Exploration Geophysics

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Introduction

- The science of geophysics is based on the principles of physics to the study of the whole of earth e from the deepest interior to the surface.
- The subject of geology, geography, geochemistry and geophysics together play a key role in earth science.
- The former two disciplines involve direct observations of rock exposures on the surface or subsurface workings or borehole cores.
- These are more often descriptive and qualitative. Geochemistry is partly descriptive and mainly quantitative.
- The geophysical tools operate much above the ground from aircraft or helicopter platform fitted with multisensors or on the ground in general.
- **Geophysics** is the application of physical principles and methods to problems in Earth Sciences
- Geophysical studies are always quantitative and involve real measurements based on the variation of response pattern or contrast of propagating waves passing through nonhomogeneous medium.
- The propagation parameters are seismicity, density, magnetic susceptibility, electrical conductivity, resistivity, electromagnetic (EM) and radiometric radiance.

Passive versus Active methods

- **Passive methods:**
  Use naturally present sources/fields to investigate properties of the subsurface

  Examples:
  - Gravity
  - Earth's magnetic field
  - Earthquakes

- **Active methods:**
  Use man-made source to image structure of subsurface

  Examples:
  - Dynamite, air guns, …
  - EM waves
  - Electrical currents

Applied geophysics

To select the most appropriate geophysical method to investigate a certain task/problem, following aspects need to be considered:

- What are the relevant ***physical properties***? (porosity, pemeability, seismic velocity, density, …)
- What ***spatial scales*** are relevant?
- What are the ***field conditions***? (e.g. urban, offshore, …)
- Which ***acquisition geometries*** are optimal? (e.g. 2D vs 3D seismics)
- Is there useful ***a priori information***?
- Is there a ***cheaper*** alternative?

The answer to these questions will depend strongly on the particular task/problem

Why geophysics?

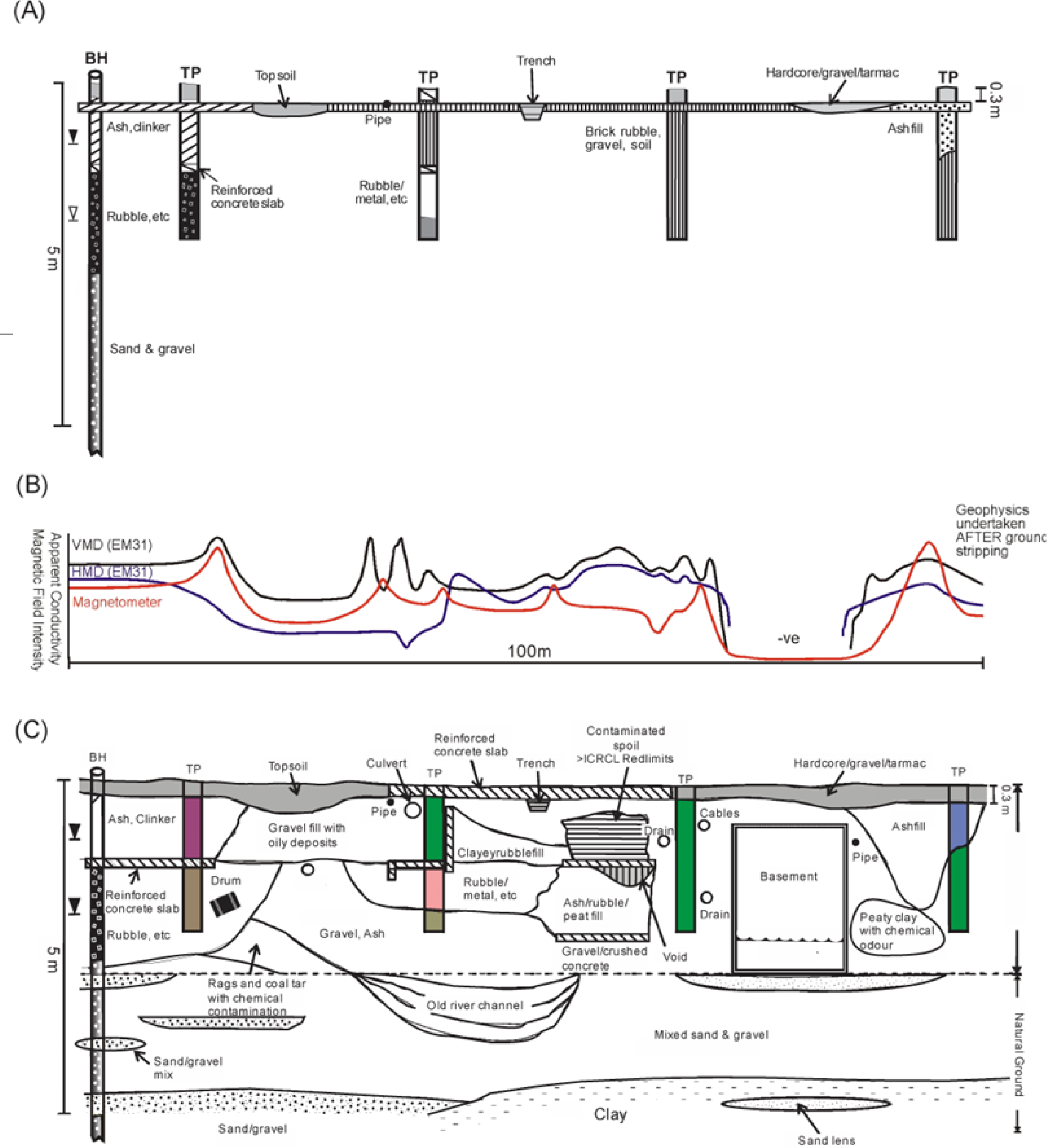

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Figure 1.2 Ground models derived from (A) an intrusive investigation only, (B) a combined profile from a comprehensive geophysical survey, and (C) final interpretation of a subsequent intrusive investigation targeted on the geophysical anomalies. [C]

Geophysical Surveying Methods with Parameters and Properties Suitable for Type Deposits

Method	Measured parameters	Operative physical property	Suitable deposit type
Seismic	Travel time of reflected and refracted seismic waves.	Density and elastic mode velocity	Oil and gas, layered sedimentary basin.
Gravity	Spatial variation in the strength of Earth's gravitational field.	Density contrast between the surrounding host rocks	Massive sulfides, chromite, salt dome, barite, kimberlite, concealed basin.
Magnetic	Spatial variation in the strength of geomagnetic field.	Magnetic susceptibility	Magnetite, ilmenite, pyrrhotite-rich sulfides.
Electrical			
1. Resistivity	Earth's resistance	Electrical conductivity	Groundwater, sulfide ore.
2. Induced Potential (IP)	Polarization voltage/frequency development of ground resistance	Electrical capacitance	Large sulfide dissemination, graphite.
3. Self-Potential (SP)	Electrical potential	Electrical conductivity	Sulfide veins, graphite, groundwater.
EM	Response to EM radiation	Electrical conductivity and inductance	Sulfide ore, graphite deposits.
Radiometric	Gamma radiation	Gamma ray	Thorium, uranium, radium.
Borehole geophysics and Mise-á-la-Masse	Down-hole probe	All types	Continuity of mineralization in strike and dip.

Applied geophysics infers property contrasts inside the earth from surface (borehole) measurements
→ Remote sensing

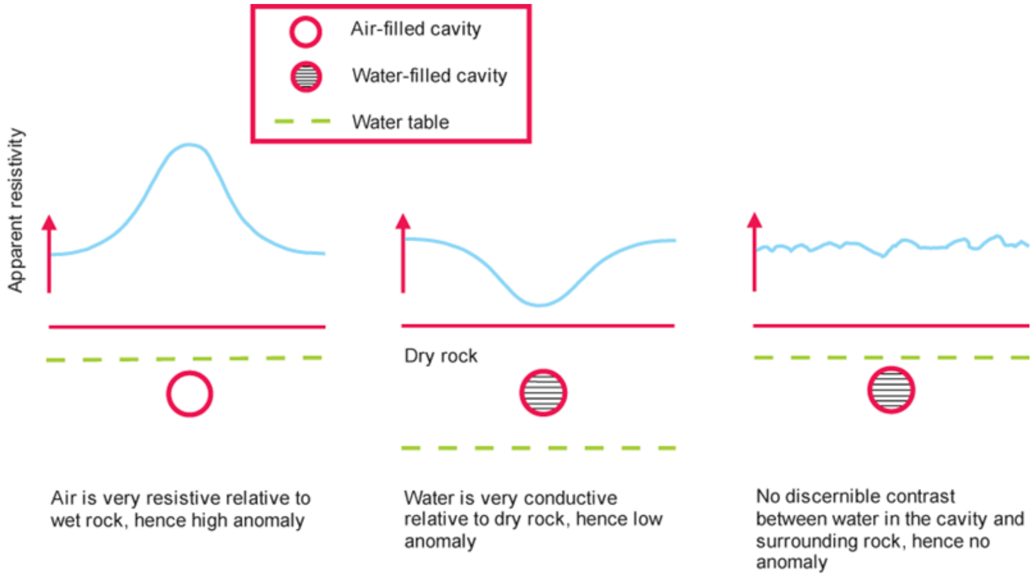

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Figure 1.6 Contrasts in physical properties from different geological targets give rise to a target. When there is no contrast, the target is undetectable geophysically. [C]

Table 1.1 Geophysical methods and their main applications

Geophysical method	Chapter number	Dependent physical property	Applications (see key below) 1	2	3	4	5	6	7	8	9	10
Gravity	2	Density	**P**	**P**	s	s	s	s	!	!	s	!
Magnetic	3	Susceptibility	**P**	**P**	**P**	s	!	m	!	**P**	**P**	!
Seismic refraction	4,5	Elastic moduli; density	**P**	**P**	m	**P**	s	s	!	!	!	!
Seismic reflection	4,6	Elastic moduli; density	**P**	**P**	m	s	s	m	!	!	!	!
Resistivity	7	Resistivity	m	m	**P**	**P**	**P**	**P**	**P**	s	**P**	m
Spontaneous potential	8	Potential differences	!	!	**P**	m	**P**	m	m	m	!	!
Induced polarization	9	Resistivity; capacitance	m	m	**P**	m	s	m	m	m	m	m
Electromagnetic (EM)	10	Conductance; inductance	s	**P**	**P**	**P**	**P**	**P**	**P**	**P**	**P**	m
EM–VLF	11	Conductance; inductance	m	m	**P**	m	s	s	s	m	m	!
EM – ground penetrating radar	12	Permitivity; conductivity	!	!	m	**P**	**P**	**P**	s	**P**	**P**	**P**
Magneto-telluric	11	Resistivity	s	**P**	**P**	m	m	!	!	!	!	!

P = primary method; s = secondary method; m = may be used but not necessarily the best approach, or has not been developed for this application; (!) = unsuitable

Applications

1 Hydrocarbon exploration (coal, gas, oil)
2 Regional geological studies (over areas of 100s of km^2)
3 Exploration/development of mineral deposits
4 Engineering site investigations
5 Hydrogeological investigations
6 Detection of sub-surface cavities
7 Mapping of leachate and contaminant plumes
8 Location and definition of buried metallic objects
9 Archaeogeophysics
10 Forensic geophysics

Be aware of biased data!

The data need to record the true signal

Noise is also an issue

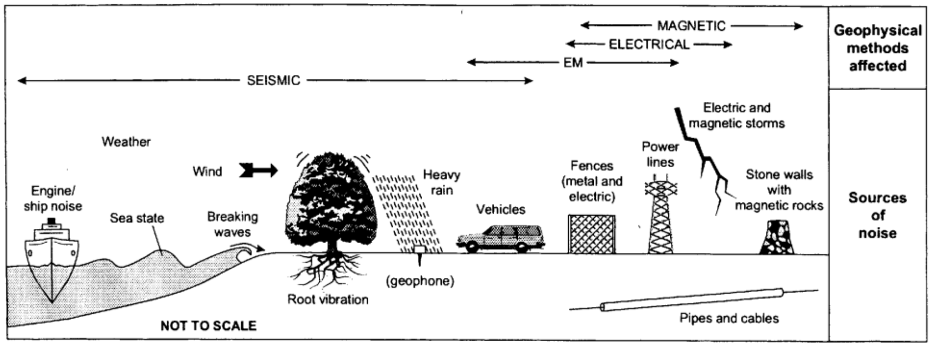
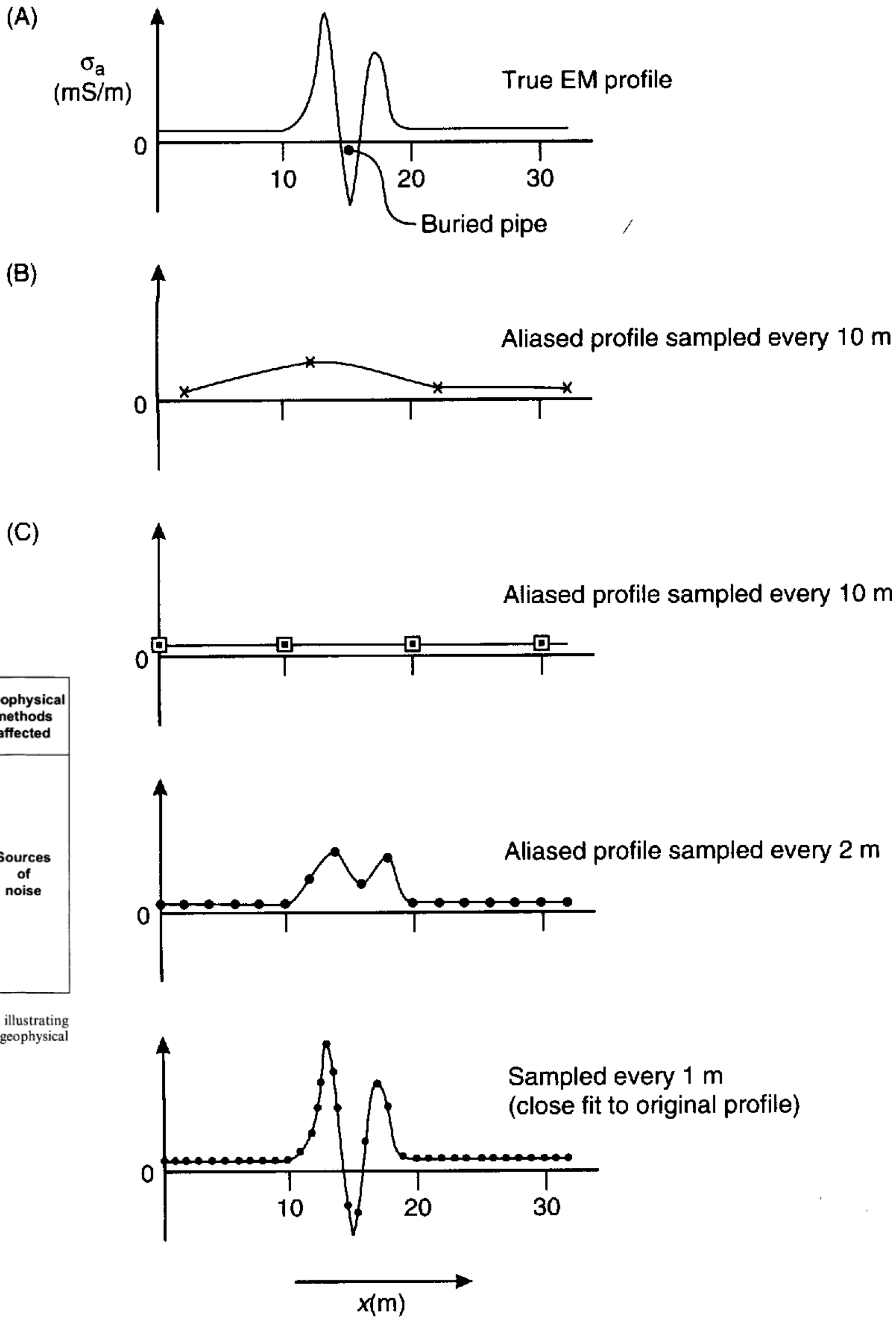


Figure 1.10 Schematic illustrating some common sources of geophysical noise



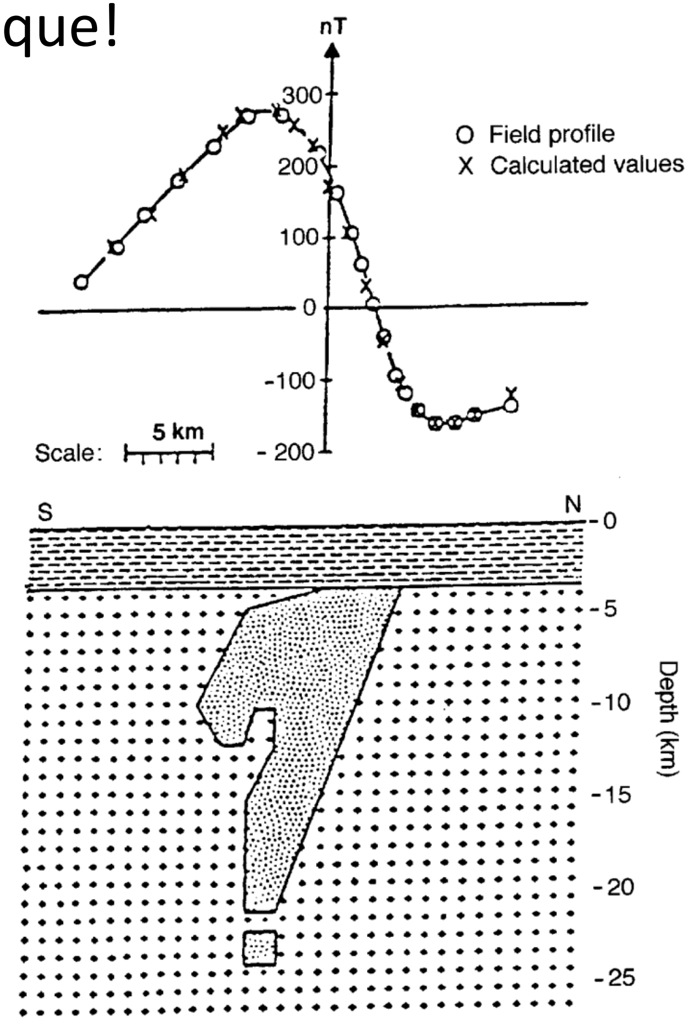
Be aware of a biased interpretation!

A physical theory calculates observables given appropriate model parameters and theory → forward modelling

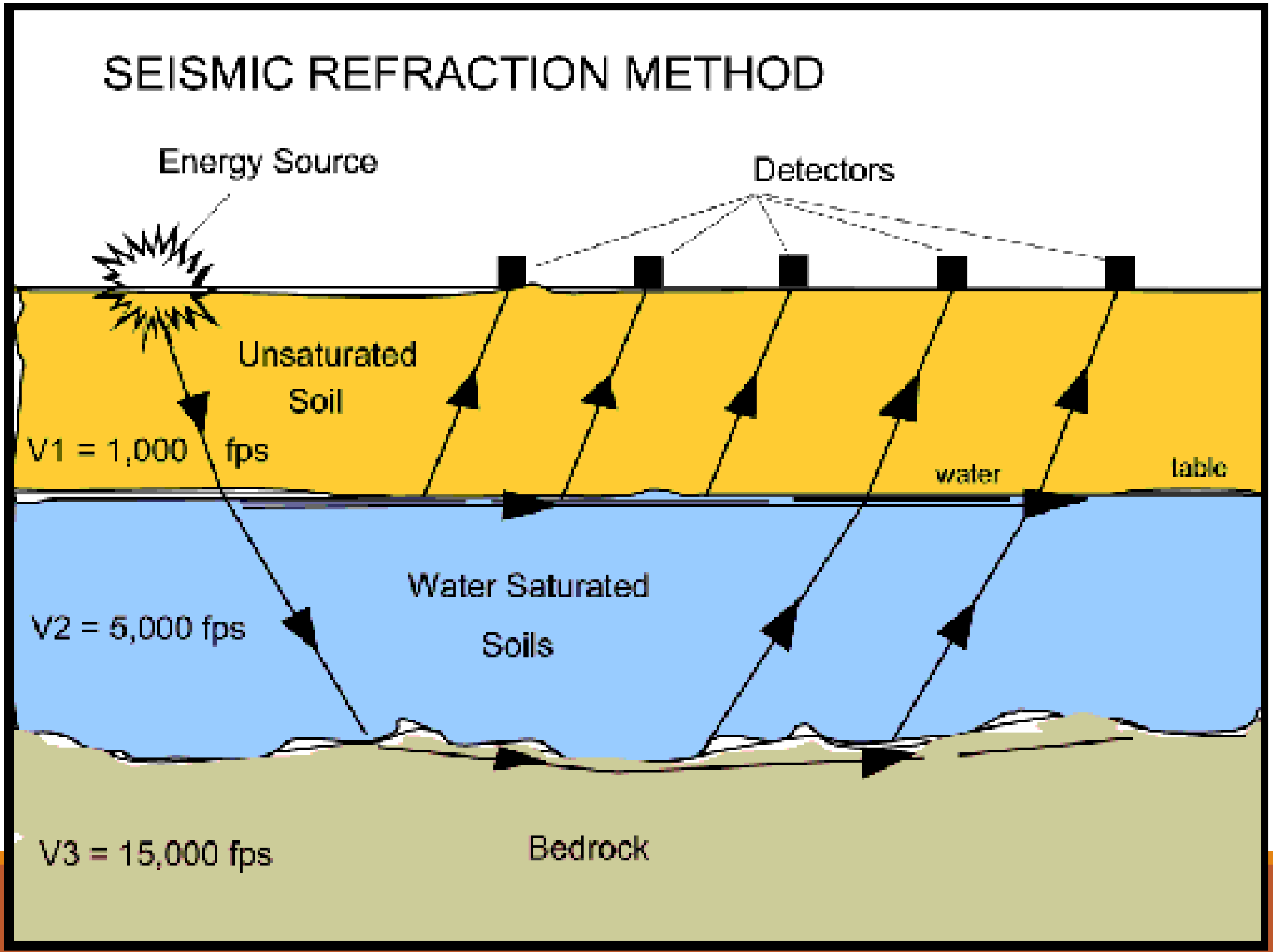
The inverse problem is often non-unique!

Several geophysical methods should be used together

Interpretation requires geological knowledge



Seismic methods
Mainly measure travel times and amplitudes which depend on density and elastic moduli



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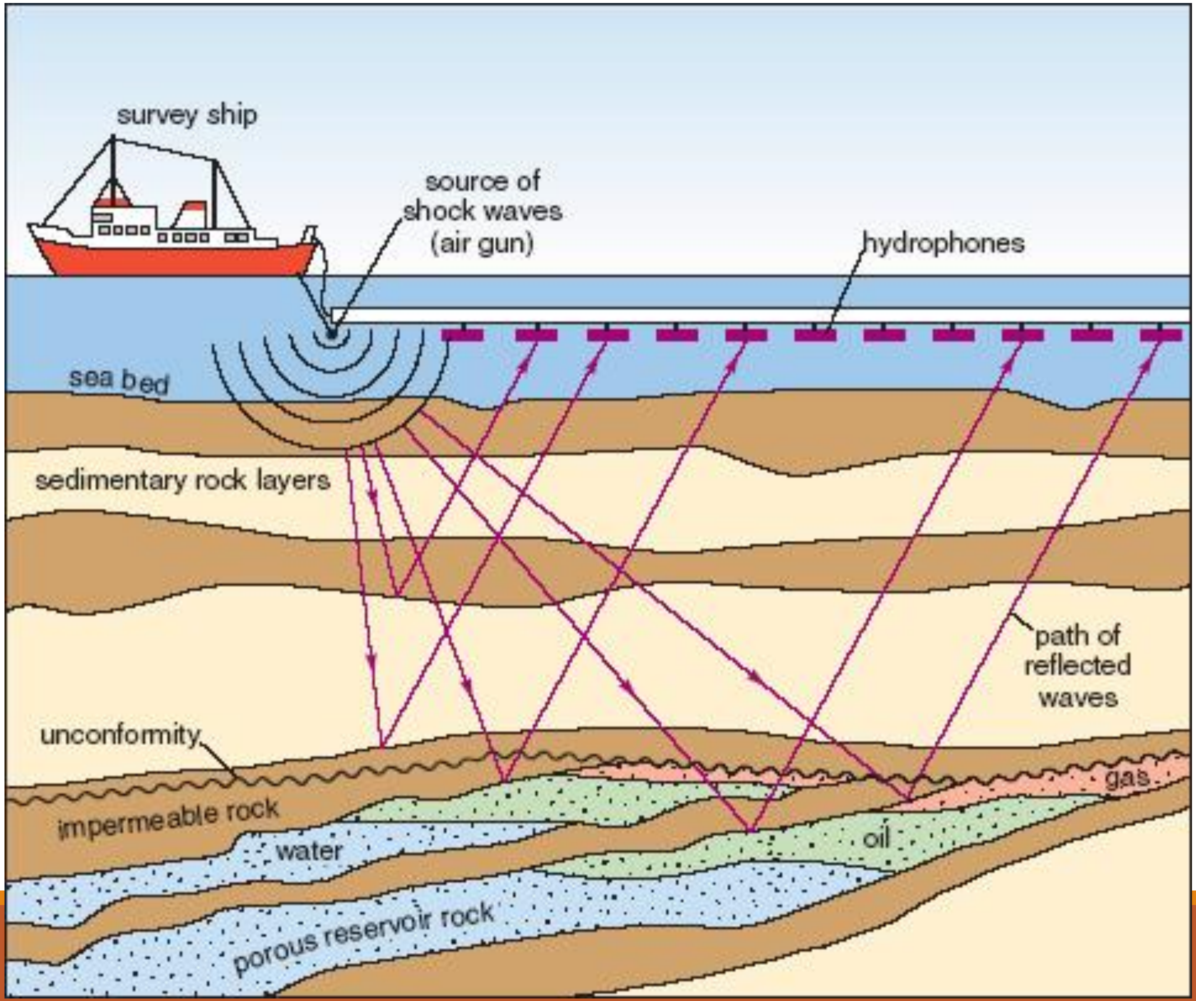

Table 4.1 Derived information and applications of exploratior seismology.

Gross geological features:
- Depth to bedrock
- Measurement of glacier thickness
- Location of faults and fracture zones
- Fault displacement
- Location and character of buried valleys
- Lithological determinations
- Stratigraphy
- Location of basic igneous dykes

Petrophysical information:
- Elastic moduli
- Density
- Attenuation
- Porosity
- Elastic wave velocities
- Anisotropy
- Rippability

Applications:
- Engineering site investigations
- Rock competence
- Sand and gravel resources
- Detection of cavities
- Seabed integrity (for siting drilling rigs)
- Degassing or dewatering of submarine sediments
- Preconstruction site suitability for:
  - new landfill sites
  - major buildings
  - marinas and piers
  - sewage outfall pipes
  - tunnel construction, etc.
- Hydrogeology and groundwater exploration
- Ground particle velocities
- Forensic applications:
  - location of crashed aircraft on land
  - design of aircraft superstructures
  - monitoring Nuclear Test Ban Treaty
  - location of large bore military weapons
- Location of trapped miners
- Seismic hazard zonation

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
Pemafrost (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 for polar ice (Kohnen, 1974).

Potential Field methods

Gravity measures spatial variations of the gravitational field due to lateral variations in density.

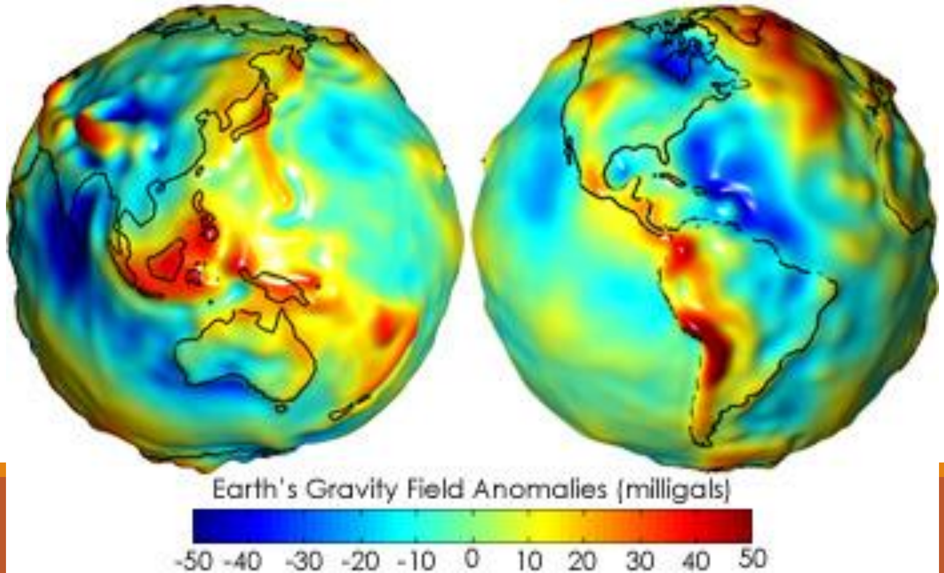

Table 2.1 Applications of gravity surveying.

Hydrocarbon exploration
Hydrocarbon reservoir monitoring
Monitoring of CO_2 containment underground
Regional geological studies
Isostatic compensation determination
Exploration for, and mass determination of, mineral deposits
Detection of subsurface cavities (micro-gravity), e.g. mine workings, caves, solution features, tunnels
Location of buried rock valleys
Determination of glacier thickness
Tidal oscillations
Archaeogeophysics (micro-gravity), e.g. location of tombs, crypts
Shape of the earth (geodesy)
Military (especially for missile trajectories)
Satellite positioning
Monitoring volcanoes
Hydrological changes in the geoid

Table 2.2 Densities of common geological materials (modified from Telford *et al.*, 1990).

Material type	Density range (Mg/m^3)	Approximate average density (Mg/m^3)
Sedimentary rocks		
Alluvium	1.96-2.00	1.98
Clay	1.63-2.60	2.21
Gravel	1.70-2.40	2.00
Loess	1.40-1.93	1.64
Silt	1.80-2.20	1.93
Soil	1.20-2.40	1.92
Sand	1.70-2.30	2.00
Sandstone	1.61-2.76	2.35
Shale	1.77-3.20	2.40
Limestone	1.93-2.90	2.55
Dolomite	2.28-2.90	2.70
Chalk	1.53-2.60	2.01
Halite	2.10-2.60	2.22
Glacier ice	0.88-0.92	0.90
Igneous rocks		
Rhyolite	2.35-2.70	2.52
Granite	2.50-2.81	2.64
Andesite	2.40-2.80	2.61
Syenite	2.60-2.95	2.77
Basalt	2.70-3.30	2.99
Gabbro	2.70-3.50	3.03
Metamorphic rocks		
Schist	2.39-2.90	2.64
Gneiss	2.59-3.00	2.80
Phyllite	2.68-2.80	2.74
Slate	2.70-2.90	2.79
Granulite	2.52-2.73	2.65
Amphibolite	2.90-3.04	2.96
Eclogite	3.20-3.54	3.37

Potential Field methods

Geomagnetics measures spatial variations of the intensity of the magnetic field due to lateral variations in magnetic susceptibility.

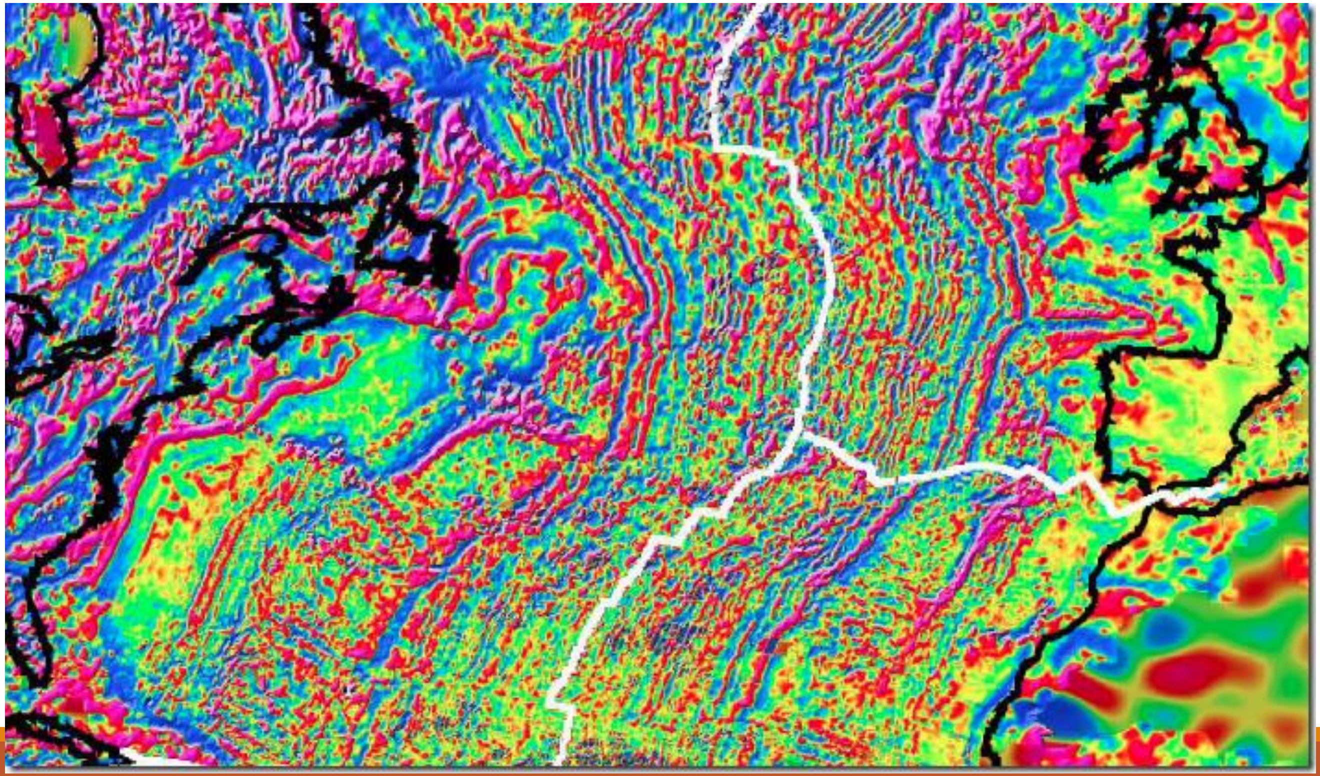

Table 3.1 Applications of geomagnetic surveys.

Locating

- Pipes, cables and ferrous metallic objects
- Buried military ordnance (shells, bombs, etc.)
- Buried metal drums (of contaminated or toxic waste, etc.)
- Concealed mine shafts and adits

Mapping

- Archaeological remains
- Concealed basic igneous dykes
- Metalliferous mineral lodes
- Geological boundaries between magnetically contrasting lithologies, including faults
- Large-scale geological structures

Table 3.2 Susceptibilities of rocks and minerals (rationalised SI units).

Mineral or rock type	Susceptibility*
Sedimentary	
Dolomite (pure)	−12.5 to +44
Dolomite (impure)	20,000
Limestone	10 to 25,000
Sandstone	0 to 21,000
Shales	60 to 18,600
Average for various	0 to 360
Metamorphic	
Schist	315 to 3000
Slate	0 to 38,000
Gneiss	125 to 25,000
Serpentinite	3100 to 75,000
Average for various	0 to 73,000
Igneous	
Granite	10 to 65
Granite (m)	20 to 50,000
Rhyolite	250 to 37,700
Pegmatite	3000 to 75,000
Gabbro	800 to 76,000
Basalts	500 to 182,000
Oceanic basalts	300 to 36,000
Peridotite	95,500 to 196,000
Average for acid igneous	40 to 82,000
Average for basic igneous	550 to 122,000
Minerals	
Ice (d)	−9
Rocksalt (d)	−10
Gypsum (d)	−13
Quartz (d)	−15
Graphite (d)	−80 to −200
Chalcopyrite	400
Pyrite (o)	50 to 5000
Hematite (o)	420 to 38,000
Pyrrhotite (o)	1250 to 6.3×10^6
Illmenite (o)	314000 to 3.8×10^6
Magnetite (o)	70,000 to 2×10^7

(d) = diamagnetic material; (o) = ore; (m) = with magnetic minerals.
* $\kappa \times 10^6$ rationalised SI units; to convert to the unrationalised c.g.s units, divide by 4π.
Data from Parasnis (1986), Sharma (1986) and Telford *et al.* (1990)

Electro magnetics

Table 10.1 The range of applications for EM surveying.*

Mineral exploration
Mineral resource evaluation
Hydrocarbon exploration
Monitoring hydrocarbon reservoirs
Groundwater surveys
Mapping contaminant plumes
Geothermal resource investigations
Contaminated land mapping
Landfill surveys
Detection of natural and artificial cavities
Location of geological faults
Geological mapping
Permafrost mapping
Brownfield site mapping
UneXploded Ordnance (UXO)
Sea-ice thickness mapping
Archaeological investigations

*Independent of instrument type.

Ground penetrating radar

measures travel times of reflected radar waves

velocity is controlled by the dielectric constant

Table 13.1 Range of applications of ground-penetrating radar.

Geological:
- Detection of natural cavities and fissures
- Subsidence mapping
- Mapping sand body geometry
- Mapping of superficial deposits
- Soil stratigraphy mapping
- Glacial geological investigations
- Mineral exploration and resource evaluation
- Peat thickness mapping and resource evaluation
- Permafrost investigations
- Location of ice wedges
- Fracture mapping in rock salt
- Location of faults, (mineralised) dykes, coal seams, etc.
- Lake and riverbed sediment mapping

Environmental:
- Contaminant plume mapping and monitoring remediation
- Mapping and monitoring pollutants within groundwater
- Landfill investigations including capping effectiveness
- Location of buried fuel tanks and oil drums
- Mapping animal burrows and tree roots
- Groundwater investigations
- Detection of UXO

Glaciological:
- Ice thickness mapping
- Determination of internal glacier structures
- Ice movement studies
- Detection of concealed surface and basal glacier crevasses
- Mapping water conduits within glaciers
- Determination of thickness and type of sea and lake ice
- Subglacial mass balance determination
- Snow stratigraphy mapping
- Subglacial landform mapping
- Glacial hazard assessment

Engineering and construction:
- Road pavement analysis
- Railway trackbed testing
- Void detection
- Location of reinforcement (rebars) in concrete
- Location of public utilities (pipes, cables, etc.)
- Testing integrity of building materials
- Concrete testing
- Looking-ahead/sideways during horizontal directional drilling

Archaeology:
- Location of buried structures, graves, post-holes, etc.
- Detection and mapping of Roman roads, foundations, etc.
- Pre-excavation mapping
- Detection of voids (crypts, undercrofts, burial mounds, etc.)
- Investigation of ancient monuments, statues, building façades

Forensic science:
- Location of buried targets (e.g. bodies and bullion, etc.)