ETH
Eidgenössische Technische Hochschule Zürich
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Electromagnetic surveying

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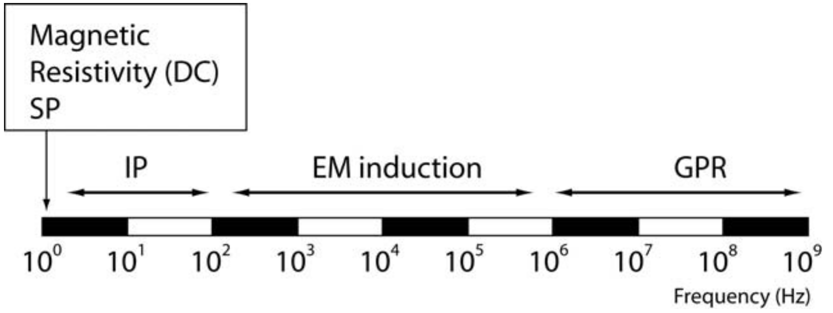
Introduction

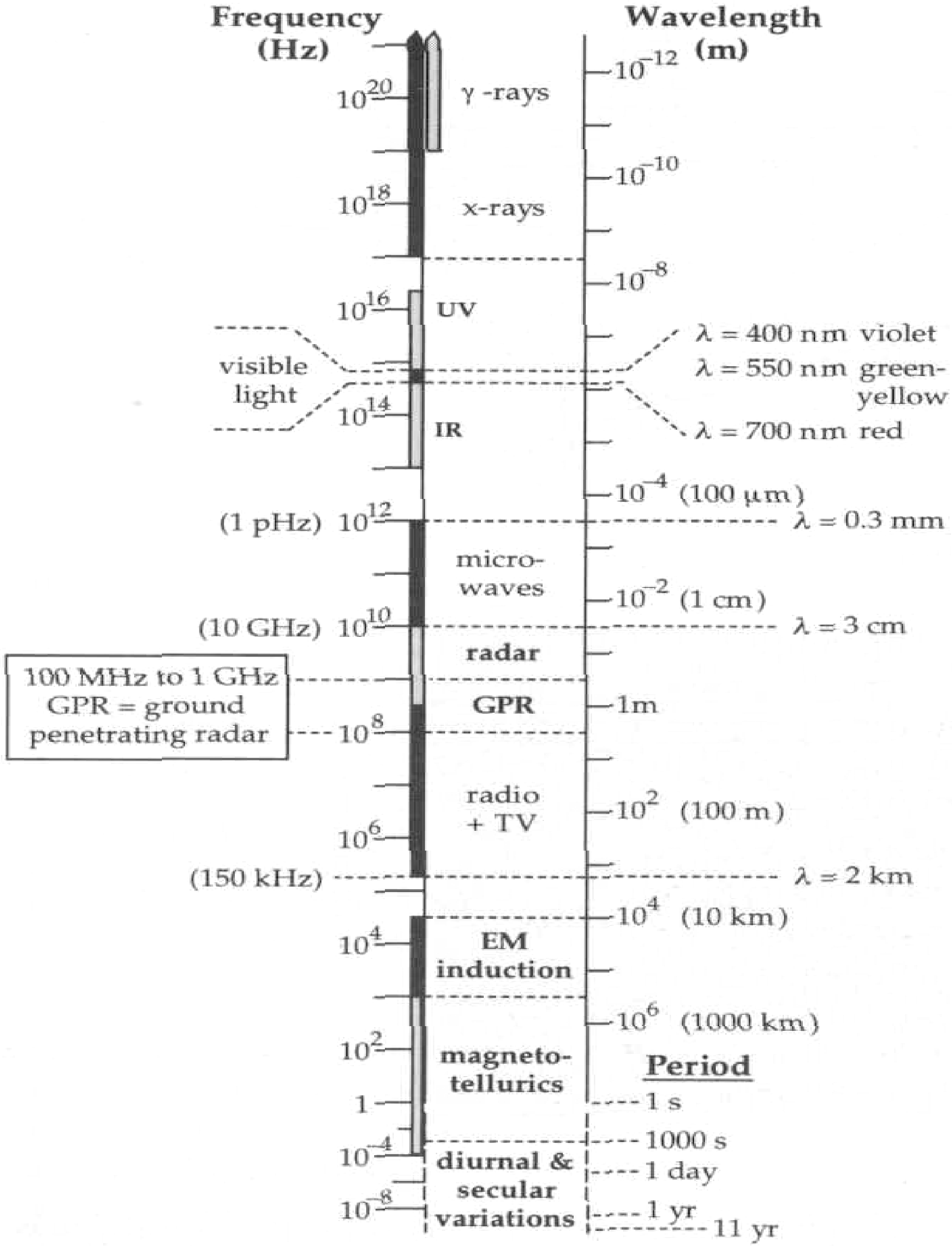


Electrical surveying…

- Resistivity method
- Induced polarization method (IP)
- Self-potential (SP) method

Higher frequency methods (electromagnetic surveys):

- Electromagnetic induction methods
- Ground penetrating radar (GPR)



Frequency (Hz)
Wavelength (m)
10^{20}
γ -rays
10^{-12}
10^{-10}
10^{18}
x-rays
10^{-8}
10^{16}
UV
visible light
λ = 400 nm violet
λ = 550 nm green-yellow
λ = 700 nm red
10^{14}
IR
10^{-4} (100 µm)
(1 pHz) 10^{12}
λ = 0.3 mm
micro-waves
10^{-2} (1 cm)
(10 GHz) 10^{10}
λ = 3 cm
radar
100 MHz to 1 GHz
GPR = ground penetrating radar
GPR
1m
10^{8}
radio + TV
10^{2} (100 m)
10^{6}
(150 kHz)
λ = 2 km
10^{4} (10 km)
10^{4}
EM induction
10^{6} (1000 km)
10^{2}
magneto-tellurics
Period
1
1 s
1000 s
10^{-4}
diurnal & secular variations
1 day
10^{-8}
1 yr
11 yr

Electromagnetic method

Electromagnetic (EM) surveying methods make use of the response of the ground to the propagation of electromagnetic field. This response vary according to the conductivity of the ground (in S/m).

- Primary EM fields are generated using a alternating current in a loop wire (coil) or a natural EM source
- The response of the ground is the generation of a secondary EM field
- The resultant field is detected by the alternating currents that they induce in a receiver coil

Application

- Exploration of metalliferous mineral deposits
- Exploration for fossil fuels (oil, gas, coal)
- Engineering/construction site investigation
- Glaciology, permafrost
- Geology
- Archaeological investigations

Structure of the lecture

1. Equations in electromagnetic surveying
2. Survey strategies and interpretation
3. Conclusions

1. Equations in electromagnetic surveying

Maxwell equations

$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$ Faraday induction

$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$$ Ampère – Maxwell

$$\nabla \cdot \vec{D} = p \quad \text{or} \quad \nabla \cdot \vec{j} = \frac{\partial p}{\partial t}$$

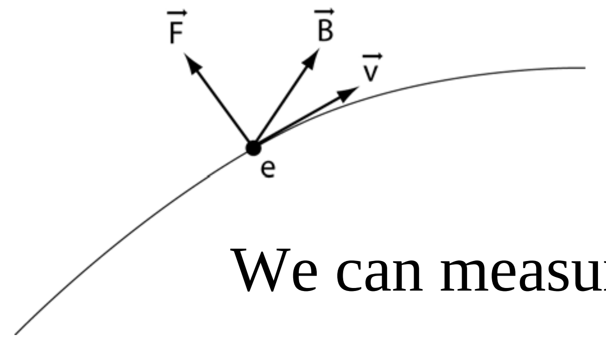
$$\nabla \cdot \vec{B} = 0$$

$\vec{E}$	electrical field	(V/m)
$\vec{B}$	magnetic induction field	(Vs/m^2)
$\vec{H}$	magnetic field strenght	(A/m)
$\vec{D}$	displacement field	(C/m^2)
$\vec{j}$	current density	(A/m^2)
p	charge density	(C/m^3)

B and H fields

$$\vec{F} = e\vec{v} \times \vec{B}$$

$$\vec{H} = \frac{\vec{B}}{\mu_0 \mu}$$



We can measure *B*, not *H*!

Example of values for μ:

Hematite, quartz: $\mu \cong 1$

Magnetite: $\mu \cong 5$

$\mu_0 = 4\pi 10^{-7} \left(\frac{\text{Vs}}{\text{Am}}\right)$ permeability for vacuum

μ permeability of material

$\vec{B}$ magnetic induction field (Vs/m^2)

$\vec{H}$ magnetic field strenght (A/m)

Frequencies

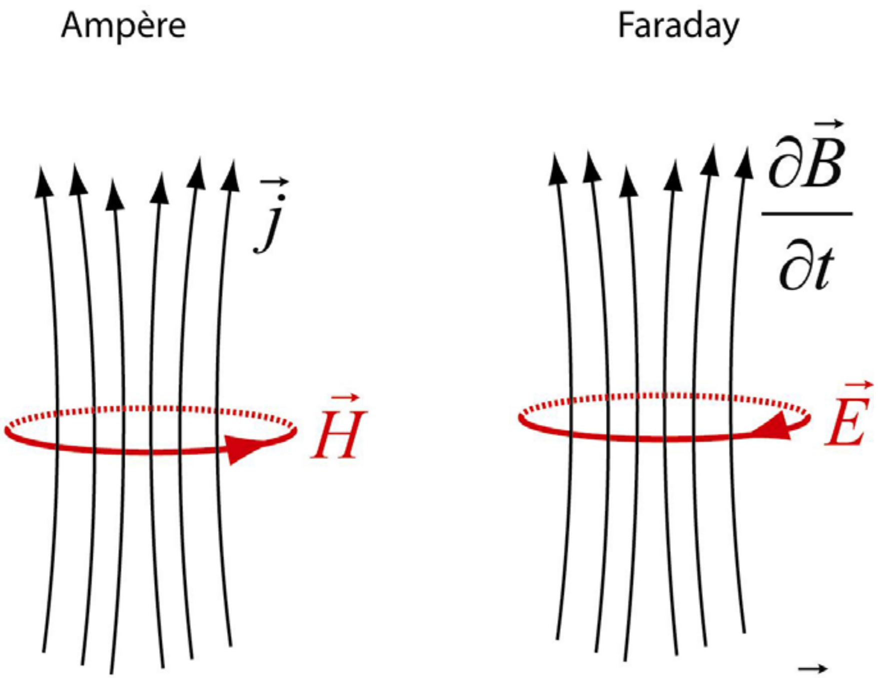
$$\omega = 2\pi\ f = 2\pi \frac{1}{T}$$

f	frequency (Hz)
T	period (s)
ω	angular velocity (rad/s)

In the field, some frequencies are considered as noise and must be filtered out:

- Light 50 Hz
- CFF/SBB 16.6 Hz
- 3^{rd} harmonic 150 Hz

Basic theory: induction EM



$$\nabla \times \vec{H} = \vec{j} \qquad \nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t}$$

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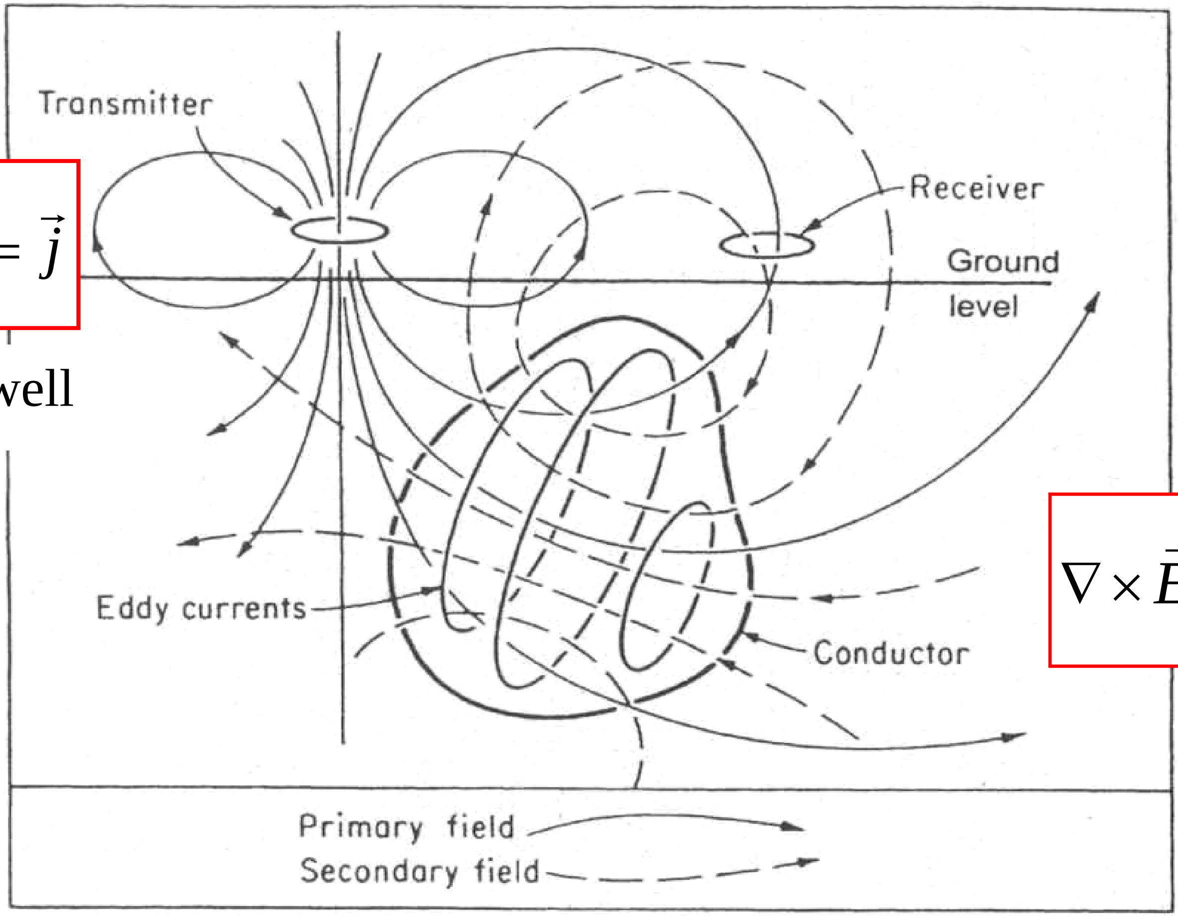
Basic theory: induction EM

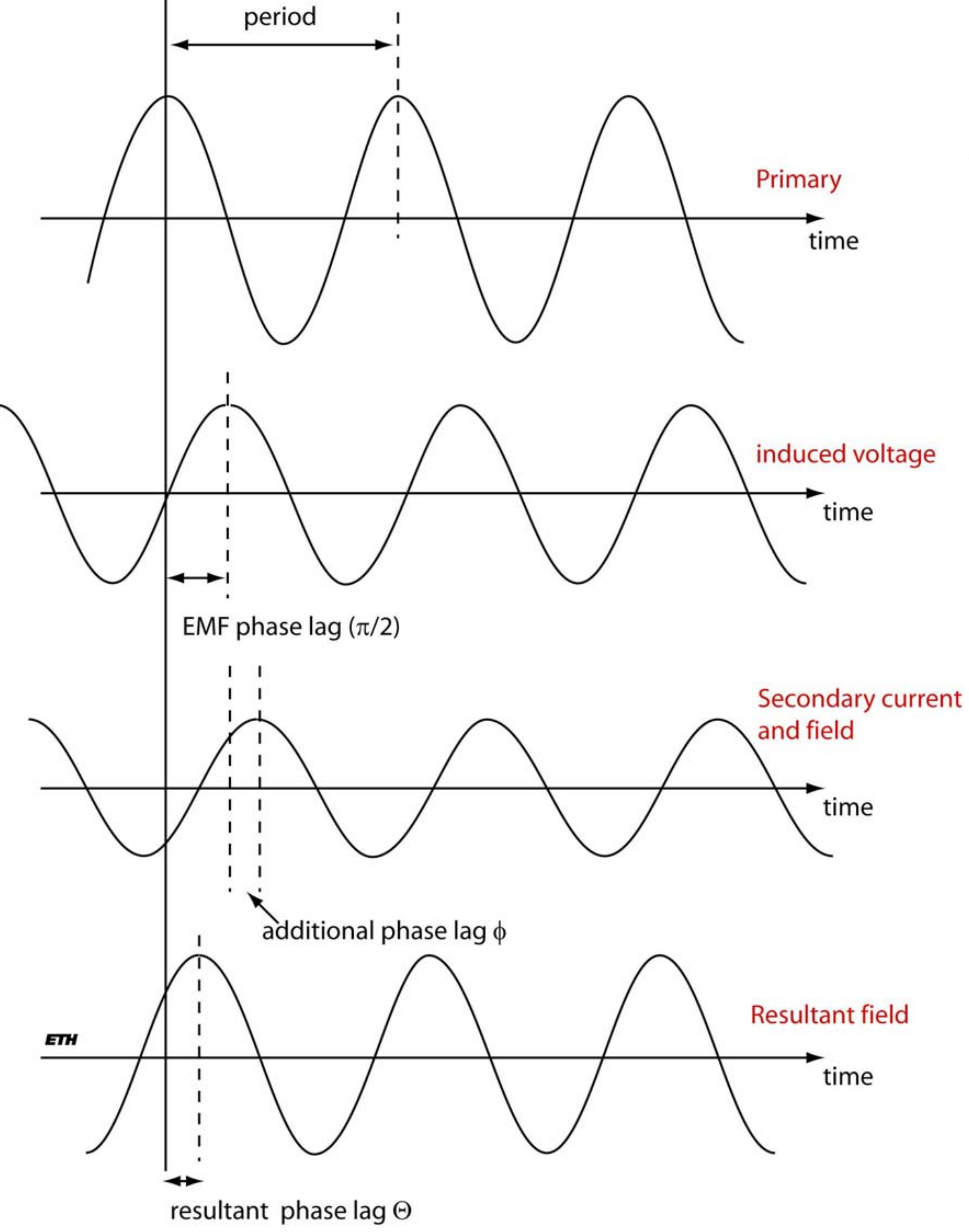
$$\nabla \times \vec{H} - \frac{\partial \vec{D}}{\partial t} = \vec{j}$$

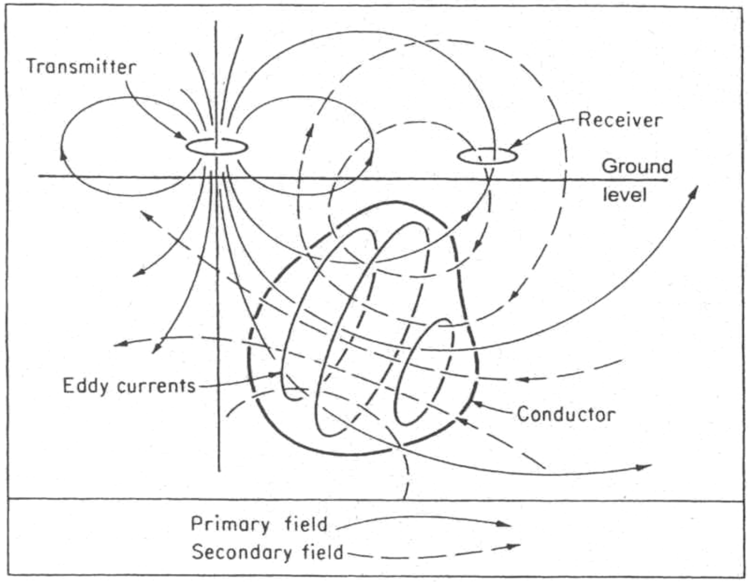
Ampère-Maxwell



$$\nabla \times \vec{E} + \frac{\partial \vec{B}}{\partial t} = 0$$

Faraday





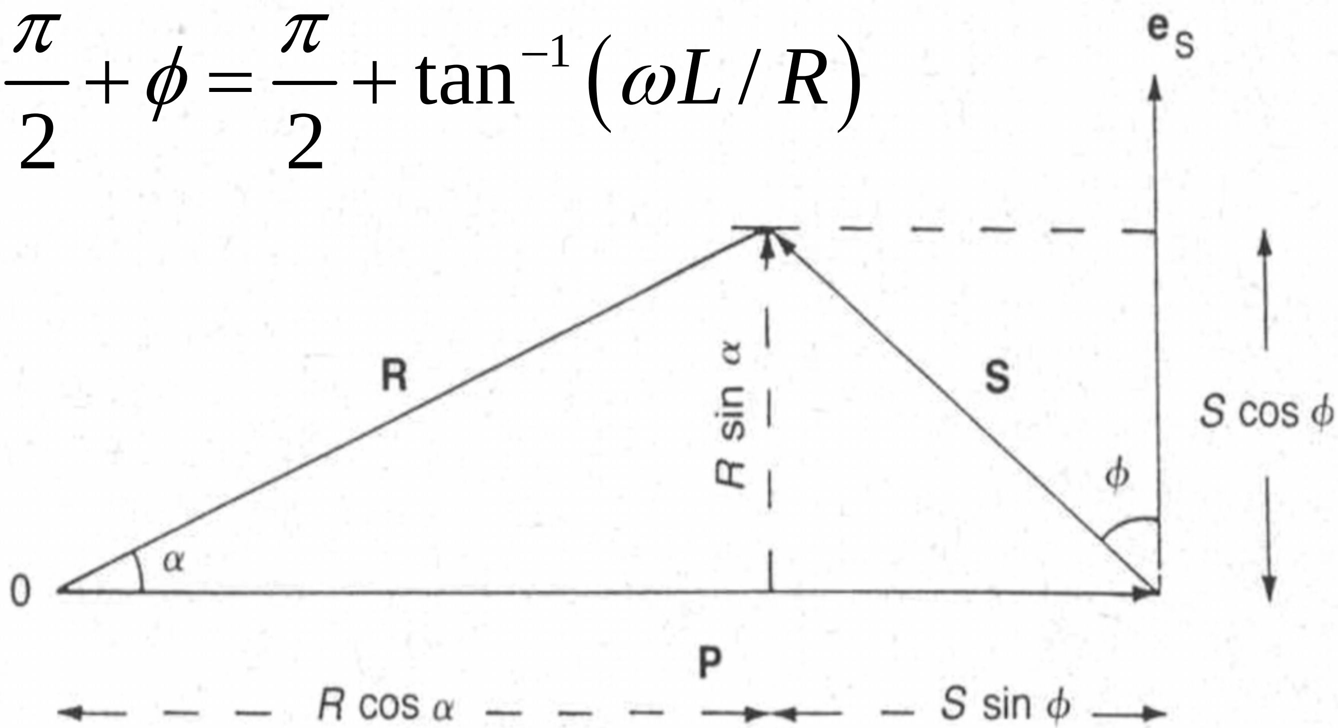
$$\Theta = \frac{\pi}{2} + \phi = \frac{\pi}{2} + \tan^{-1}\left(\omega L / R\right)$$

R is the resistance of the conductor

L is the inductance of the conductor (or its tendancy to oppose a change in the applied field)

Real and imaginary components

$$\Theta = \frac{\pi}{2} + \phi = \frac{\pi}{2} + \tan^{-1}\left(\omega L / R\right)$$



S sinϕ in-phase component (real)

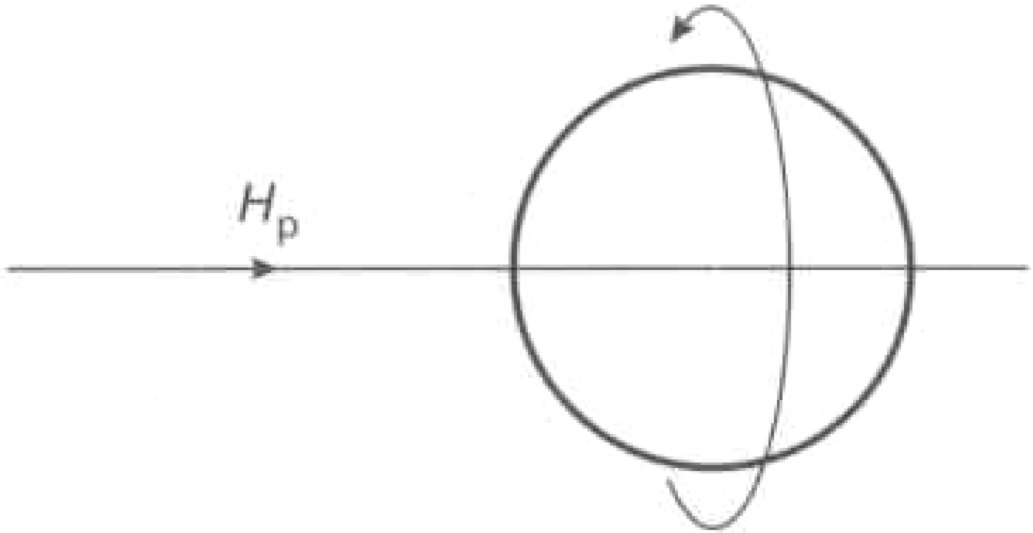
S cosϕ out-of-phase component (imaginary)

Effect of a conductive body

$$\Theta = \frac{\pi}{2} + \phi = \frac{\pi}{2} + \tan^{-1}\left(\omega L / R\right)$$

- Large conductivity ($R \to 0$ and $\phi \to \pi/2$): $\Theta \to \pi$
- Low conductivity ($R \to \infty$ and $\phi \to 0$): $\Theta \to \pi/2$

Tilt-angle methods



The receiving coil is turned until a null position is reached (no-signal): the plane of the coil then lies in the direction of the arriving field

Depth of penetration and skin depth

Skin depth: depth δ at which the amplitude of the field reaches 1/e of its original value a the source

$$\delta = \sqrt{\frac{2\rho}{\mu_0 \omega}} \approx 503\sqrt{\frac{\rho}{f}}$$

Depth of penetration: maximum depth z_e at which a conductor may still produce a recognizable EM anomaly (empirical relation)

$$z_e \approx \frac{100}{\sqrt{\sigma \ f}}$$

2. Survey strategies and interpretation

Classification of EM methods

Uniform field methods

- Magnetotelluric (MT)
- Audio-magnetotelluric (AMT)
- Very-Low Frequency (VLF-tilt, VLF-R)
- Controlled source audio-magnetotelluric (CSAMT)

Dipolar field methods

- Twin-coil or slingram systems: dipole source is used

Time-domain EM

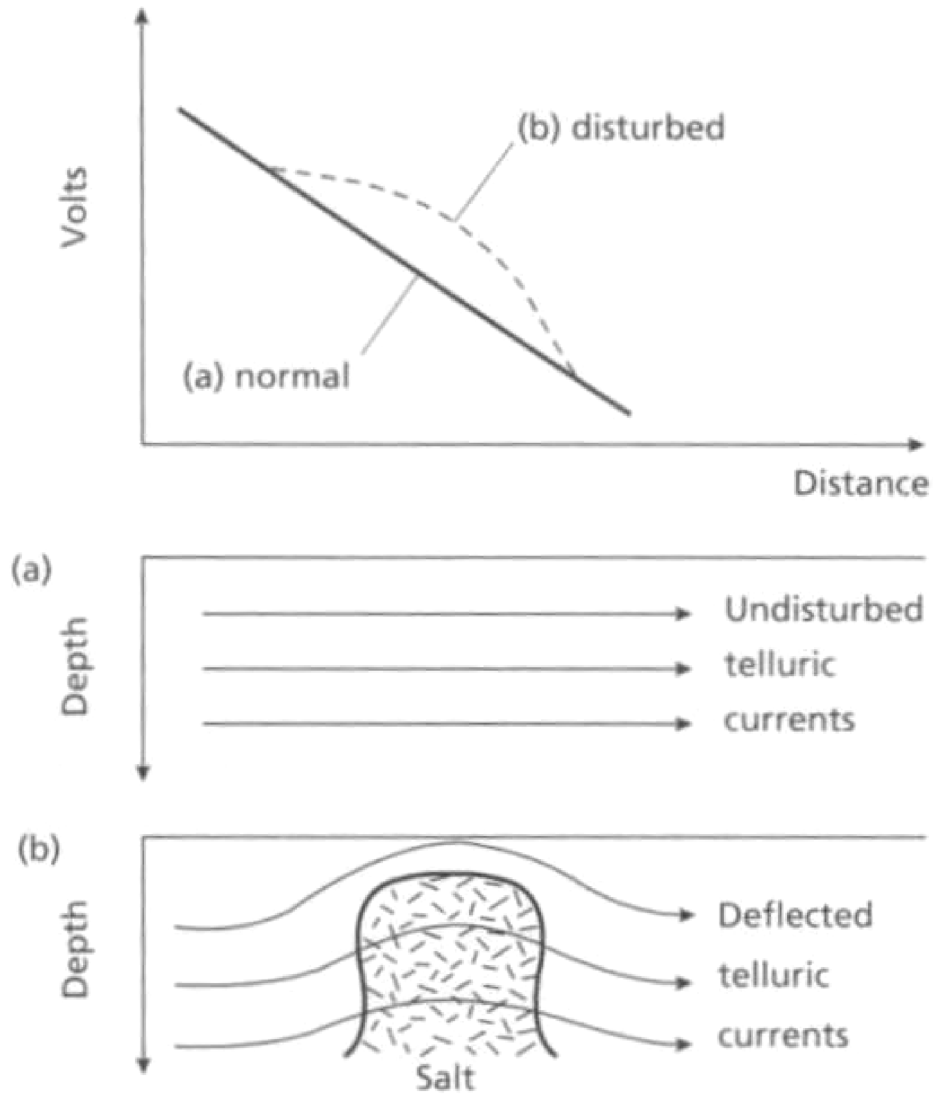
- Transient EM (TEM)

Magnetotelluric (MT)

- The source are fields of natural origin (magneto-telluric fields) resulting from flows of charged particles in the ionosphere, correlated with diurnal variations in the geomagnetic field caused by solar emissions

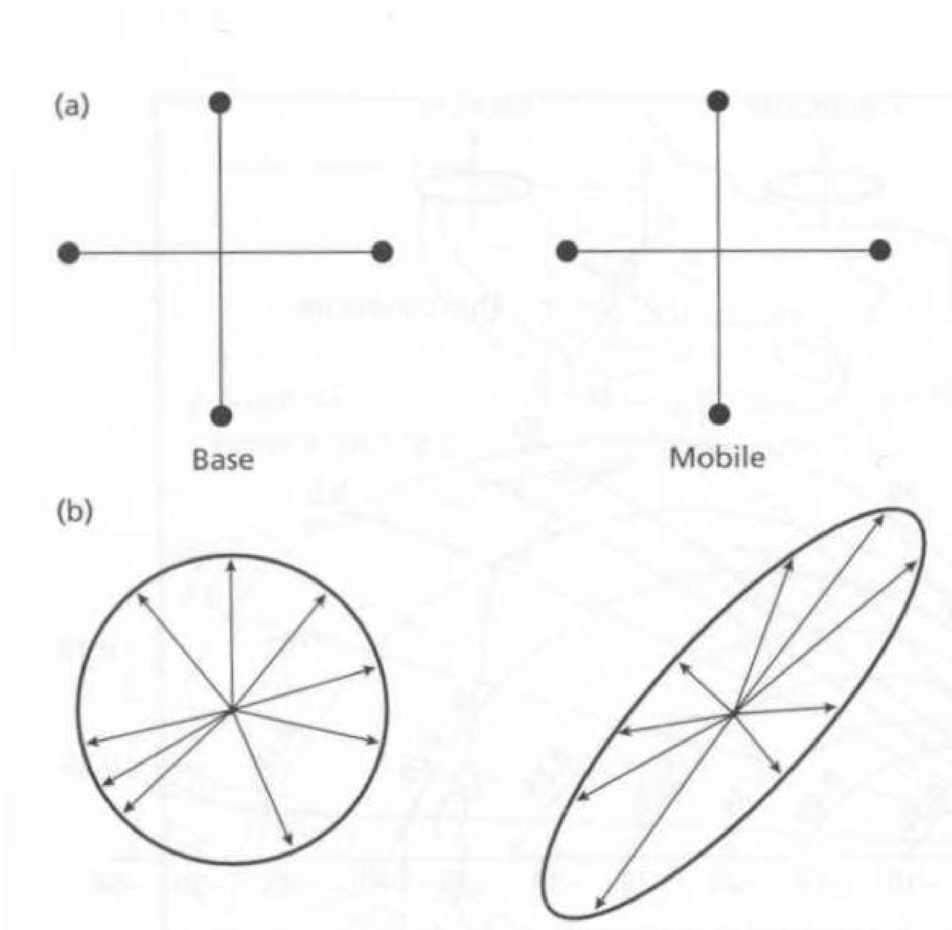
- The only electrical technique capable of penetrating to the depths of interest to the oil industry (mapping salt domes and anticlines)

- Frequencies range from 10^{-5} Hz to 20 kHz

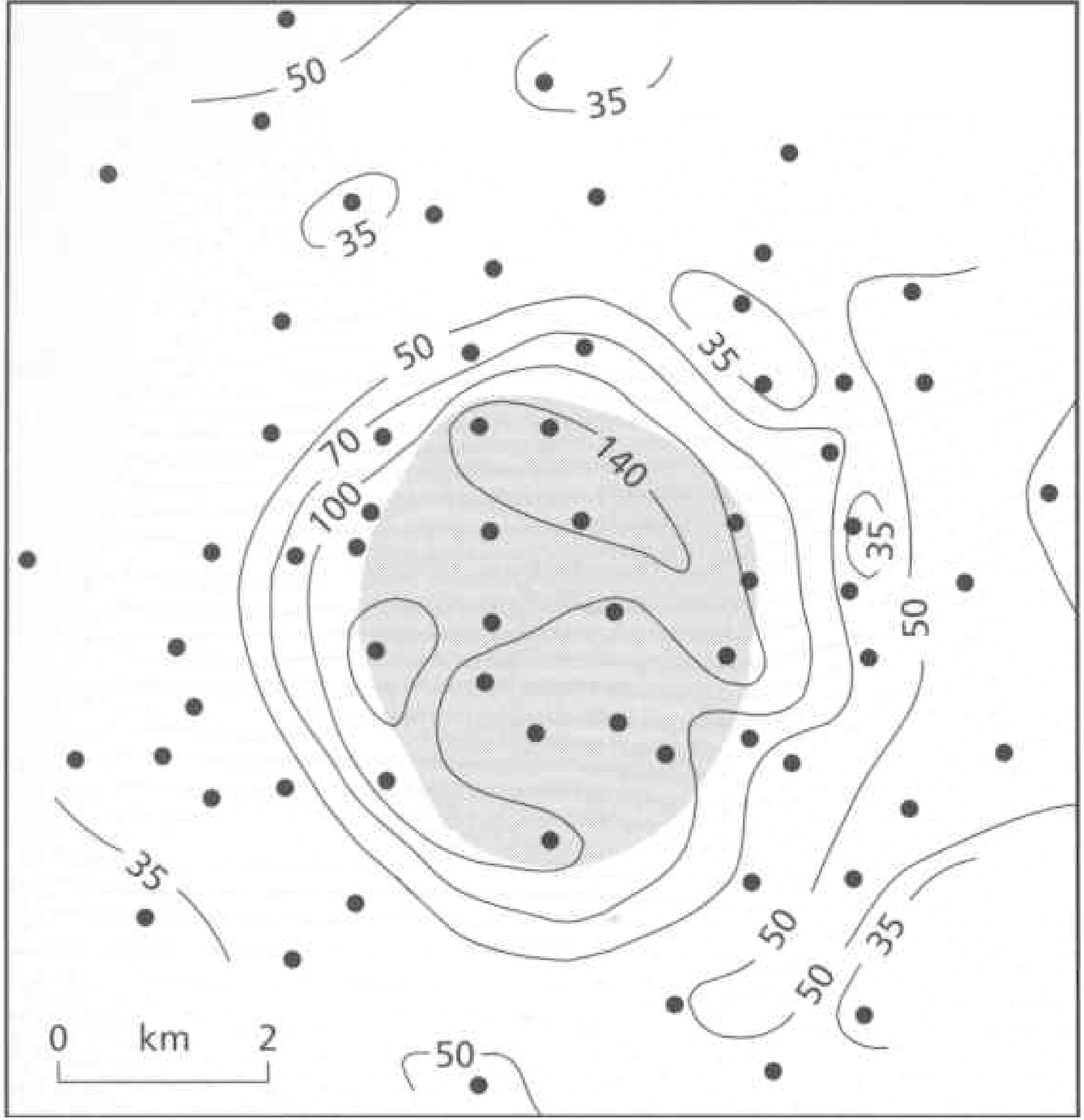


Volts
(b) disturbed
(a) normal
Distance
(a)
Depth
Undisturbed
telluric
currents
(b)
Depth
Deflected
telluric
currents
Salt

Telluric measurements

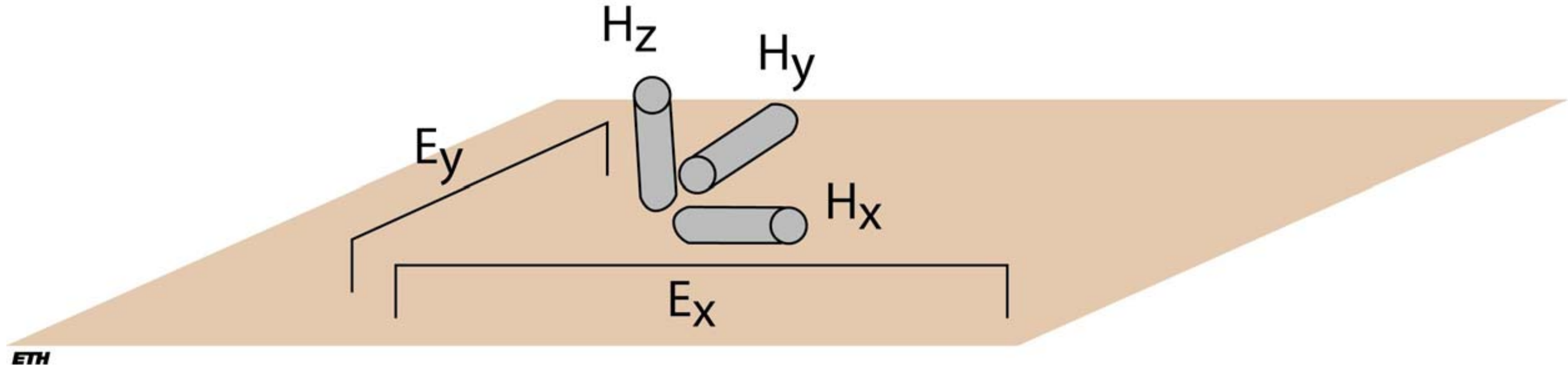


unit base circle area (A_1) measured ellipse area (A_2)



Map of A_2/A_1 for a salt dome

MT measurements



$$\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|Z(\omega)\right|^2 = \frac{1}{\omega\mu_0}\left|\frac{E_x(\omega)}{H_y(\omega)}\right|^2$$

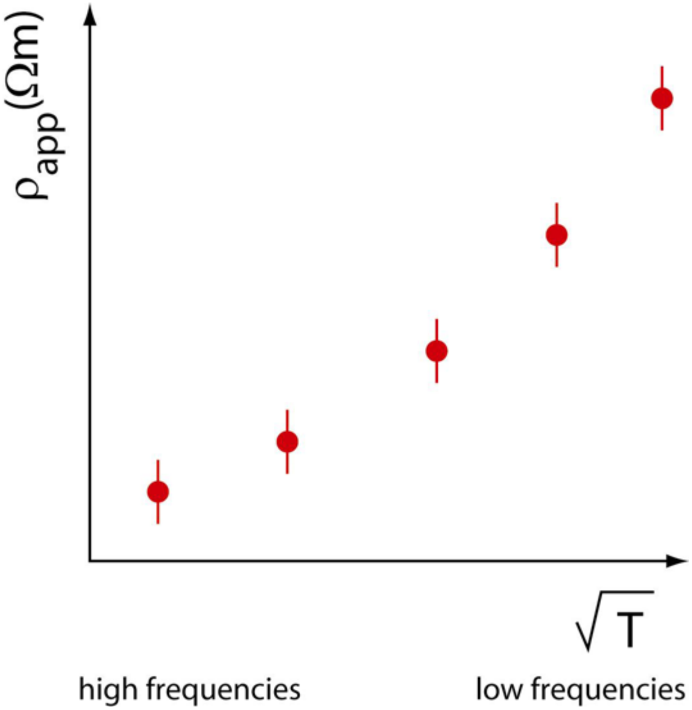
Audio-magnetotelluric (AMT)

- Use equatorial thunderstorms as sources (1 to 20 kHz). These EM fields are called sferics. Sferics propagated around the Earth between the ground and the ionosphere

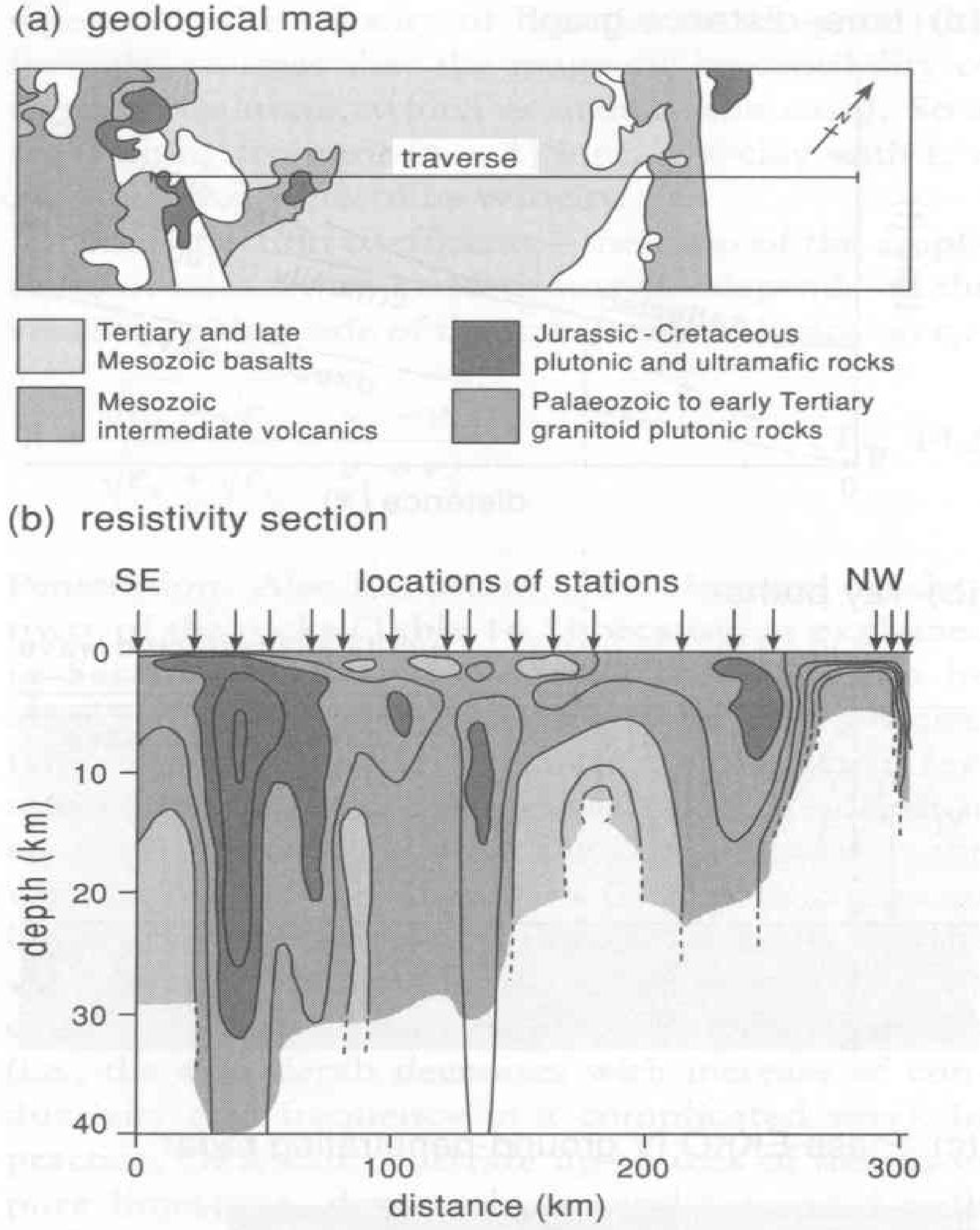
- The very broad frequency spectrum can be filtered to select a depth of investigation up to 1 km (AMT soundings)

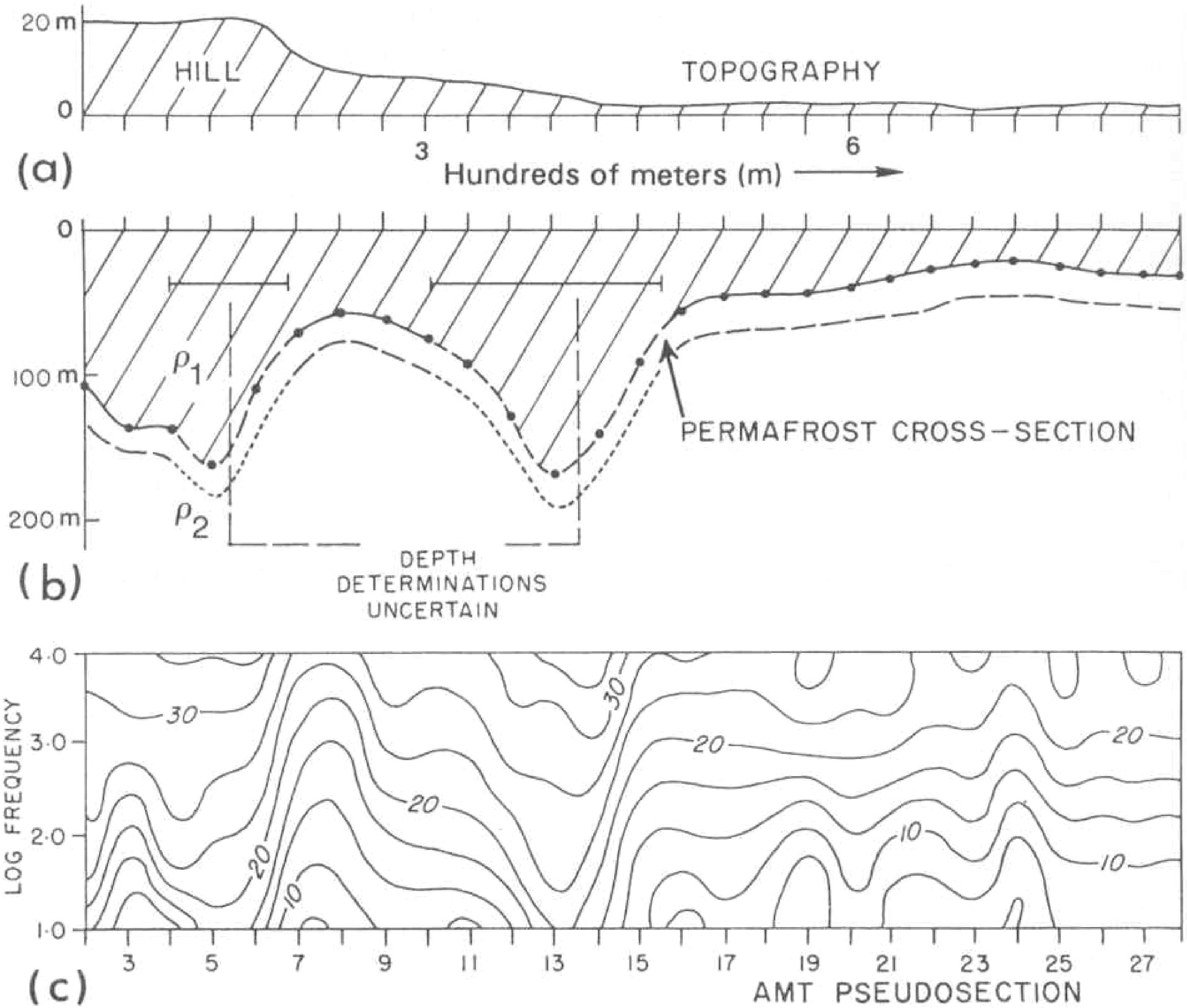
- Method sensitive to noise in urban areas

AMT-MT sounding



$$\rho_a = \frac{0.2}{f}\left(\frac{E}{H}\right)^2$$


(a) geological map
traverse
N
Tertiary and late Mesozoic basalts
Jurassic-Cretaceous plutonic and ultramafic rocks
Mesozoic intermediate volcanics
Palaeozoic to early Tertiary granitoid plutonic rocks
(b) resistivity section
SE
locations of stations
NW
depth (km)
0
10
20
30
40
0
100
200
300
distance (km)

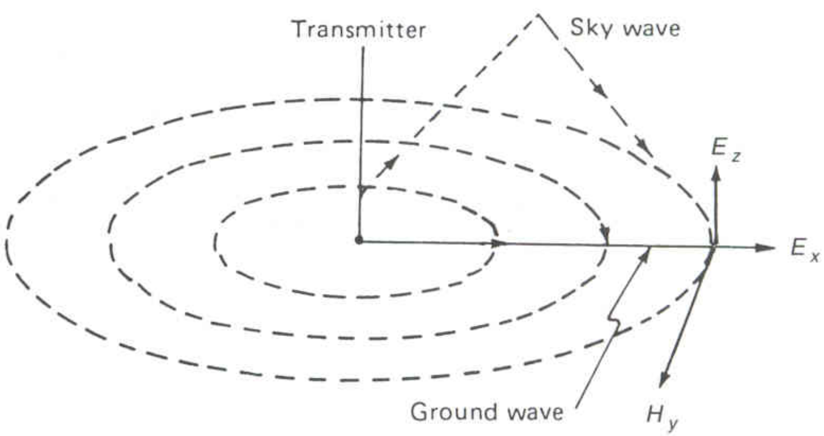


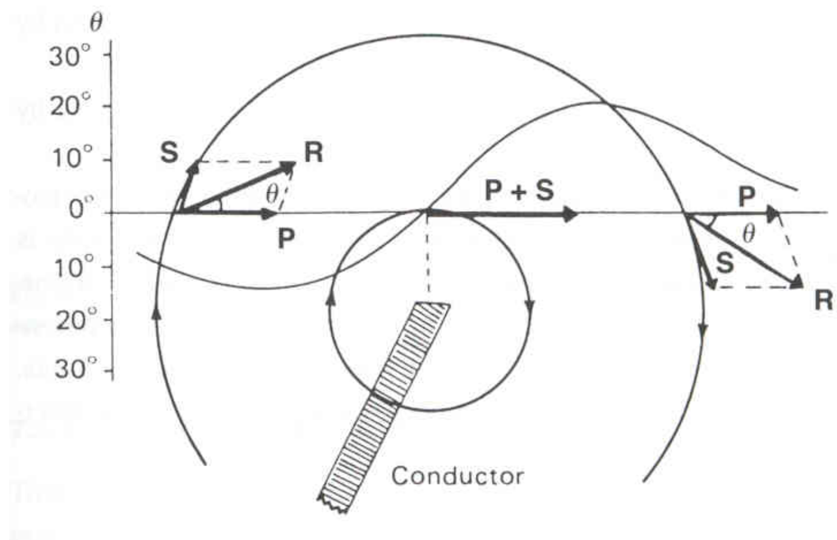
20 m
0
HILL
TOPOGRAPHY
3
6
(a)
Hundreds of meters (m)
0
100 m
200 m
ρ_1
ρ_2
PERMAFROST CROSS-SECTION
(b)
DEPTH
DETERMINATIONS
UNCERTAIN
LOG FREQUENCY
4.0
3.0
2.0
1.0
30
20
10
3
5
7
9
11
13
15
17
19
21
23
25
27
(c)
AMT PSEUDOSECTION

Very-Low Frequency (VLF-tilt)

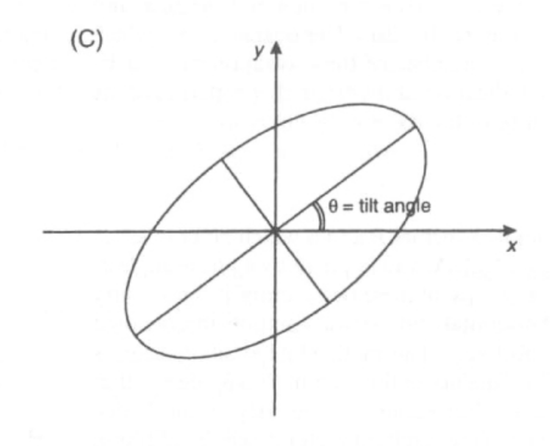
- Use submarine communication waves as sources (10 to 30 kHz). The transmitters are very powerful (>1 MW).The primary EM field is planar and horizontal
- The depth of investigation mainly depends on the conductivity of rocks and the transmitter chosen (from 10m to 100m)
- Disadvantages: transmission frequently broken, difficult to find a transmitter in an appropriate direction
- Advantages: light, fast and easy to use

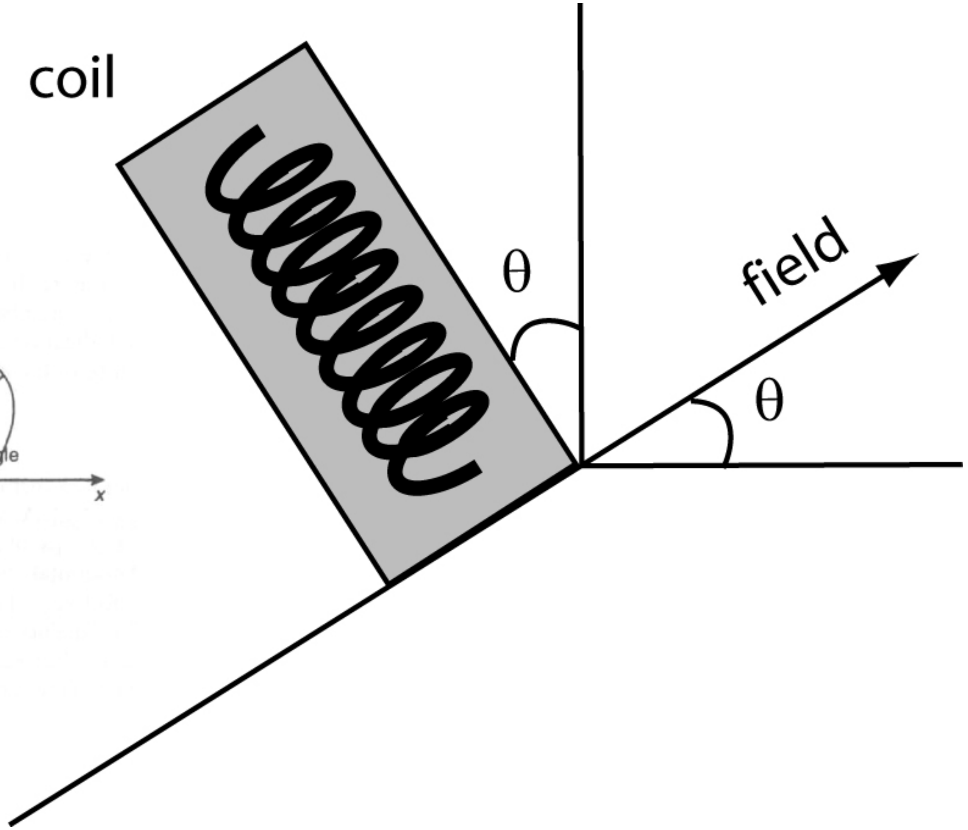
VFL-tilt measurements





VFL-tilt measurements

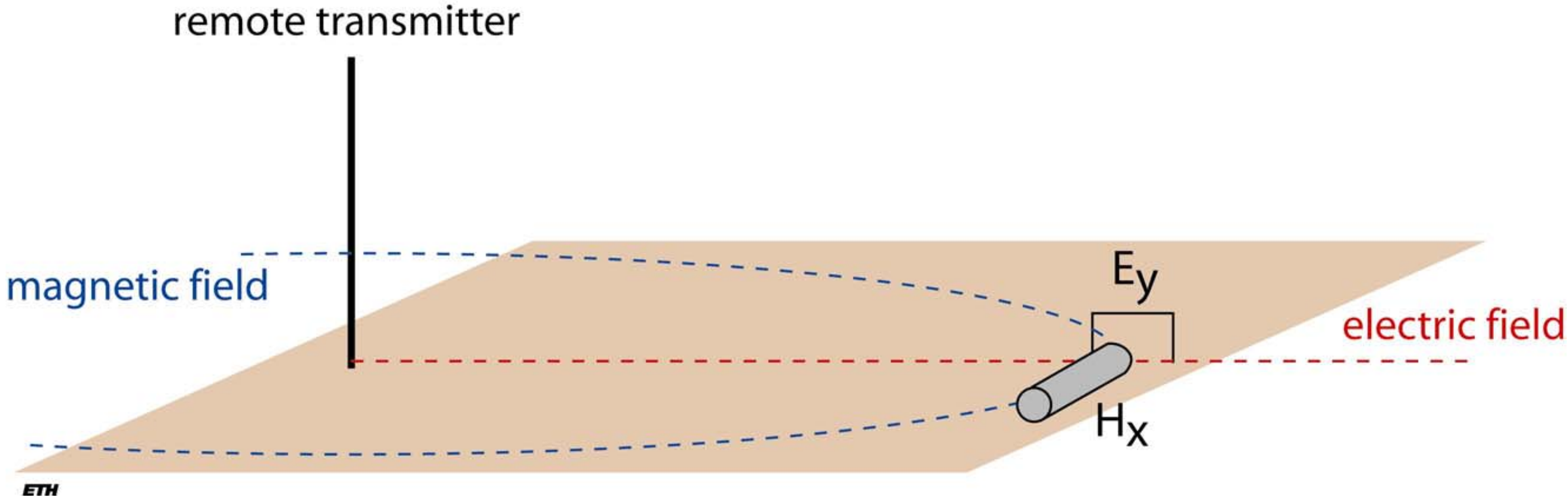




Very-Low Frequency (VLF-R)

- Gives apparent resistivity of the ground and phase shift by measuring *H* and *E*
- Various local radio waves can be used to chose a depth of investigation (frequency can be chosen)

VLF-R measurements



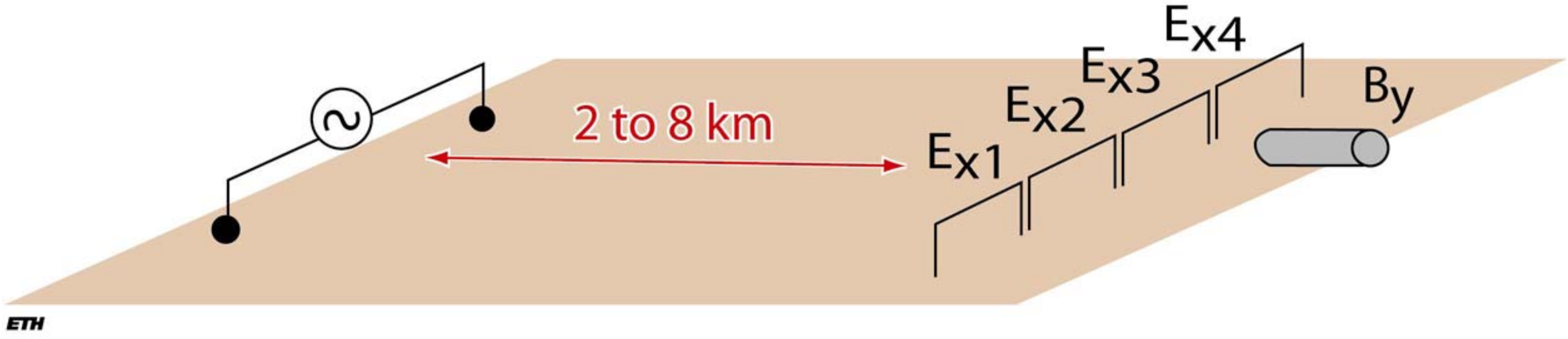
$$\rho_a = \frac{0.2}{f}\left(\frac{E}{H}\right)^2$$

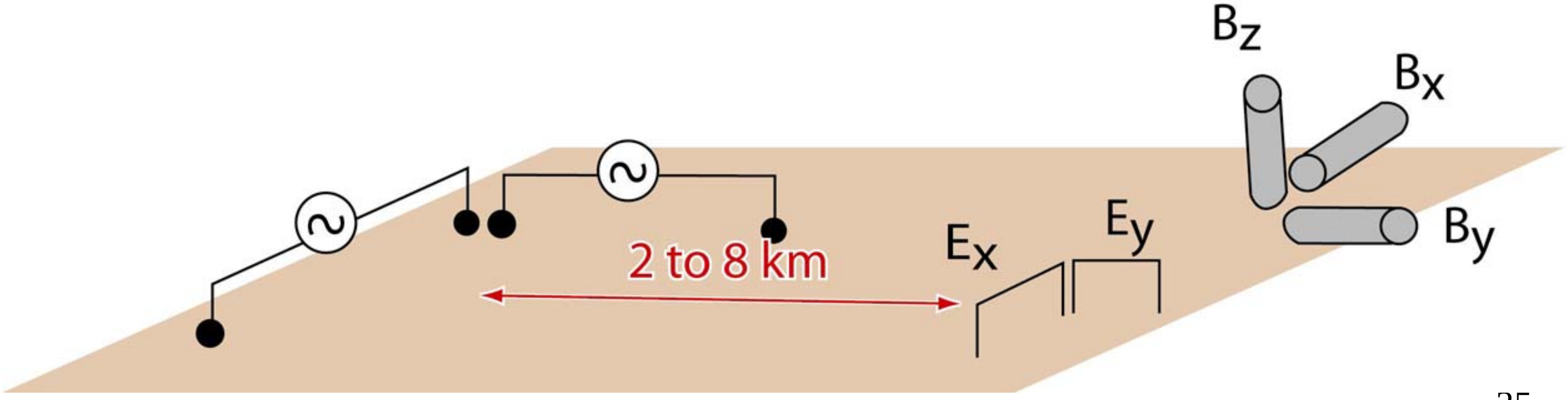
Controlled source AMT (CSAMT)

- Similar to MT but using a remote (2 to 8 km) electrical dipole as source (1 Hz to 10 kHz)

- The source frequency and location is known

CSAMT measurements



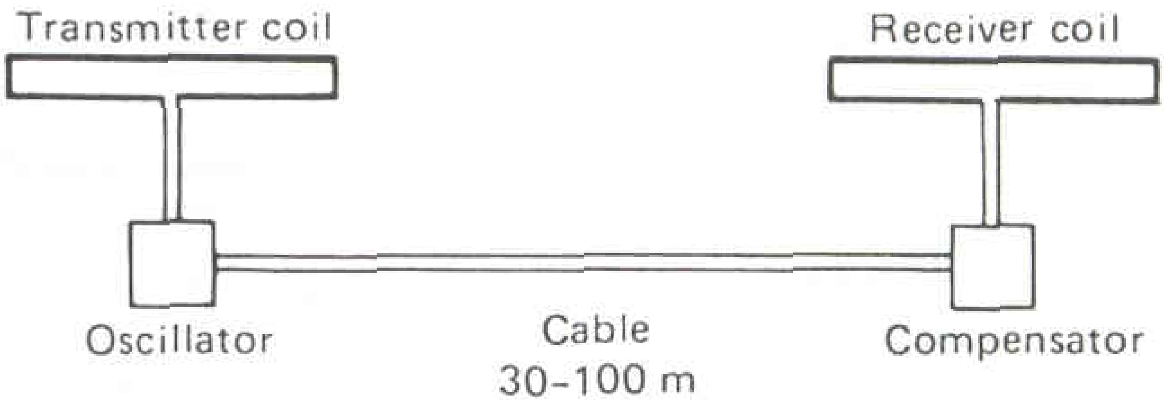


Dipole-source methods

- Measurements tolls called twin-coil or slingram systems

- Tx and Rx are coils (about 1m diameter) linked by a cable which carries a reference signal in order to compensate the effect of the primary field. By this means, the system subsequently responds only to the secondary fields

- A decomposer spilt the secondary field into real and imaginary components (display the result as a percentage of the primary field)

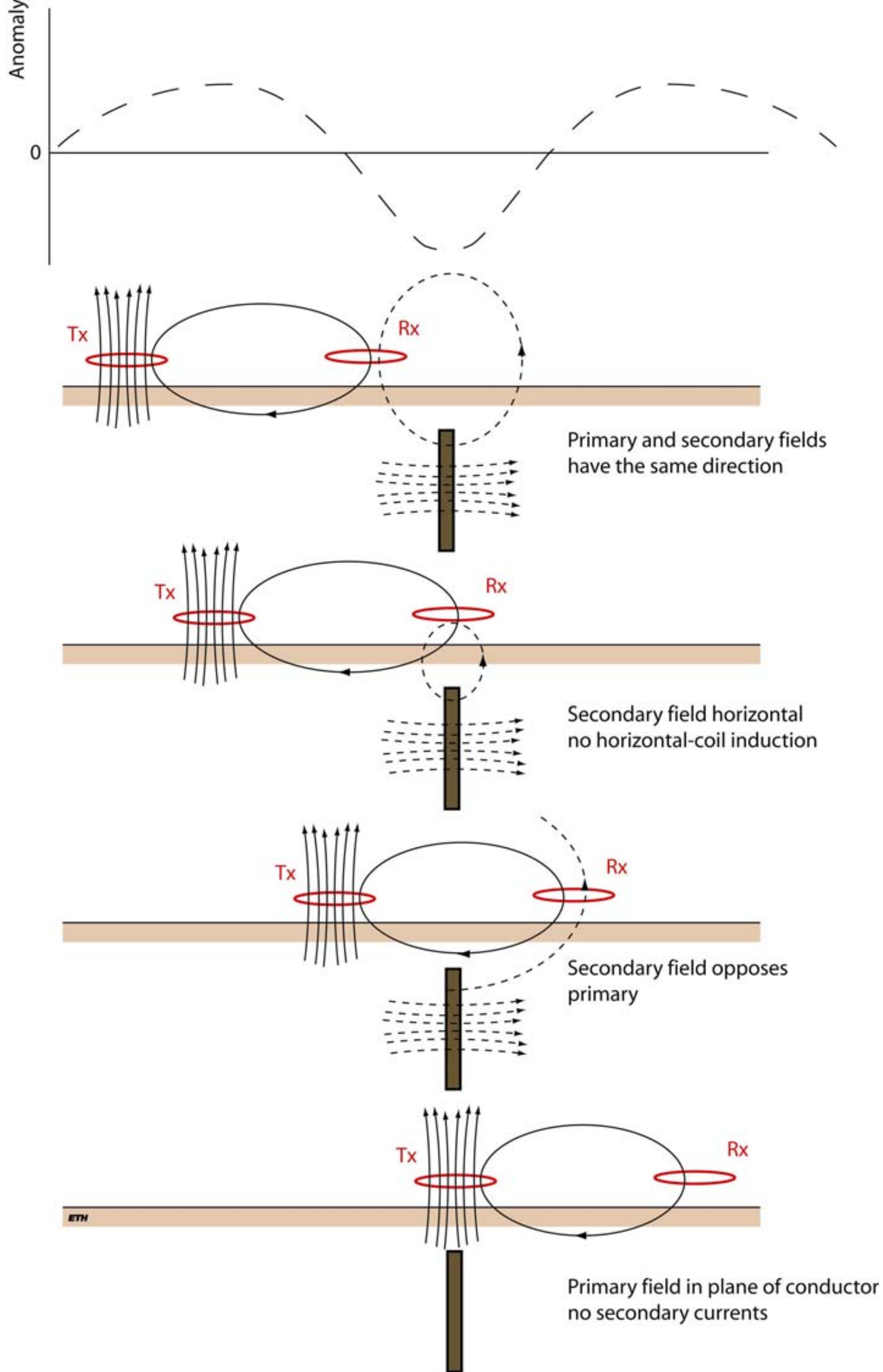

Transmitter coil
Receiver coil
Oscillator
Cable
30-100 m
Compensator

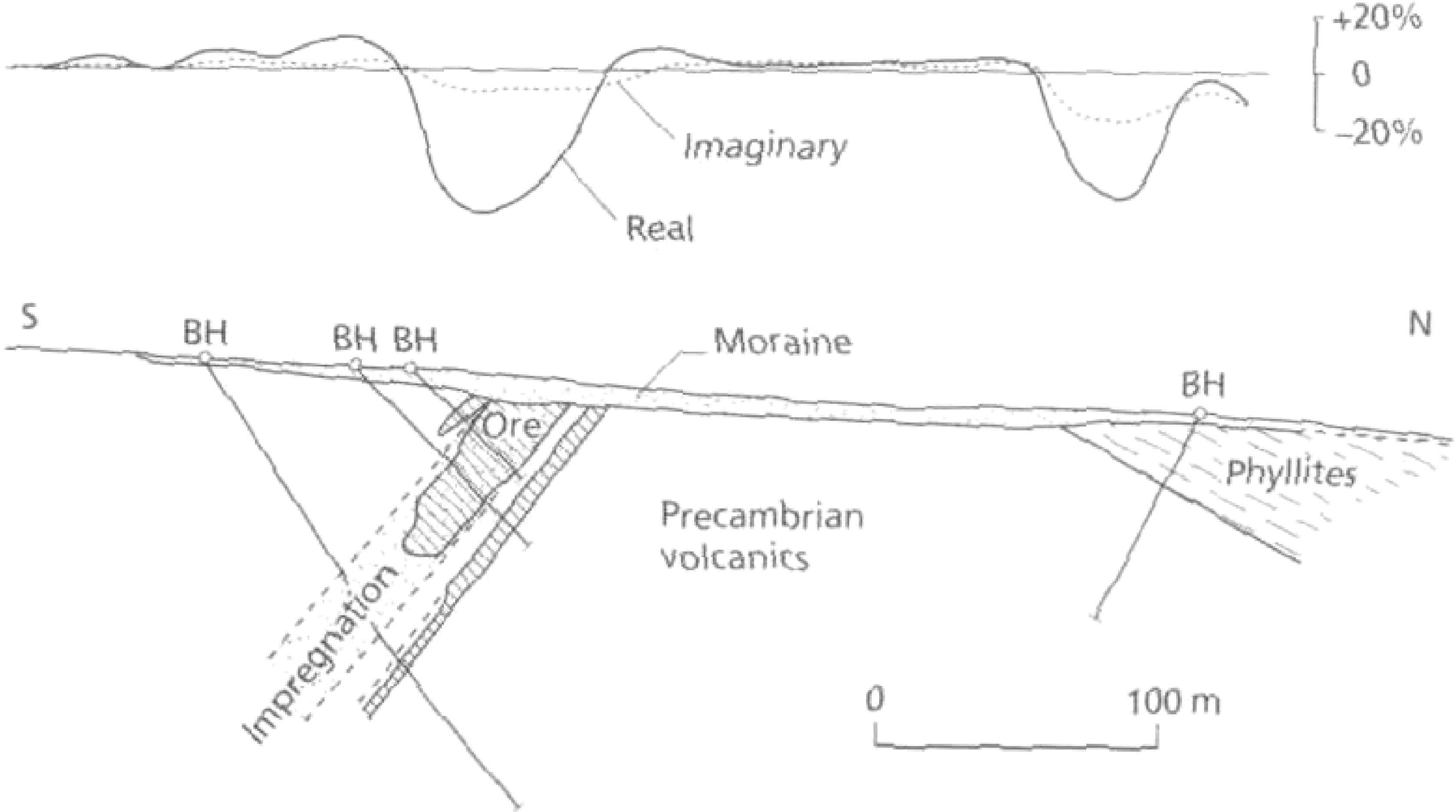
EM31 (Geonics), 9.8 kHz, *s*=3.66 m

EM34 (Geonics), 6.4 kHz for *s*=10 m
1.6 kHz for *s*=20 m
0.4 kHz for *s*=40 m

EM38 (Geonics), 14.6 kHz, *s*=1 m

s: Rx-Tx distance


Anomaly
0
Tx
Rx
Primary and secondary fields
have the same direction
Tx
Rx
Secondary field horizontal
no horizontal-coil induction
Tx
Rx
Secondary field opposes
primary
Tx
Rx
ETH
Primary field in plane of conductor
no secondary currents


+20%
0
−20%
Imaginary
Real
S
BH
BH BH
Moraine
N
BH
Ore
Phyllites
Precambrian volcanics
Impregnation
0
100 m

EM at low induction numbers (LIN)

- Depth of investigation depends on the distance Tx-Rx
- The response is proportional to ground conductivity
- Manufacturer adapts the Rx-Tx distance (s) and frequency (f) for a LIN approximation, i.e. $s \ll \delta$:

$$N_B \ll 1 \Rightarrow \frac{H_S}{H_P} \frac{4}{i\mu_0 \omega \sigma s^2} \cong \sigma_a$$

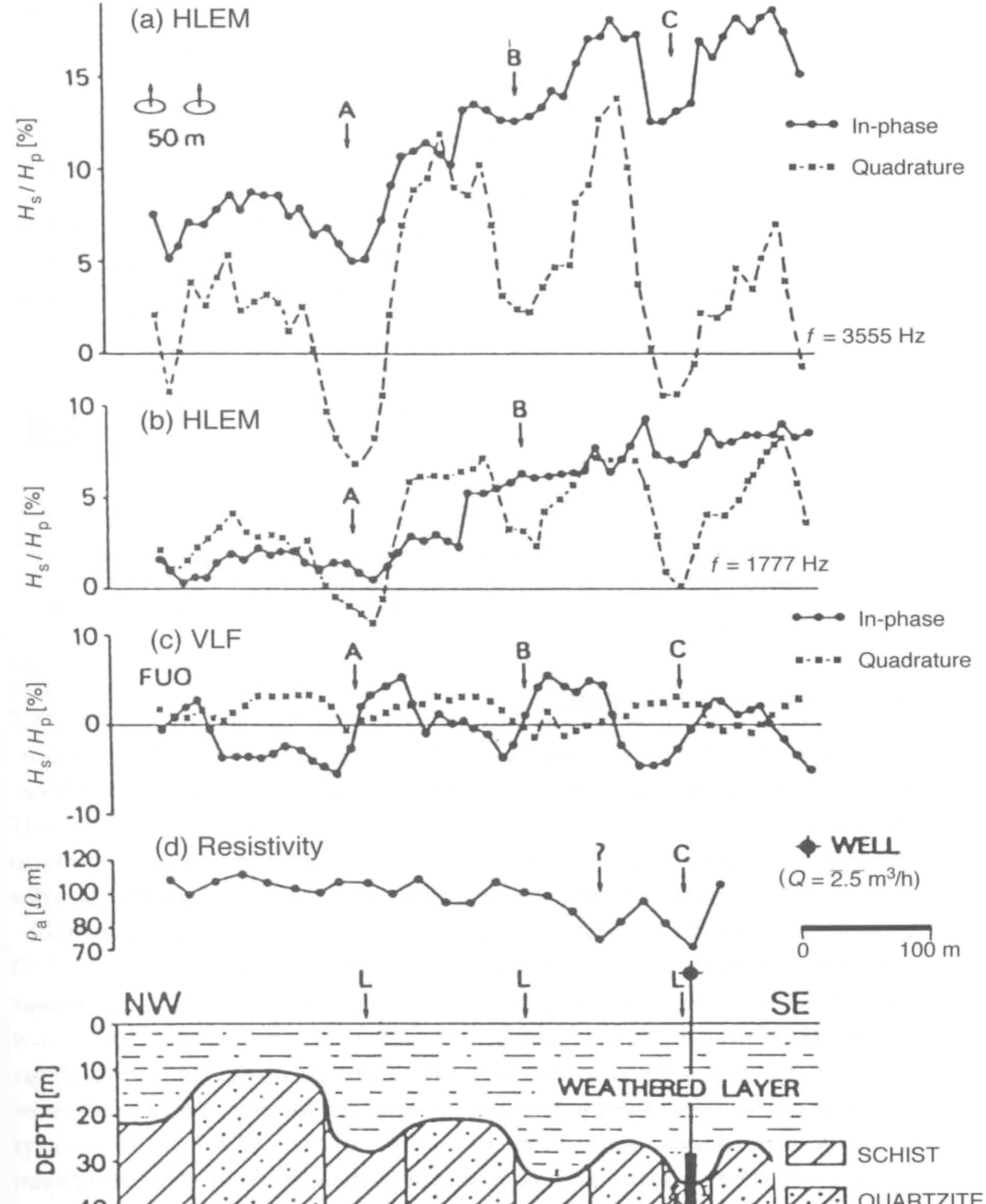
$N_B = s / \delta$ is the induction number

$$\delta \cong 503 \sqrt{\frac{\rho}{f}}$$

CST and VES using LIN

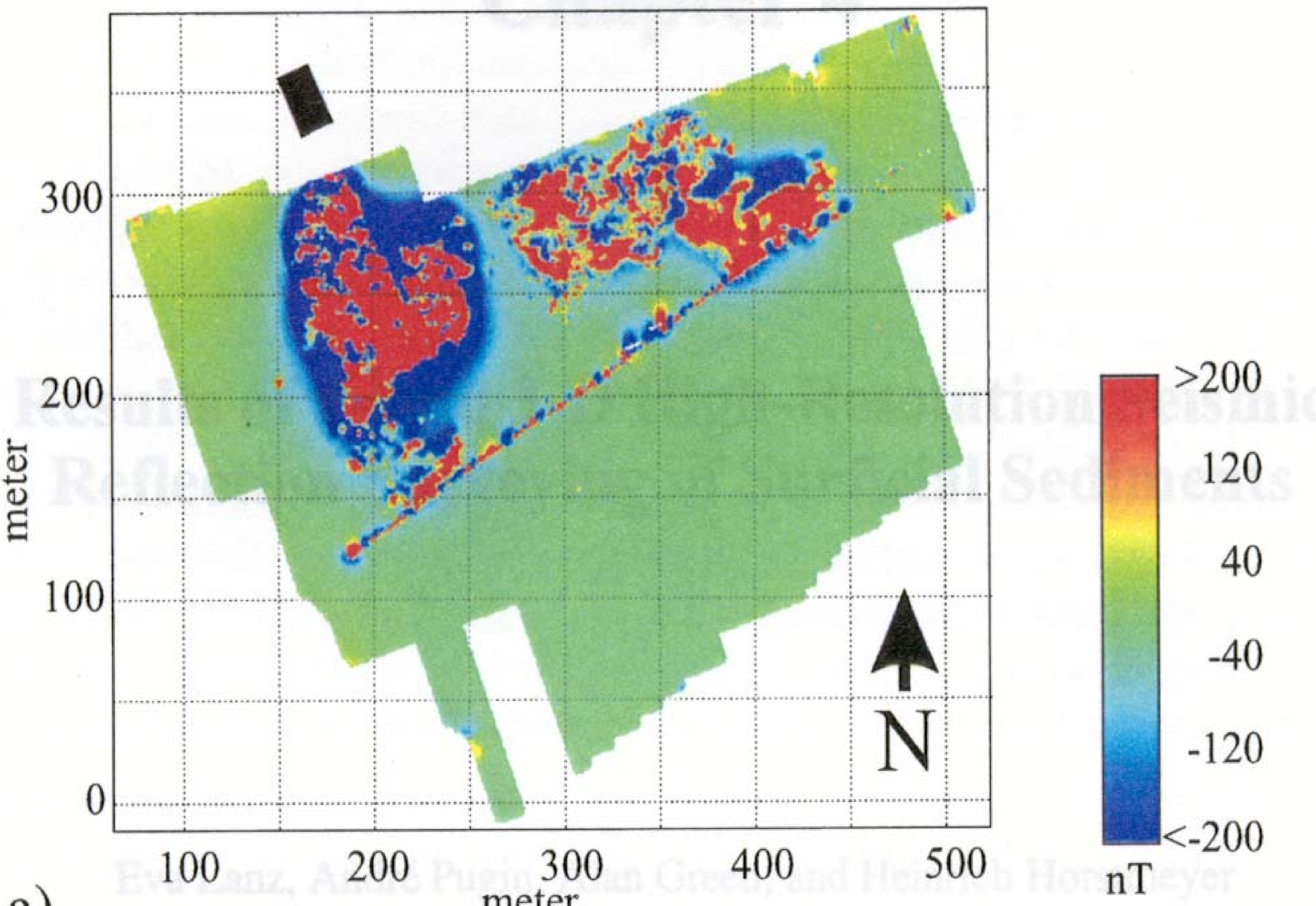
- CST: moving vertical and horizontal dipoles with various constant depth (survey principle similar to resistivity CST and tomography)

- VES: increasing Tx-Rx spacing around a same location point and using vertical and horizontal dipoles (survey principle similar to resistivity VES)

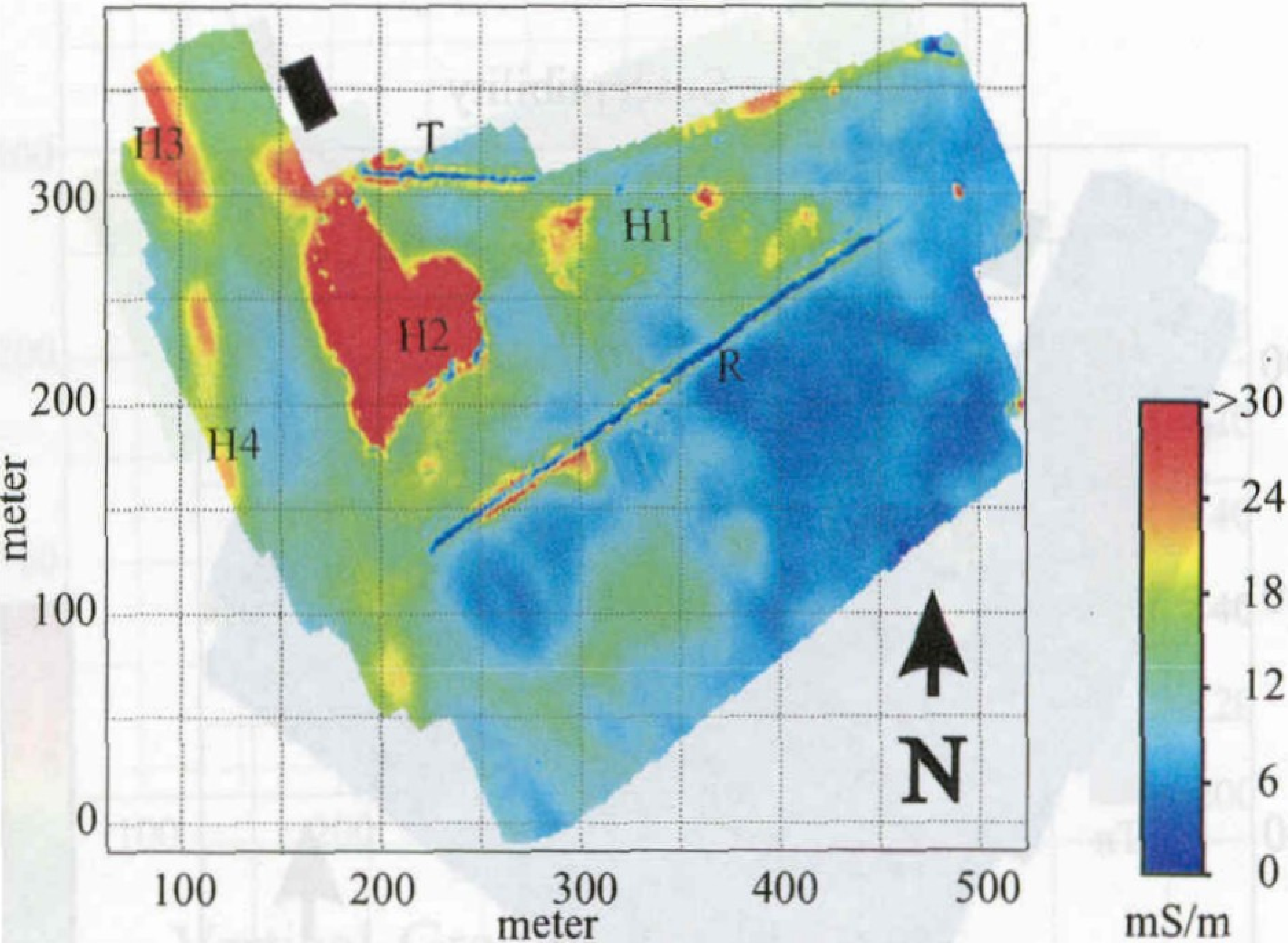


(a) HLEM
50 m
A
B
C
In-phase
Quadrature
f = 3555 Hz
H_s / H_p [%]
(b) HLEM
f = 1777 Hz
(c) VLF
FUO
(d) Resistivity
?
WELL
(Q = 2.5 m³/h)
0
100 m
ρ_a [Ω m]
NW
SE
L
WEATHERED LAYER
DEPTH [m]
SCHIST
QUARTZITE

Bottom Sensor Total-Field Magnetic



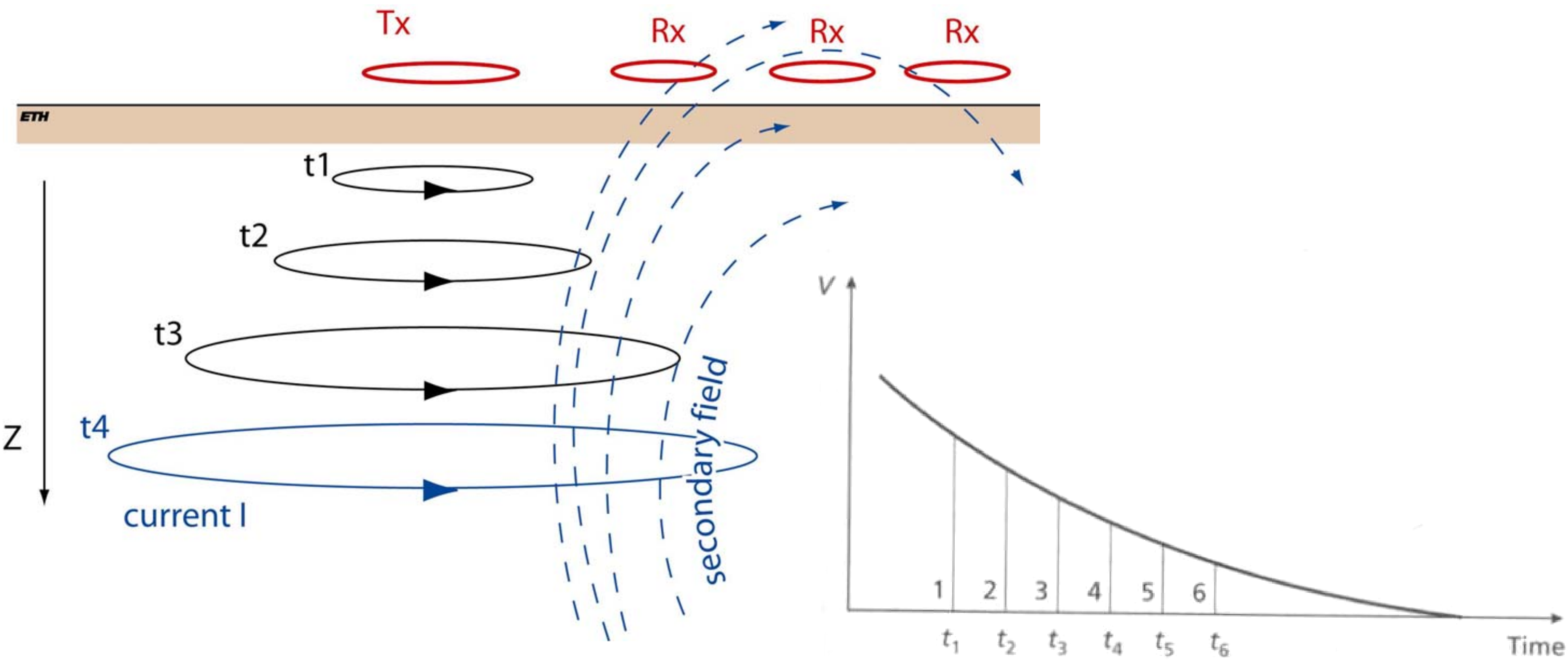
a)


H3
T
H1
H2
R
H4
300
200
100
0
meter
100
200
300
400
500
meter
N
>30
24
18
12
6
0
mS/m

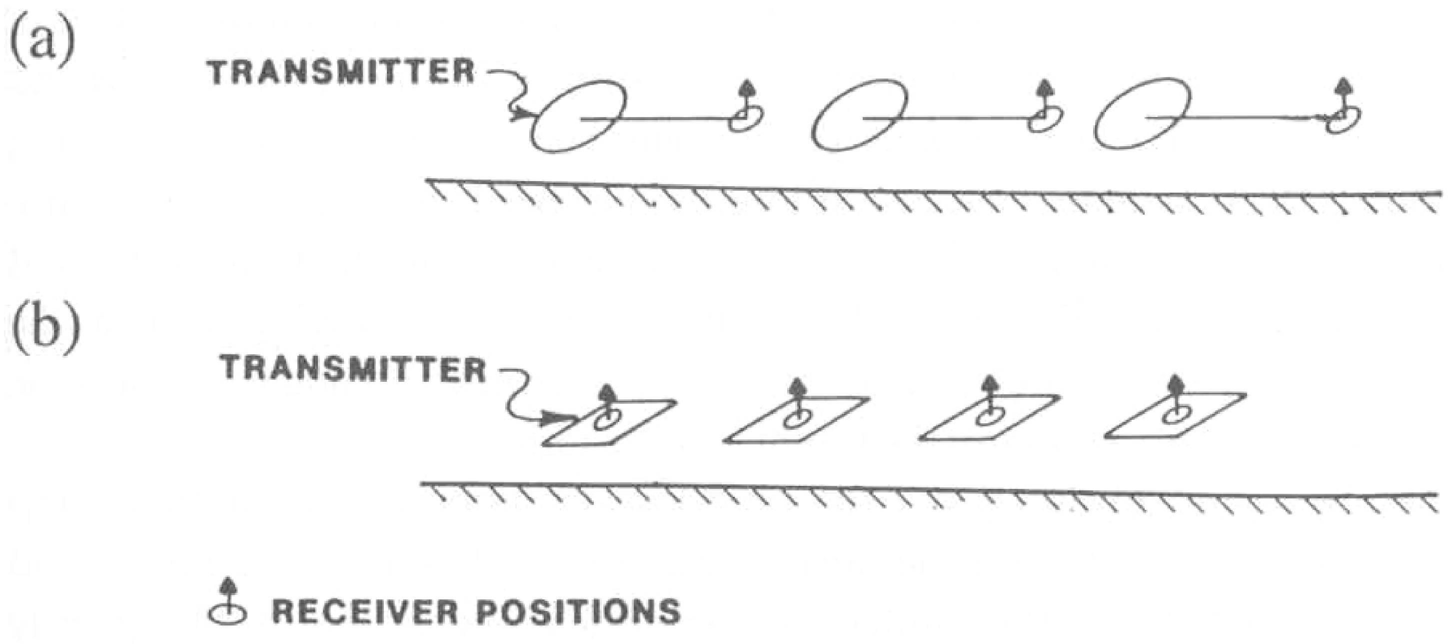
Transient EM (TEM)

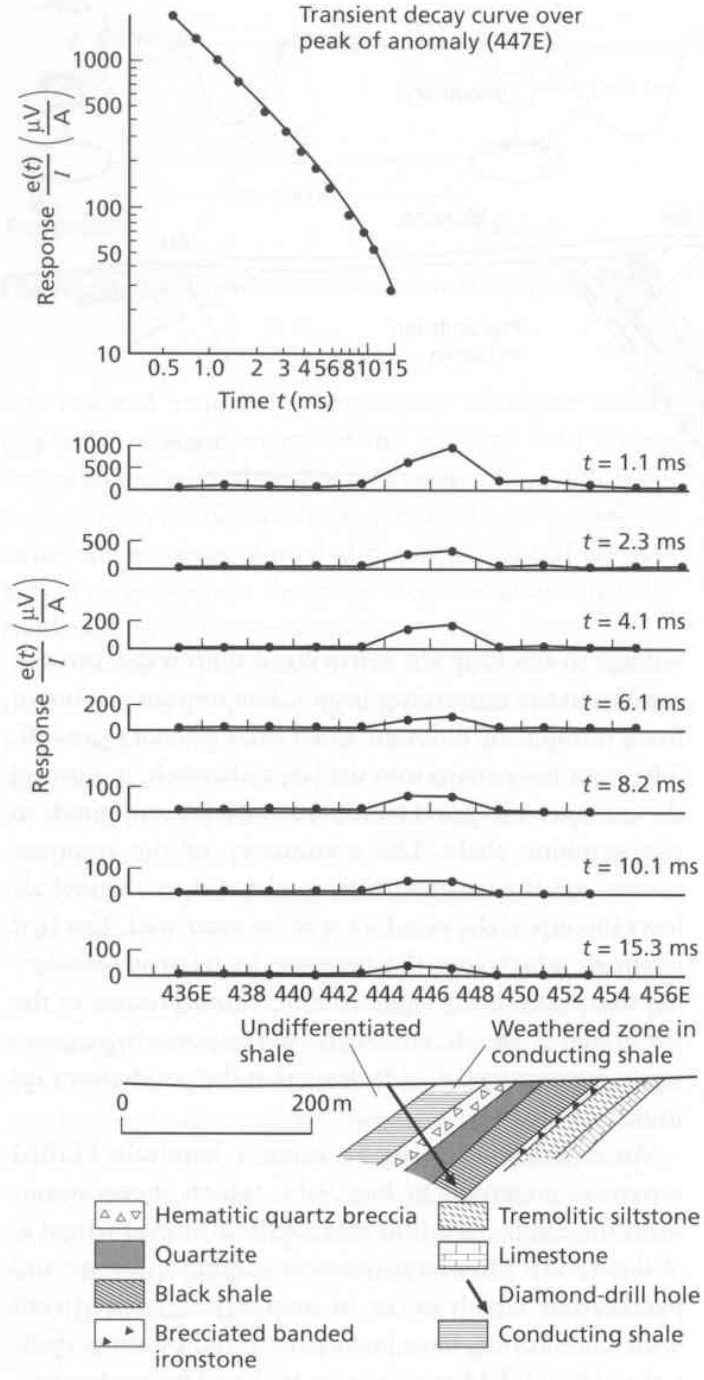
- TEM uses a primary field which is not continuous but consists of a series of pulses separated by measurement periods when the transmitter is inactive
- Primary and secondary fields are clearly separated
- Investigation depth up to several km could be achieved, but difficult to use in shallow geophysics (no reliable information in the 0-10 m depth range)

TEM measurements

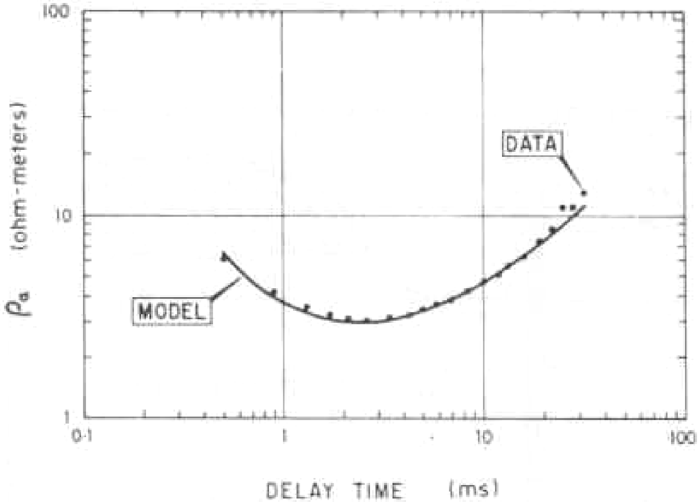


TEM measurements




Transient decay curve over peak of anomaly (447E)
Response e(t)/I (μV/A)
1000
500
100
50
10
0.5 1.0 2 3 4 5 6 8 10 15
Time t (ms)
t = 1.1 ms
t = 2.3 ms
t = 4.1 ms
t = 6.1 ms
t = 8.2 ms
t = 10.1 ms
t = 15.3 ms
436E 438 440 442 444 446 448 450 452 454 456E
Undifferentiated shale
Weathered zone in conducting shale
0
200 m
Hematitic quartz breccia
Quartzite
Black shale
Brecciated banded ironstone
Tremolitic siltstone
Limestone
Diamond-drill hole
Conducting shale

SIROTEM STATION 150 E

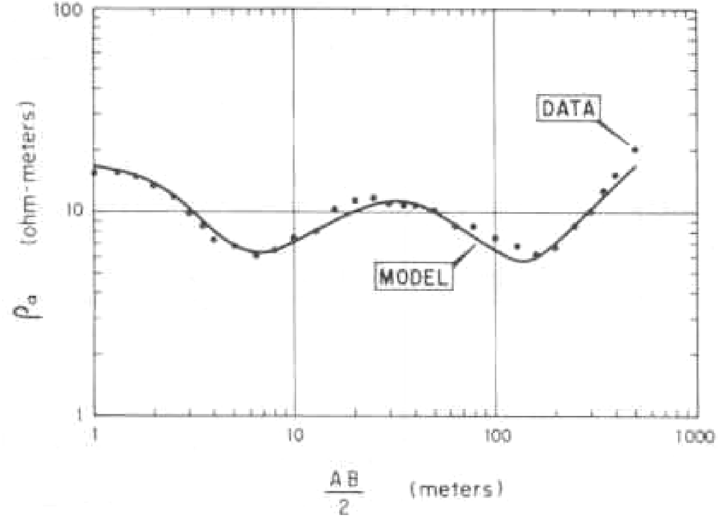


LAYER	THICKNESS (meters)	RESISTIVITY (ohm-meters)
1	1·5 *	17 *
2	3·0 *	3·1 *
3	24 **	21
4	36 **	1·4 **
5		380

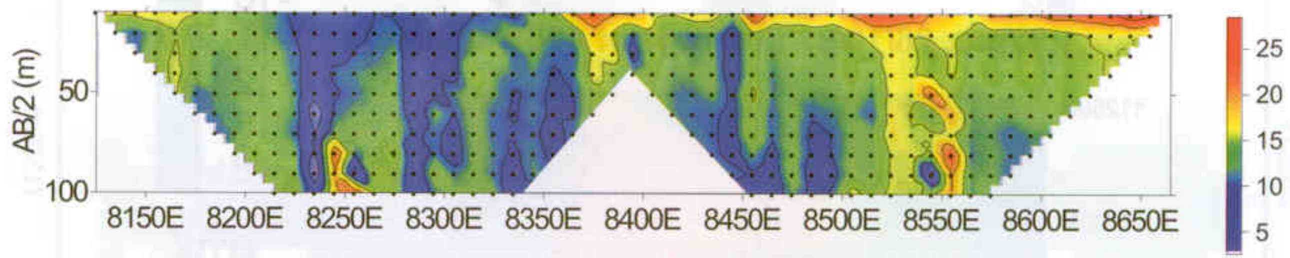
* Fixed parameter

** Influential parameter

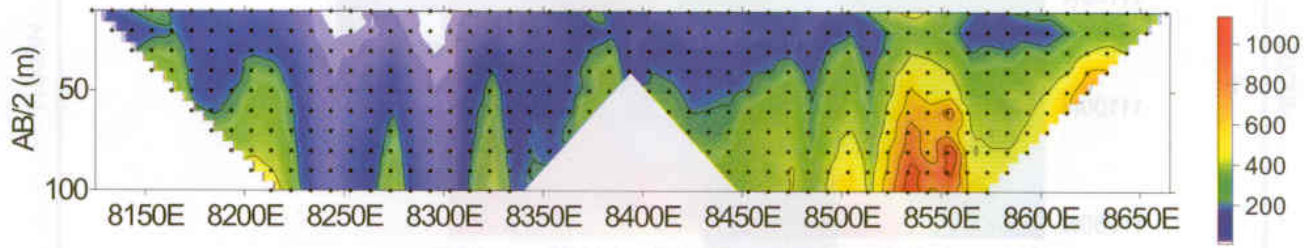
VES 1



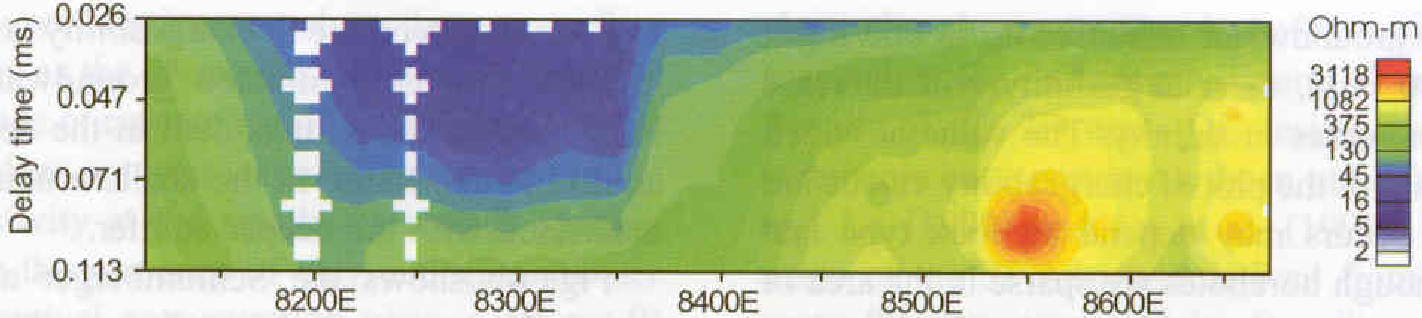
LAYER	THICKNESS (meters)	RESISTIVITY (ohm-meters)
1	1·5	17
2	3·0	3·1
3	20·0	22·0
4	43·0	1·6
5		250·0



(a) Chargeability (ms)



(b) Apparent resistivity (ohm-m)



Remarks on interpretation

- Indirect approach using theoretical computations of simple geometry shapes (spheres, cylinders, thin sheets, horizontal layers)
- Laboratory modeling (using special scaling rules)
- Use of master curves for simple Earth structures
- Mainly qualitative. Quantitative inversion in development, soundings very used

3. Conclusions

Advantages

- Surveys are easy to carry out, non-expensive (require less field operators than resistivity methods)
- Rapid qualitative overview
- No galvanic coupling with the ground required
- Theoretically less sensitive to non-unicity in the solution than resistivity

Drawbacks

- Quantitative interpretation of EM anomalies is complex
- Penetration not very great if very conductive superficial layers are present