7_2 Exploration and Characterization - Geophysics

Recap:

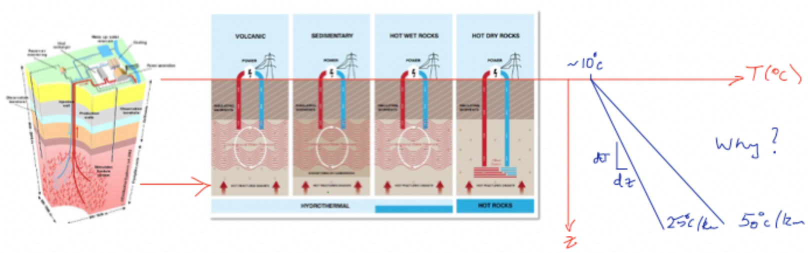
1. Geological setting provides information on global location of resources
2. Location specific structure will differ in various environments

Movies: https://www.energy.gov/eere/forge/sandia-national-laboratories-west-flank

Resources: WG7

Motivation:

1. Motivation [10%] Provide context for the topic. *Use of relevant public domain videos* are a useful method for this. Why is this particular topic or sub-topic important in the broad view of geothermal energy engineering?



Quality of resource defined by Thermal_power = Mass_rate * c * delta_T
Therefore prospect for:
(i) High Mass_rate/permeability/overpressure - define fast flow paths, and
(ii) High T at shallow depth
Less crucial in "engineered" systems - "EGS" and "GSHP"

Scientific Questions:

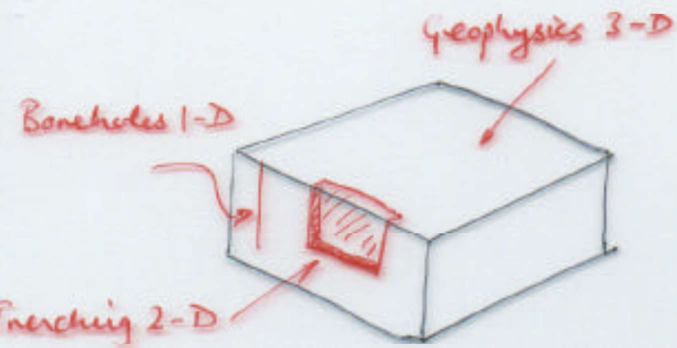
2. Scientific Questions to be Answered/Outline [10%] What questions arise from the motivation. What are the sub-topical areas that address these scientific questions.

1. How do we locally define the reservoir and the distribution of:
   A. Temperatures - as shallow as possible
   B. Permeable pathways - as distributed as possible or high flow rates

GEOPHYSICS

1. Geomagnetic methods
2. Geoelectric methods DC/AC/EM
3. Seismic methods
4. Gravity methods
5. Borehole methods - Well logging

GEOPHYSICAL METHODS OF INVESTIGATION



Investigation Scales

small scale – representativeness of sample
– large scale structures
v. imp for groundwater since large scale structure controls flow/transport behavior.
– use of pump tests.

large scale – – big picture
– correlation with real behavior through boreholes.

Geophysical Methods:

Fast/ large volume/area coverage → inexpensive.

1. Geomagnetic methods
2. Geoelectric methods
   - 2.1 Direct Current
   - 2.2 Electromagnetic (Radar)
3. Seismic methods
   - 3.1 Refraction
   - 3.2 Reflection
4. Gravity methods

Miscellaneous: Well logging.

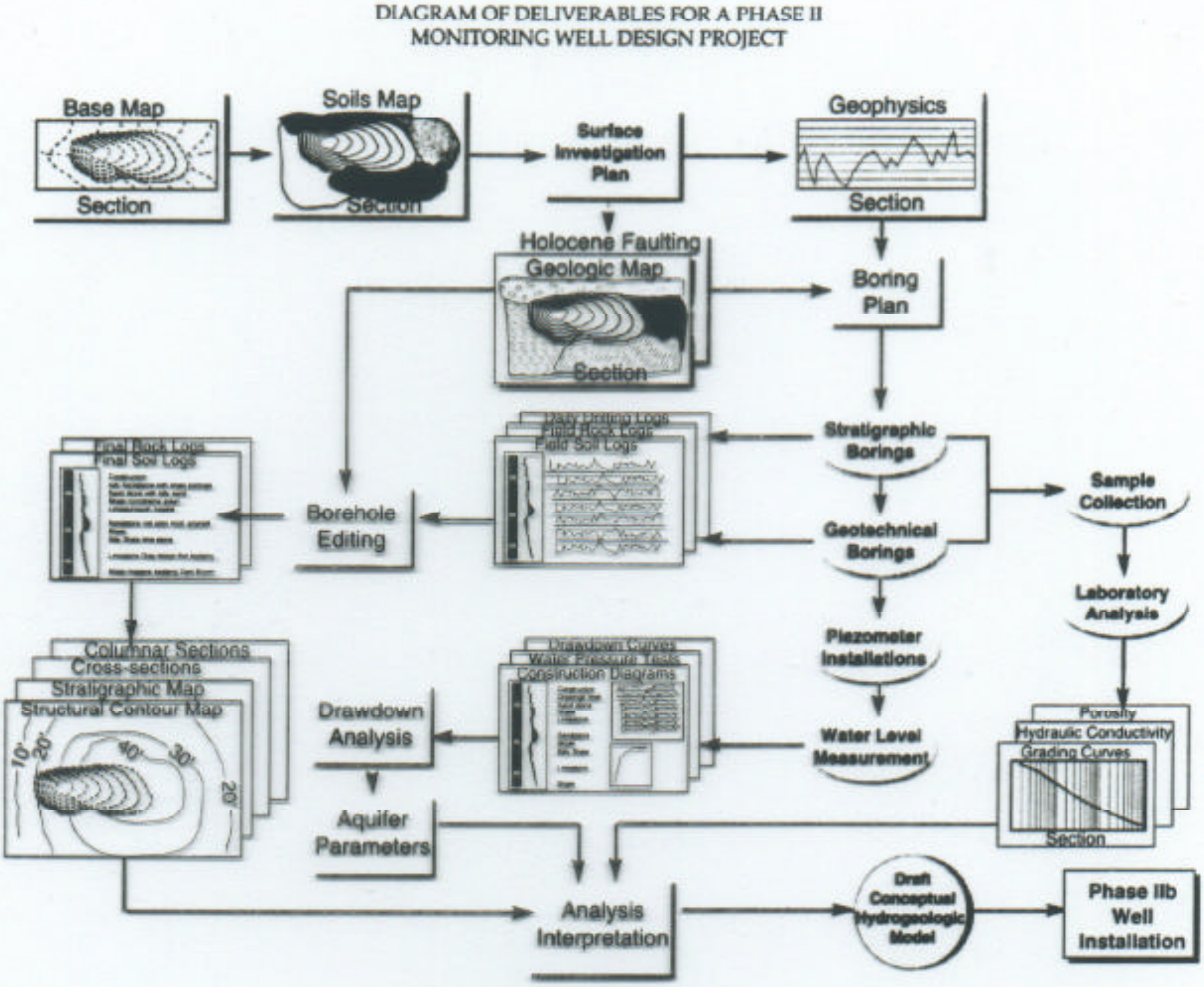


Figure 3-3a Phase II Flow Diagram

CONCEPTS OF SCALE

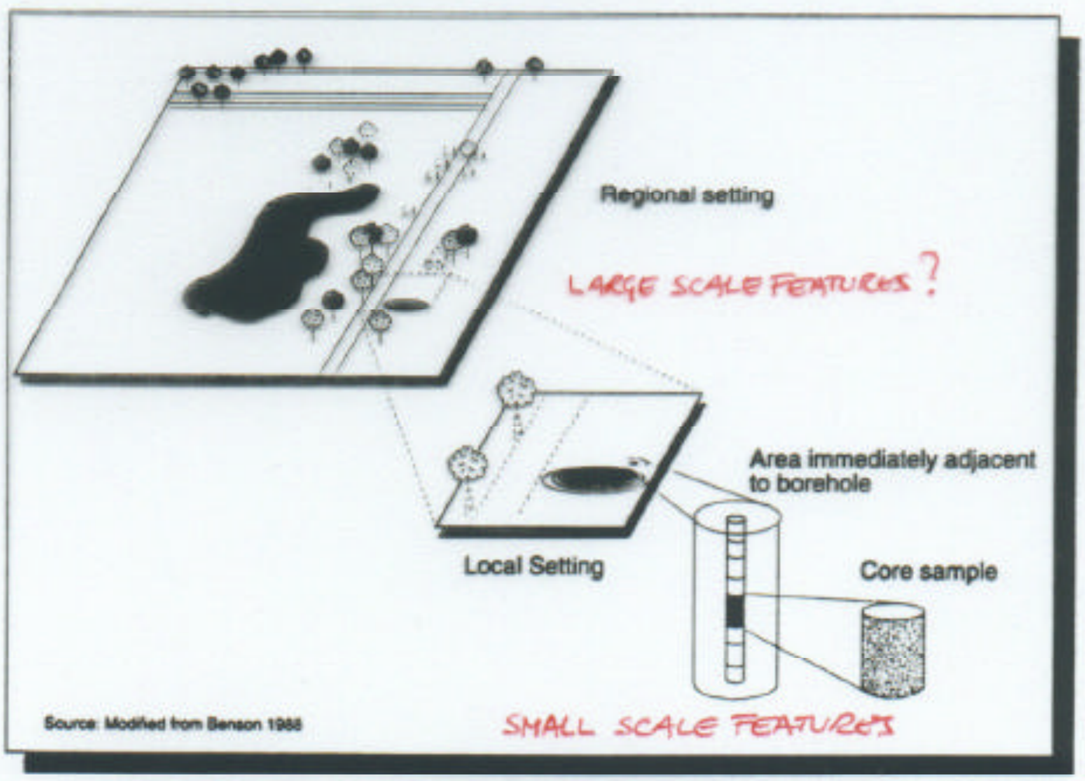


Figure 3-12 Regional to Core Sample Scales

1. GEOMAGNETIC METHODS

- Measure change in Earth's mag. field
  ∴ Locates ferrous targets

- Response proportional to
  1. Mass of target, M.
  2. $\frac{1}{r^3}$ separation of target.

- Susceptibility to urban utilities
  ∴ rural areas better

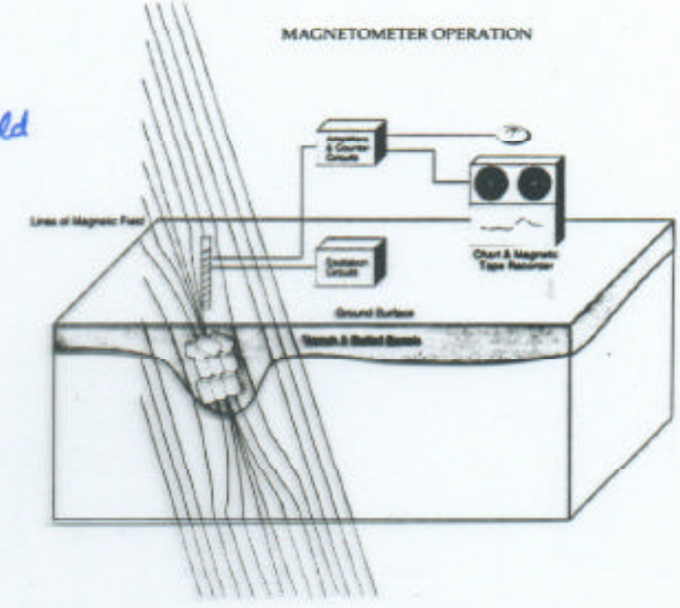


Figure 3-20 Magnetometry

- Measurement in nTeslas
  i.e. 10^{-9} Teslas
- Resolution ↓ with
  ↑ target depth since $1/r^3$

Max Depths

- 1 drum @ 10 ft.
- Multi-drums @ 30 ft.

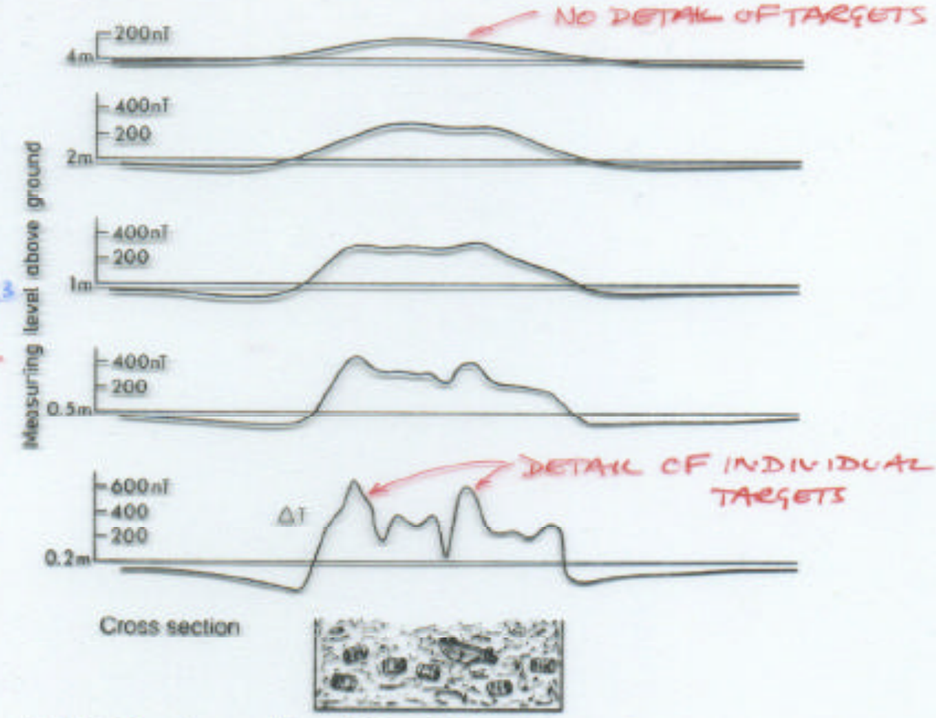


Fig. 2.1. Magnetic anomalies at different heights above ground

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Anomaly influenced by inclination of Earth's mag. field. (60° in U.S.)

Max to South

Depth = $\frac{1}{2}L$.

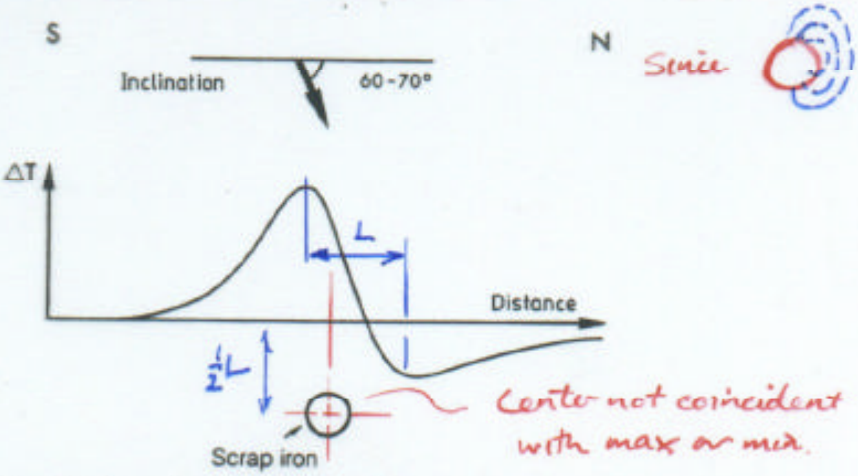


Fig. 2.2. Magnetic section of the total intensity DT over a globe-shaped concentration of scrap iron at 65° latitude

Two types of magnetometers

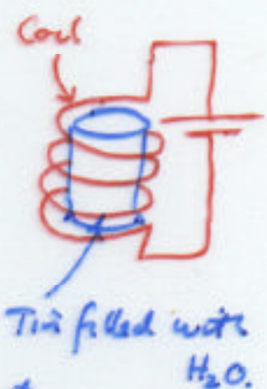
1. Permanent Magnet Magnetometers

{ Magnetic field balance
{ Torsion magnetometer

- Measures ↑ and → magnetic components
- Accuracy 1 nT
- Slow but v. accurate

2. Proton Magnetometers

- Measures total field, T, or variations, ΔT.
- Principle: - Apply a strong 1 second duration magnetic field
  - Causes hydrogen protons to spin (changes spin)
  - Shut off magnetic field and measure spin frequency.



- Fast, but records only max field component
- Accuracy $\frac{1}{2}$ nT

2. GEOELECTRIC METHODS

- D.C. METHODS
  - PROFILING
  - SOUNDING
- ELECTROMAGNETIC (GPR)

DC. METHODS

- Uses electrical conductivity/resistivity contrasts.
- Apply D.C. field.
- Measure modified field

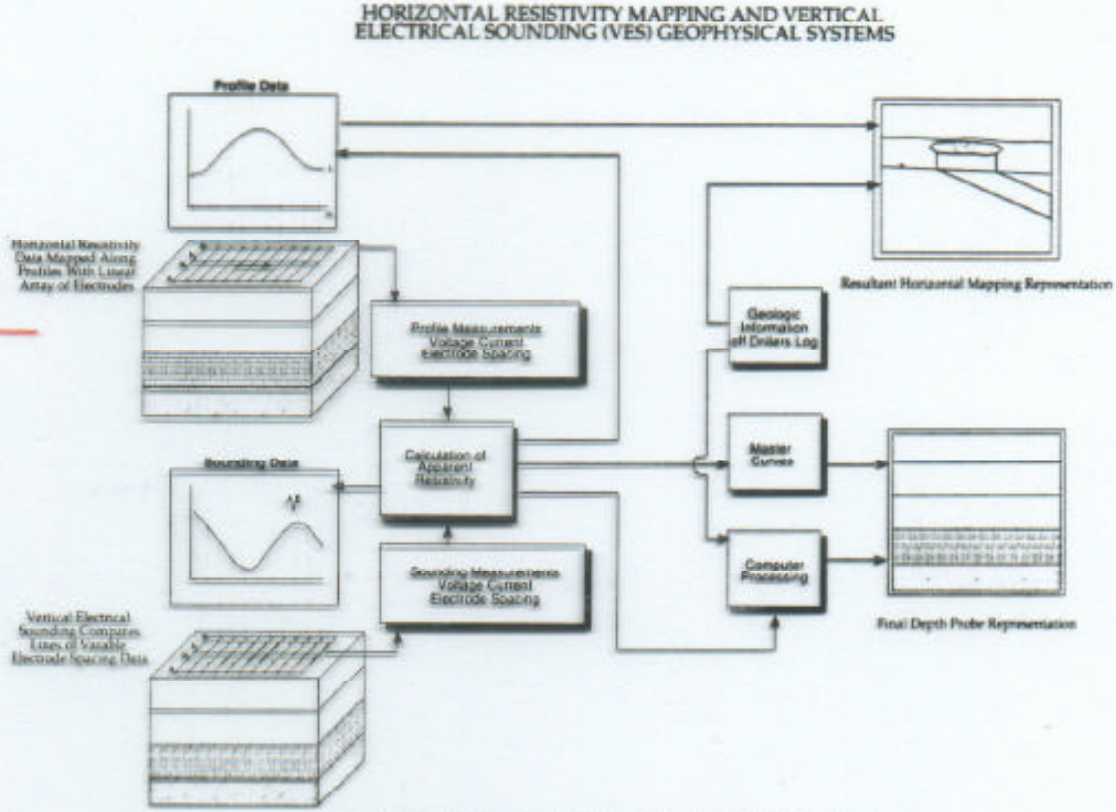


Figure 3-27 Resistivity Geophysical Method

Ohm's Law

$$U = I \cdot R$$

R = resistance [Ω]

$$R = \frac{b}{q} \rho$$

ρ = Specific resistivity [Ωm]

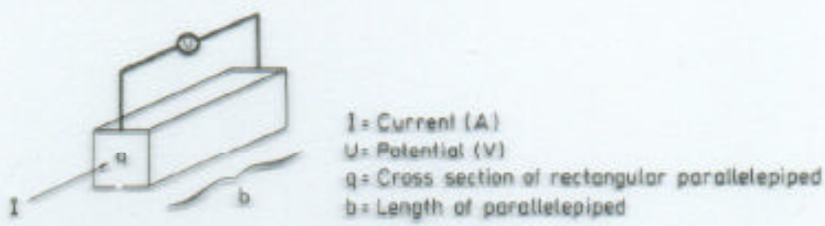


Fig. 2.3. Current flow through a limited conductor

Method

Apply 1. DC
2. AC @ low frequency (< 100Hz)

- Two stakes with high conductivity.
- Causes potential field
- Measure field by increasing spacing of input electrodes to ↑ depth penetration.
- Infer distribution of conducting layers.

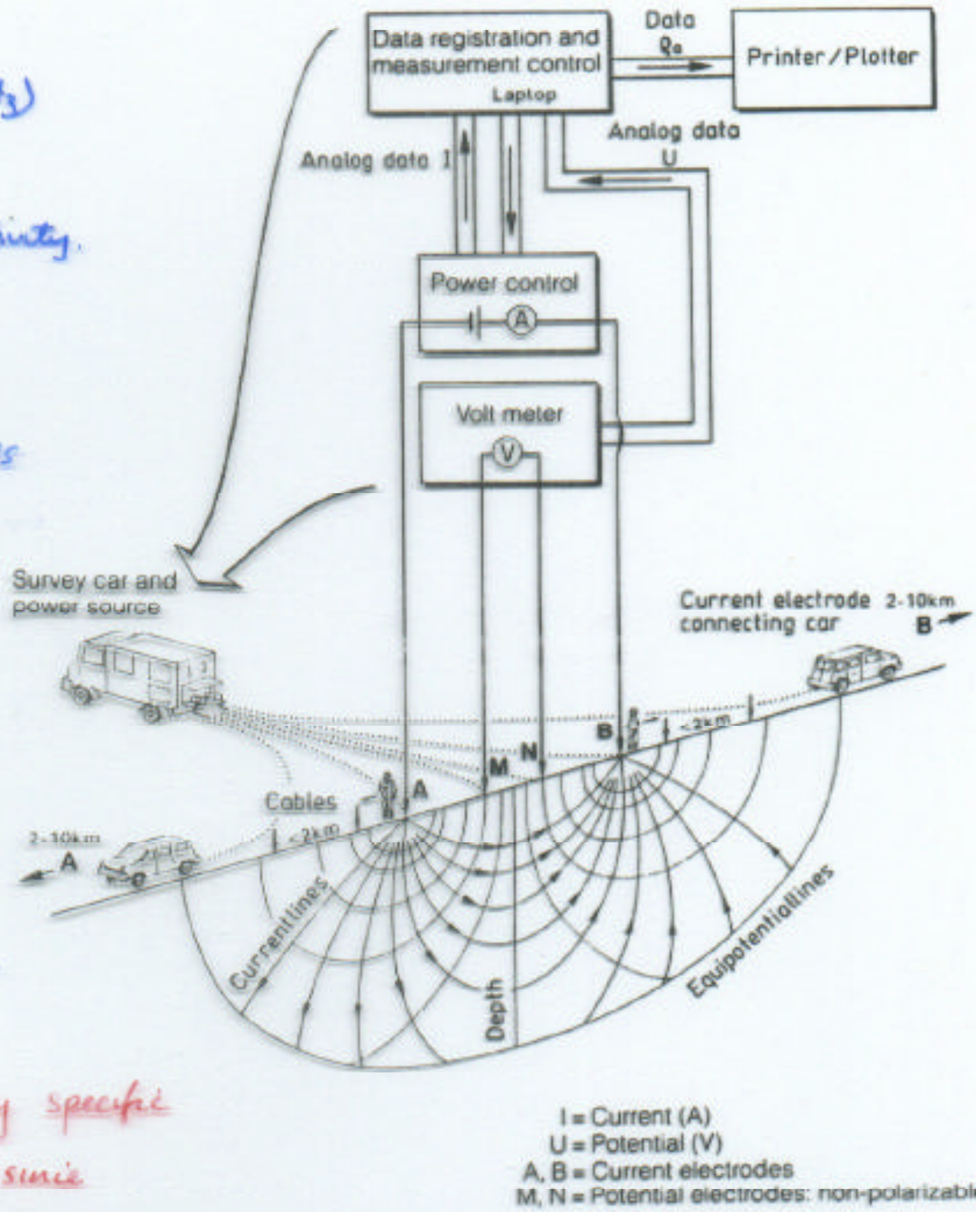


Fig. 2.4. Principle of measurement and potential field for geoelectric DC surveys

Data Reduction

Plot $\frac{U}{I}$ at variable separation.

$\frac{U}{I} \approx R$ but are really specific resistivities, ρ_a, since measured at top of half-space.

Correct to specific resistivities as:

$$\rho_s = K\left(\frac{U}{I}\right)$$

	K
Schlumberger	$\frac{\pi}{a}\left[\left(\frac{1}{2}L\right)^2 - \left(\frac{1}{2}a\right)^2\right]$
Wenner	$2\pi a$
Dipole-dipole	$\pi a \cdot n(n+1)(n+2)a$

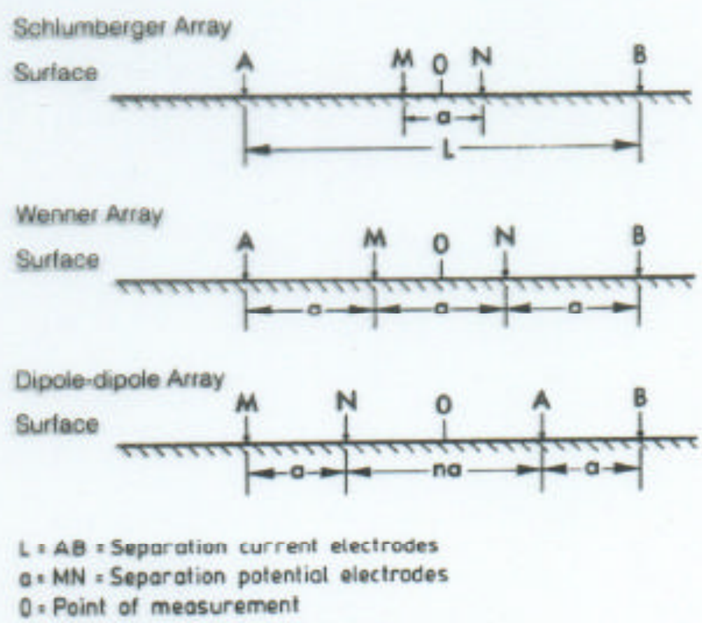
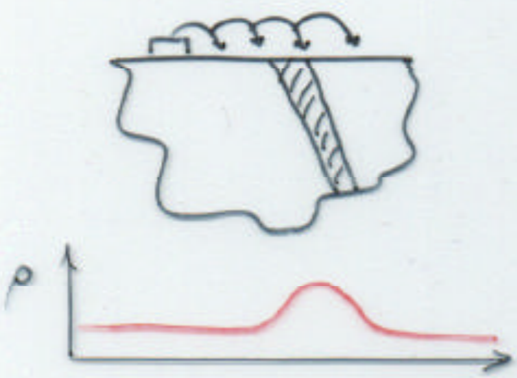


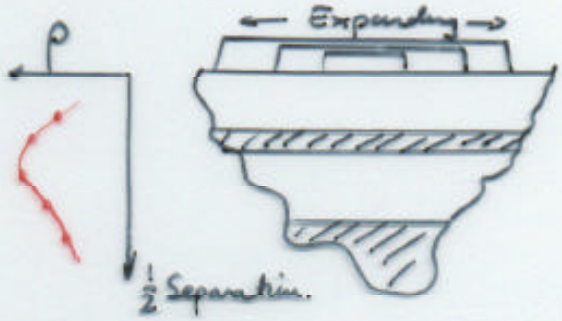
Fig. 2.5. Arrays for geoelectric mapping and sounding

Connect the magnitudes to ρ_s:

Method depends on resistivity contrast between layers

Mapping | **Sounding**





Mapping

- Locate rim of disposal sites / or drums / or plumes

- Fixed array separation ∴ locate changes in ρ_s or absolute magnitude of ρ_s

- Separation between electrodes chosen for sampling depth.
  Wenner array commonly used.

- Require contrasts in ρ_s

Garbage	< 20 Ωm	
Gravel/sandstone	1000 Ωm	Contrast ok
Clays	3–30 Ωm	No contrast

SOUNDING

Determine:

1. Apparent resistivities of strata
2. Thickness and depth of interfaces

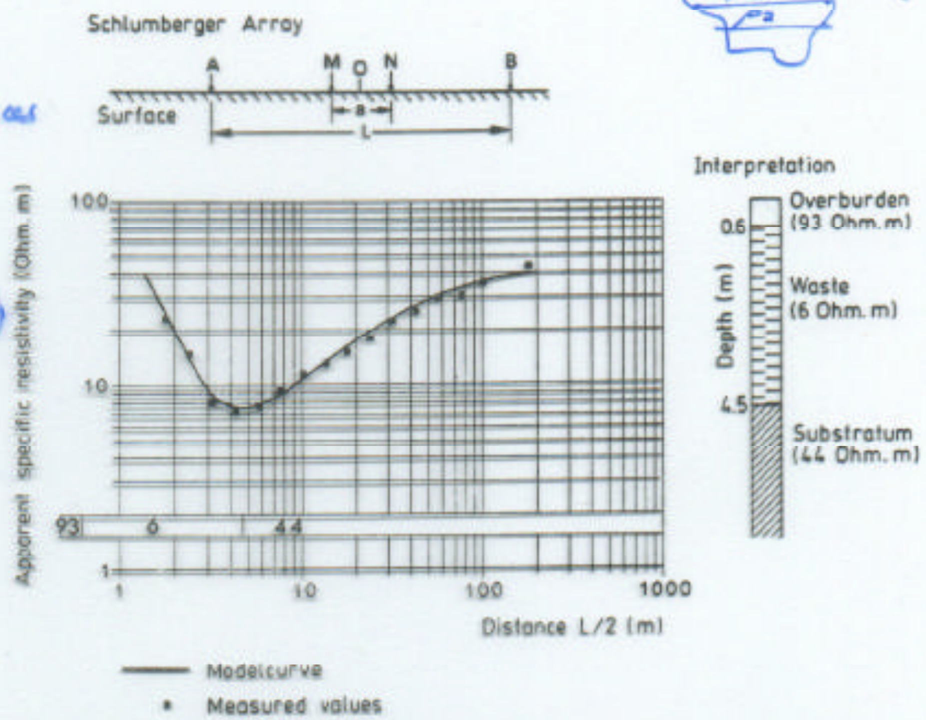


Fig. 2.6. Geoelectric sounding curve (VES) of a Schlumberger array with digital interpretation and computed model curve of the minimum type "H"

Mainly Schlumberger array

1. Increase separation logarithmically
2. Plot $\rho_a = \frac{U}{I}$ with half spacing L/2
3. Match with model type curves, or invert numerically.

Problems

1. Omitted beds

   Thin layers or layers masked by very conductive beds

2. Equivalence

   Non-unique curves since equivalence of behavior

Table 2.1. Specific resistivities

Rock type/Material	Specific resistivity [Ωm]
Rock type	
clay, marl, rich	3 – 30
clay, marl, meagre	10 – 40
clay, sandy, silt	25 – 150
sand, with clay	50 – 300
sand, gravel in ground water	200 – 400
sand, gravel, dry	800 – 5000
rubble, dry	1000 – 3000
limestone, gypsum	500 – 3500
sandstone	300 – 3000
salt beds and salt domes	> 10000
granite	2000 – 10000
gneis	400 – 6000
Deposited refuse	
domestic garbage	12 – 30
debris and dumped soil	200 – 350
industrial mud	40 – 200
scrap metal	1 – 12
pieces of broken glass and porcelain	100 – 550
casting sand	400 – 1600
wastepaper (wet)	70 – 180
contaminated plume of domestic-garbage dump	1 – 10
used oil	150 – 700
tar	300 – 1200
cleaning clothes and materials	30 – 200
used lacquer and paint	200 – 1000
barrels (empty)	5 – 20

Equivalence

- Non-unique solution
- Match with borehole data
- Effect of saturant may influence results.

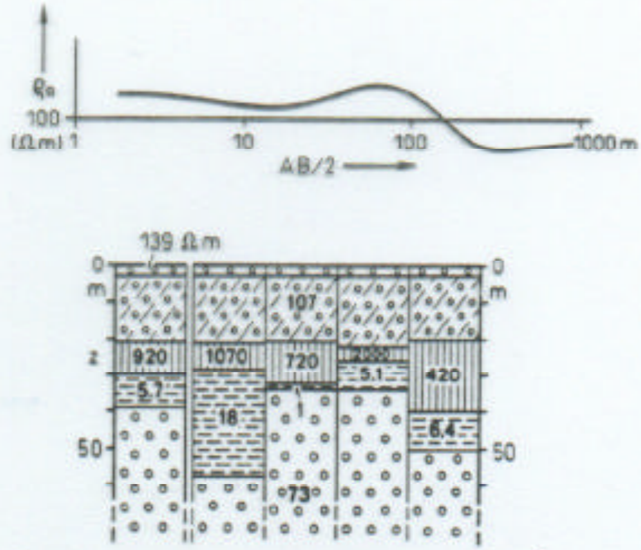


Fig. 2.7. Equivalent digital interpretations of a Schlumberger sounding curve. Left column = mathematically best model. The selection of the most suitable model has to consider neighboring curves and the known geology

Fracture detection methods

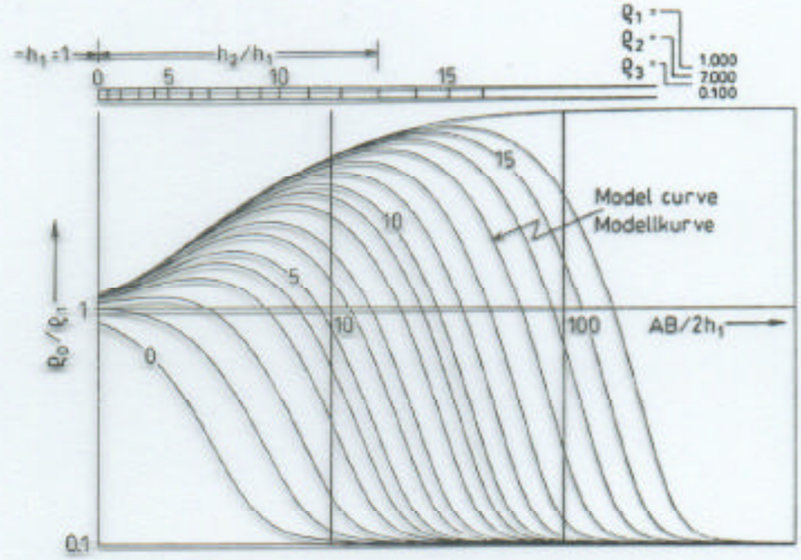
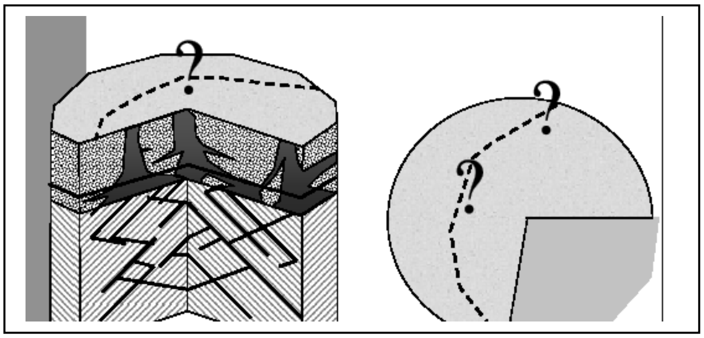


Fig. 2.8. Three-layer master curves in a log-log graph of the INGESO atlas. The resistivities of the three beds are in the ratios 1 : 7 : 0.1; first layer : second layer : third layer. The sounding curve, which has been drawn on log-log graph paper in the field, is laid on top of the master curve and moved around until one of the master curves tallies with the field curve. The thickness of the second layer, which has here seven times the ρa-value of the first layer (see the resistivity values at the top right) can be found by the number of the curve no. 13. On the thickness beam at the top left, which is divided from 0 to 16, the thickness h_2 can be directly determined

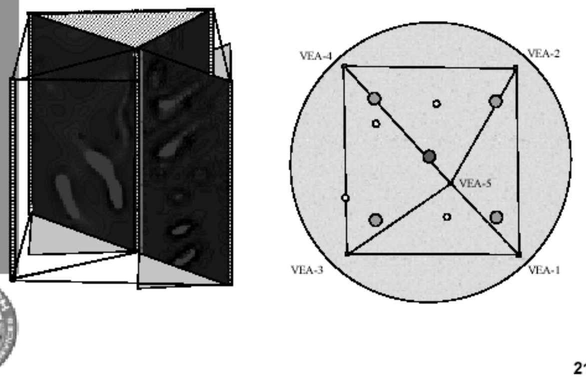
Edwards AFB, CA – Thermal Remediation Monitoring with ERT

Edwards Air Force Base, Edwards, CA

Contaminants Treated:	TCE
Hydrology:	Groundwater at 30 feet bgs
Geology:	Fractured granite
Starting Contaminant Levels:	DNAPL expected
Cleanup Levels Achieved:	Project Awarded in 2000
Remediation Time Period:	May-June 2002
Client Reference:	Scott Palmer, Earth Tech, San Jose CA, (408)-232-2826
Remediation Design Engineers:	Dr. Gorm Heron, Dr. Steve Carroll, Mr. Hank Sowers



ERT data planes



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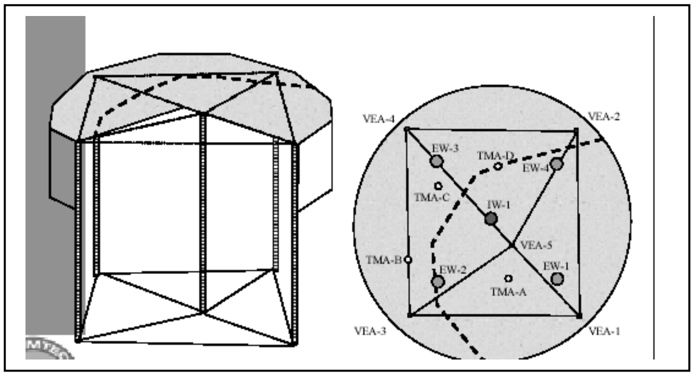
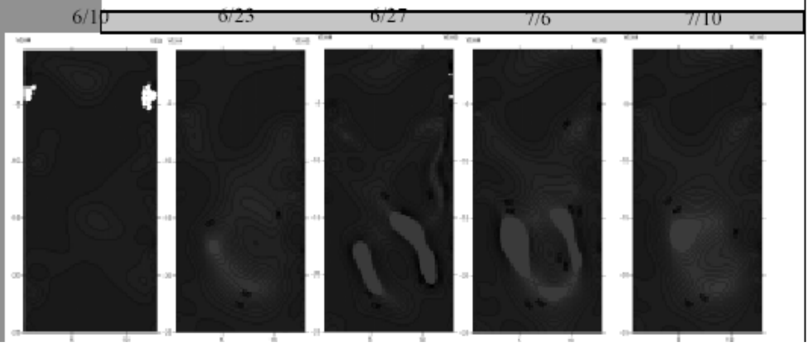


Example ERT data plane



Magnetotellurics

Measure electrical resistivity from current generated by the Earth's (natural) magnetic field.

e.g. West Flank Coso:
https://www.energy.gov/eere/forge/sandia-national-laboratories-west-flank

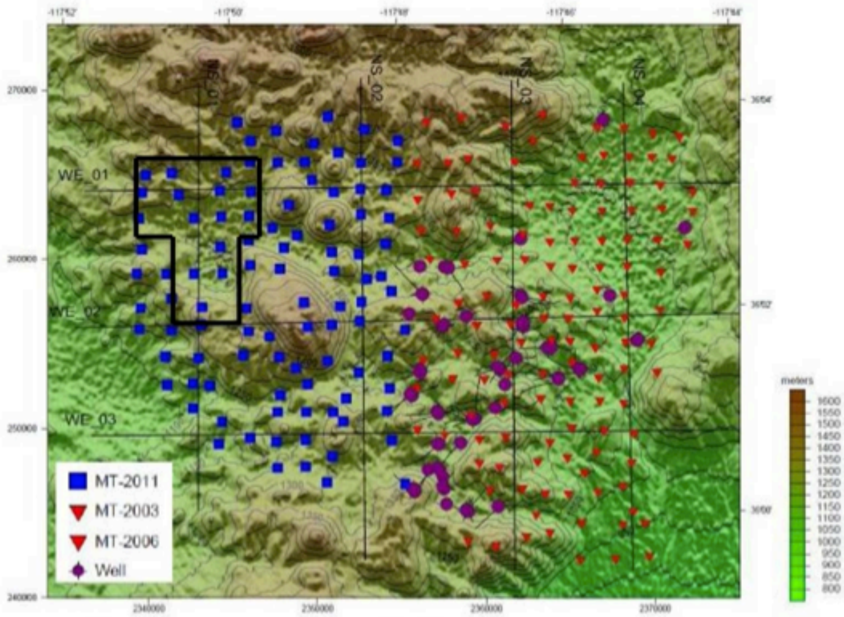


Figure 23. MT survey points throughout the Coso Volcanic Field starting in 2003 through 2011. The West Flank FORGE test area polygon is pictured for reference.

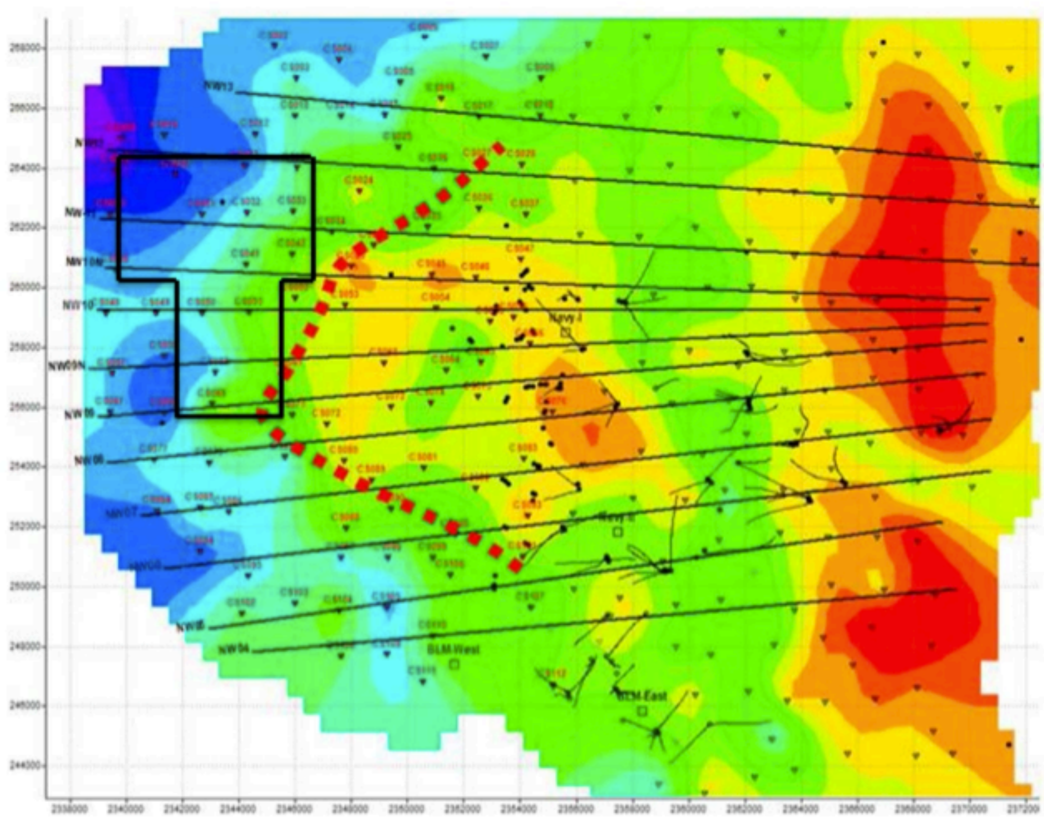


Figure 24. Map of MT conductance at ~600 meters depth of a 1D inversion. The red dashed line is the mapped extent of the hydrothermal system at Coso. The West Flank FORGE test polygon is drawn on top for reference.

INDUCED POLARIZATION (INDUCED POTENTIAL)

- Apply DC current as Wenner or Schlumberger.
- Cut current and measure voltage decay with time 1s – 8s
- Reverse current to erase remnant charge

Effective depth penetration, D

$D \sim a(n+1)\frac{1}{2}$

Dipole lengths n = 1 to 6

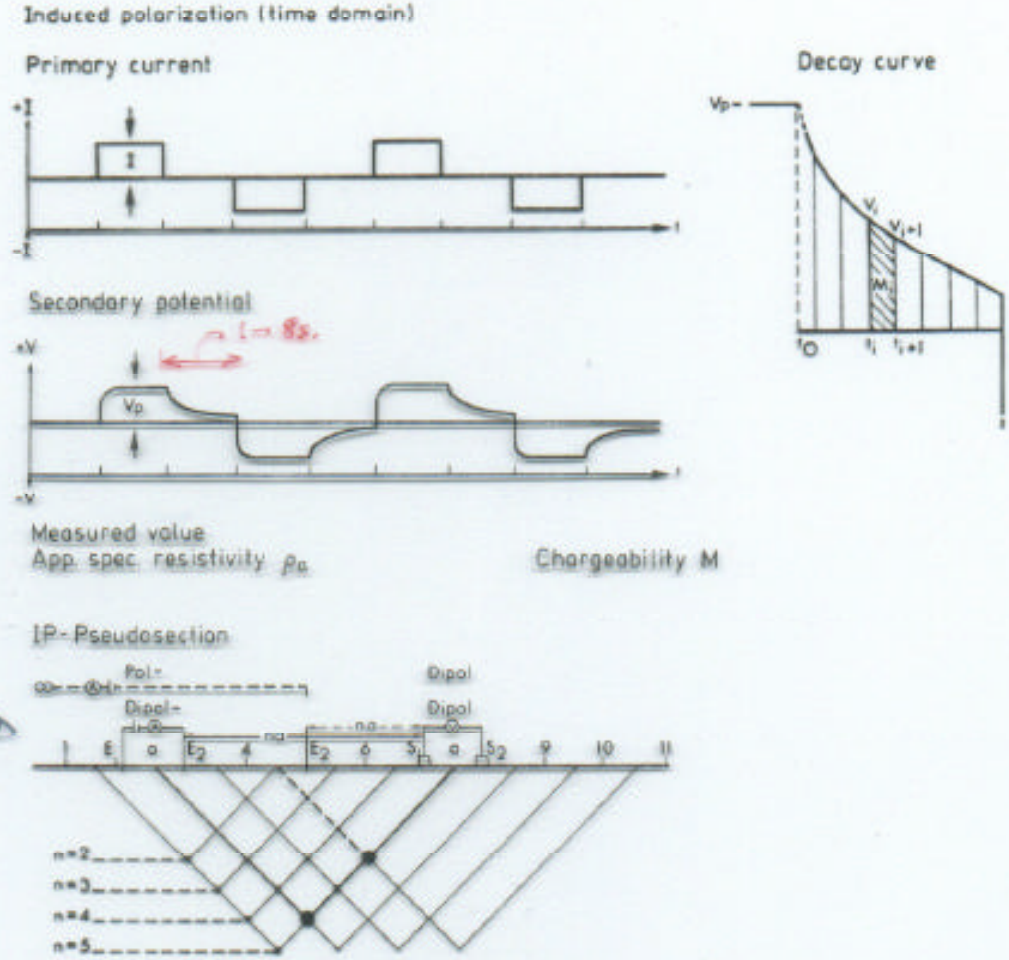


Fig. 2.9. Principle of induced polarization (IP)

SELF POLARIZATION

- Measures natural geo-electric field
- Results from chemical reactions (natural battery) eg Redox.

  30mV – 200 mV

  – sometimes results from rapid fluid flow < 10mV.

2.2 ELECTROMAGNETIC METHODS

NOTE: $v = f\lambda$

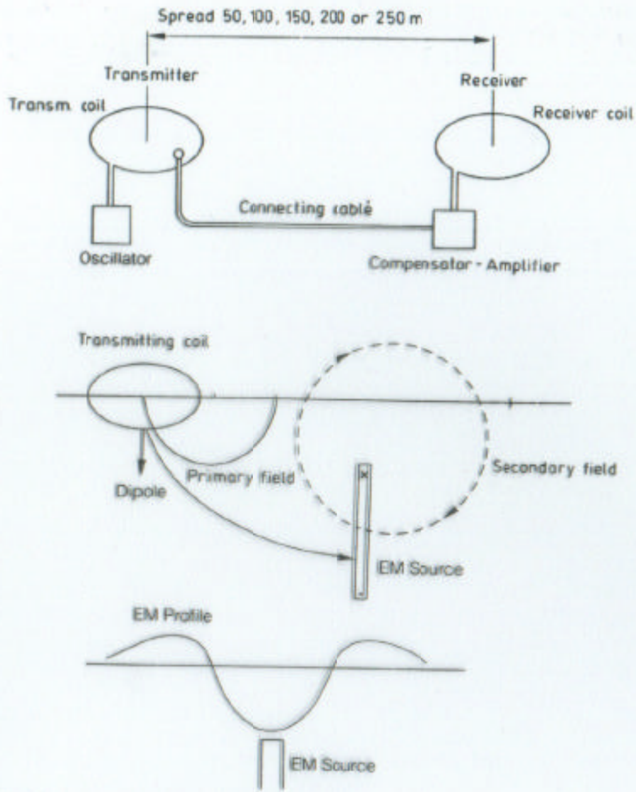
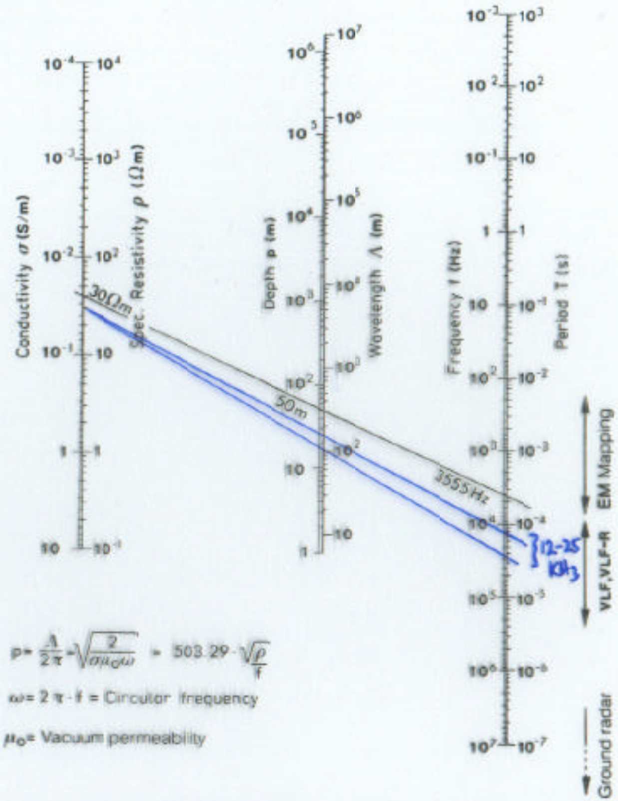


Fig. 2.11. Principle of electromagnetic mapping



$$p = \frac{\Lambda}{2\pi} = \sqrt{\frac{2}{\sigma \mu_0 \omega}} = 503.29 \cdot \sqrt{\frac{\rho}{f}}$$

$\omega = 2\pi \cdot f$ = Circular frequency

μ_0 = Vacuum permeability

Fi. 2.12. Nomogram showing the relations of specific resistivity (left column), depth of penetration (middle column) and frequency (right column) of a homogenous plane wave

EM Mapping (Longitudinal profile)

- Primary EM field by primary coil
- Induces secondary EM field in body of different specific resistivity ρ_s
- Resolve interpretation ambiguities using multiple frequencies. (perhaps 12)

EM by Distant Transmitter (VLF)

- Permanent transmitters around globe (12 - 25kHz) (Submarine navigation)
- Measure induced secondary fields & interpret.
- Set frequency ∴ depth of penetration ~15m for $\rho_a < 30\ \Omega m$.

TIME - DOMAIN ELECTROMAGNETICS (TDM)

- Similar to IP but decay of EM signal is measured with time.

- Transmitter loop of 5m to 100m diameter but achieve large depth penetration 50 - 1000m.

Applied to determine brine pools and salt water intrusion.

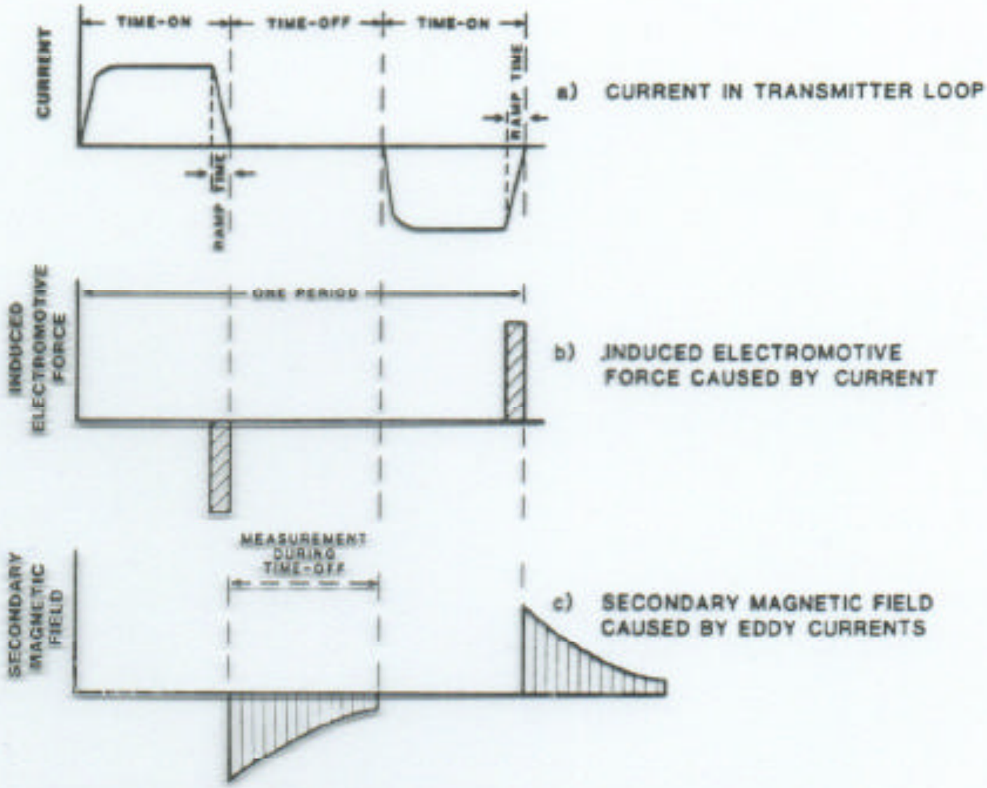
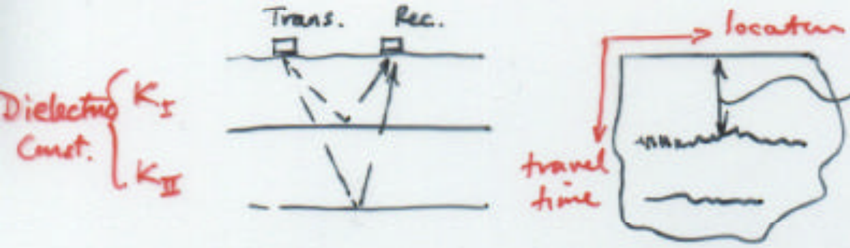


Fig. 2.15. System wave forms employed by the TDEM method

GROUND-PENETRATING RADAR (GPR)



Records travel time that must be scaled to a velocity → depth.

- Shallow depth penetration for EM waves 8 MHz – 4 GHz
  Reflection from interfaces with dielectric constant contrast, K

- Dielectric constant, $K = \dfrac{\text{Capacitance of material}}{\text{Capacitance of vacuum}} = \varepsilon$ (non-dimensional)

- Depth penetration – Limited in low conductivity (high resistivity)
  - Clays 0.2 m
  - Salt, ice, dry granite > 300 m
  - Typically 3–10 m.

- High dielectric contrast of water (80) greatly influences response
  - Changing saturation (record infiltration in real time)
  - Type of saturant (LNAPL or DNAPL)

- Depth penetration controlled by frequency
  ↑ frequency → reduce penetration and increase resolution
  (see nomogram)

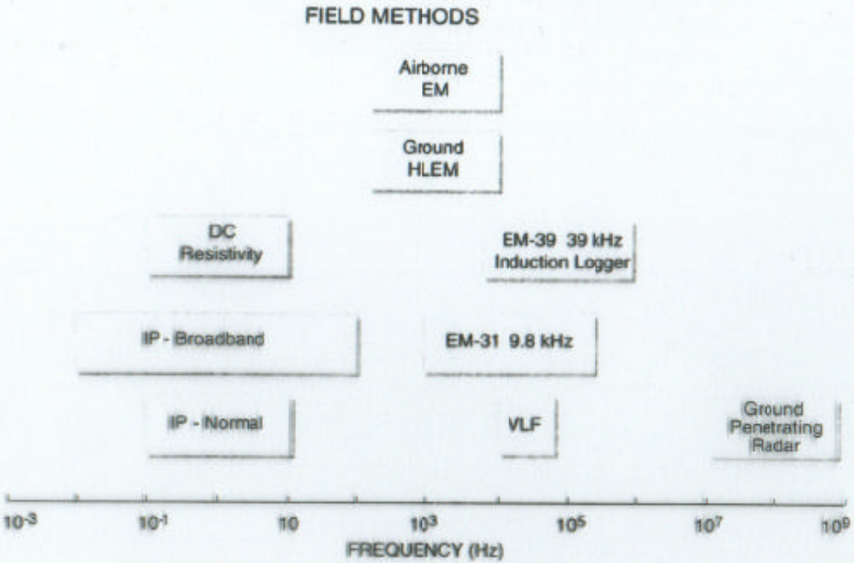


Figure 3-22 Frequencies Used By Electrical Geophysical Methods

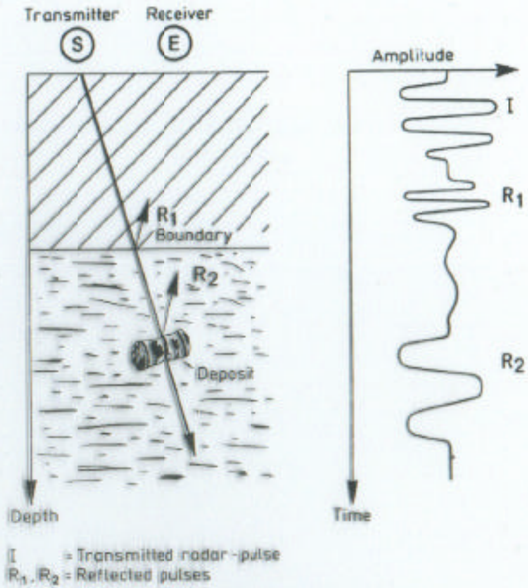


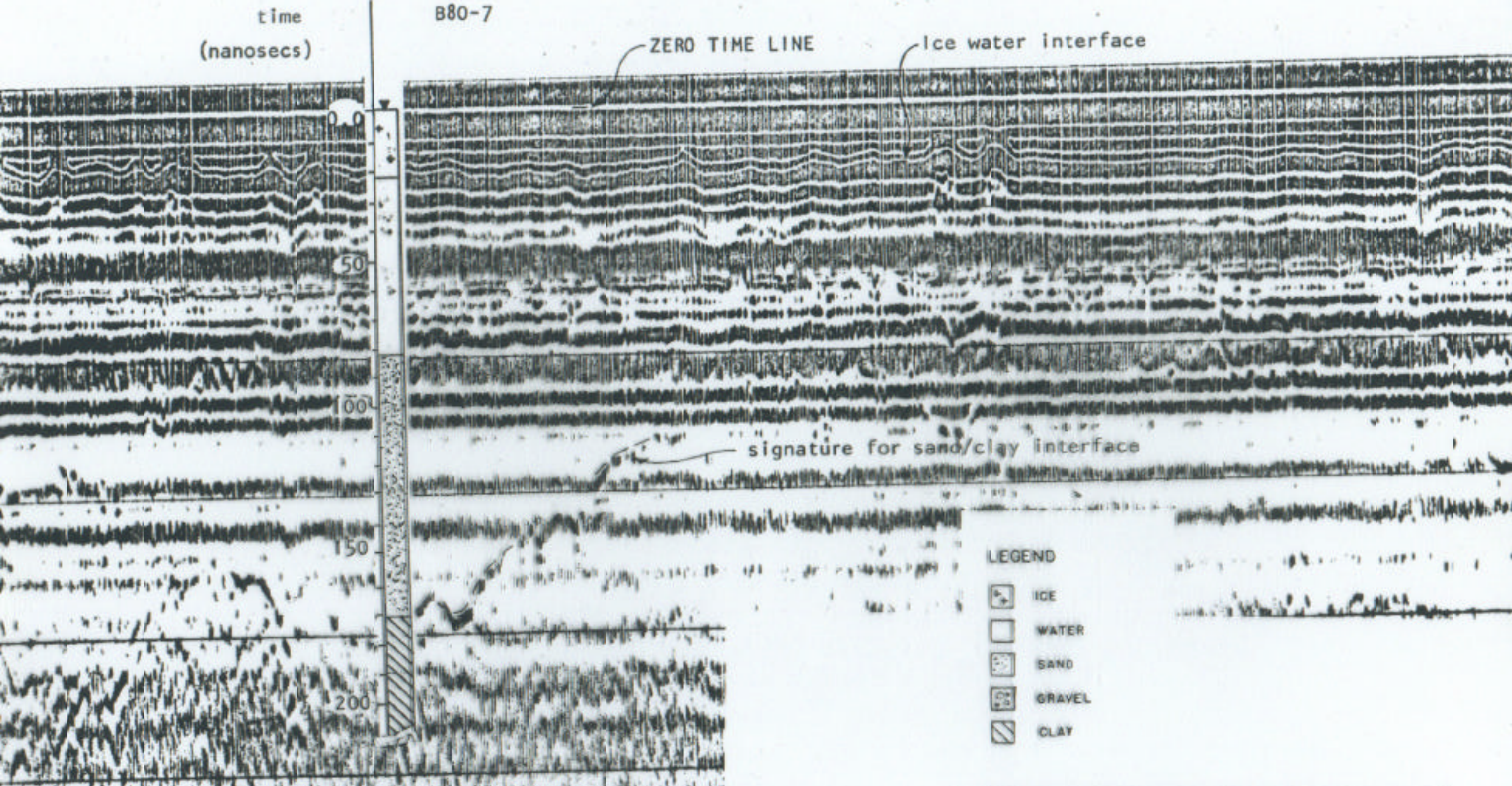
Fig. 2.17. Principle of ground radar measurements

Table 2.3. Dielectric constants (K), electric conductivity (σ), electric velocity and attenuation (a) at a frequency of 100 MHz. Davis and Anan (1989)

Material	K	σ(mS/m)	v (m/ns)	a (dB/m)
Air	1	0	0,3	0
Freshwater	80	0,01	0,33	$2 \cdot 10^{-1}$
Seawater	80	$3.0 \cdot 10^{3}$	0,01	0,1
Dry sand	4	0,01	0,15	0,01
Wet sand, Aquifer	25	$0,1^{-1}$	0,06	0,03
Limestone	6	$0,5^{-2}$	0,12	0,04
Fat clay	5–35	0,05	0,06	1,0–300
Granite	5	0,1–1	0,13	0,01
Rock salt	6	0,1–1	0,13	0,01
Slate	5–15	0,03	0,09	1,0–100

Velocity of EM wave enables calculation of reflector depth

Dielectric const defines the potential for attenuation



ESSO RESOURCES CANADA LIMITED

NORMAN WELLS EXPANSION PROJECT

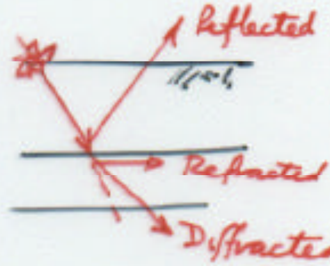
Radar trace - Line 4 showing typical sand/clay and ice/water interface signatures. (80 MH_3)

KOMEX	APPROVED	DATE May, 1981	DRAWING 921 - 6

3. SEISMIC METHODS

- Measures elastic properties of rocks (V_s = ?)
  evidenced through seismic velocity
- Locates interfaces between different V_s

At interfaces; seismic waves are { Diffracted / Refracted / Reflected

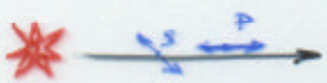


Procedure

1. Arrange geophones along single line
2. Provide initial shock input. Hammer/Drop hammer/Explosive/Air gun.
3. Record first (primary) and sometimes secondary (shear wave) arrivals

↓

Evaluate { 1. Bed thickness / 2. Seismic velocity



1. Primary compressional wave (P wave)
2. Shear wave (slower) S-wave.

S wave attenuated by fluid saturated materials
eg fluid filled fractures.

Typically:

1. V_s increases with depth (due to ↑E)
2. Weathered surface zones have ↓ V_s
3. Two methods of interpretation

    3.1 Seismic Refraction

    3.2 Seismic Reflection.

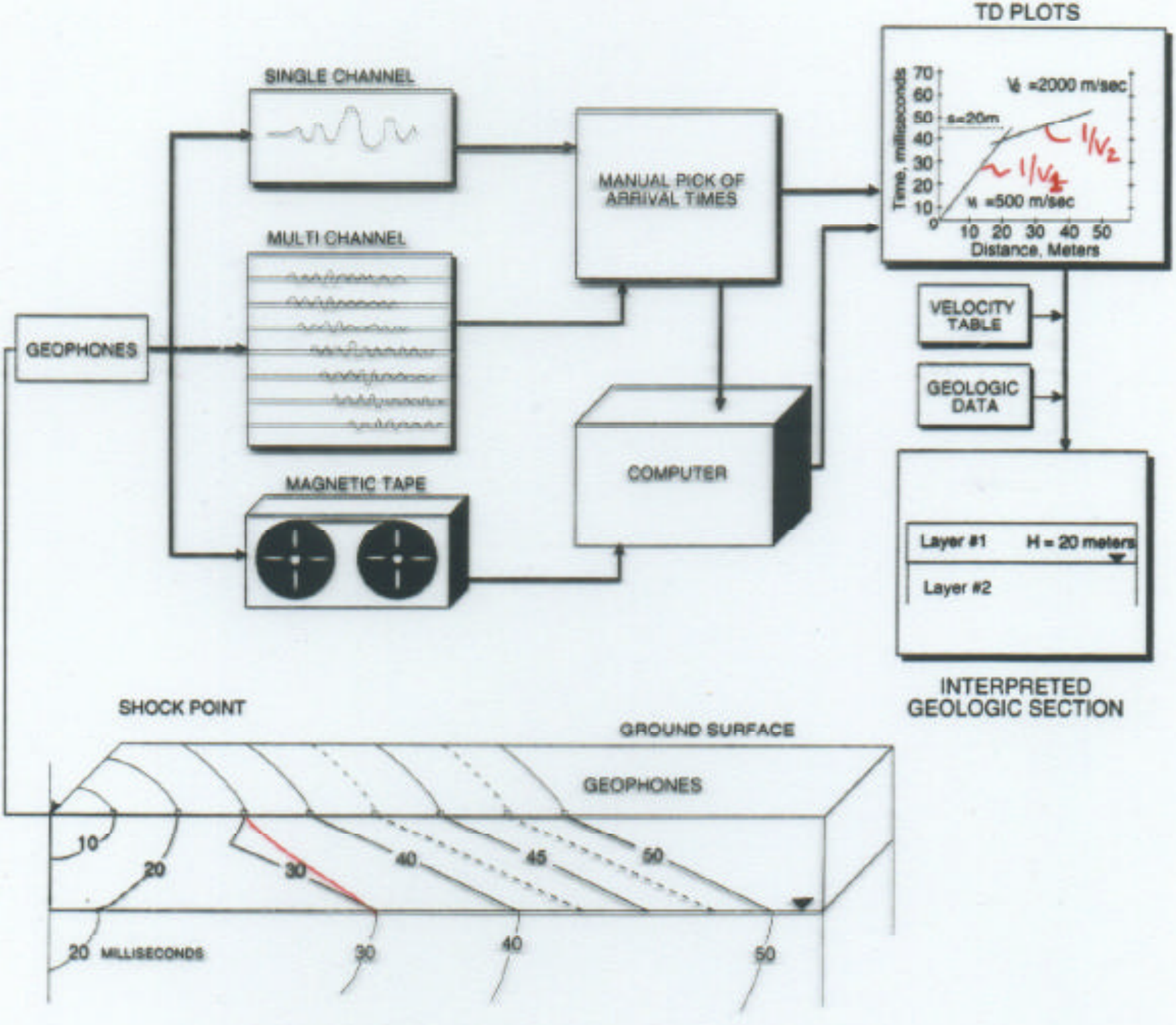


Figure 3-15 Seismic Geophysical Method

3.1 SEISMIC REFRACTION

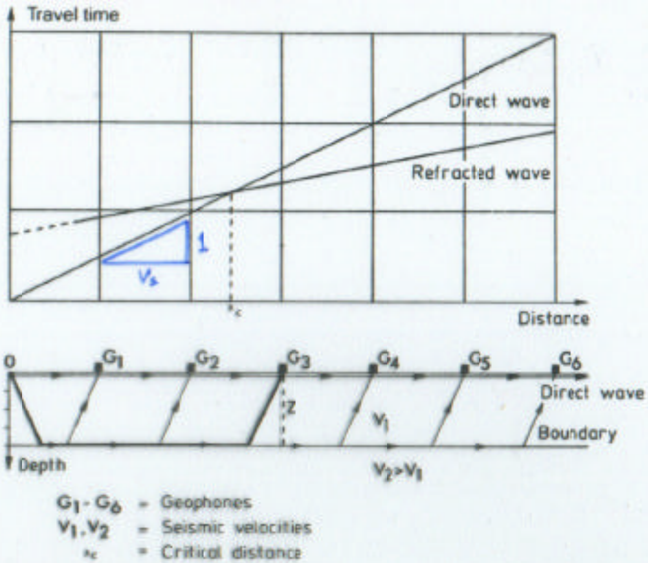


Fig. 2.18. Principle of seismic refraction

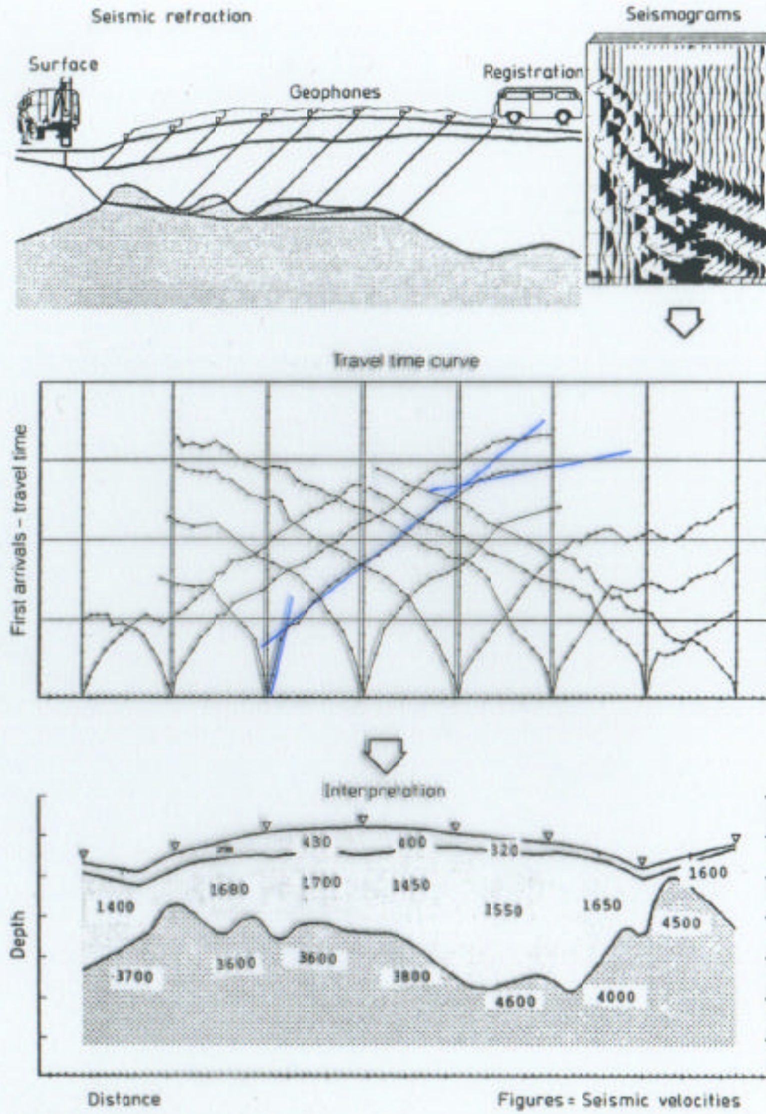


Fig. 2.19. Pattern of seismic refraction

1. Fire shot and plot time distance graph of first arrivals.
2. Evaluate unit velocities of units from slope of curve
3. Evaluate layer depths from inflection points

String length defines depth penetration

String length ÷ 5 = desired penetration depth

typical depths of < 50m

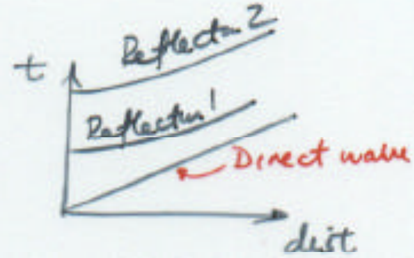
Ambiguities – weathering

water table

3.2 SEISMIC REFLECTION

Source impulse creates shock front reflected by interfaces.

Reflection occurs @ interfaces with "seismic impedence" changes. Seismic impedence = ρV_s (density → ρ)



Measure arrival times and plot as time - distance.

Advantages over Refraction

1. Increased depth penetration with small string length

Disadvantages

1. Reflected wave arrives so quickly that surface waves are present and must be filtered out.

To use @ depth < 50 m, need:

① Receivers with high sampling rate and high frequency source

② Sophisticated filtering and data analysis methods.

REFLECTION

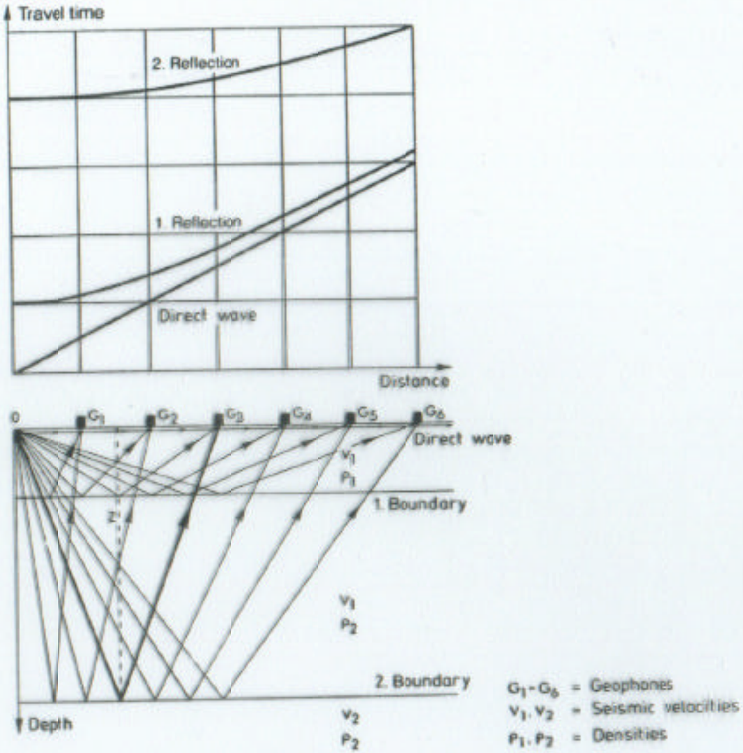


Fig. 2.21. Principle of seismic reflection

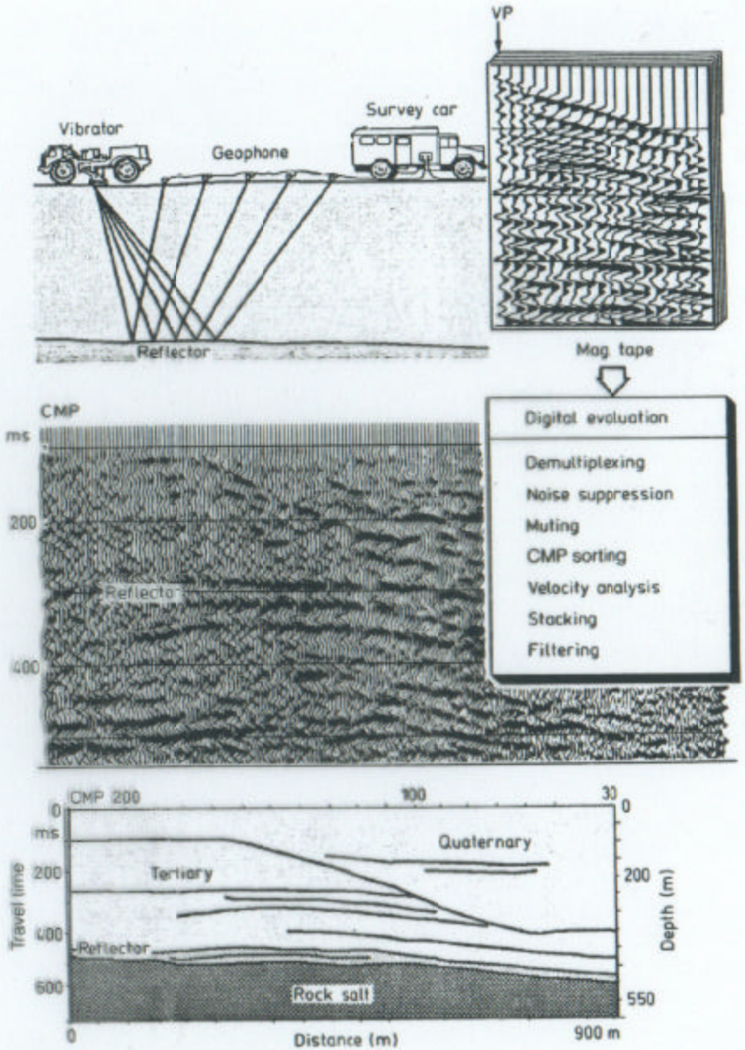


Fig. 2.22. Pattern of seismic reflection

4. GRAVITY METHODS

Detects changes in density according to Newton's Law of gravitational attraction

$$g = \frac{F}{m_2} = \frac{GM_e}{R^2}$$

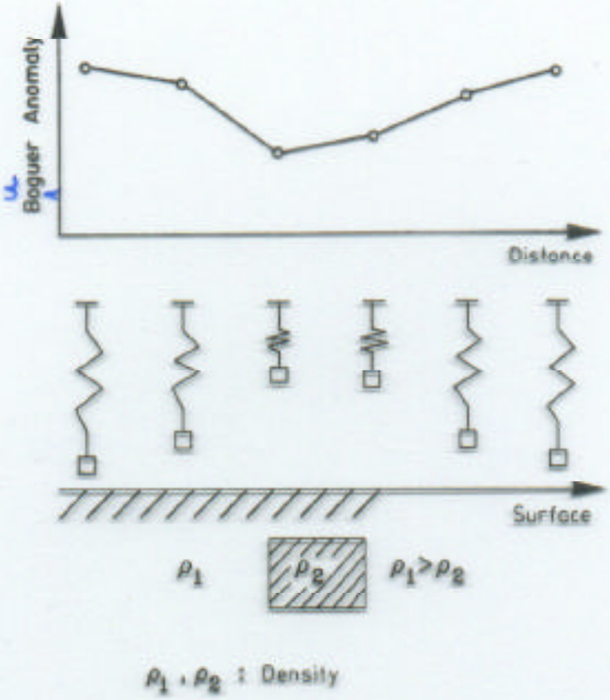


Fig. 2.23. Principle of gravity measurements

G = gravitational constant 6.67 x 10^{-8} degree $\frac{cm^2}{g^2}$

g = grav. accn.

Gravitometers measure variation in $g = 9.8\,m/s^2$ of $10^{-5}\,m/s^2$

Gravity depends on:

1. Latitude (Non-perfect sphere)
2. Elevation (R) [Free air correction]
3. Topography (m_2) [Terrain correction]
4. Earth tides [Isostatic correction]
5. Density variations in subsurface [Bouguer correction]

Density is the only important factor in gravity measurements, but effect is much less than all other factors

Limited applicability to Environmental Surveys:

1. Small signal
2. High cost.

5. WELL LOGGING

- Applicable to materials in vicinity of wellbore
- Variety of logging signals available
- Recorded continuously with depth.

Methods

Gamma Ray
- Measures natural gamma radiation
- Pick up clay layers to .3m resolution

Density Log
- Artificial source ^{137}Cs @ probe base and gamma detector @ top
- Adsorption of gamma radiation by rock is proportional to density (Compton effect)

Neutron Log
- Artificial Neutron source
- Measure backscattering to determine moisture content (presence of Hydrogen) → porosity log.

Electric Log
- Apparent resistivity in sidewall rock (Multiple pt. arrays)
- May simultaneously measure self potential
- Records mixed resistivity ∴ correct for mud/water effects

Salinometer
- Resistivity of borehole fluid.

Temperature

Sonic velocity

Caliper

Flowmeter

Deviation

Table 2.4. Logging methods, measured parameters and objects of investigation

Symbol	Parameter	Result	Object
GR	count of natural gamma radiation	natural radioactivity of rocks	petrography clay content
D	counts of compton scattered rays	density of rocks	fracturing, porosity
N	counts of secondary neutron-neutron rays	lithology	stratigraphy porosity
EL, ES	apparent resisitivity	true resistivity	hydraulics, lithology
ML, MLL	apparent resistivity at borehole wall	true resistivity small scale	lithology, hydraulics
IEL	app. conductivity, focused induction	true conductivity	lithology
FEL, LL	focused electric log	true resistivity of rock	lithology
SP	self-potential (probe-to-surface)	sources of electric potentials	oxidizing bodies
SAL	resistivity of borehole fluid	salinity	total salt content of fluid
TEMP	temperature of borehole fluid	geothermal field	thermal gradient
SONIC SV	travel time of seismic waves	seismic velocity	seismic velocity
CAL	borehole diameter	shape of borehole walls	correction of other logs
FLOW	revolutions of a spinner	velocity of fluid flow	zones of in- and outflow of water
DV	compass and dipmeter	inclination + azimuth of borehole	spatial drill path
OPT	video signals, photography	state of borehole walls	direct view of lithology

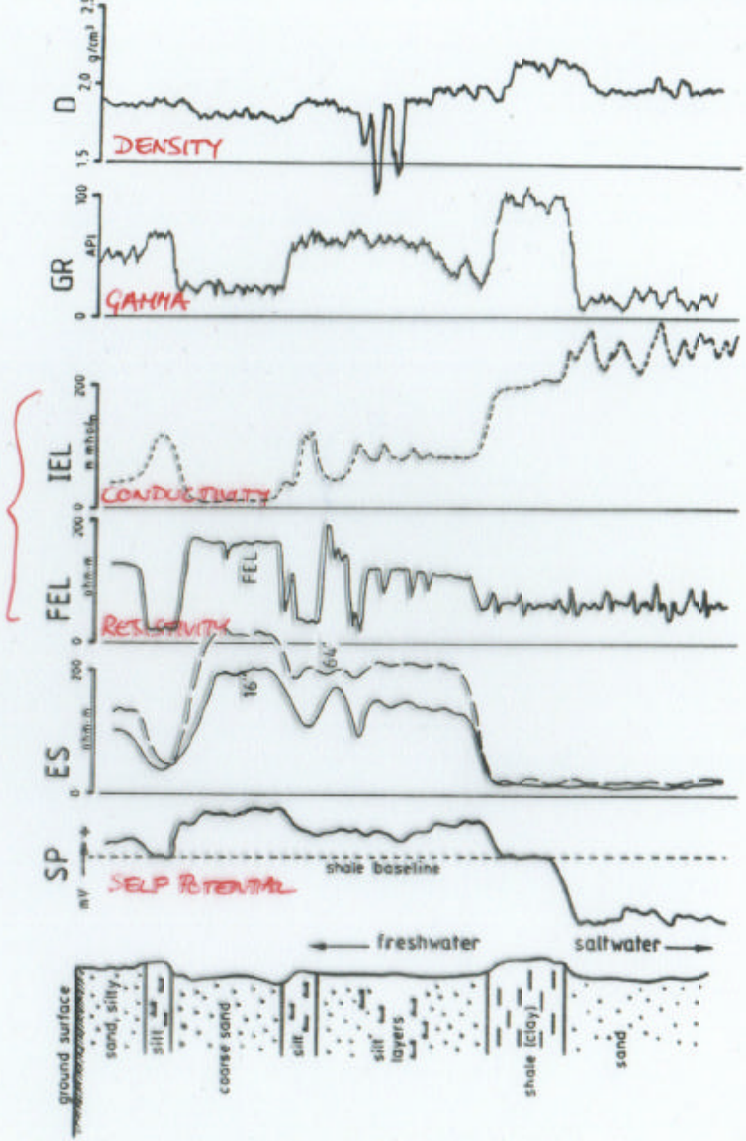


Fig. 2.24. Comparison of different logs with the lithology of cores.
SP = self-potential survey; ES = electrical survey measures resistivity in 16" and 64" point array; FEL = focused electrical log for thin layers; IEL = induction electric log measures electric conductivity; GR = gamma ray measures natural radiation; D = density log by artificial gamma source and detector

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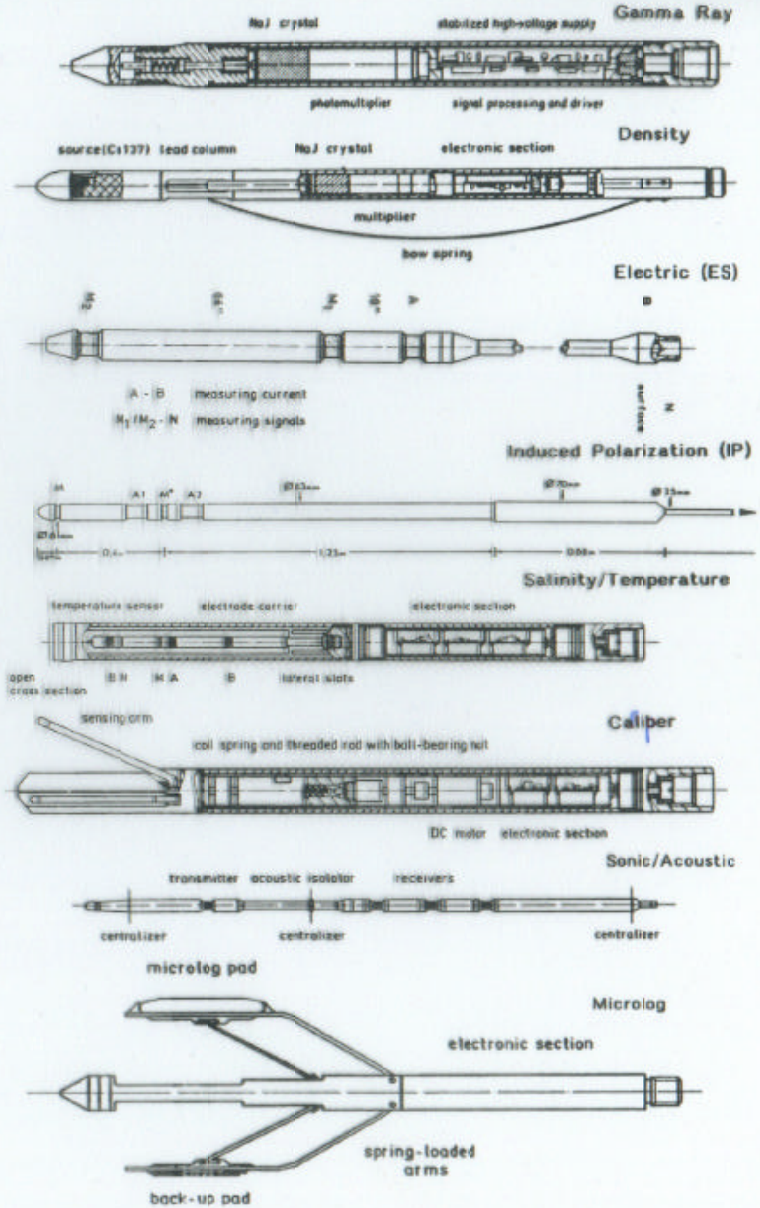

Fig. 2.25. Probes for geophysical well logging

This table is intended as a general guide. The application ratings given are based upon actual experience at a large number of sites. The rating system is based upon the ability of each method to produce results under general field conditions when compared to other methods applied to the same task. One must consider site-specific conditions before recommending an optimum approach.

In some cases a method rated 3 or NA may in fact solve the problem due to unique circumstances. For example, seismic refraction is rated NA for evaluating organic contaminants. However, in some cases where the contaminant flow is controlled by bedrock, the seismic method may provide an effective evaluation by mapping bedrock depth.

Organic Vapor Analysis

Application	GPR	EM	Res.	Seis.	MD	Mag.	OVA
Evaluation of natural geologic and hydrologic conditions							
Depth and thickness of soil and rock layers and vertical variations	1[a]	2	1	1	NA	NA	NA
Mapping lateral variations in soil and rock (fractures, karst features, etc.)	1[a]	1	2	2 (Refr.) 1 (Refl.)	NA	NA	NA
Depth of water table	3	2	1		NA	NA	NA
Evaluation of subsurface contamination and post-closure monitoring							
Inorganics (high TDS and electrically conducive)							
Early warning contaminant detection	3	1	2	NA	NA	NA	NA
Detailed lateral mapping	3	1	2	NA	NA	NA	NA
Vertical extent	3	2	1	NA	NA	NA	NA
Changes of plume with time (flow direction and rate)	3	1	2	NA	NA	NA	NA
Post cleanup/closure monitoring	3	1	2	NA	NA	NA	NA
Organics (typically nonconducive)							
Early warning contaminant detection	3	3	3	NA	NA	NA	1
Detailed lateral mapping	2[a]	2	3	NA	NA	NA	1
Vertical extent	2[a]	3	2	NA	NA	NA	2
Changes of plume with time (flow direction and rate)	3	3	3	NA	NA	NA	1
Post cleanup/closure monitoring	3	3	3	NA	NA	NA	1
Location of buried wastes and delineation of trench boundaries							
Bulk waste trenches—without metal	1	1	2	3	NA	NA	NA[d]
Bulk waste trenches—with metal	1	1	2	3	1[c]	1[b]	NA[d]
Depth of trenches and landfills	2	3	2	2	NA	NA	NA[d]
Detection of 55-gal steel drums	2[a]	2	NA	NA	1[c]	1	NA[d]
Estimates of depth and quantity of 55-gal steel drums	2[a]	3	3	NA	2	1	NA[d]
Location of utilities							
Buried pipes and tanks	1	1[c]	NA	NA	1[c]	1[b]	NA[c]
Potential pathways of contaminant migration via conduits and permeable trench backfill	1	2	NA	NA	2	2	NA[d]
Abandoned wells with metal casing	3	NA	NA	NA	2	1[b]	NA[d]

1 = Primary choice under most field conditions.
2 = Secondary choice under most field conditions.
3 = Limited field application under most field conditions.
NA = Not applicable.
[a] Shallow.
[b] Assumes ferrous metals to be present.
[c] Assumes metals to be present.
[d] Assumes no vapors present.
Note: Many site-specific conditions may dictate the choice of a method rated 2 or 3 in preference to a 1.

Magnetic detector

Source: Benson, 1988

Table 3-3 Applications of Selected Field Investigation Techniques for Waste Disposal Sites

APPLICATIONS	SEISMIC	SEISMIC MONITORING	SONAR	GRAVITY	MAGNETIC	RESISTIVITY	ELECTROMAGNETIC	RADAR	TIME-DOMAIN REFLECTOMETRY	RADIOMETRICS	BOREHOLE LOGGING
DEPTH TO BEDROCK	●					○	○	●			
FAULT DETECTION	●				●		●				●
FRACTURES IN ROCK		○						○		○	●
BURIED CHANNELS	●			○		●	●	●			
GROUND WATER SURFACE	○					○	○	●	○		●
SOIL WATER CONTENT	○					○	○	●	●	●	●
WATER DEPTH			●					●			
SUB-BOTTOM STRATIGRAPHY	●		●					●			
SEA BED SCOUR			●								
ICE THICKNESS							○	●			
PERMAFROST MAPPING	●					●	●	●	○		
PEAT THICKNESS	○					●	●	●			
SOIL STRATIGRAPHY	●					○	○	●		○	●
SAND & GRAVEL MAPPING	○					●	●	●			
LEACHATE PLUMES						●	●	○		●	●
SALT WATER INTRUSION						●	●	○	○		○
BURIED DRUMS					●	○	●	○			
BURIED PIPES & CABLES					○		●	○			
BURIED CAVITIES & TUNNELS	●			○	○		●	●			
VOIDS AROUND PIPES		○						○			
SUBSIDENCE (SLOPES & TUNNELS)	●	●		○			○	●	○		
PHYSICAL PROPERTIES	●	○		○	○	○	○	○	●	●	●
ELECTRICAL GROUNDING						●	●				
RIPPABILITY	●										
RADIOACTIVE HAZARDS											

SOURCE: Modified From MultiVIEW Geoservices Inc.

● OFTEN APPLICABLE
○ SOMETIMES APPLICABLE

Figure 3-12 Summary geophysical techniques