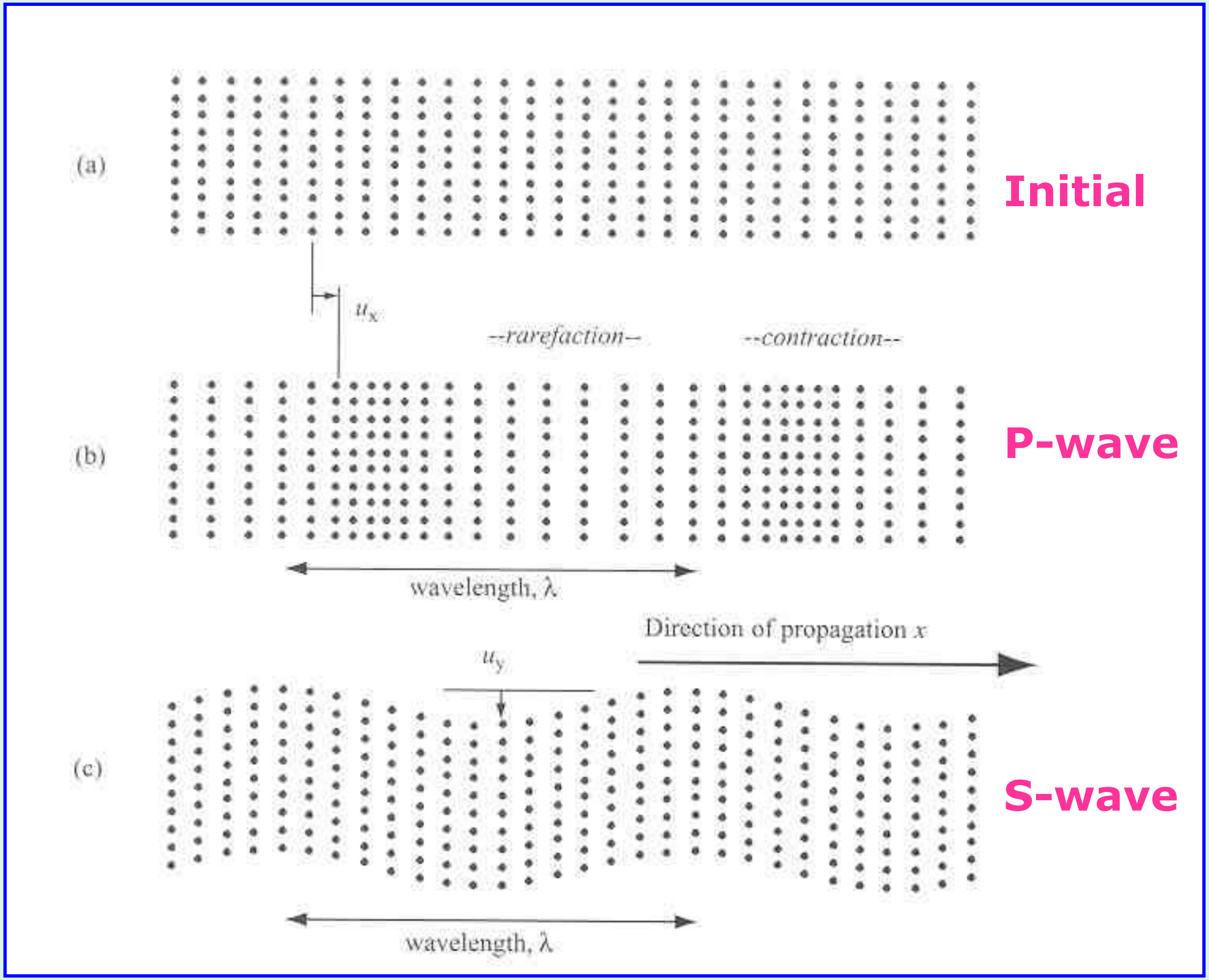
Mechanical Wave Geophysics

- Nondestructive measurements ($\gamma_s < 10^{-4}\%$)
- Both borehole geophysics and non-invasive types (conducted across surface).
- Measurements of wave dispersion: velocity, frequency, amplitude, attenuation.
- Determine layering, elastic properties, stiffness, damping, and inclusions
- Four basic wave types: Compression (P), Shear (S), Rayleigh (R), and Love (L).

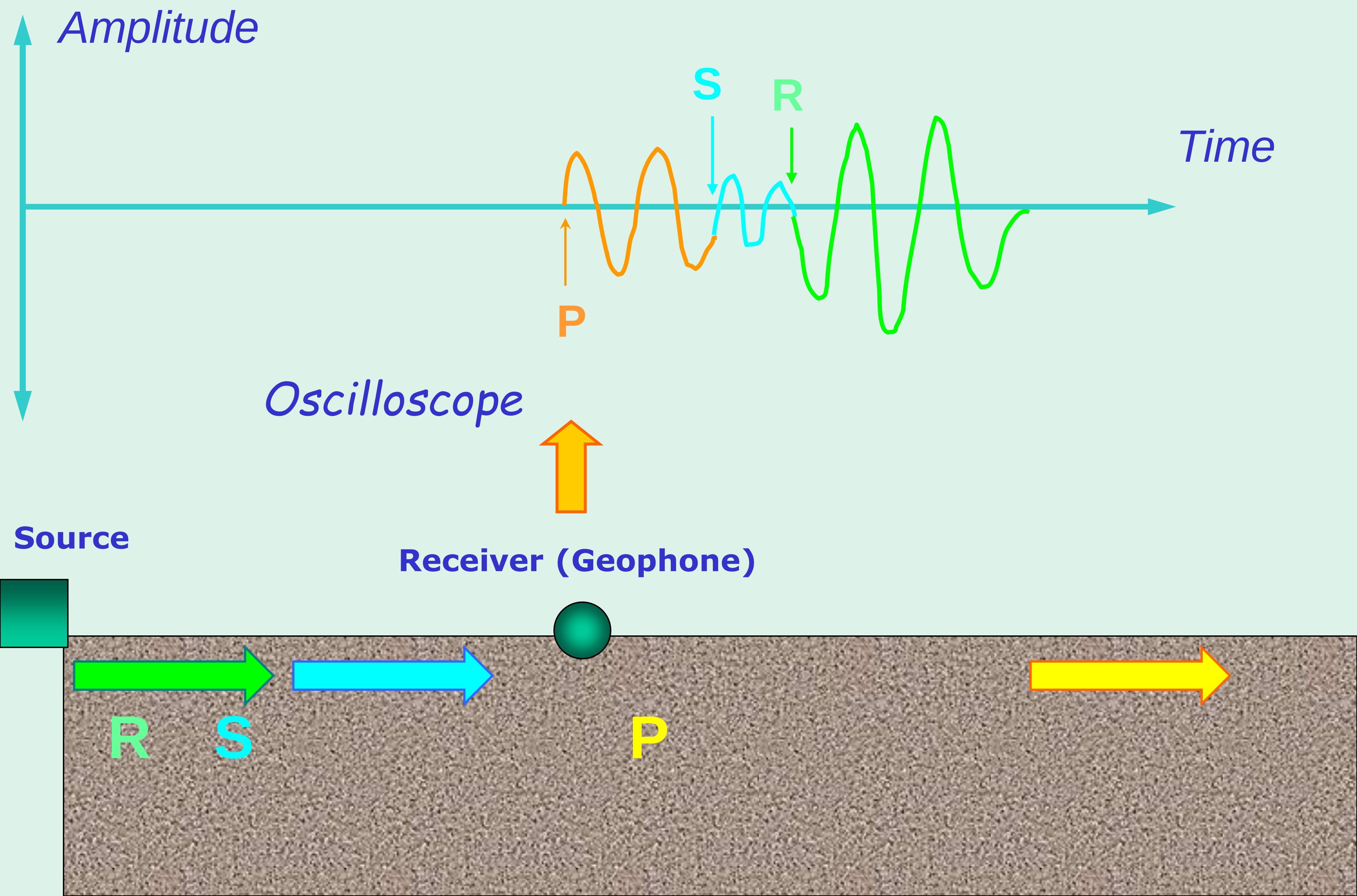
Mechanical Wave Geophysics

- Compression (P-) wave is fastest wave; easy to generate.
- Shear (S-) wave is second fastest wave. Is directional and polarized. Most fundamental wave to geotechnique.
- Rayleigh (R-) or surface wave is very close to S-wave velocity (90 to 94%). Hybrid P-S wave at ground surface boundary.
- Love (L-) wave: interface boundary effect

Mechanical Body Waves



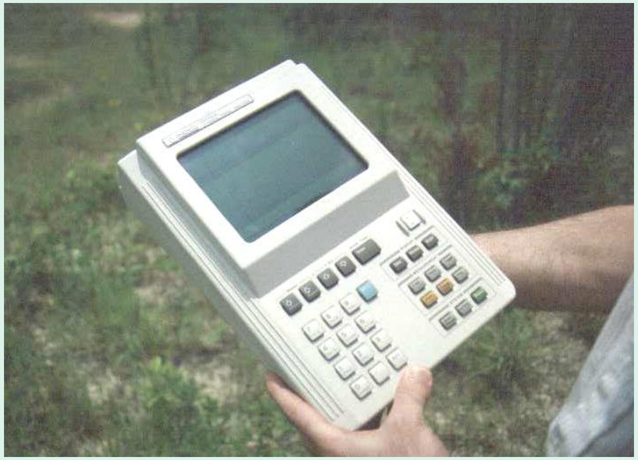
Mechanical Body Waves



Geophysical Equipment

Seismograph

Spectrum Analyzer



Portable Analyzer

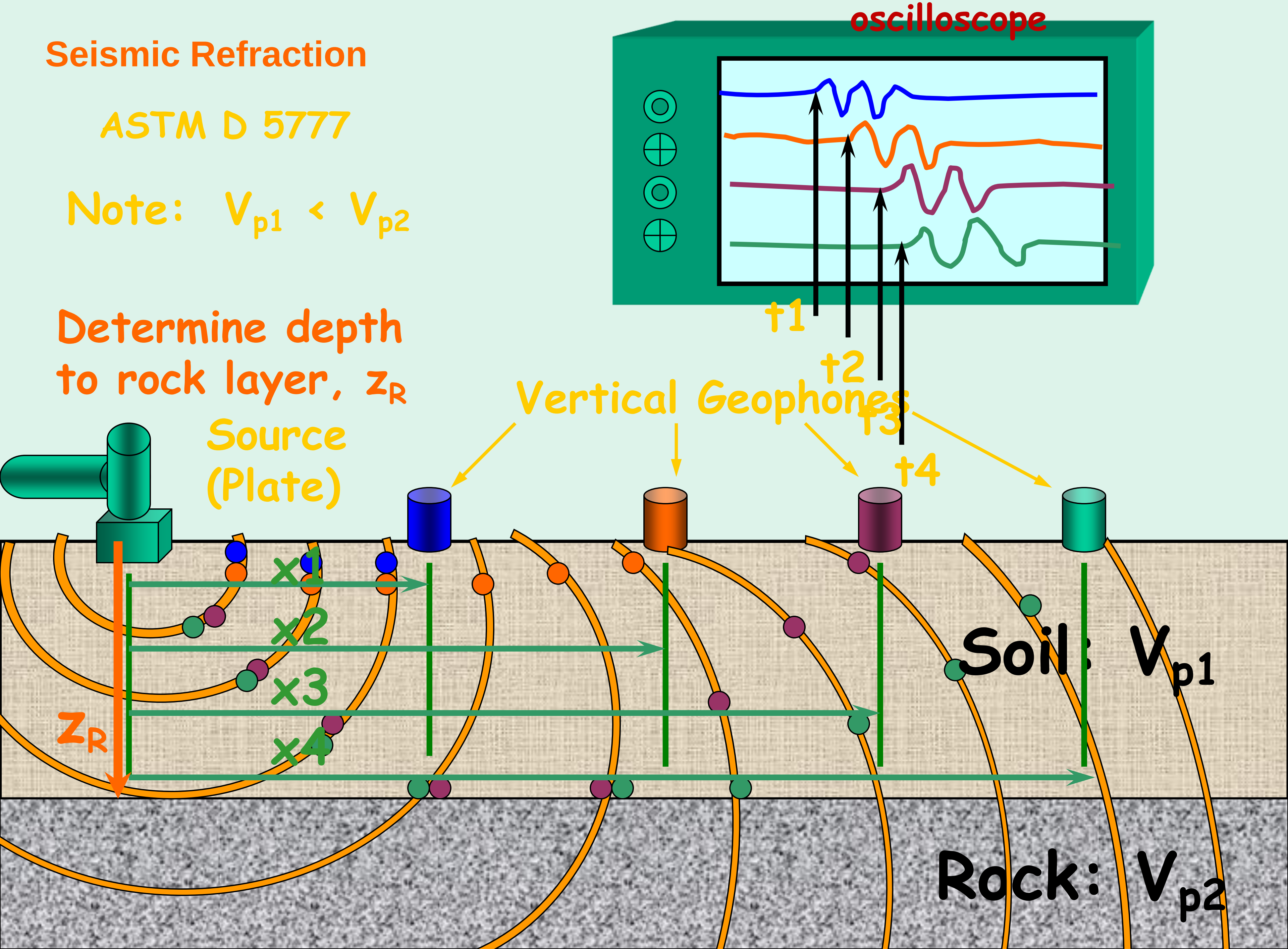
Velocity Recorder

Seismic Refraction

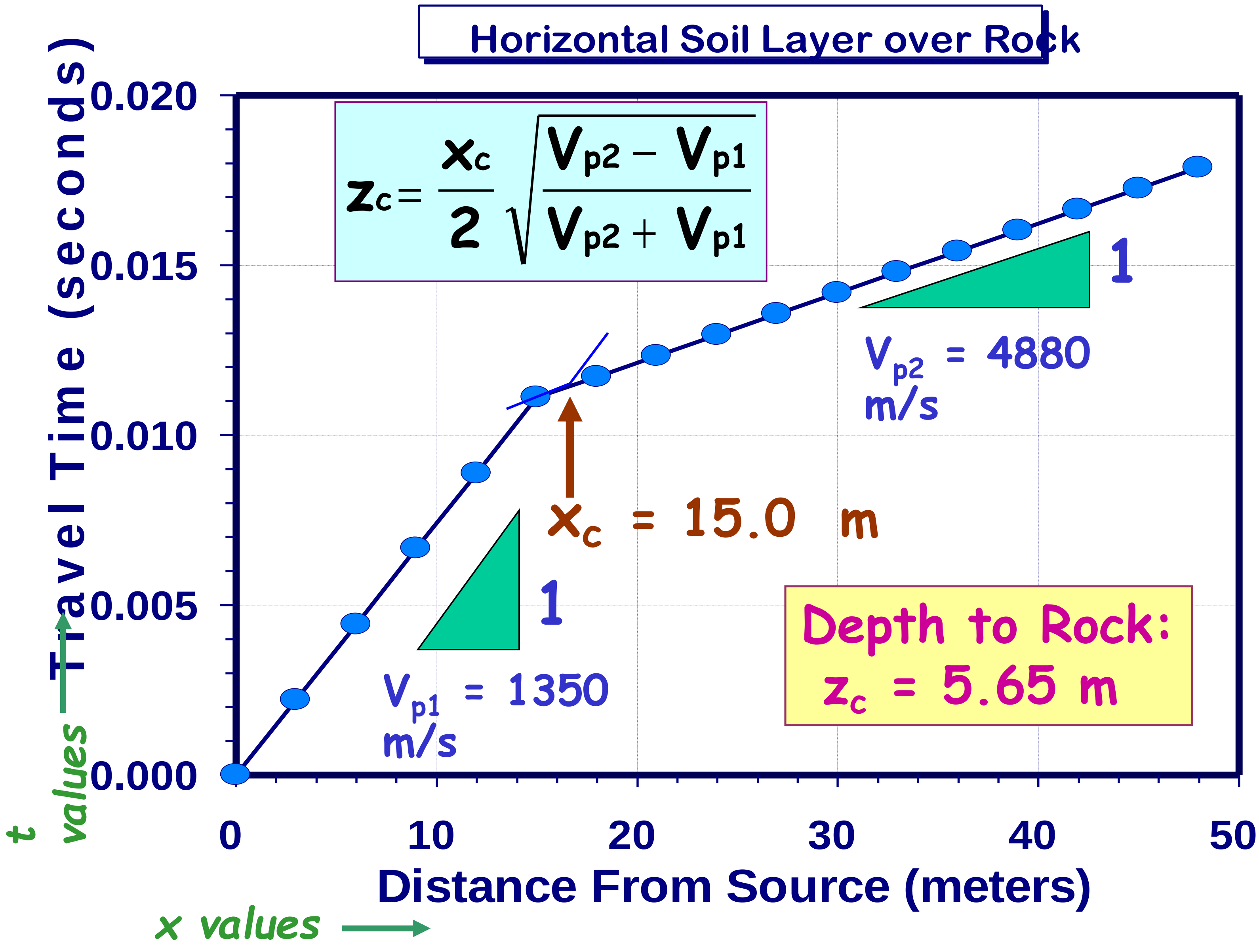
ASTM D 5777

Note: $V_{p1} < V_{p2}$

Determine depth to rock layer, z_R

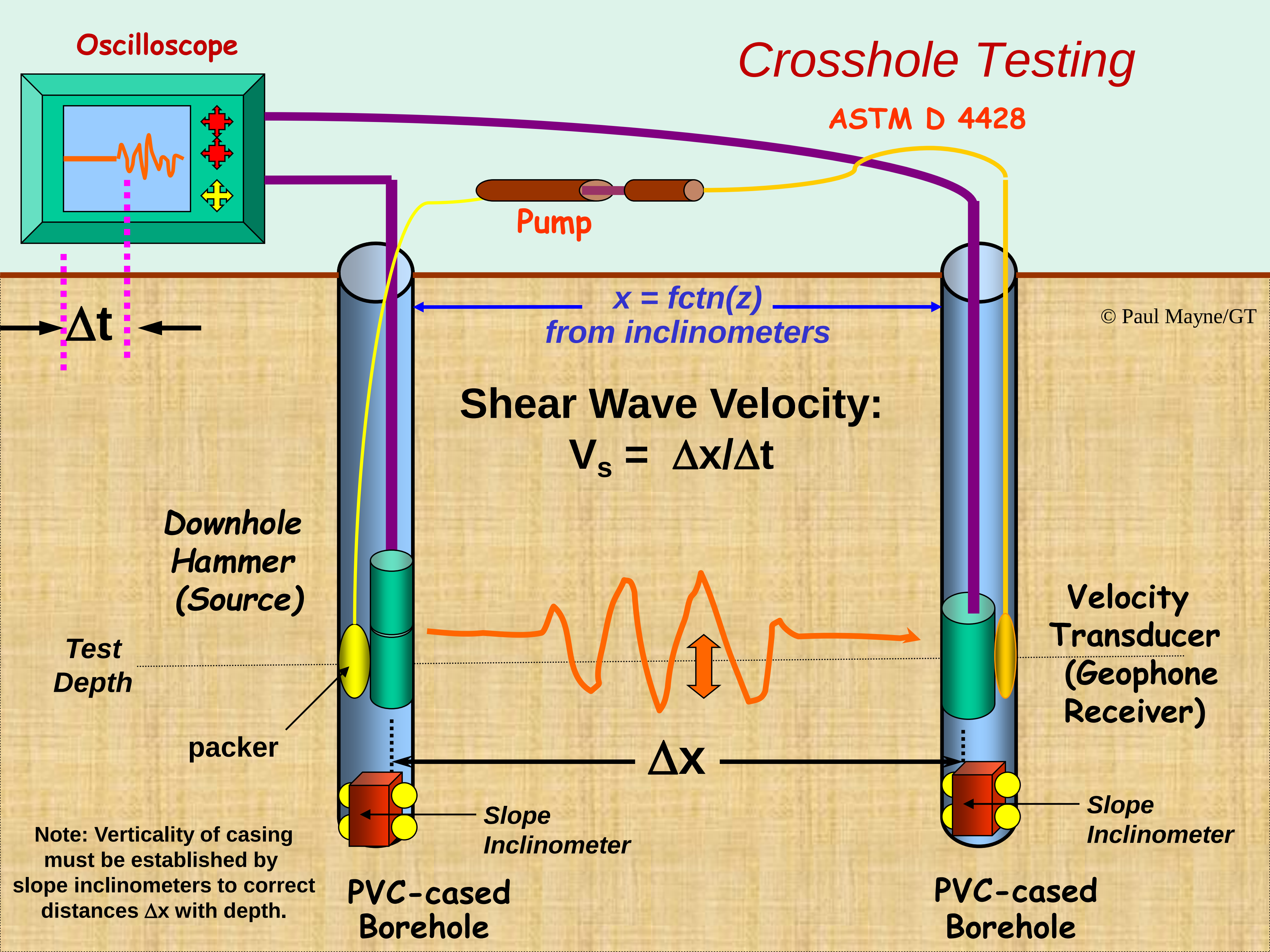


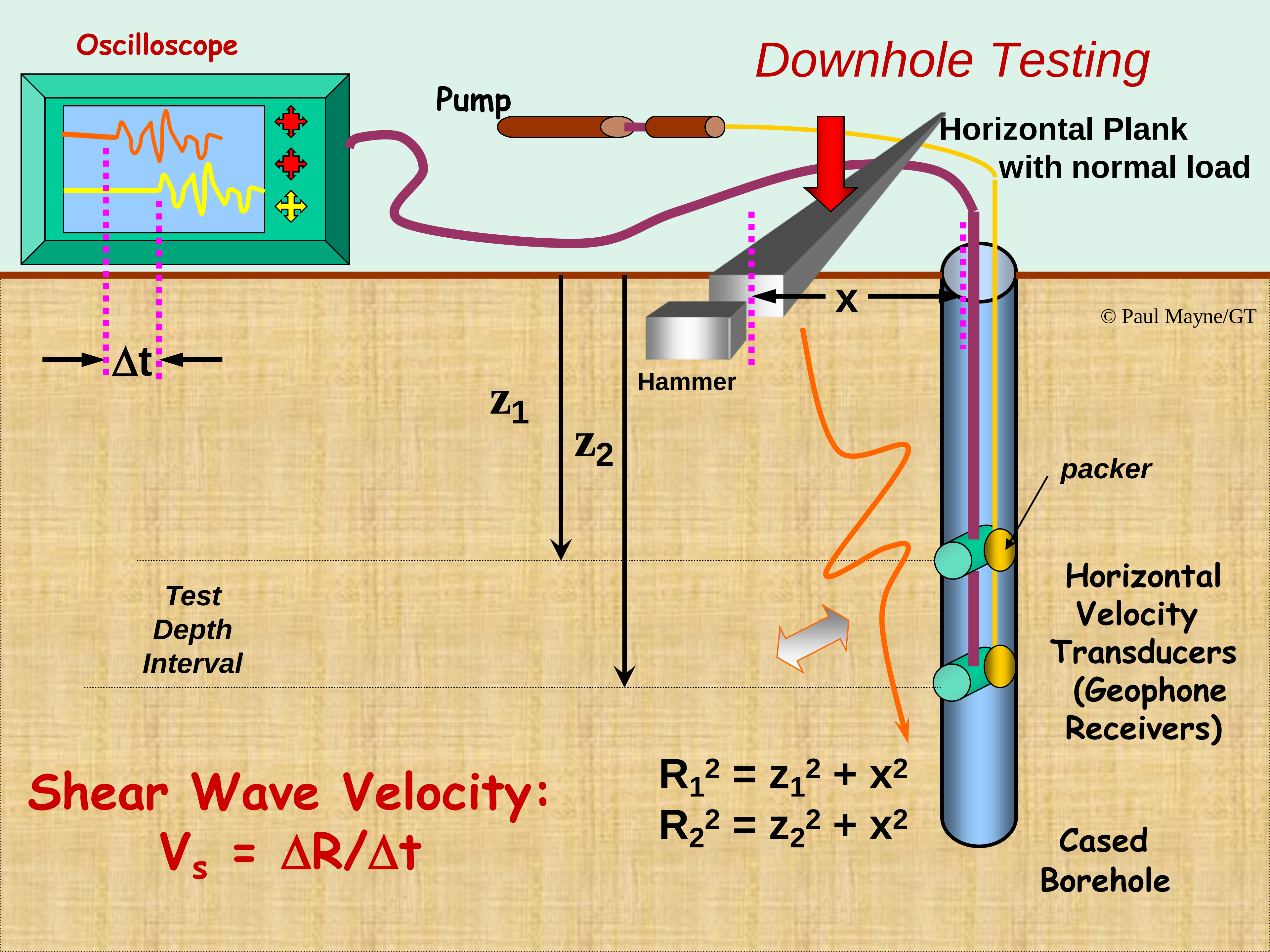
Seismic Refraction



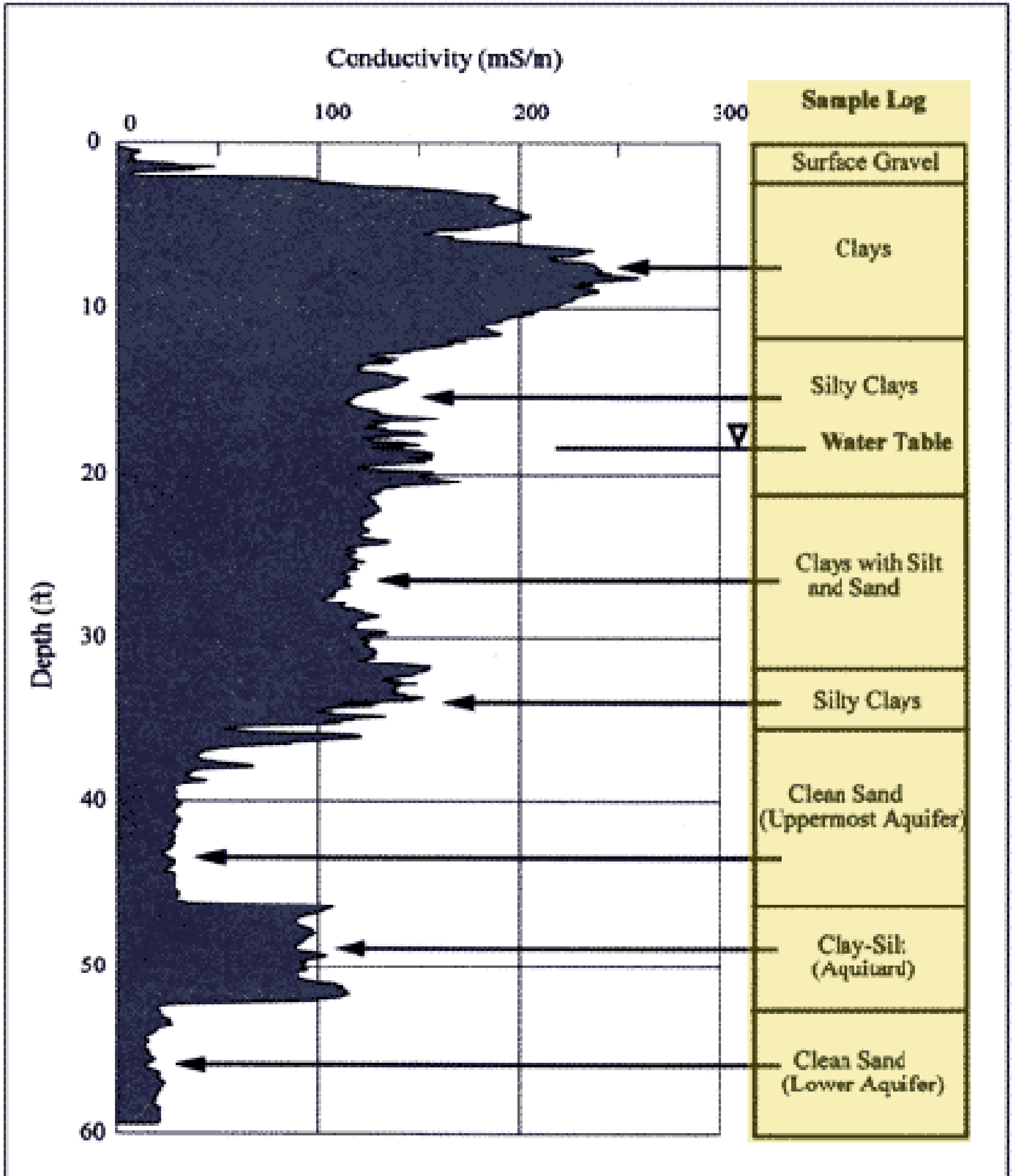
Shear Wave Velocity, V_s

- Fundamental measurement in all solids (steel, concrete, wood, soils, rocks)
- Initial small-strain stiffness represented by shear modulus: $G_0 = \rho_T V_s^2$ (alias $G_{dyn} = G_{max} = G_0$)
- Applies to all static & dynamic problems at small strains ($\gamma_s < 10^{-6}$)
- Applicable to both undrained & drained loading cases in geotechnical engineering.


Crosshole Testing
ASTM D 4428
Oscilloscope
Pump
Δt
x = fctn(z)
from inclinometers
© Paul Mayne/GT
Shear Wave Velocity:
$V_s = \Delta x/\Delta t$
Downhole Hammer (Source)
Test Depth
packer
Velocity Transducer (Geophone Receiver)
Δx
Slope Inclinometer
Slope Inclinometer
Note: Verticality of casing must be established by slope inclinometers to correct distances Δx with depth.
PVC-cased Borehole
PVC-cased Borehole



Downhole Testing
Oscilloscope
Pump
Horizontal Plank
with normal load
Δt
x
© Paul Mayne/GT
Hammer
z_1
z_2
packer
Test
Depth
Interval
Horizontal
Velocity
Transducers
(Geophone
Receivers)
$R_1^2 = z_1^2 + x^2$
$R_2^2 = z_2^2 + x^2$
Cased
Borehole
Shear Wave Velocity:
$V_s = \Delta R/\Delta t$


Conductivity (mS/m)
0
100
200
300
Sample Log
Surface Gravel
Clays
Silty Clays
Water Table
Clays with Silt and Sand
Silty Clays
Clean Sand (Uppermost Aquifer)
Clay-Silt (Aquitard)
Clean Sand (Lower Aquifer)
Depth (ft)
0
10
20
30
40
50
60

Resolution and Ambiguity

- Geophysical data suffer from two generic problems:
  - **Active methods: there is a trade-off between image resolution and depth of penetration into the ground**
  - **Passive methods: there is an inherent ambiguity in field strength data, since a wide shallow object generates the same field anomaly as a compact, deeper object.**

Resolution and Ambiguity

- Most sources input their energy as a waveform of some type, which propagates through the ground.
- The theoretical resolution of any feature illuminated by a waveform is about one half wavelength. This applies to all types of waveform: acoustic, microwave and light.
- Thus a higher frequency means better resolution.

Resolution and ambiguity

- **However, there is always a loss of energy (attenuation) during propagation and the loss is usually a constant ratio per wavelength.**
- **Thus a higher frequency (shorter wavelength) signal will lose more energy over a given distance than will a lower frequency signal.**
- **The loss is thus cumulative with distance. This is an example of the Beer-Lambert absorption law.**

Resolution and Ambiguity

- Thus there is a trade-off between resolution and depth of penetration.

- **The terms of this trade-off must be decided in the light of the aims of the survey and the level of detail required.**

Resolution and Ambiguity

- **Ambiguity arises in the interpretation of interface depths if the velocity of propagation is not accurately known.**
- **The recorded data are the two-way arrival times. These are converted to depths using the velocity. Thus, if the seismic velocity is in error by say 10%, the depth will be in error by 10% also.**
- **This is a particular problem with GPR data, since the velocity an the electrical signal in soil is sensitive to water content, which is highly variable and unlikely to be known accurately in advance.**

Resolution and ambiguity

- Ambiguity also arises in the interpretation of field strength data.

- It can be shown mathematically that an identical field anomaly can be produced by differing structures at differing depths.

Resolution and Ambiguity

- **Thus the interpretation of an observed anomaly is indeterminate in the absence of other evidence.**
- **Such evidence would be provided by a different geophysical method or by direct observation (borehole e.g.)**
- **In general, all geophysical methods are better used in combination than on their own.**