Geophysics for Environmental and Geotechnical Applications

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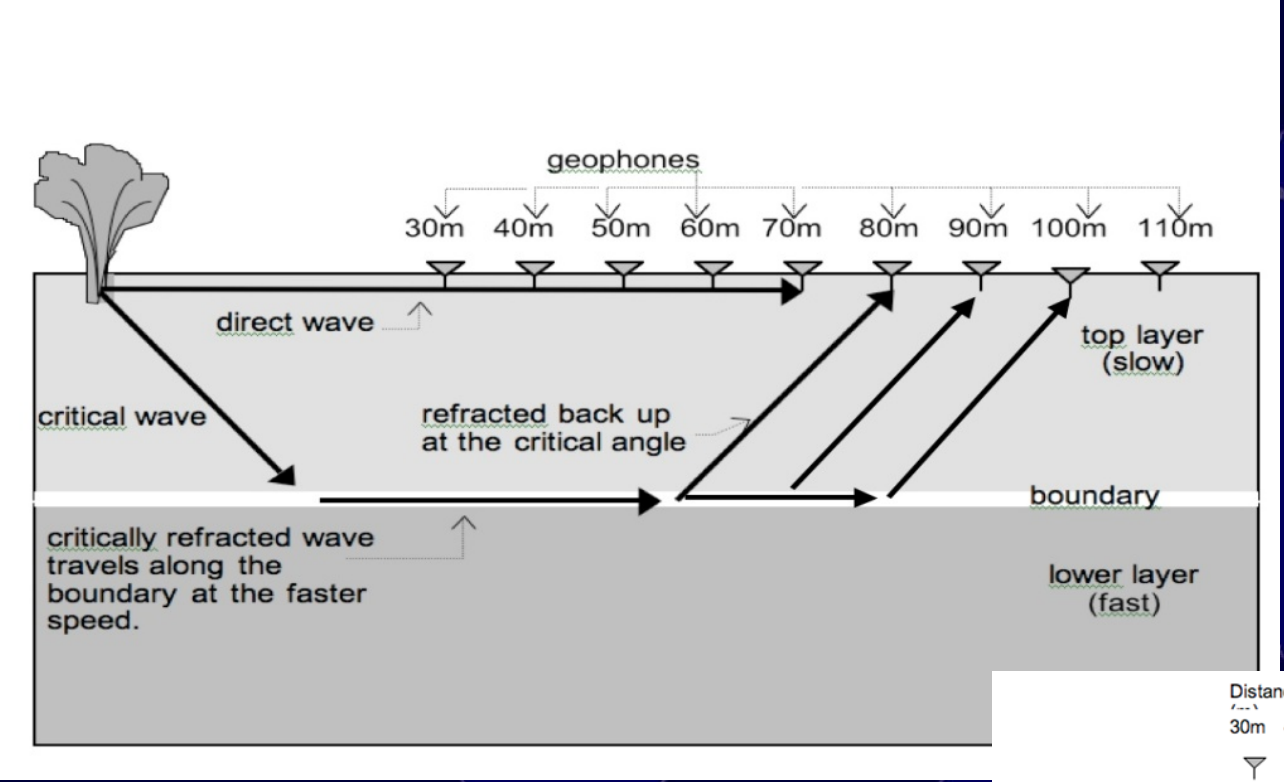
Why Use Geophysics?

- Improve the quality of site characterization (higher resolution and increased area covered)
- Reduce the cost of site characterization
- Non-invasive
- Provides a method to optimally locate exploratory boreholes
- Cost-effective means of establishing control between boreholes

Geophysical Techniques:

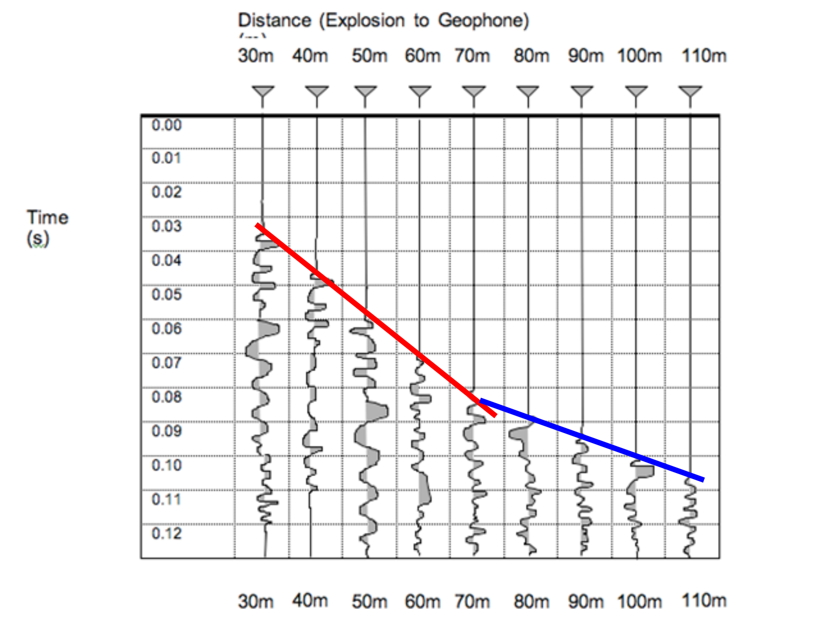
- Seismic
- Electromagnetic
- Resistivity
- Ground Penetrating Radar
- Magnetic
- Gravity

Seismic Refraction

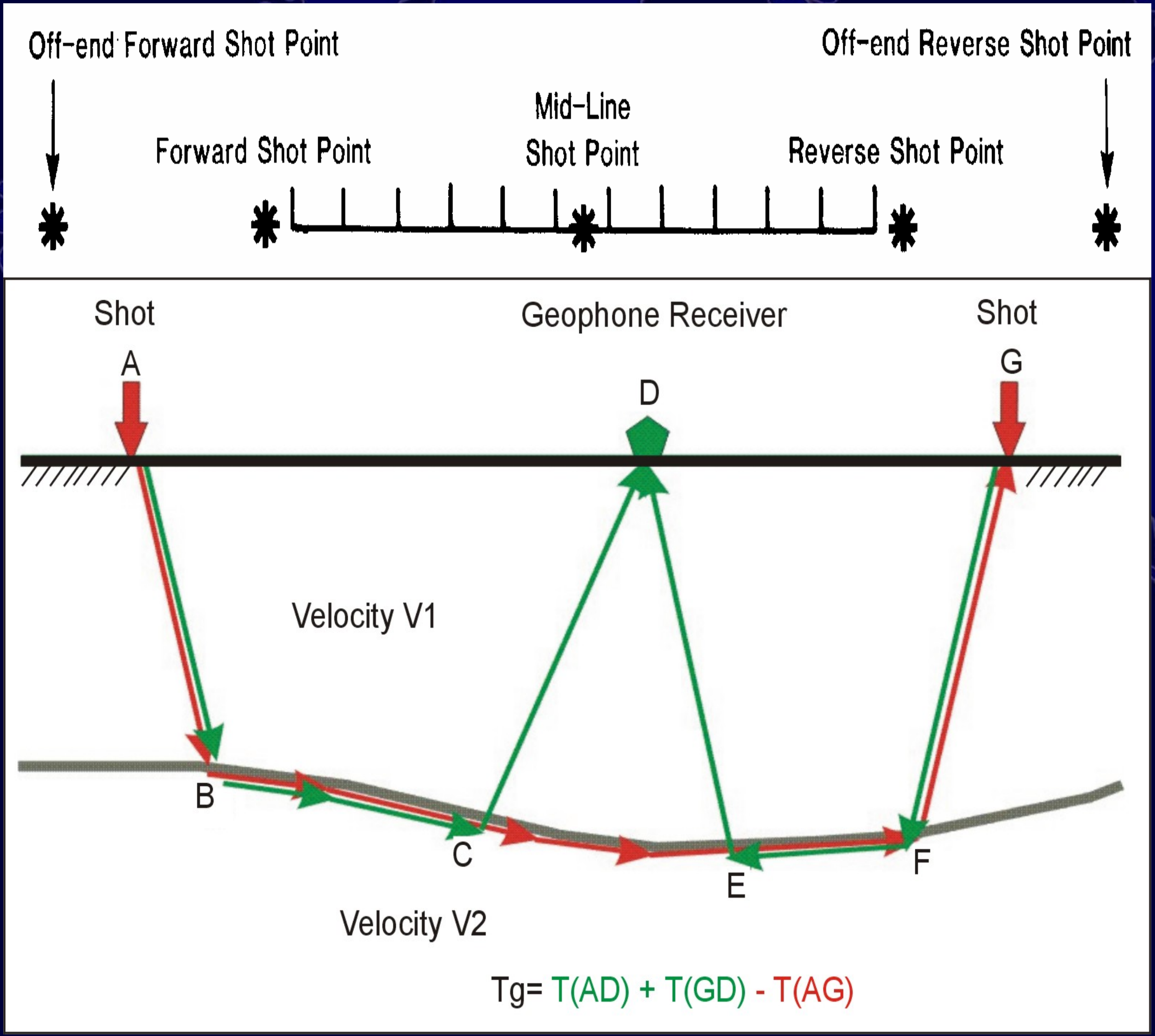


An acoustic source is discharged at the earth's surface. Energy travels directly to the sensors or is critically refracted from prominent subsurface interfaces and is recorded by sensors placed at multiple locations.

The "travel times" (arrival times) of direct and refracted acoustic energy are plotted as a function of source-sensor separation.



Seismic Refraction



If the subsurface is irregular, sources are discharged at multiple locations (typically five). This multiplicity of travel time data allows depths to be estimated with a higher degree of precision.

Seismic Refraction

Table 4.2 Examples of P-wave velocities

Material	V_P (m/s)
Air	330
Water	1450–1530
Petroleum	1300–1400
Loess	300–600
Soil	100–500
Snow	350–3000
Solid glacier ice*	3000–4000
Sand (loose)	200–2000
Sand (dry, loose)	200–1000
Sand (water saturated, loose)	1500–2000
Glacial moraine	1500–2700
Sand and gravel (near surface)	400–2300
Sand and gravel (at 2 km depth)	3000–3500
Clay	1000–2500
Estuarine muds/clay	300–1800
Floodplain alluvium	1800–2200
Permafrost (Quaternary sediments)	1500–4900
Sandstone	1400–4500
Limestone (soft)	1700–4200
Limestone (hard)	2800–7000
Dolomites	2500–6500
Anhydrite	3500–5500
Rock salt	4000–5500
Gypsum	2000–3500
Shales	2000–4100
Granites	4600–6200
Basalts	5500–6500
Gabbro	6400–7000
Peridotite	7800–8400
Serpentinite	5500–6500
Gneiss	3500–7600
Marbles	3780–7000
Sulphide ores	3950–6700
Pulverised fuel ash	600–1000
Made ground (rubble etc.)	160–600
Landfill refuse	400–750
Concrete	3000–3500
Disturbed soil	180–335
Clay landfill cap (compacted)	355–380

* Strongly temperature dependent (Kohnen 1974)

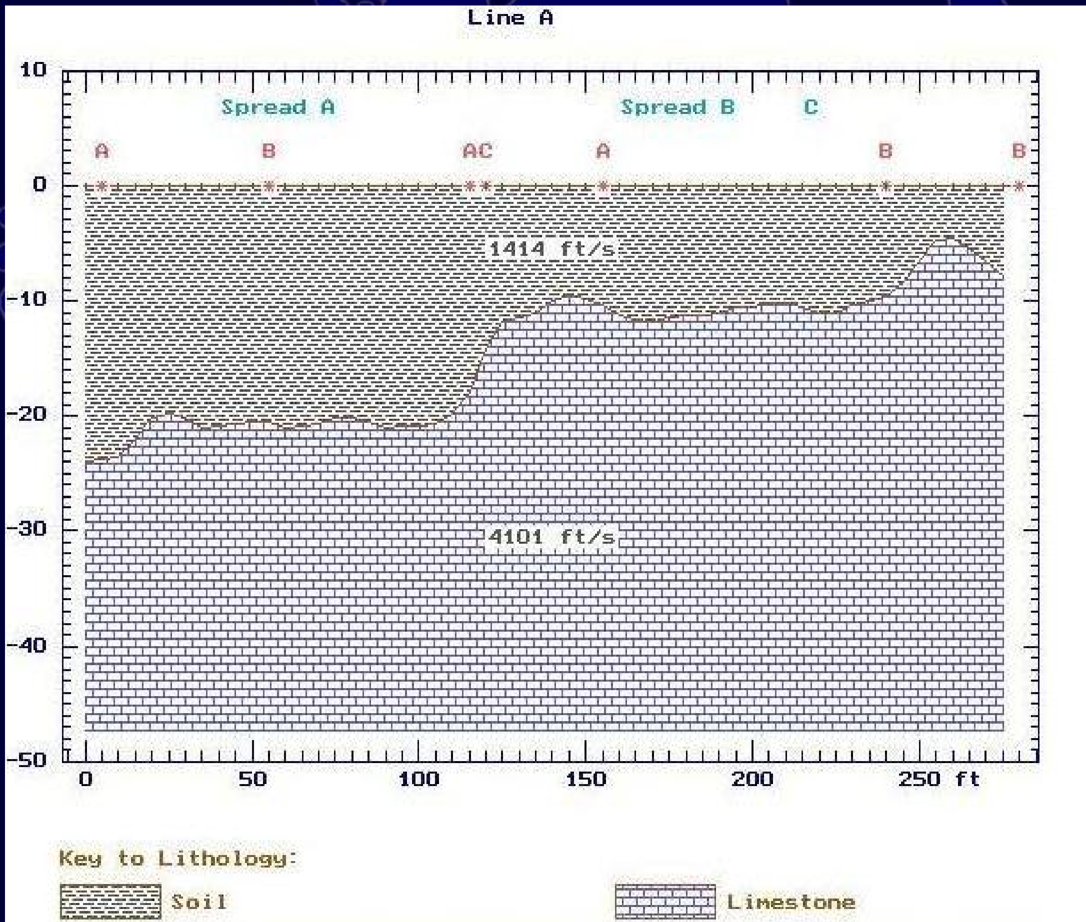
From *An Introduction to Applied and Environmental Geophysics*, by John Reynolds, 2007.

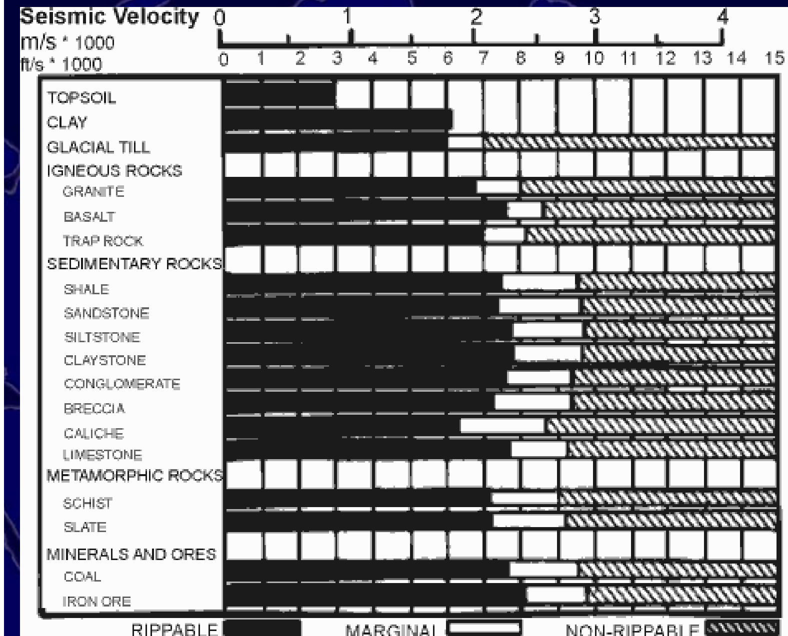
Seismic Refraction

Applications:

- Depth to bedrock
- Depth to water table
- Bedrock type
- Bedrock rippability
- Mapping bedrock interfaces
- Mapping bedrock channels
- Identifying faults and fracture zones

Seismic Refraction





From: Handbook of Ripping, 8th Edition, by The Caterpillar Company

2-D refraction data can often be transformed into realistic 2-D geologic models. The accuracy of such models will be increased if external constraints (borehole control) are available. Note that low velocity layers are “invisible” and never imaged with refraction techniques.

Seismic Refraction

Strengths:

•Provides accurate 2-D or 3-D subsurface images

•Provides information on material type

•Data acquisition is straightforward

•Data processing and interpretation are straightforward

•Less expensive

Limitations:

•Depth penetration depends on source used; simplest sources have relatively shallow depth penetration

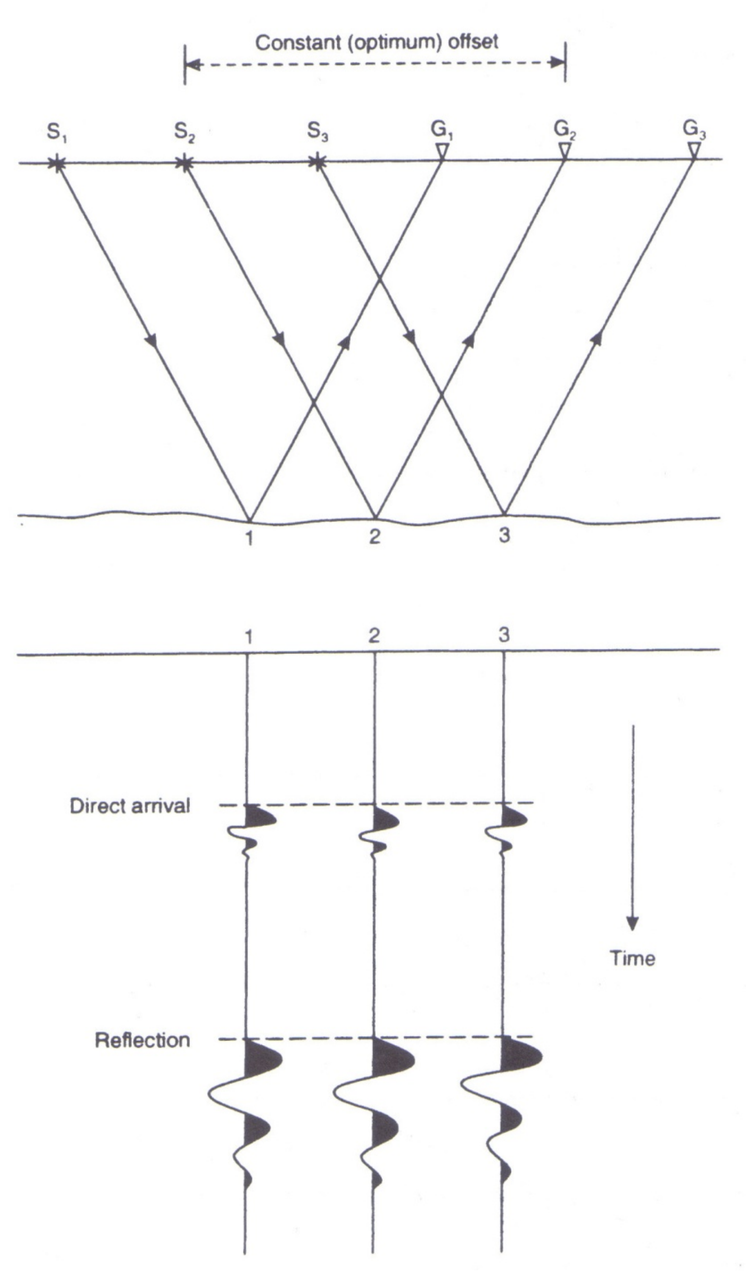
•Relatively slow data acquisition, as sensors (geophones) must be coupled to the ground

•Data are difficult to interpret beyond ~4 interfaces

•Low velocity layers and thin layers (<3 m) cannot be distinguished

•Doesn't work well in "acoustically" noisy areas

Seismic Reflection



An acoustic pulse is generated by a surface source. Some of this downgoing energy is reflected at each subsurface interface. The two-way travel time and magnitude of the reflected pulses are recorded by surface receivers (geophones). Magnitudes and average velocities of the reflected pulses are a function of the density and acoustic velocity of the subsurface layers.

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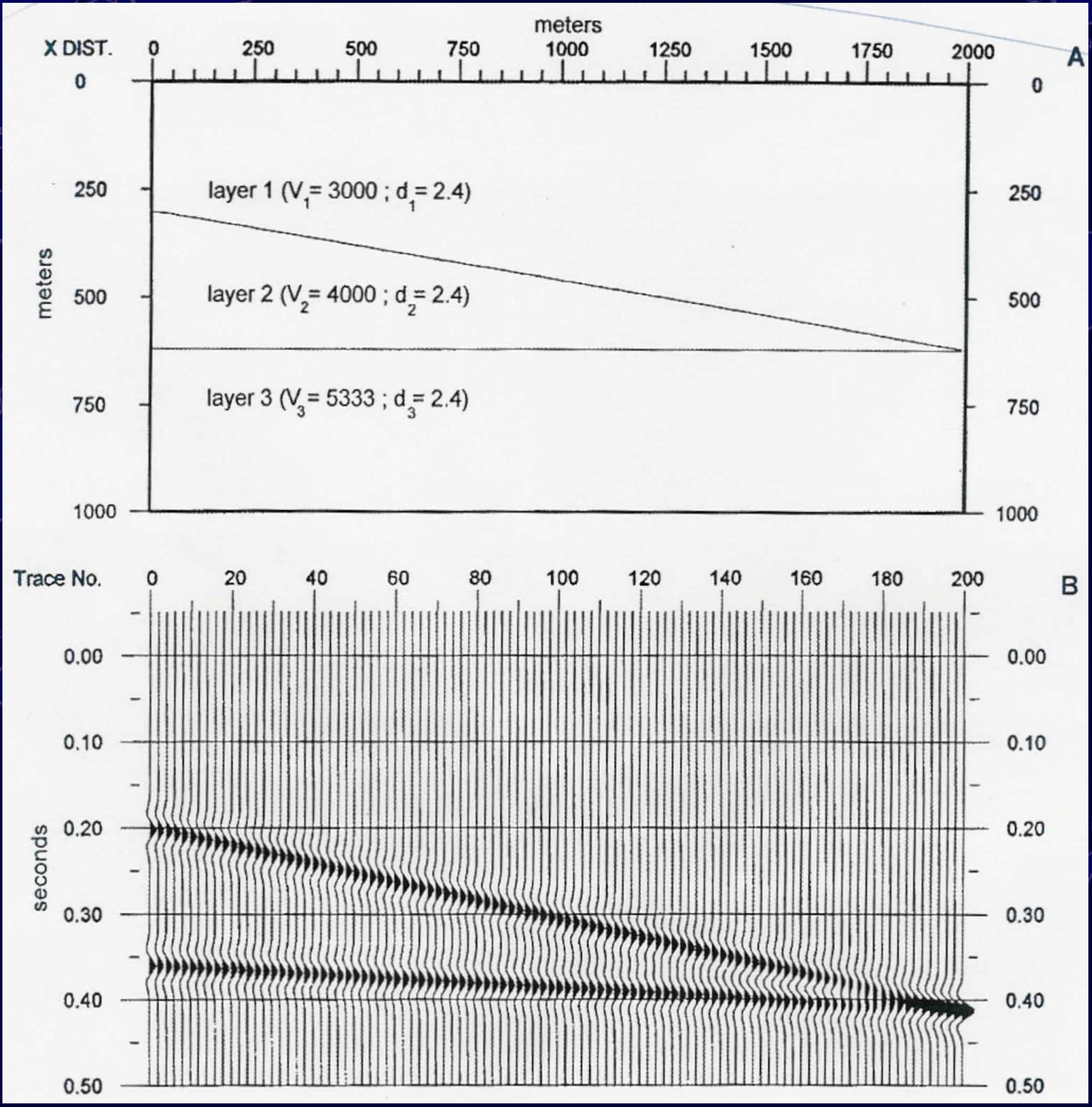
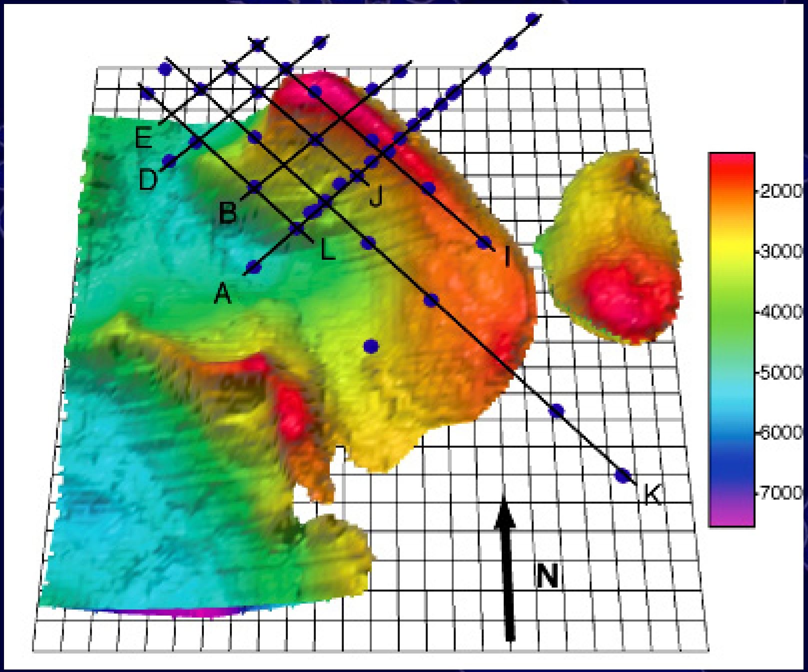
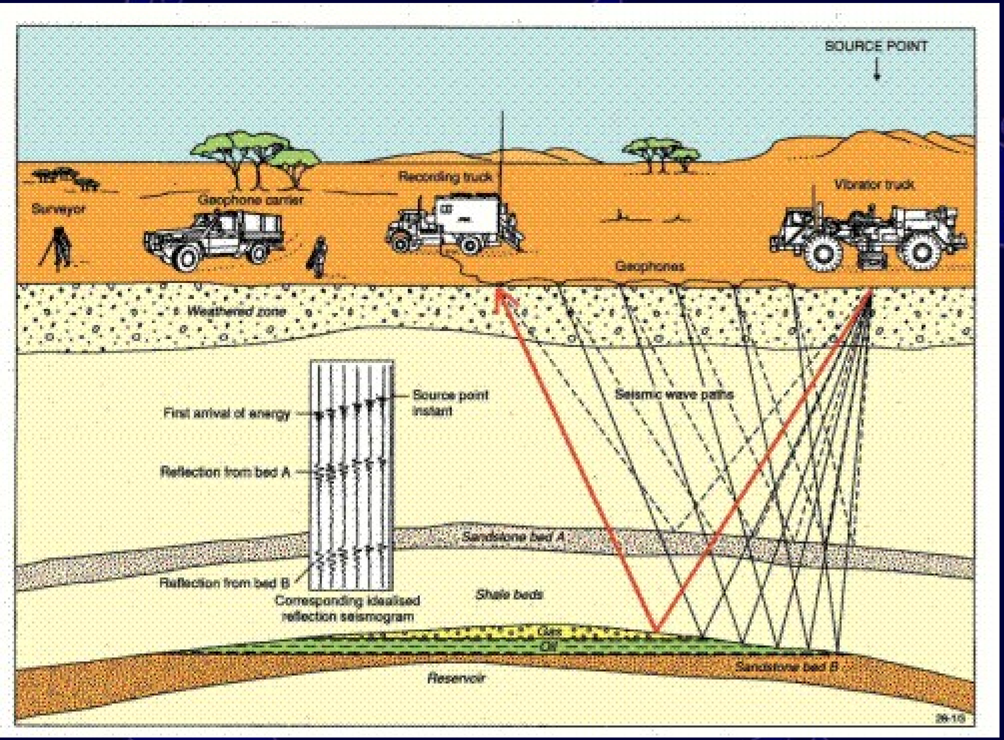
Seismic Reflection



Seismic Reflection

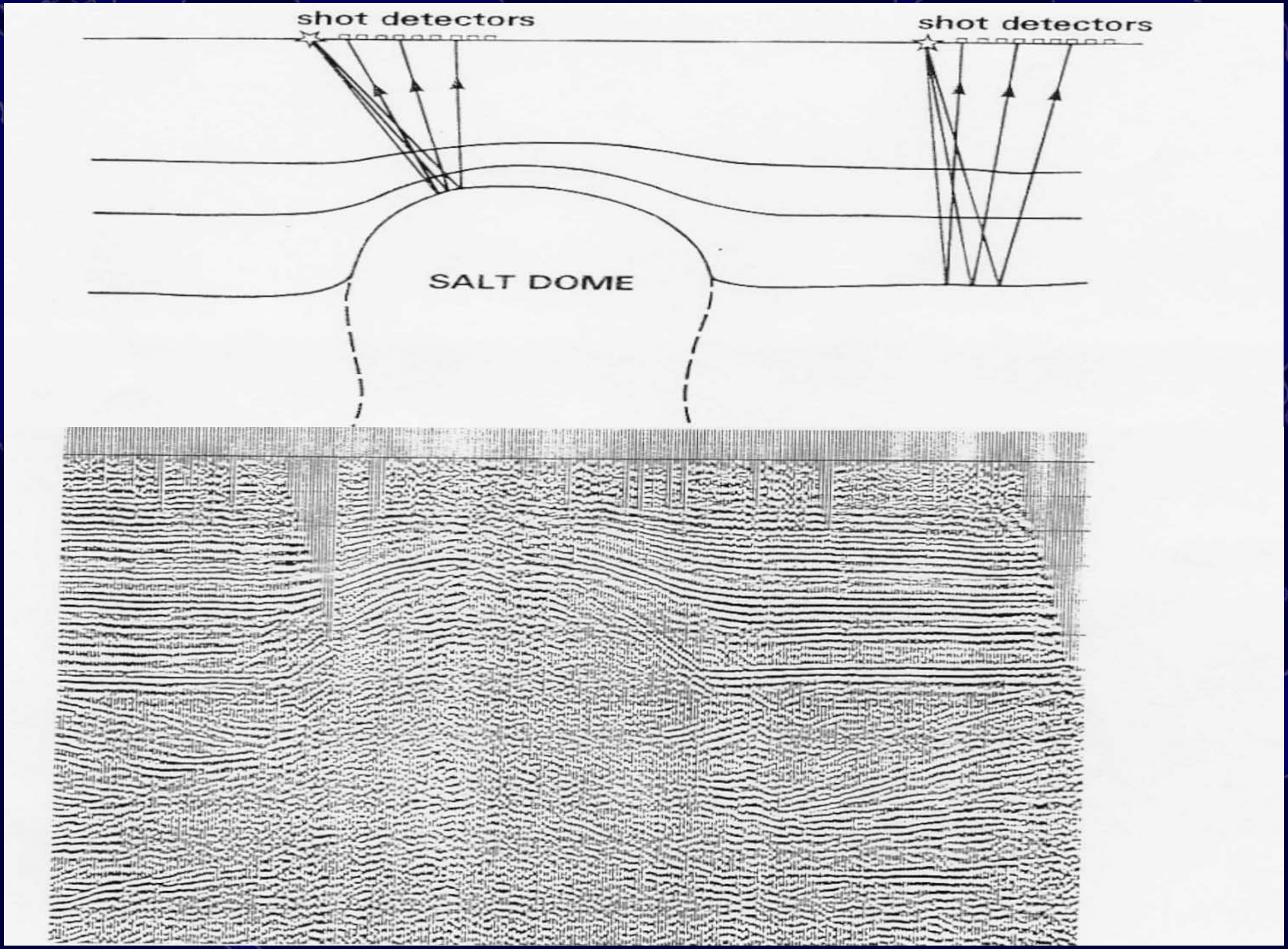




Three-dimensional seismic reflection surveys are becoming more common for environmental and engineering applications. The data acquisition and processing are much more complicated than for 2-D reflection or refraction surveying.

Seismic Reflection

(b)



(a)

2-D reflection profiles can be converted into 2-D lithology/structure sections.

Seismic Reflection

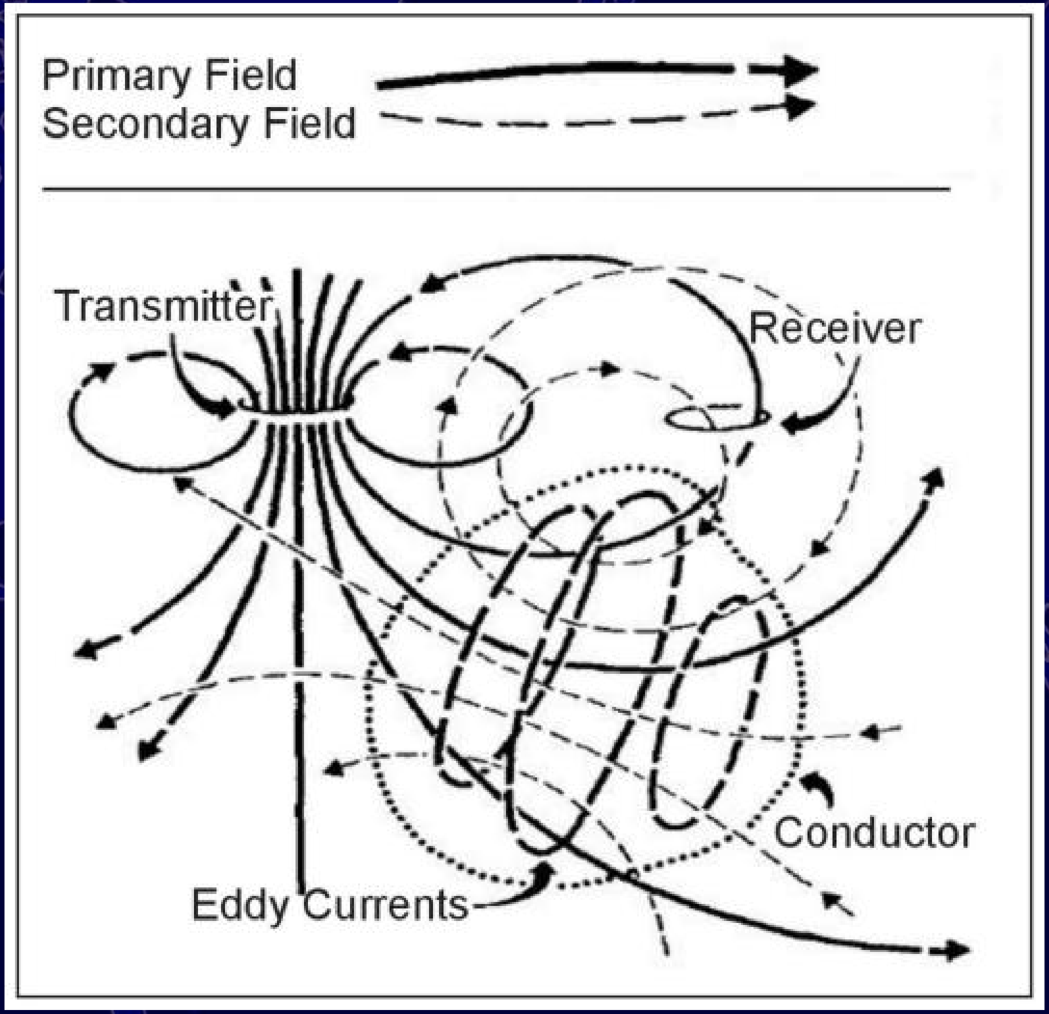
Strengths (compared to refraction):

- Can provide continuous images of the subsurface structure
- Can image low-velocity layers
- Better lateral resolution (used for finding abandoned underground mines)
- Can provide 3-D image of the subsurface

Limitations (compared to refraction):

- Cannot image shallow layers (≤15 m)
- Data acquisition is slower
- Data processing is much more complicated
- Much more expensive (typically 3 to 5 times more expensive than refraction surveys)

Electromagnetic Methods (EM)



"The electromagnetic induction process is conceptually summarized in figure 1 from Klein and Lajoie (1980). "

Electromagnetic Methods (EM)

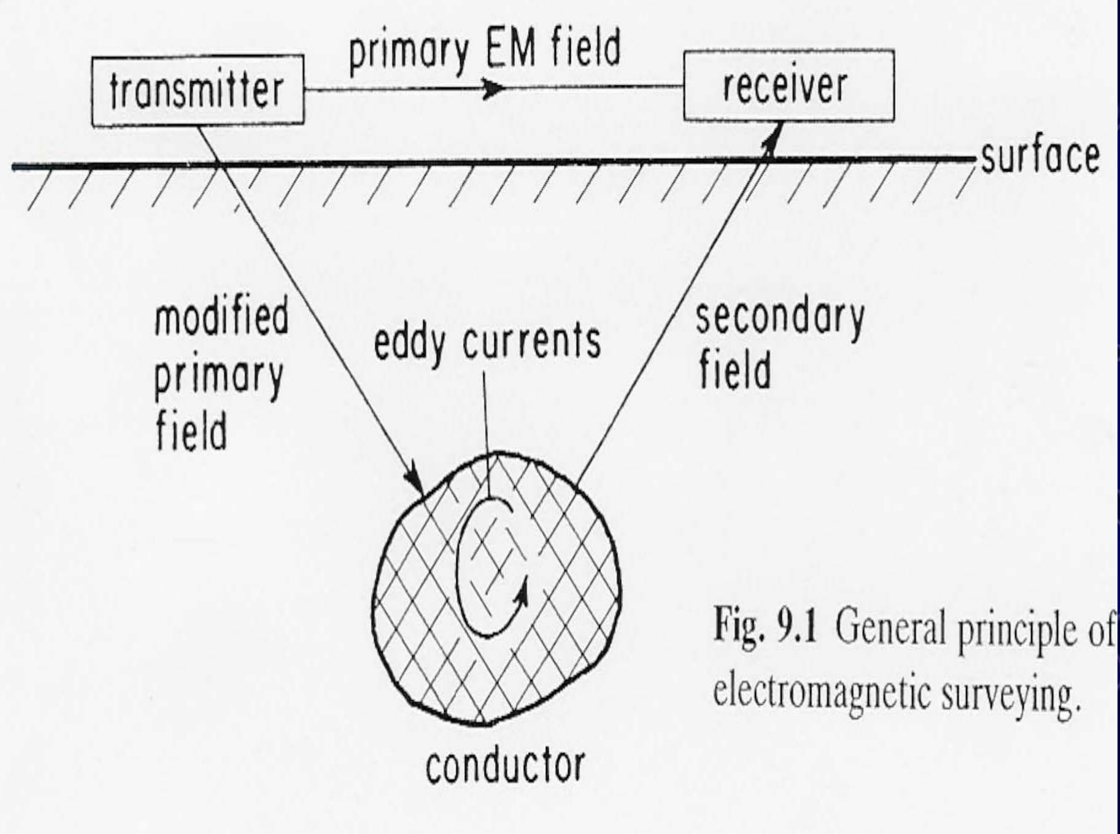


Fig. 9.1 General principle of electromagnetic surveying.

1. When AC current is passed through a coiled wire conductor (transmitter), EM radiation (primary field) of the same frequency is emitted from the coil.
2. When this primary EM radiation passes through a subsurface conductor, a secondary AC current is induced in the conductor.
3. This secondary current causes the conductor to emit secondary EM radiation.
4. This secondary EM radiation is measured and recorded by the receiver coil. The apparent electrical conductivity is determined by comparing the magnitudes of the primary and secondary EM fields.

Electromagnetic Methods (EM)

Measure the earth’s response to EM radiation

↓

Map spatial variations in the electrical conductivity of the subsurface

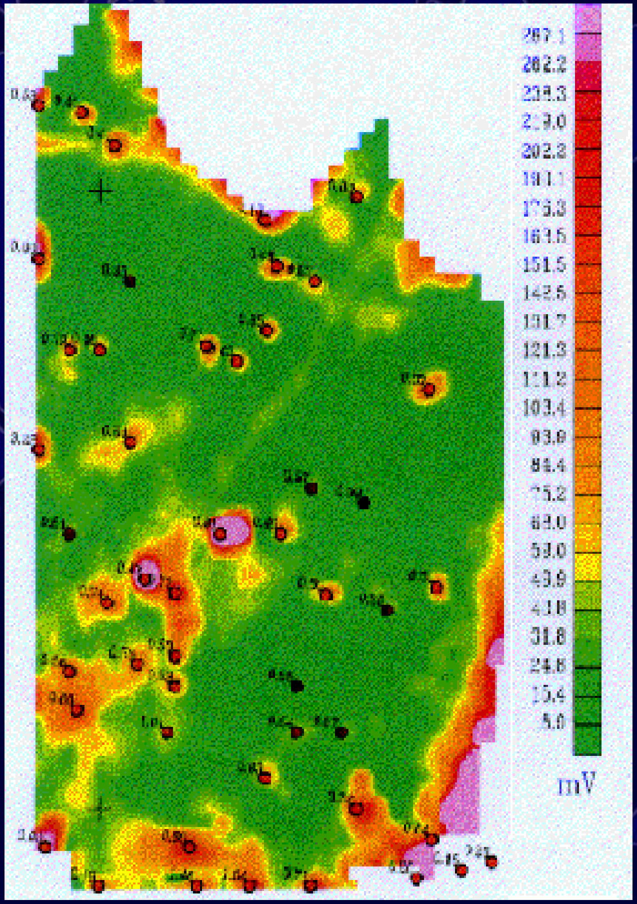
↓

Electrical conductivity can be related to soil or rock properties

Electromagnetic Methods (EM)

Applications:

- Depth to bedrock
- Depth to water table
- Mapping contaminant plumes
- Landfill delineation
- Locating USTs
- Locating buried utilities
- Mapping clay lenses
- Mapping faults, fractures, or weathered zones
- Variations in porosity, saturation, or salinity
- Mapping salt water intrusion



Electromagnetic Methods (EM)

Strengths:

•Do not need to be coupled to earth, so data can be acquired rapidly and inexpensively

•Data can often be acquired by one person

•Multiple tools available (simple to sophisticated)

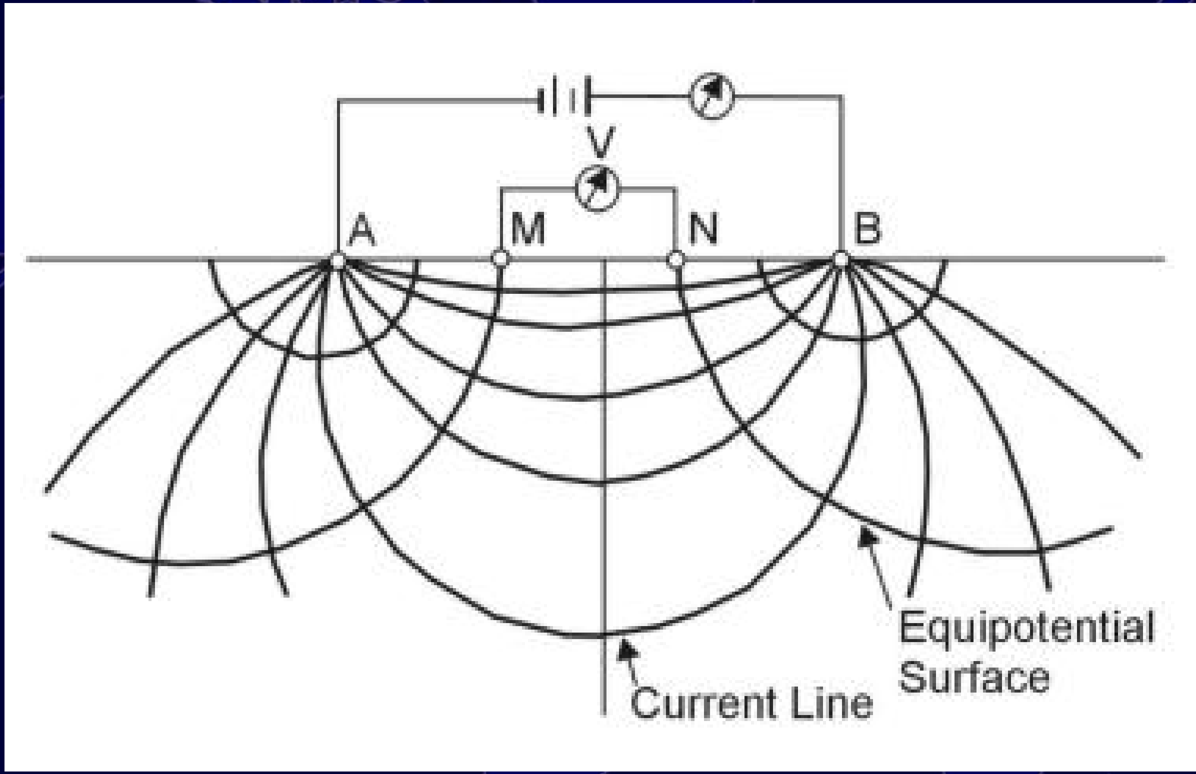
•Provides 1-D, 2-D or 3-D conductivity images of subsurface, depending on technique used

Limitations:

•Vertical resolution diminishes with depth

•Cultural features can create problems (metal fences, buried pipelines, electric power lines, etc.)

Resistivity



Current flow in the subsurface is electrolytic (via the movement of cations and anions) rather than electronic.

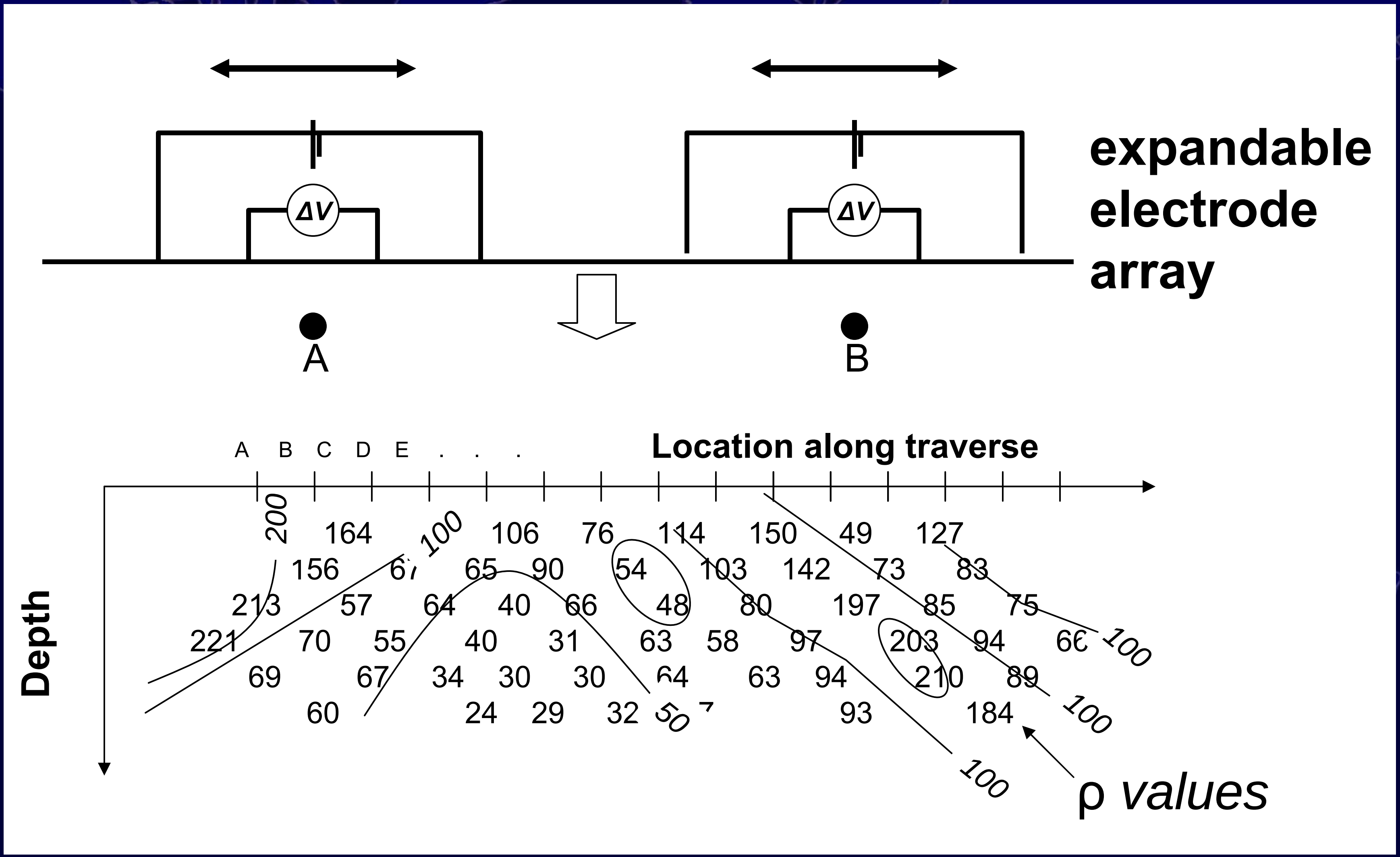
A known AC current (I) is input into the ground using a battery or a generator, and potential differences (ΔV) are measured using a voltmeter.

The resistance (R) of the subsurface can be calculated using the well-known formula:
$\Delta V = IR$

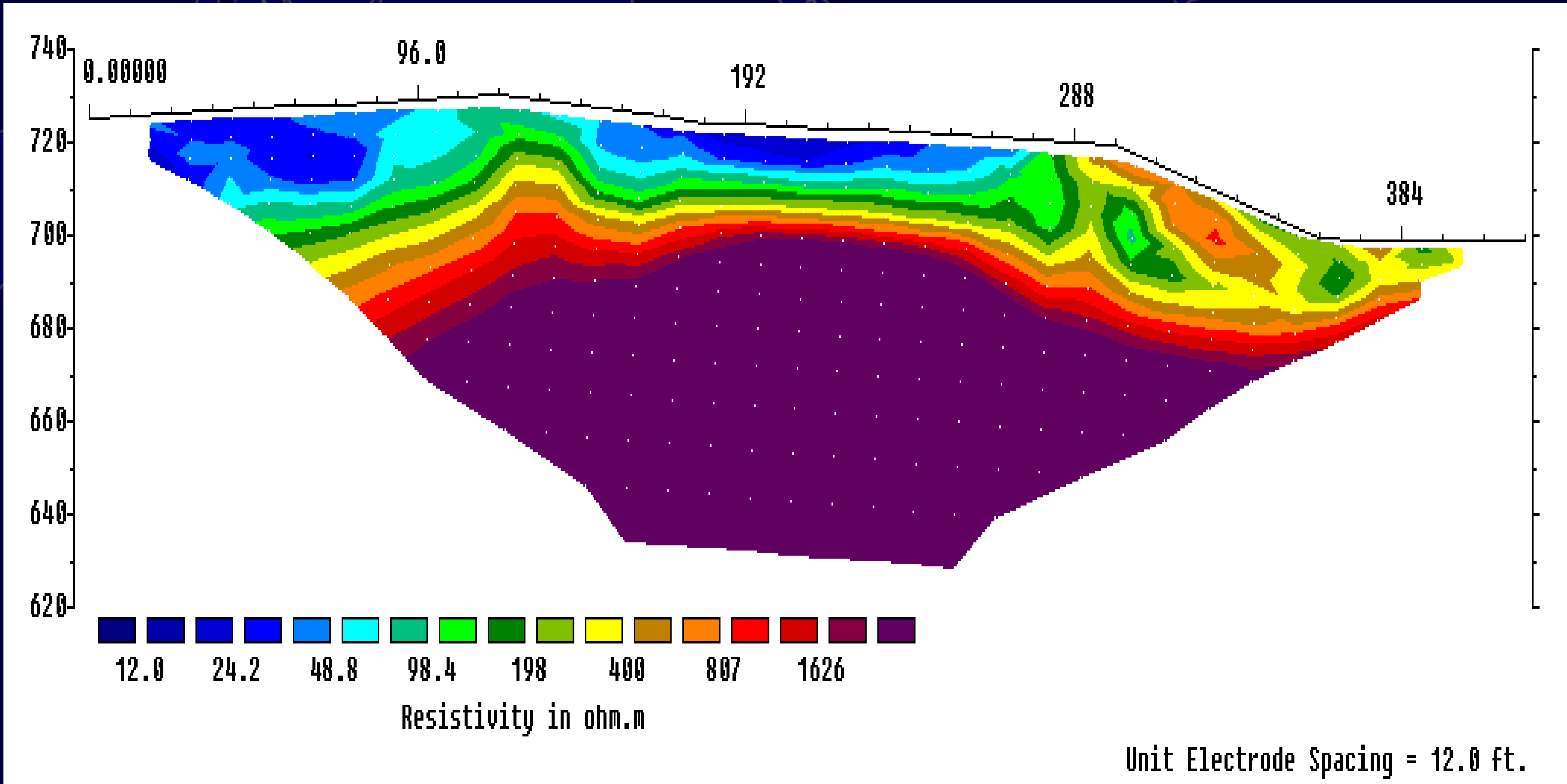
The resistivity (ρ) of the subsurface is calculated by considering the geometric arrangement of electrodes.

Resistivity

The resistivity of the subsurface at different locations and at different depths can be measured by shifting the array laterally and varying the electrode spacing.



Resistivity

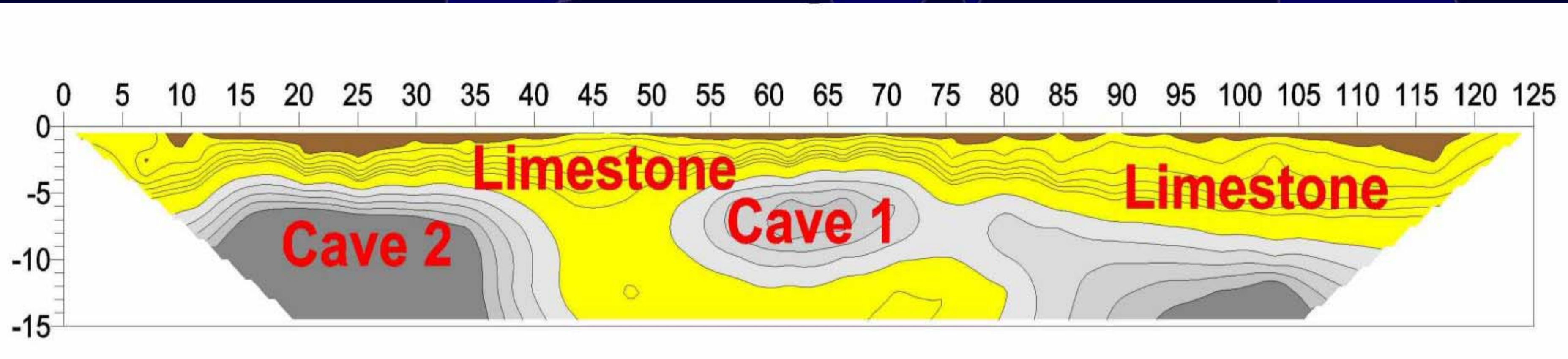


Resistivity is the inverse of electrical conductivity and is an intrinsic property of a material. Resistivity is mostly a function of lithology, porosity, clay content, permeability, fluid saturation and fluid salinity.

Resistivity

Applications:

- Lateral and vertical mapping of contaminant plumes
- Mapping sand and gravel aquifers
- Mapping clay layers and lenses
- Depth to bedrock
- Depth to water table
- Mapping faults, fractures, weathered zones
- Delineating aggregate deposits for quarry operations
- Mapping lithologic contacts
- Locate voids, abandoned mines and tunnels
- Variations in porosity, saturation, or salinity



Resistivity

Strengths:

•Acquisition is relatively straightforward

•Processing is automated

•Can provide relatively high-resolution 2-D or 3-D conductivity images of subsurface

Limitations:

•Relatively slow, as electrodes must be coupled to ground surface

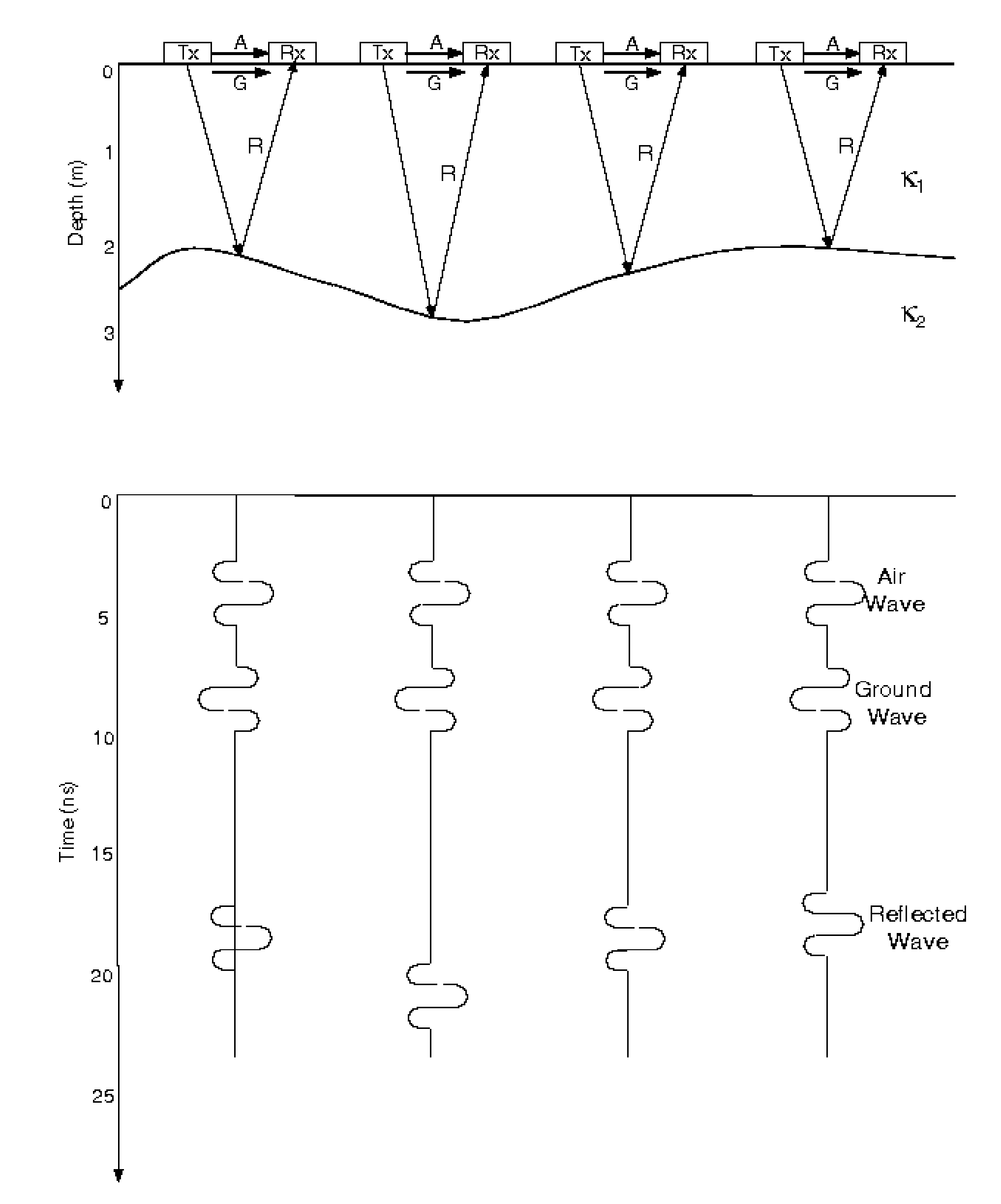
•Coupling can be a problem (rock or dry sand)

•Limited depth penetration (typically 30 m); deeper penetration depths require larger horizontal electrode spacing

•Resolution diminishes with depth

•Cultural features can create problems (metal fences, buried pipelines, electric power lines, etc.)

Ground Penetrating Radar (GPR)

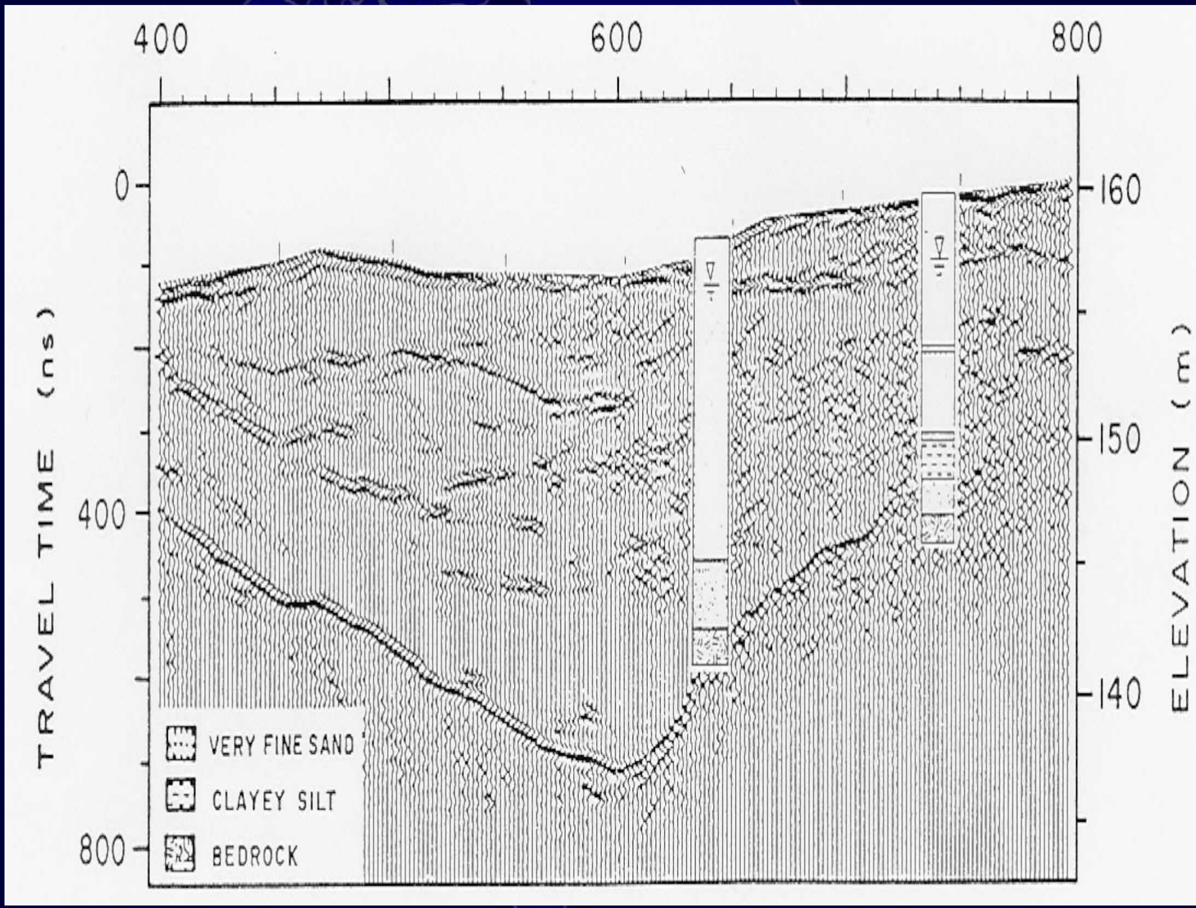


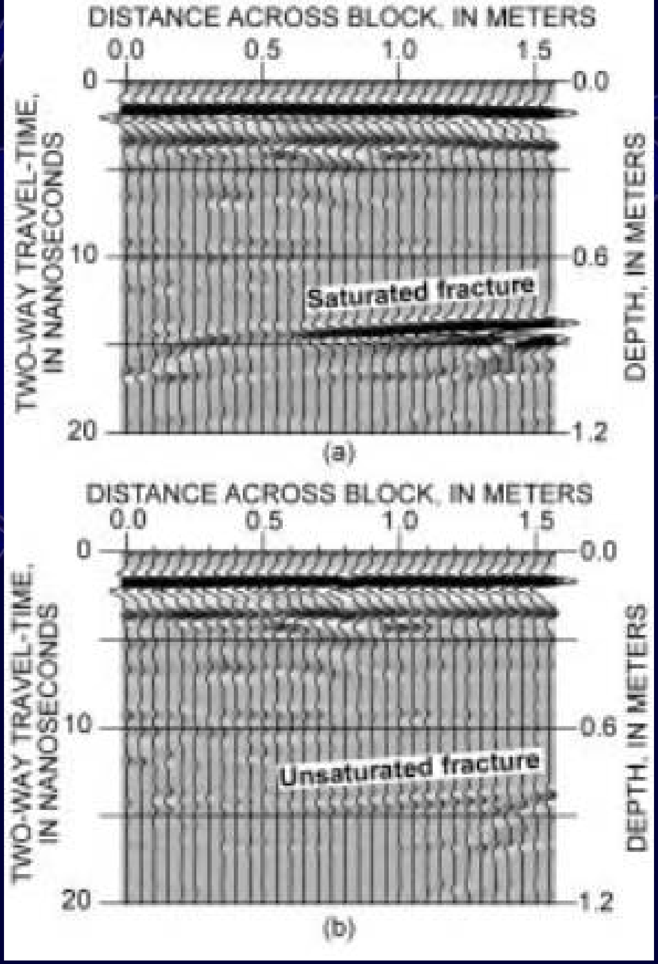
Transmitter emits pulses of EM radiation at regular intervals as it is towed across the surface.

Some of this pulsed energy is reflected from lithologic interfaces and is returned to the earth's surface.

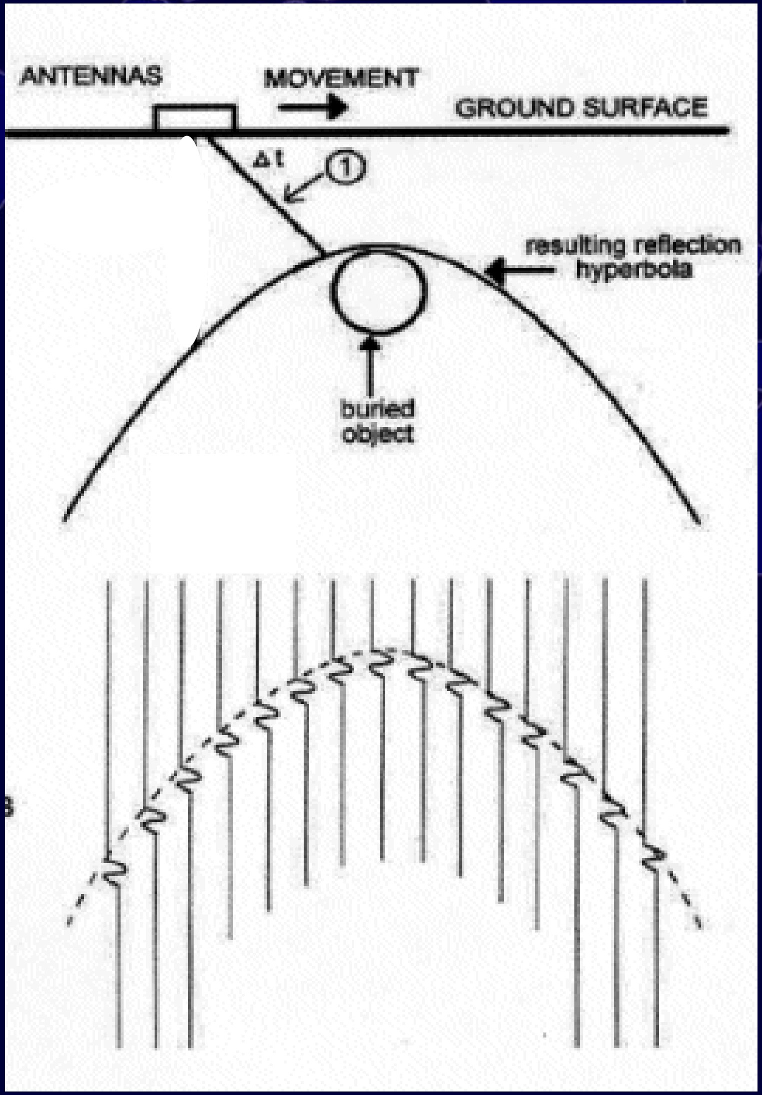
The two-way travel time and magnitude of this reflected pulsed radiation is recorded by a surface receiver and plotted on a distance vs. travel time profile.

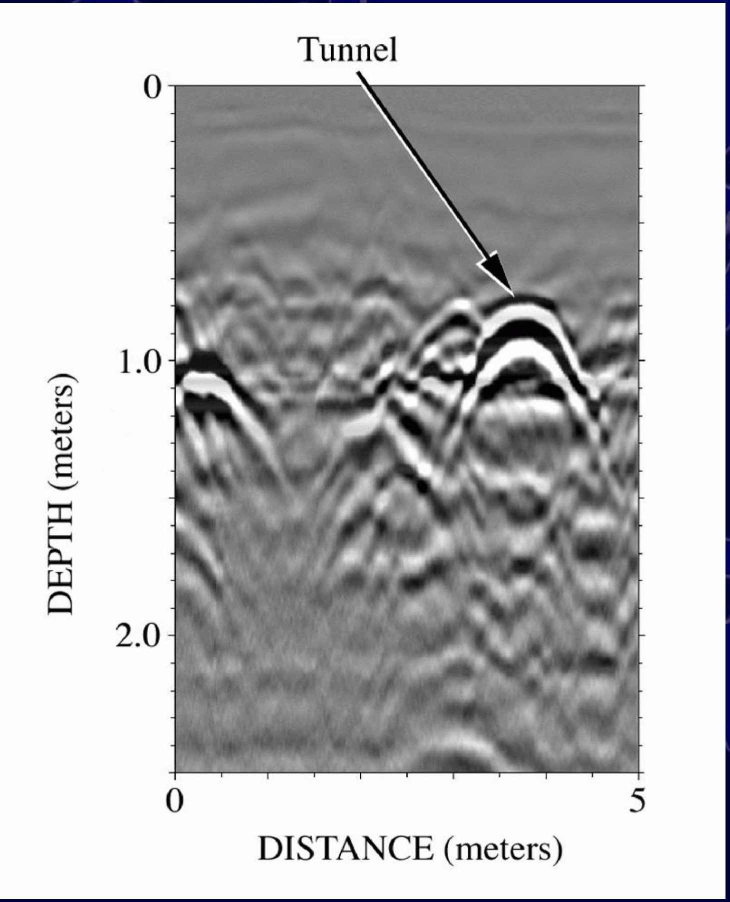
Ground Penetrating Radar (GPR)





Ground Penetrating Radar (GPR)





Ground Penetrating Radar (GPR)

Applications:

- Mapping lithology or fill boundaries
- Depth to shallow bedrock
- Depth to water table
- Mapping water depths (surface water)
- Location, depth, and orientation of USTs, pipes, utilities, trenches, and other buried materials
- Locating cavities beneath pavement
- Measuring pavement thickness
- Locating rebar in concrete
- Bridge deck integrity studies
- Archeological and forensic investigations
- Mapping contaminant plumes

Ground Penetrating Radar (GPR)

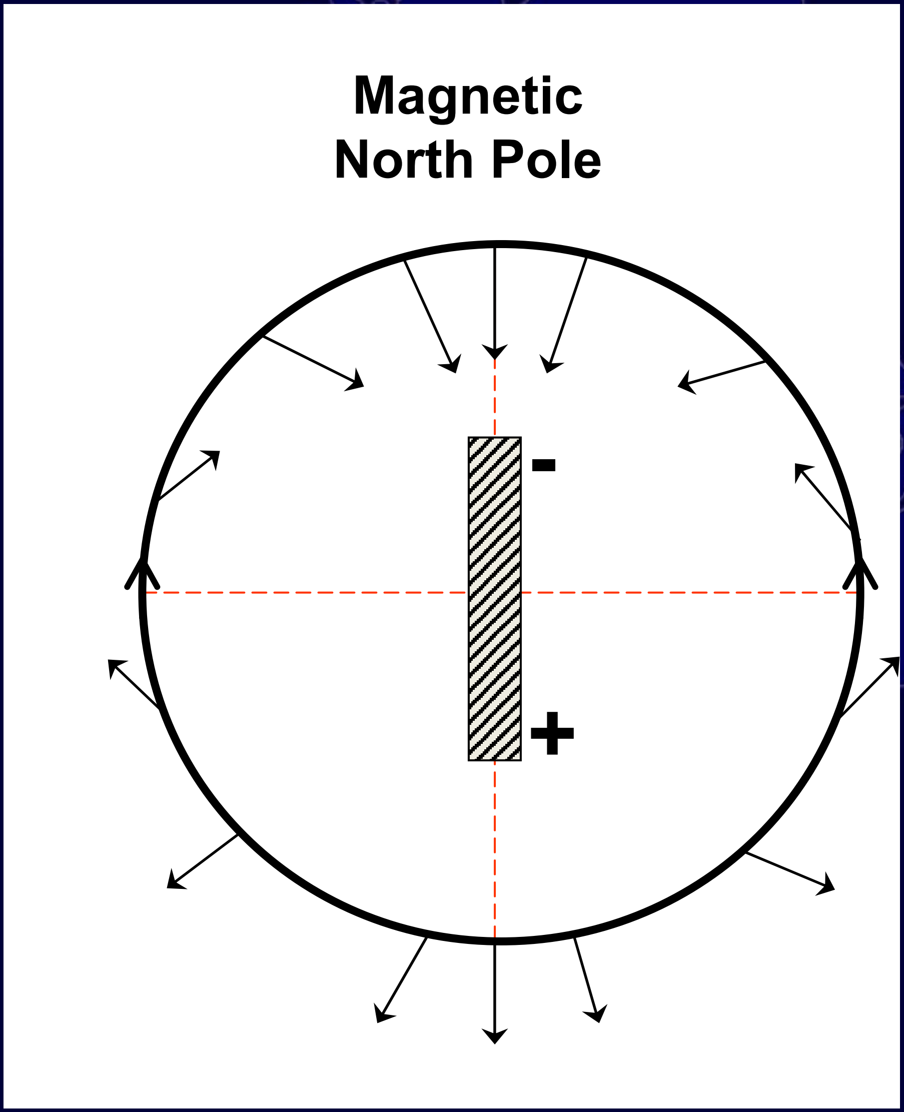
Strengths:

- Acquisition is rapid and straightforward
- Data can be acquired by one person
- Does not need to be coupled to ground
- Can provide very high-resolution images of the subsurface
- Targets do not need to be conductive or metallic

Limitations:

- Does not work well in clays or conductive soils (low depth penetration)
- Less effective in rough or cluttered terrain
- Requires a contrast in dielectric permittivity (primarily controlled by water content) to generate reflections
- Limited depth penetration ($\leq$30 m)

Magnetic Techniques

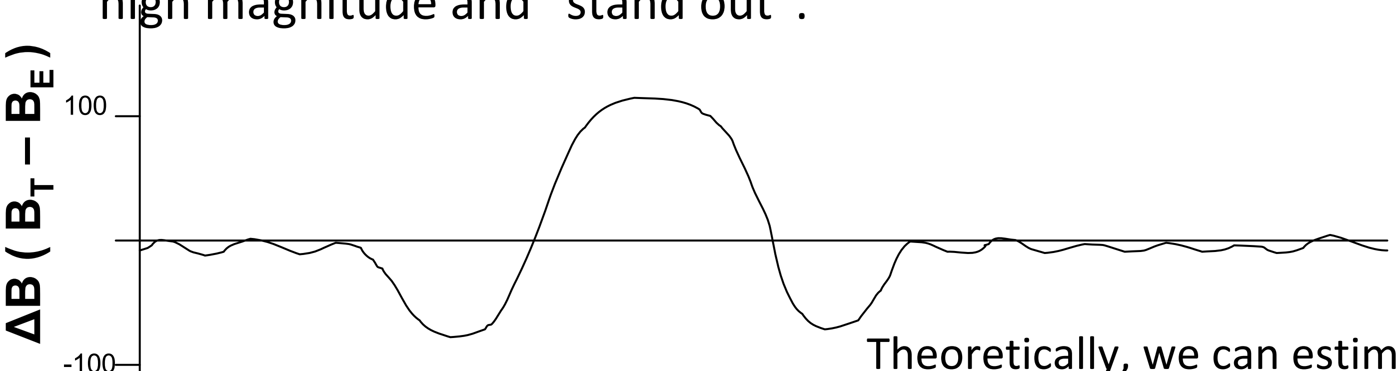


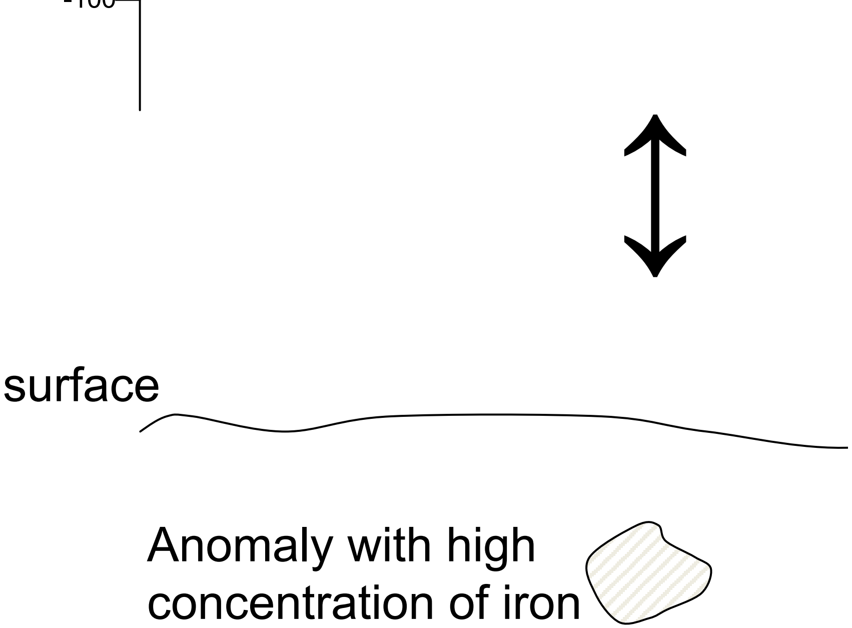
The total magnetic field at any observation point on the earth's surface is the sum of the earth's primary magnetic field (caused by circulation of fluid in the outer core) and any proximal secondary magnetic fields (generated by materials that have become slightly magnetized in the presence of the earth's magnetic field (mostly iron-bearing or magnetite-bearing material)).

We are usually only interested in the secondary magnetic field, which can be found by subtracting the contribution of the primary magnetic field from the measured total magnetic field.

Magnetic Techniques

Secondary magnetic fields (ΔB) associated with man-made iron-based materials are usually very easy to identify, because they are relatively high magnitude and "stand out".





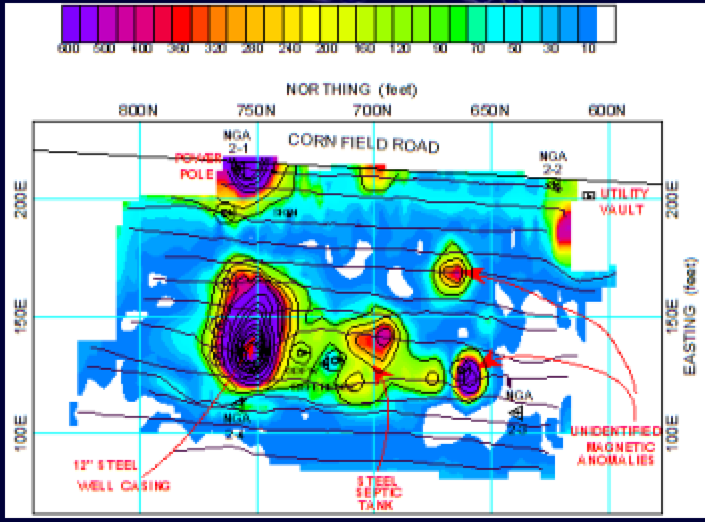
Theoretically, we can estimate the size, shape and depth of the causative body based on the width, shape, and magnitude of the residual magnetic curve (ΔB).

However, secondary magnetic field anomalies (ΔB) are usually interpreted qualitatively – instead of quantitatively – in part because they are often very complex.

Magnetic Techniques

Applications:

•Locating buried drums, pipelines and other ferromagnetic objects
•Locating buried well casings
•Locating/mapping landfills
•Locating sand and gravel deposits (that contain heavy minerals)
•Regional geologic mapping
•Rebar in concrete
•Archeological investigations
•Locating underwater ferromagnetic objects



Magnetic Techniques

Strengths:

•Data can be acquired by one person

•Does not need to be coupled to ground, so data can be acquired quickly and inexpensively

•Data are usually interpreted qualitatively and therefore require minimal post-acquisition processing

Limitations:

•Cannot locate non-ferrous materials such as plastic or concrete

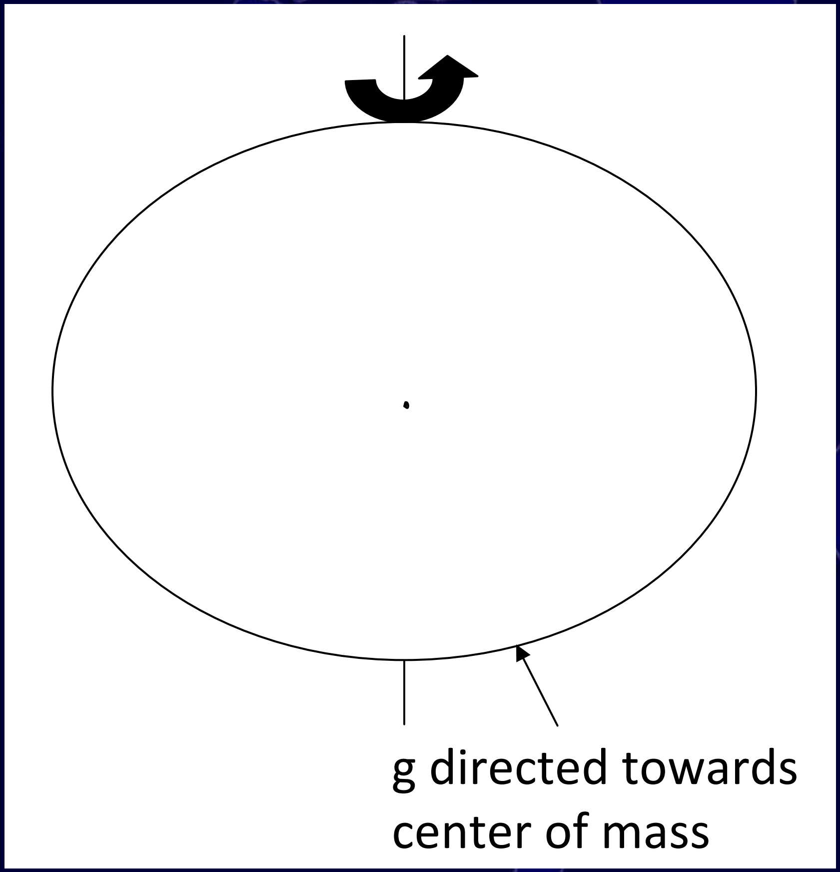
•Magnetic signatures are superposed (cannot distinguish nearby targets)

•Anomalies are generally very complex and may be extremely difficult to interpret quantitatively

•Utilities, power lines, buildings, and metallic debris can cause interference

•The size and depth of objects affect detectability

Gravity

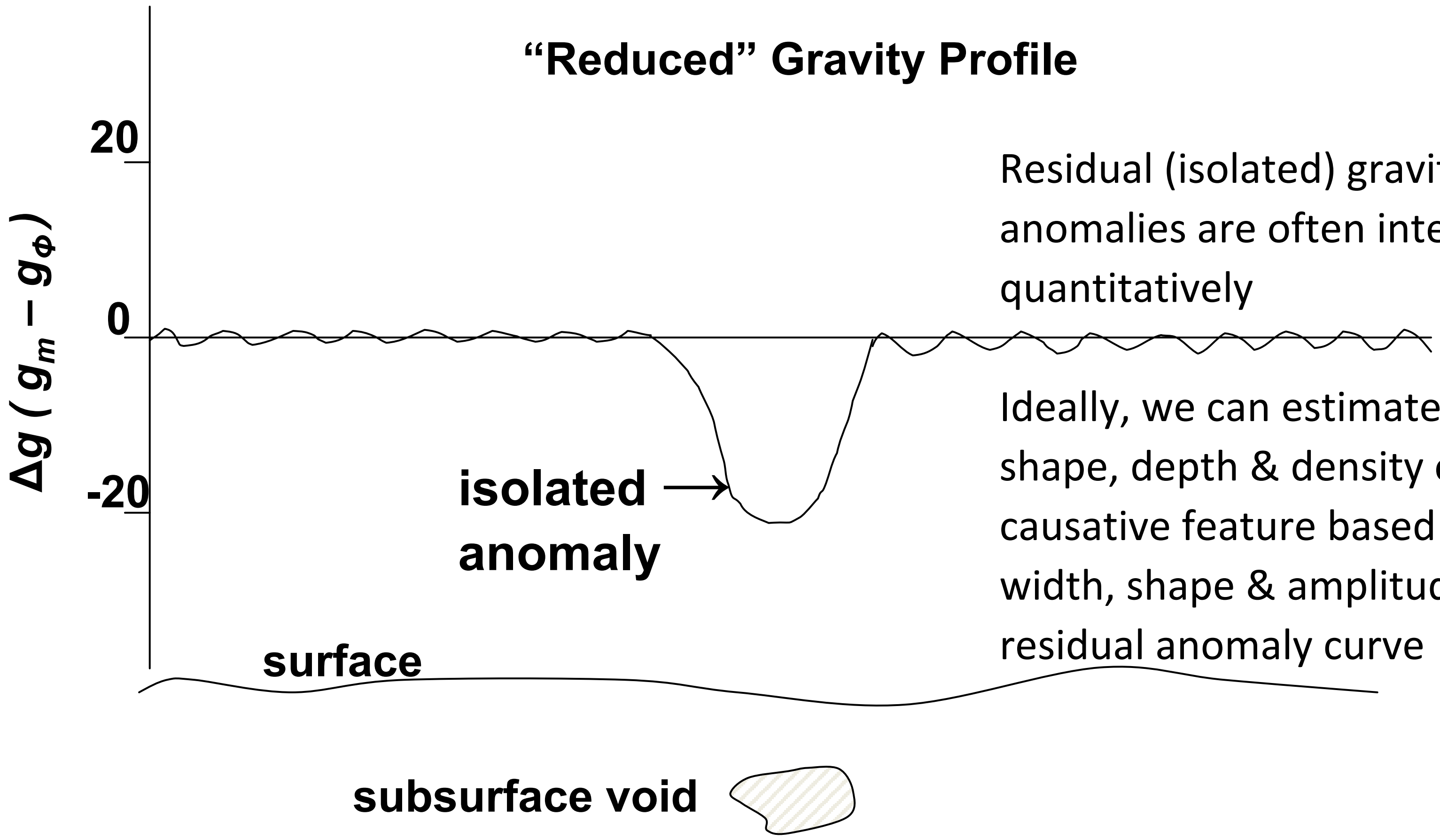


- Gravity is not uniform. It is a function of the mass of the earth, the mean radius of the earth, the angular velocity of the earth, the elevation of the observation location, and surface topography in proximity to the observation location.

- It also varies because of small-scale density variations within the earth's crust (variable depth to bedrock, presence of voids, variations in lithology, etc.).

Gravimeters are generally used to measure relative variations in the earth's gravitational field. Normally, we're only interested in variations that are caused by subsurface geological features of interest.

Gravity



Residual (isolated) gravity anomalies are often interpreted quantitatively

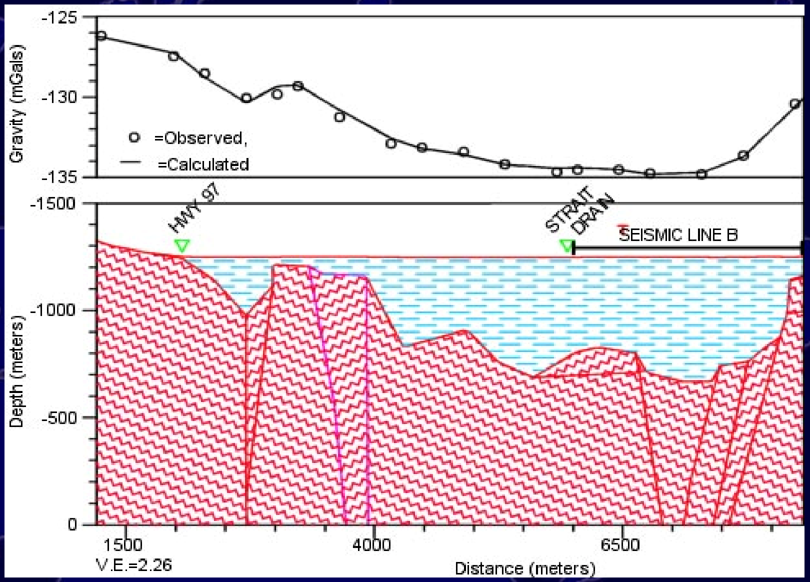
Ideally, we can estimate size, shape, depth & density of the causative feature based on the width, shape & amplitude of residual anomaly curve

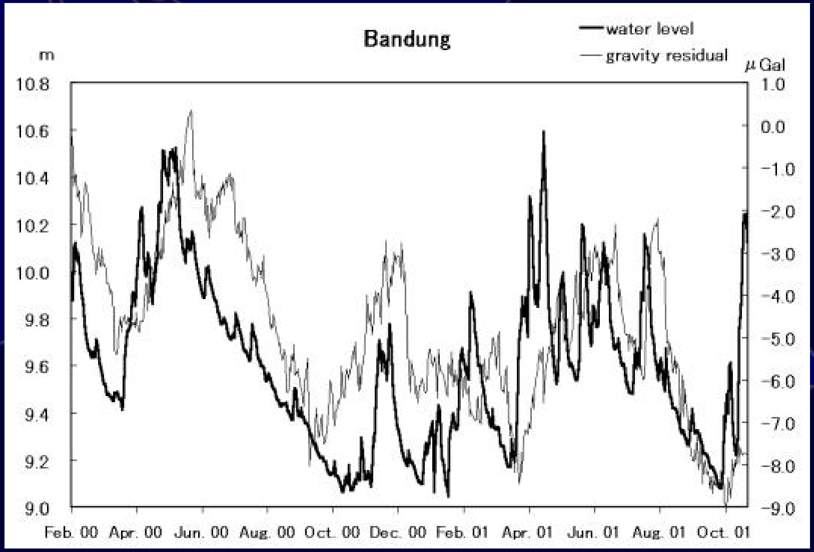
To isolate local variations in gravity (the "residual" gravity anomalies), the measured gravity is corrected to account for changes in latitude, elevation, etc.

Gravity

Applications:

- Estimating depth to bedrock
- Determining in-situ rock/soil densities
- Mapping air-filled cavities in karst terrain
- Mapping abandoned underground mines
- Estimating tonnage of ore
- Determining volumes of available fill
- Measuring changes in water table elevation





Gravity

Strengths:

•Data can be acquired by one person

•Only respond to changes in density (not affected by electrical or magnetic noise), so can be acquired in urban areas

•Data can be interpreted quantitatively - model (depth, shape, size, density) of target can often be generated

Limitations:

•Relatively slow data acquisition

•Data interpretation requires control parameters (i.e. background density)

•Data interpretation can be time consuming

•Very precise surveying control is required so that elevation and latitude corrections can be applied

•Gravity signatures are superposed (cannot distinguish nearby targets)

Final notes:

- Geophysical data can greatly improve site characterization and can reduce costs, but…

- Many geophysical techniques provide non-unique results unless they are constrained by borehole or other information.

- Use geophysical techniques in conjunction with “ground truth” measurements!

Final notes:

- The success of a geophysical survey depends on planning the survey appropriately for the site – share all available information with the geophysicists before they arrive on site!

- Using multiple geophysical techniques is often the most efficient method for accurate site characterization.