Eidgenössische Technische Hochschule Zürich
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Magnetic Surveying

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Introduction

Magnetic surveying…

Investigation on the basis of anomalies in the Earth´s magnetic field resulting from the magnetic properties of the underlying rocks (magnetic susceptibility and remanence)

Application

- Exploration of fossil fuels (oil, gas, coal)
- Exploration of ore deposits
- Regional and global tectonics
- Large scale geological structures, volcanology
- Buried conductive objects (cables, drums)
- Unexploded ordnance (UXO)
- Archaeological investigations
- Engineering/construction site investigation

Structure of the lecture

1. Equations in magnetic surveying
2. Geomagnetic field (refresher)
3. Magnetic properties of rocks (refresher)
4. Survey strategies and interpretation
5. Conclusions

We will not talk about magnetic properties at an atomic scale, paleomagnetics or the magnetic structure of the Earth. These notions were developed last year. We will focus on magnetics for environmental and engineering applications and emphasize links with gravimetry.

1. Equations in magnetic surveying

Basic magnetic theory

Let us first define the following terms…

$\vec{F}$ magnetic force

$\vec{B}$ magnetic induction field

$\vec{H}$ magnetic field strenght

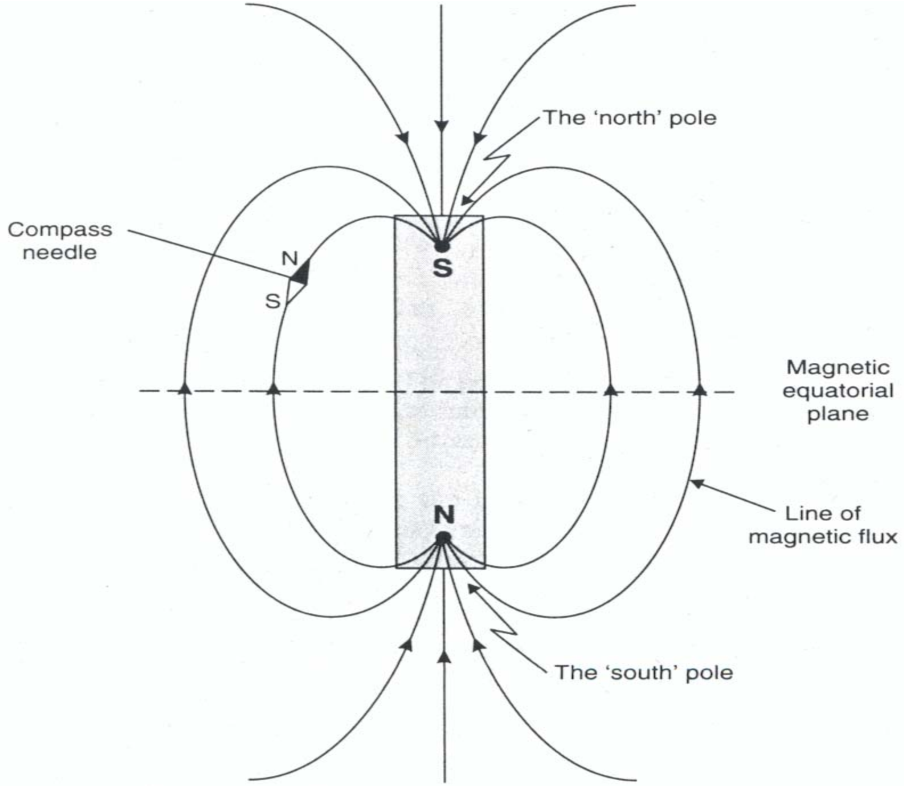
$\vec{M}$ magnetic moment

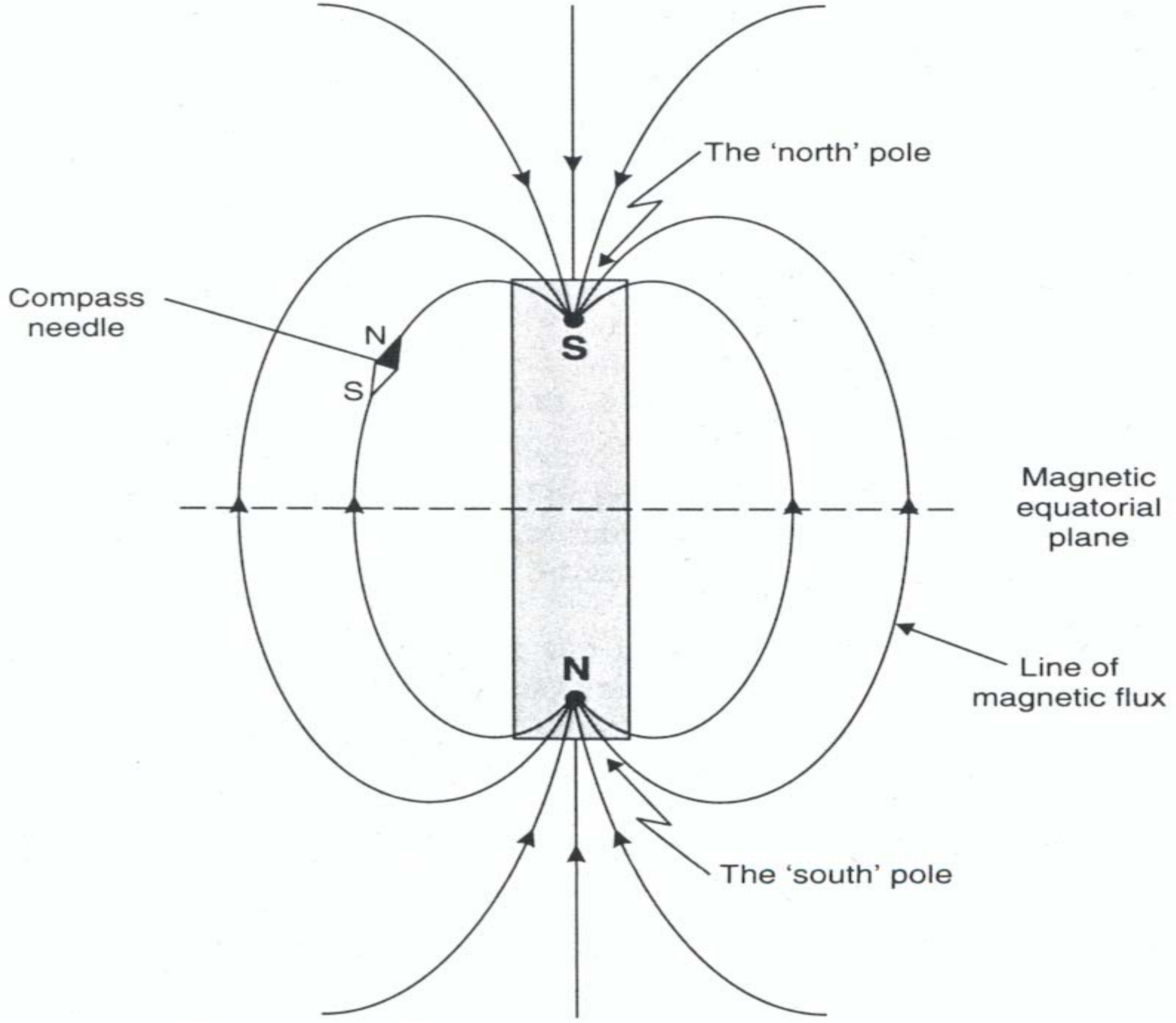
$\vec{J}_i$ intensity of induced magnetization

k magnetic susceptibility

Basic concepts

Within the vicinity of a bar magnet a magnetic flux is developed which flows from one end of the magnet to the other (the poles of the magnet).

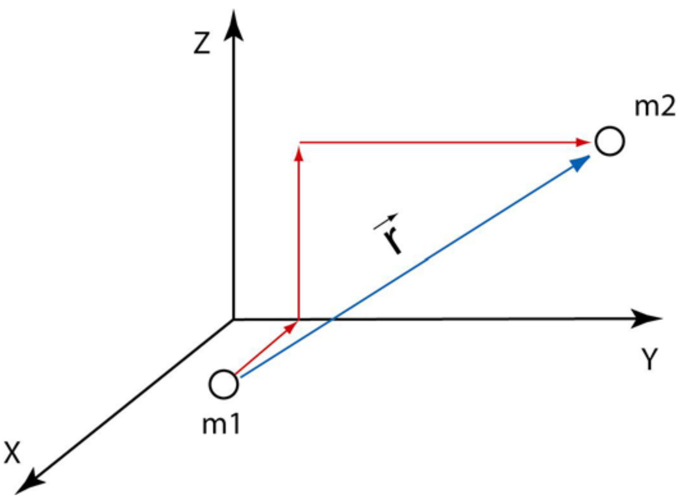




This flux can be mapped by a small compass needle suspended within it. Similarly, a magnet aligns in the flux of the Earth´s magnetic field.

Force between two poles

The force F between two magnetic poles of strengths m_1 and m_2:



$$\vec{F} = \frac{\mu_0 \, m_1 \, m_2}{4\pi\mu_r \, r^2} \, \vec{r}$$

$$|r| = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2 + (z_2 - z_1)^2}$$

magnetic permeability of vacuum: $\mu_0 = 4\pi \, 10^{-7}$ Vs/Am

relative magnetic permeability: $\mu_r = \dfrac{\mu}{\mu_0}$

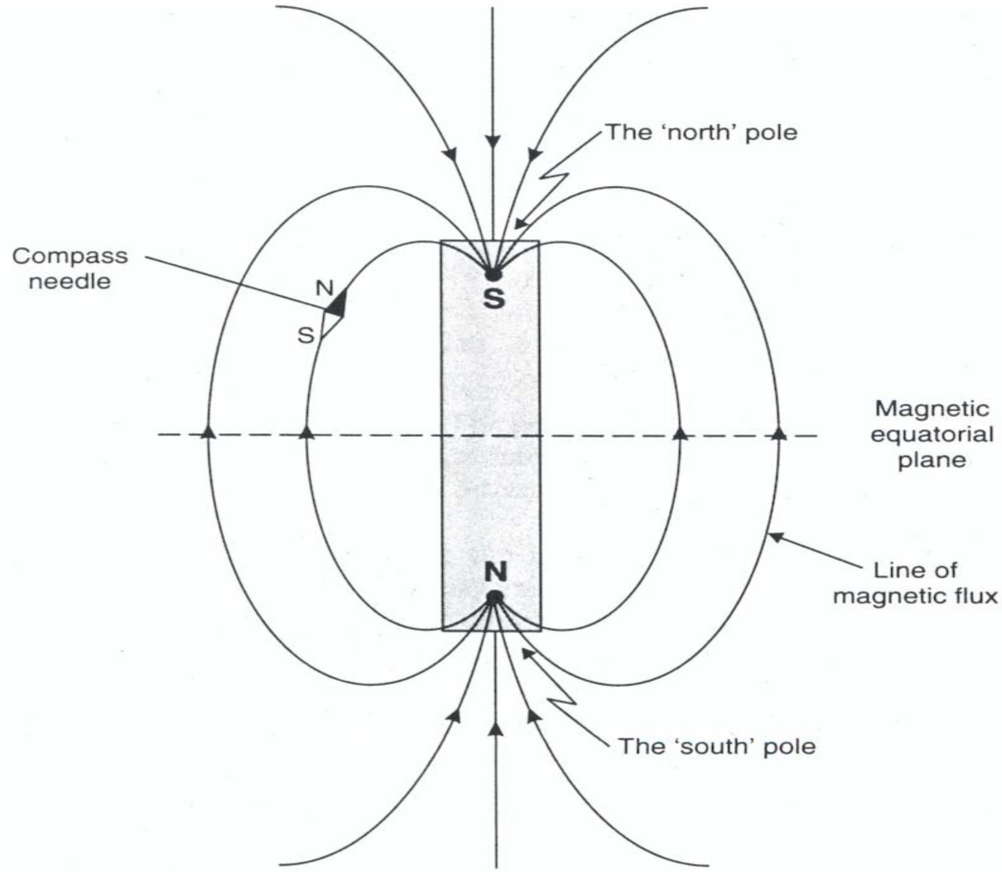
Magnetic induction field

The magnetic induction field is expressed as the force created by a pole m and applied on a unitary pole m_1

$$\vec{B} = \frac{\vec{F}}{m_1} = \frac{\mu_0 m}{4\pi\mu_r r^2}\vec{r}$$

in Vs/m^2 or Tesla (T)

Dipole

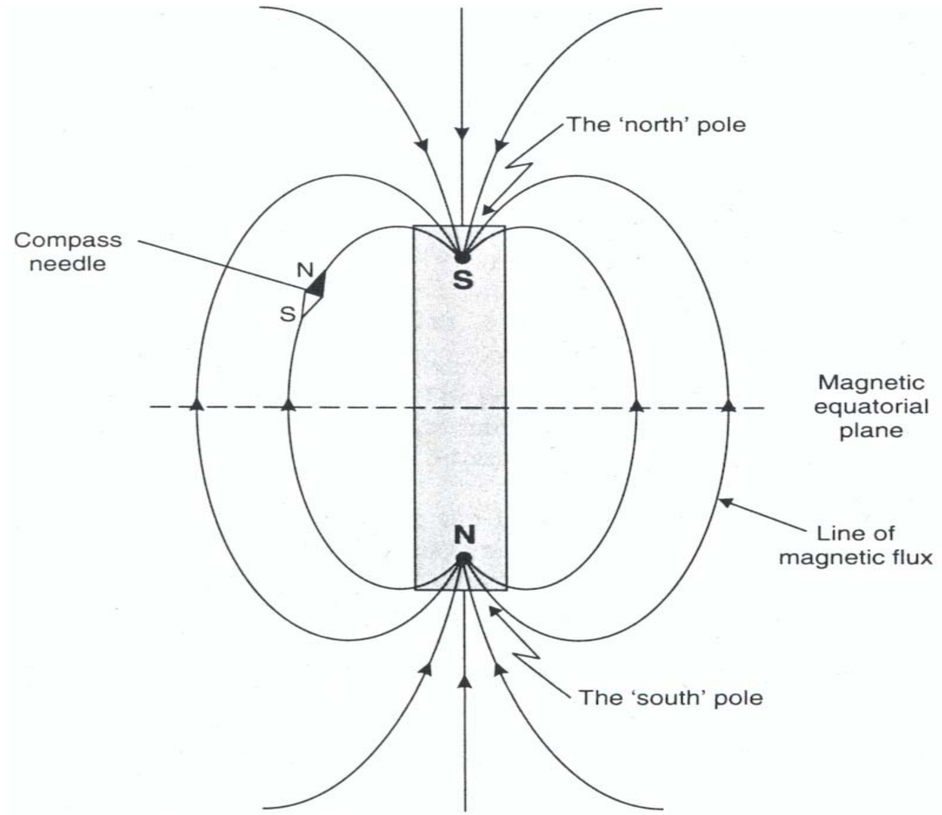

The 'north' pole
Compass needle
N
S
S
Magnetic equatorial plane
N
Line of magnetic flux
The 'south' pole

Magnetic moment

The magnetic moment is the vector joining the two poles –*m* and +*m* (at distance *l* apart)

$$\vec{M} = m\,l\,\vec{r}$$

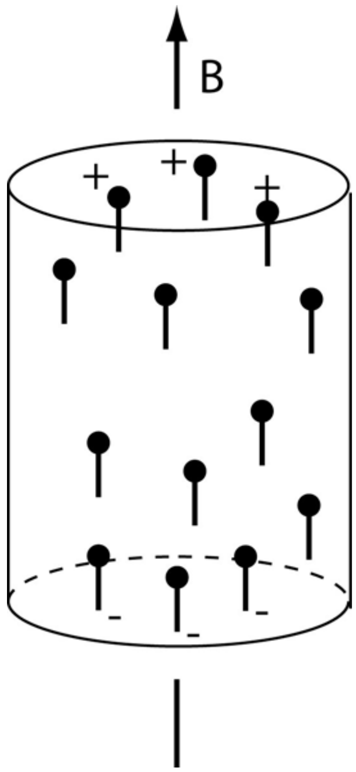
in Am^2



Induced magnetization

When a magnetic material is placed in a magnetic field, elementary dipoles in the material align in the direction of the field.

The resulting magnetization gives rise to an additional magnetic field in the region occupied by the material.



Intensity of induced magnetization

The intensity of induced magnetization is defined as the magnetic moment per unit volume of material

$$\vec{J}_i = \frac{\vec{M}}{v}$$

in A/m

Magnetic susceptibility

The magnetic susceptibility *k* is dimensionless and determines the degree of magnetization of material

$$k = \frac{\vec{J}_i}{\vec{H}}$$

H simply describes how *B* is modified by the magnetic polarization (or magnetization *M*).

In a non-polarizable body, *H* can be regarded as simply a computational parameter proportional to *B*

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

Magnetic induction

When a magnetic material is placed in a magnetic field, the resulting magnetization gives rise to an additional magnetic field in the region occupied by the material. Within the body, the total magnetic induction is given by:

$$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{J}_i = \mu_0 \vec{H} + \mu_0 k \vec{H} = (1 + k)\mu_0 \vec{H} = \boxed{\mu_r \mu_0 \vec{H}}$$

$\vec{B}$ in Vs/m^2 or T (Tesla)

magnetic permeability of vacuum: $\mu_0 = 4\pi 10^{-7}$ Vs/Am

relative magnetic permeability: $\mu_r = \dfrac{\mu}{\mu_0}$

Units of magnetism

The unit used in geomagnetic surveys is the Tesla

- 1 Tesla = 1 T = 1 N/Am
- 1 nT = 10^{-9} T=1 γ = 10^{-5} Oersted

- c.g.s unit:

  1 gauss (G)=10^{-4} T

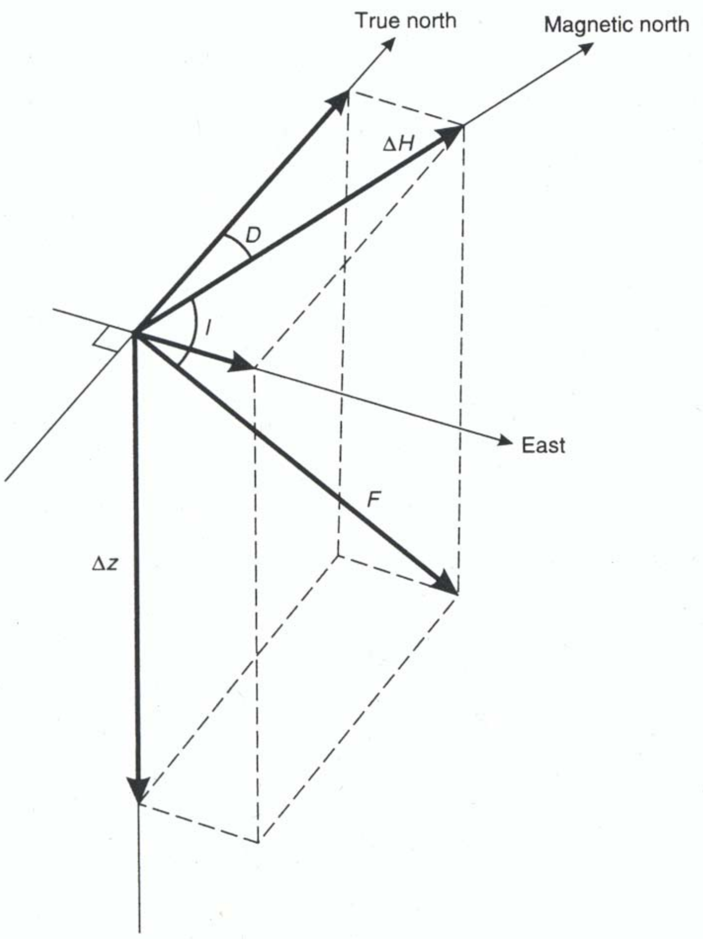
  1 gamma (γ)=10^{-5} G

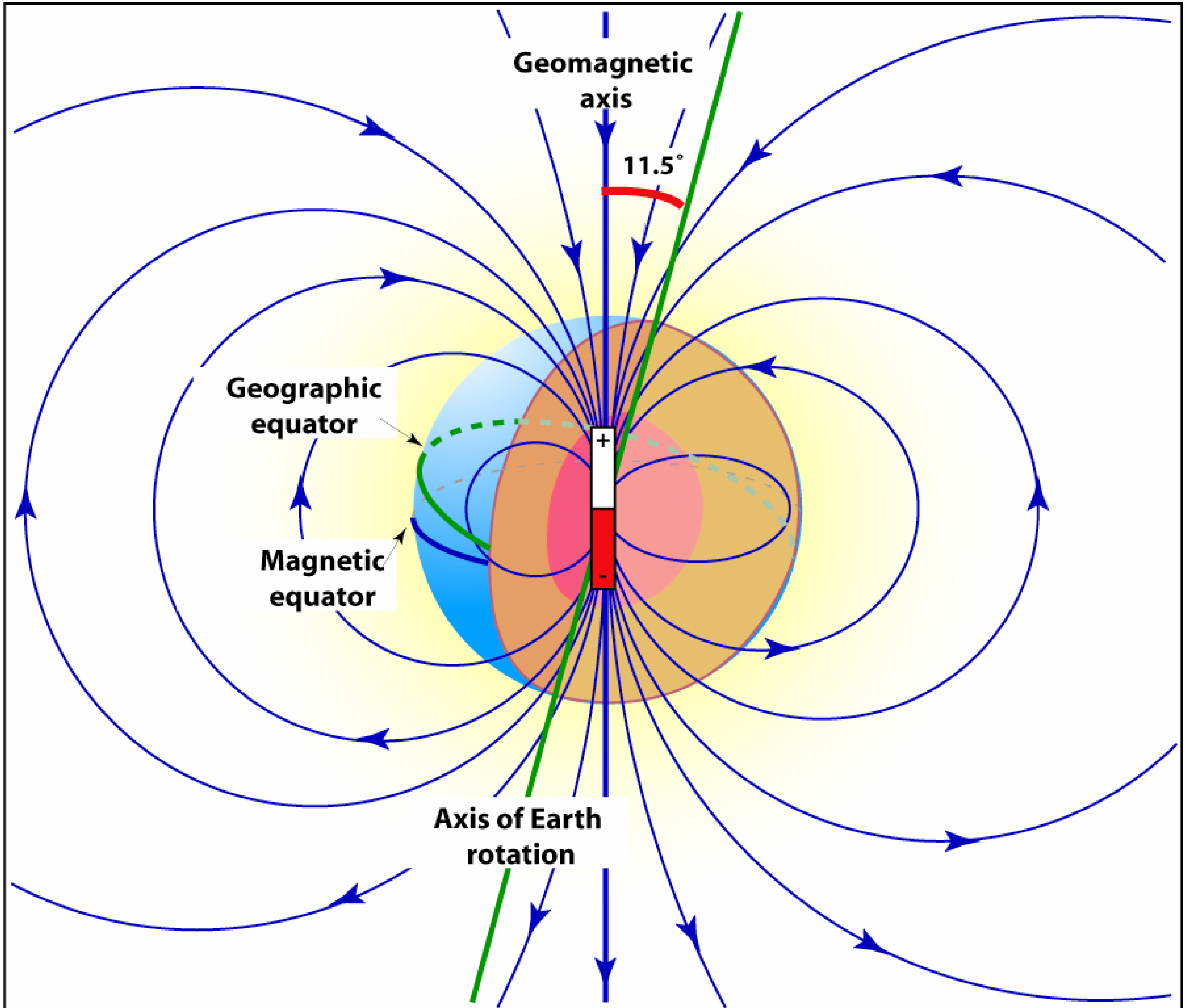
2. Geomagnetic field

Geomagnetic elements

The geomagnetic elements are…

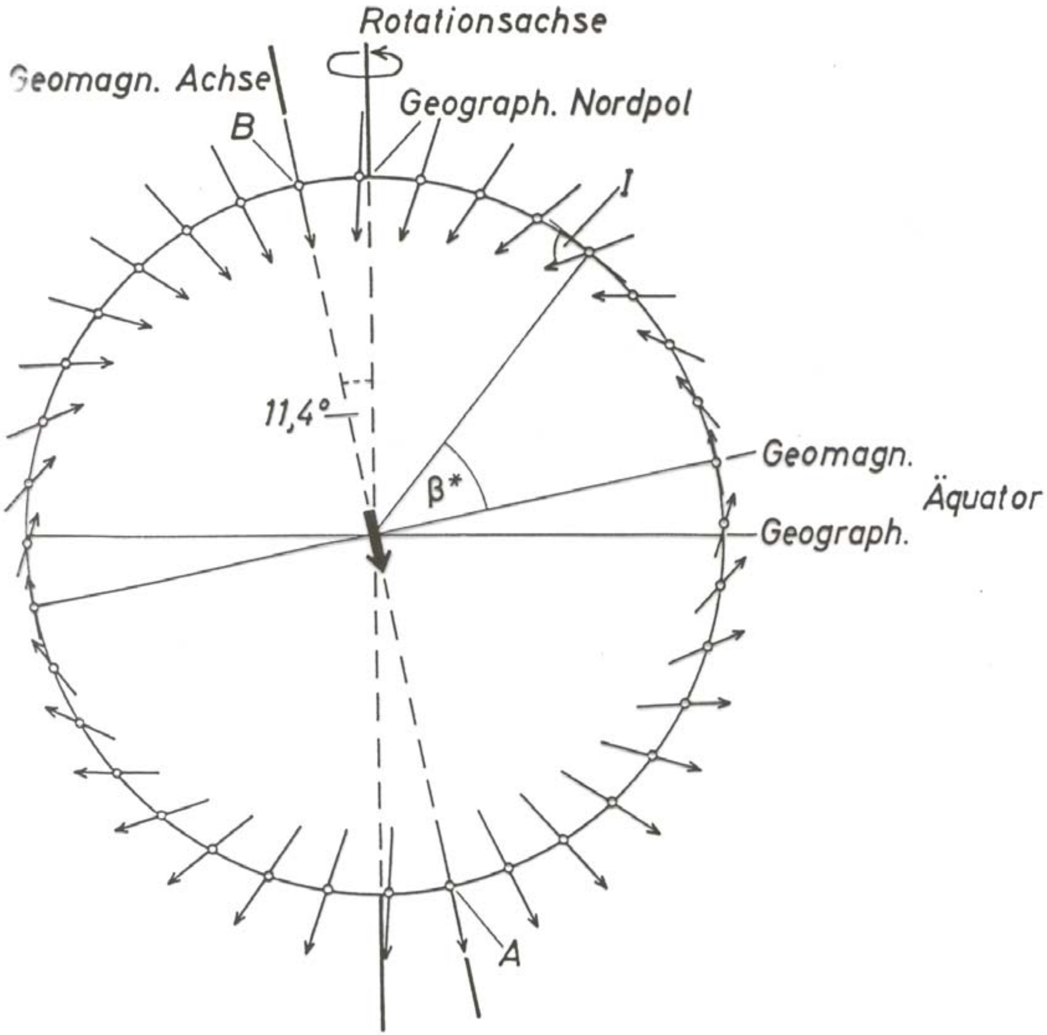
- Inclination
- Declination





Geomagnetic axis
11.5°
Geographic equator
+
-
Magnetic equator
Axis of Earth rotation

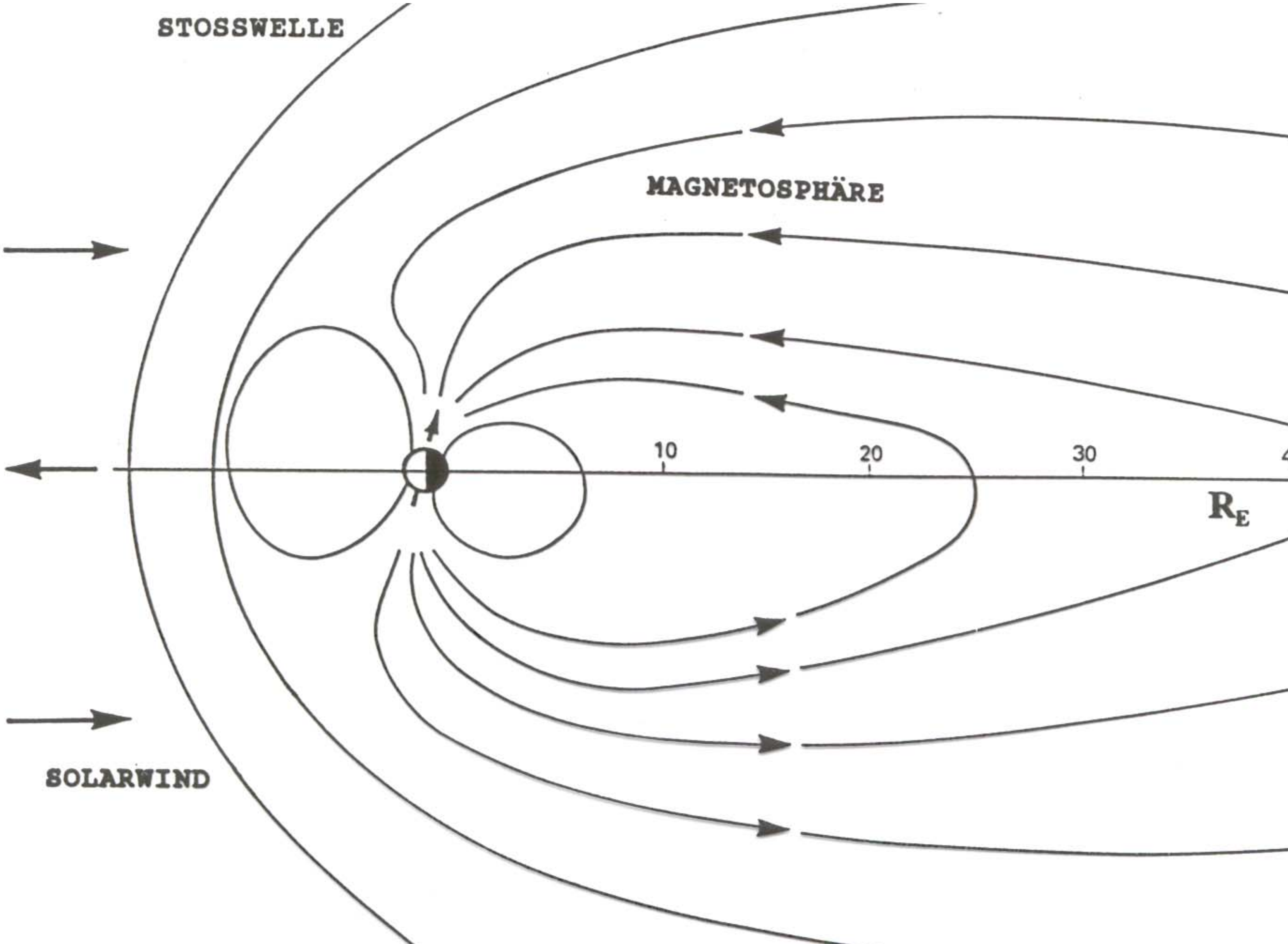
Simplified model for the Earth



More complex than the gravity field: irregular variations with latitude, longitude and time

Inclination varies depending on the hemisphere

Geocentric dipole is inclined at about 11.4°


STOSSWELLE
MAGNETOSPHÄRE
SOLARWIND
10
20
30
40
R_E

Simplified model for the Earth

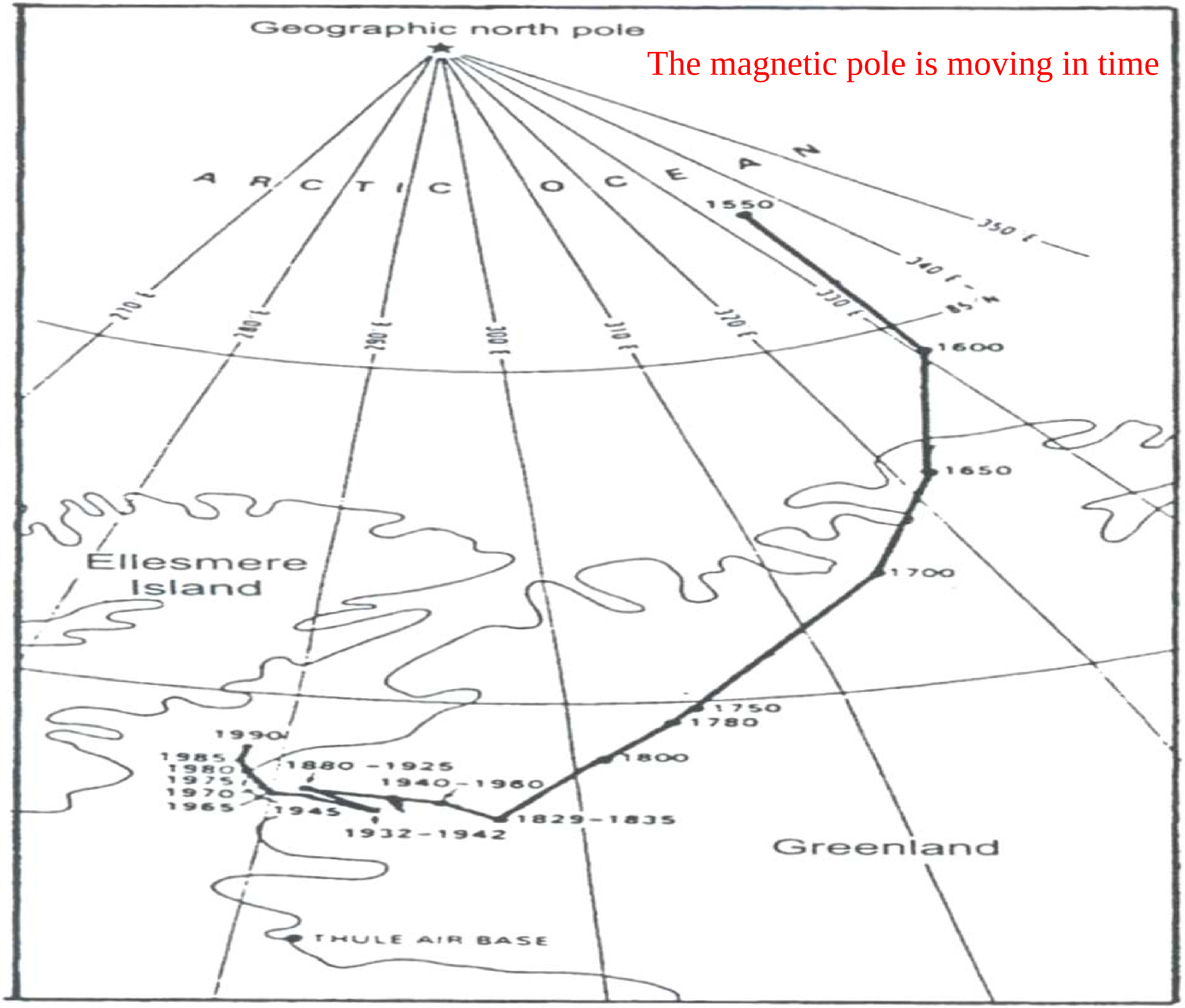
- Dipole field in first approximation
- ~ 60 000 nT (poles)
- ~ 30 000 nT (equator)
- ~ 47 000 nT in Switzerland

Changes in the geomagnetic field

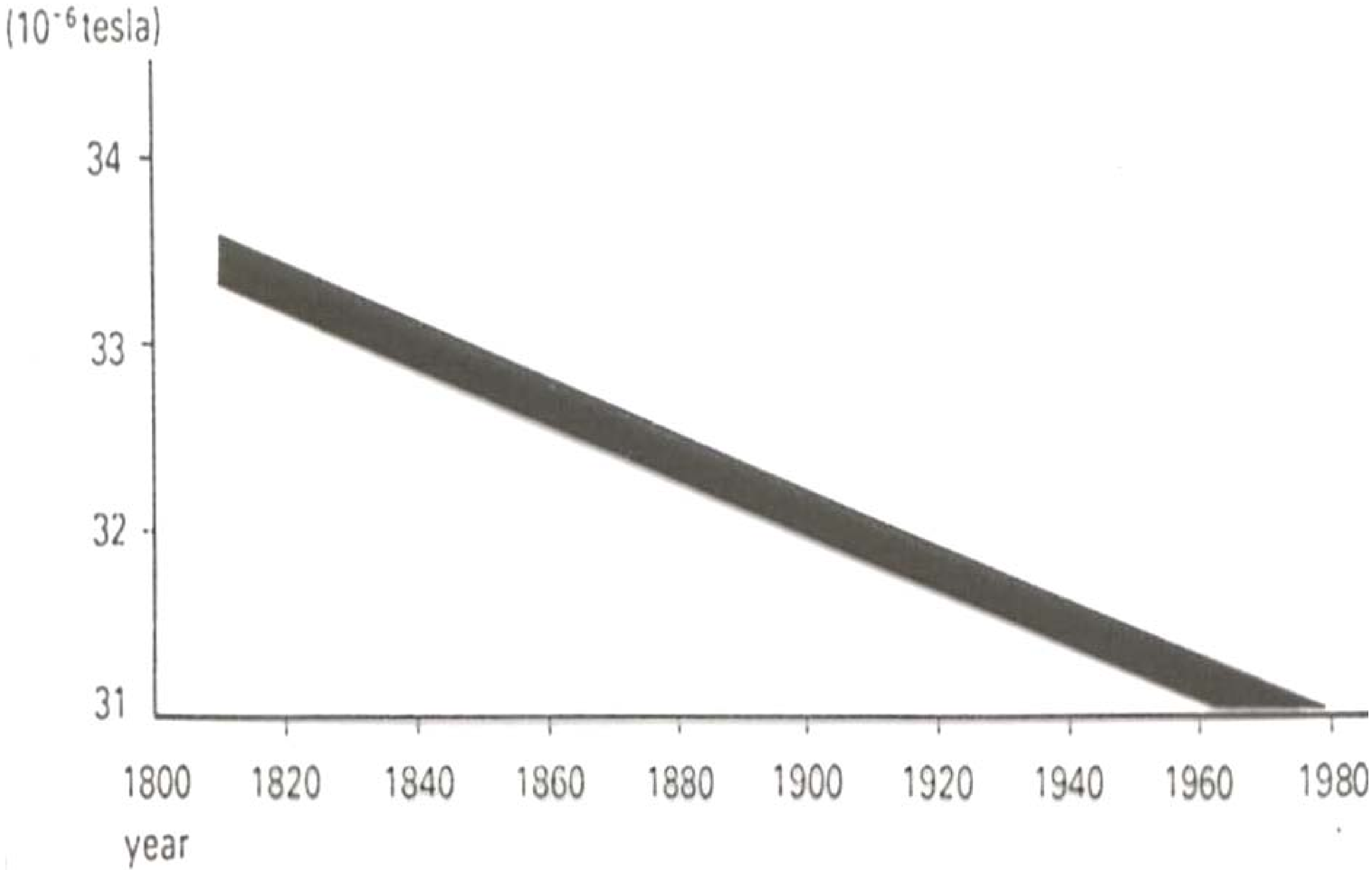
- The exchange of dominance between the cells produce the periodic changes in polarity imaged in paleomag studies

- Slow variations in the circulation patterns within the core produce temporal changes in the geomagnetic field (secular variations, e.g. gradual rotation of the magnetic pole)

The magnetic pole is moving in time

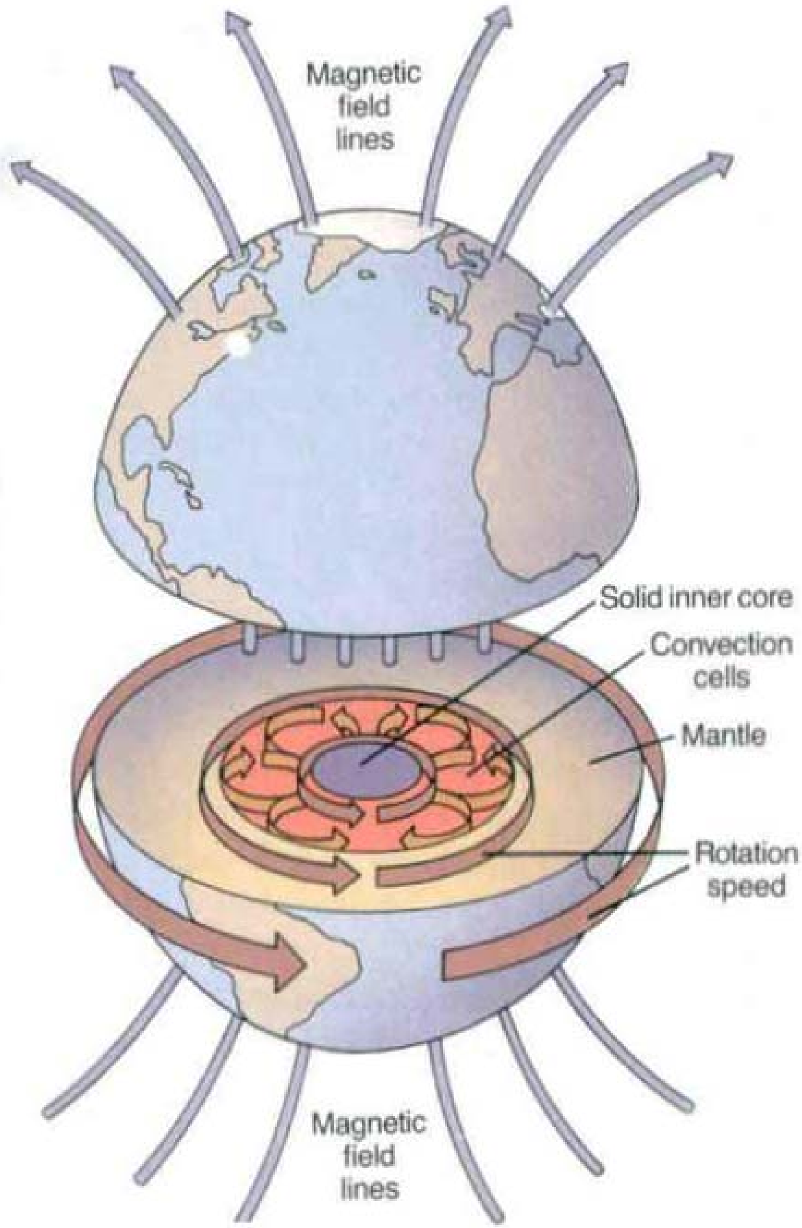


Change in the magnetic field intensity with time



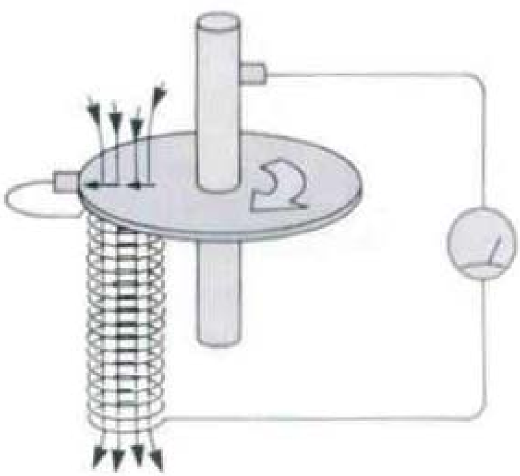
Origin of the geomagnetic field

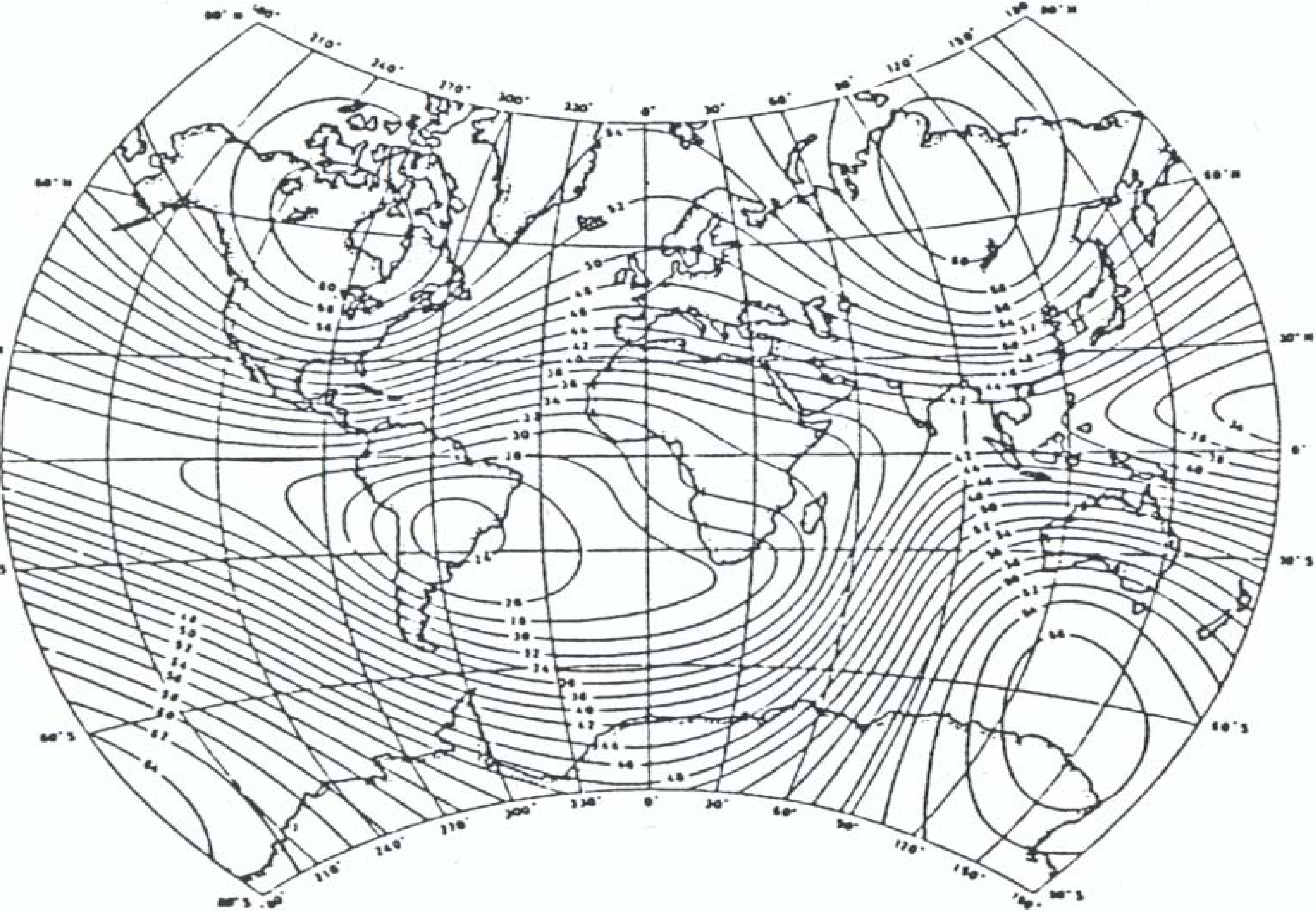
- 99 % from the Earth (94 % dipole field + 5 % non-dipole field)
- 1 % current in the ionosphere (diurnal variations, magnetic storms)



Not a remanent origin (temperature too high).

Dynamo action produced by the circulation of charged particles in couples convective cells within the outer, fluid, part of the Earth's core.





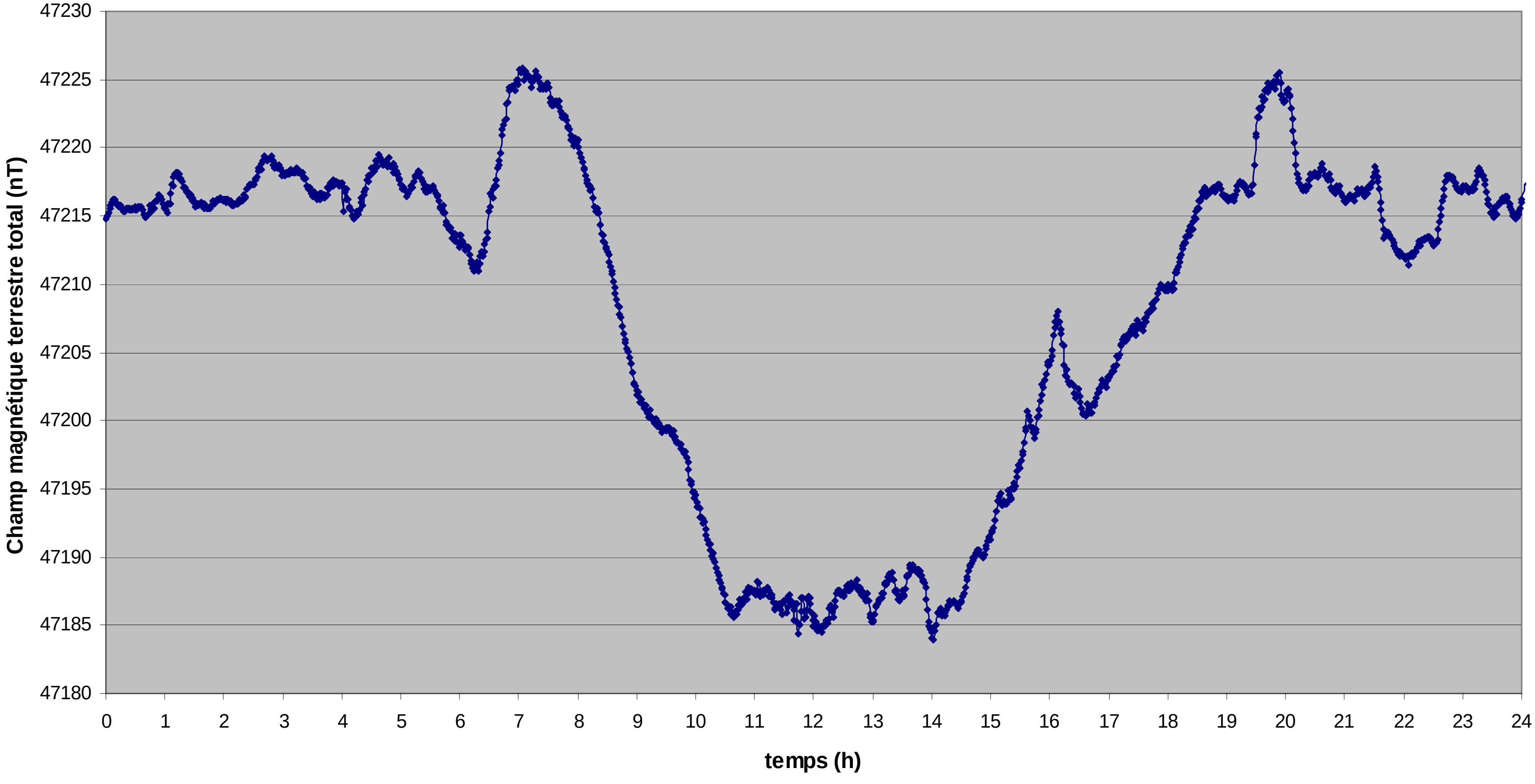
60° N
30° N
0°
30° S
60° S
180°
210°
240°
270°
300°
330°
0°
30°
60°
90°
120°
150°

Diurnal variations

- Variations of external origin. Results from the magnetic field induced by the flow of charged particles within the ionized ionosphere towards the poles
- Movements in ionosphere:

  Difference in temperature in atmosphere

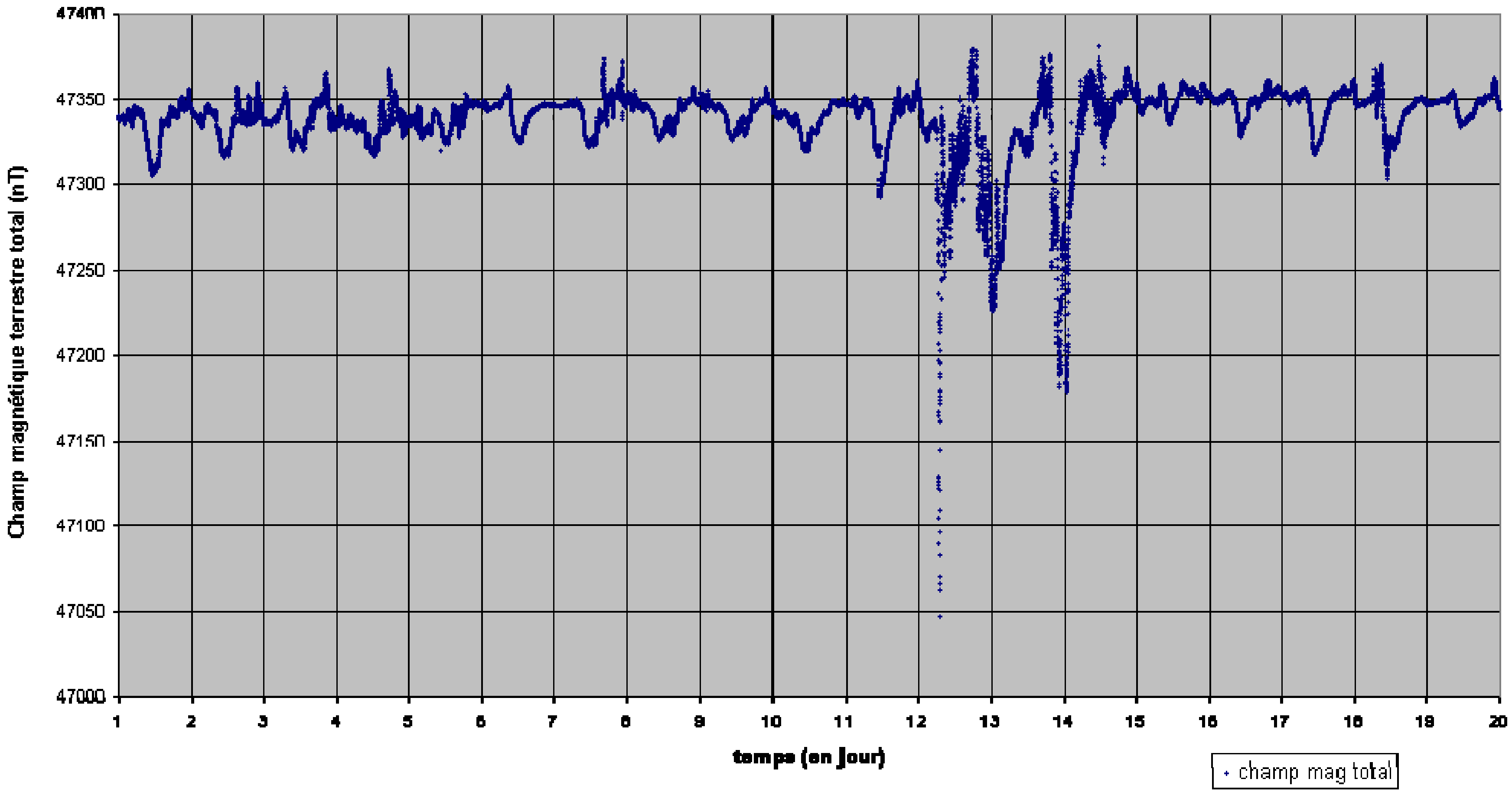
  Sun-Moon attraction
- Varies with latitude and seasons (max. in summer, max in polar regions)
- Smooth variations. Amplitude 20-80 nT



Observatory of Neuchâtel du 1 mars 2000 (1 sec)

Magnetic storms

- Associated with intense solar activity, results from the arrival in ionosphere of charged solar particles
- Less regular than diurnal variations. Amplitude up to 1000 nT!
- No magnetic surveys during storms (impossibility of correcting the data)



29 octobre at 6h 14

Perturbation more than 350 nT

Observatory of Neuchâtel (Suisse)

Period from 18 octobre to 5 novembre 2003

Geomagnetic Reference Field

- The International Geomagnetic Reference Field (IGRF) defines the theoretical undisturbed magnetic field at any point on the Earth´s surface in simulating the observed geomagnetic field by a series of dipoles

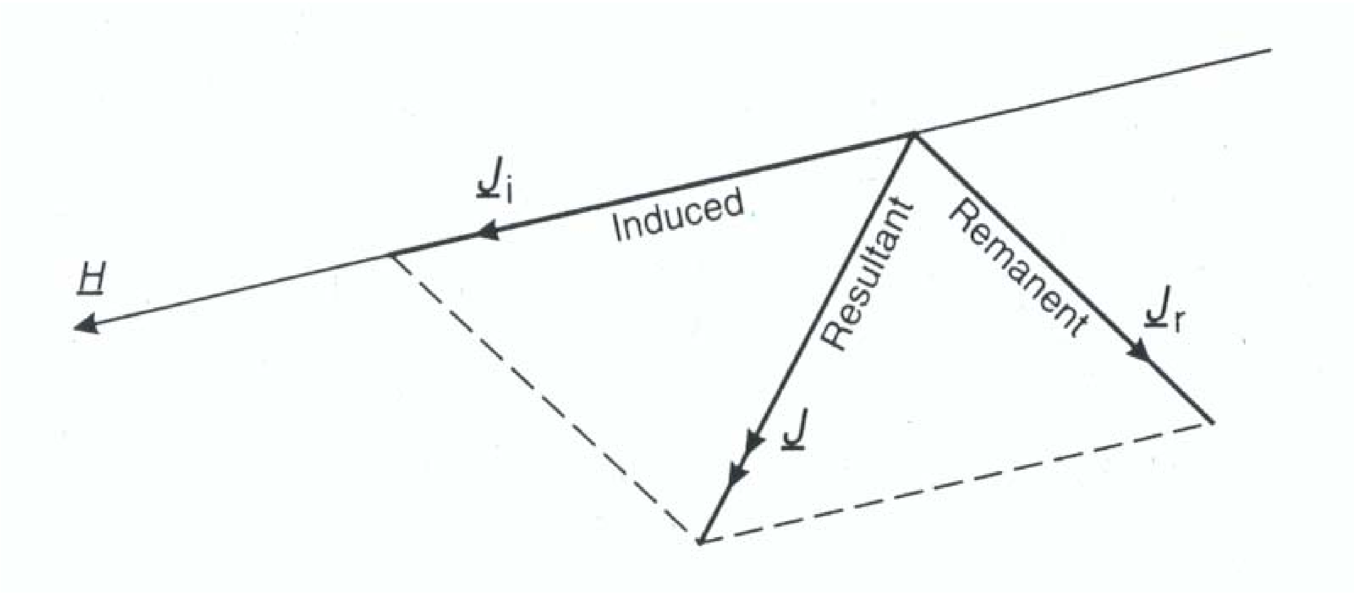
- This formula is used to remove from the magnetic data those magnetic variations attributable to this theoretical field

http://www-geol.unine.ch/GEOMAGNETISME/HomePage.html

3. Magnetic properties of rocks

Rock magnetism

The measured total magnetic field is the sum of the geomagnetic field and the remanent magnetic field



Rock magnetism

- All substances are magnetic at the atomic scale. Each atom acts as a dipole due to both the spin of its electrons and the orbital path of the electrons around the nucleus

- Two electrons can exist in the same state provided their spins are in opposite directions (paired electrons). In this case their spins cancelled. When unpaired electrons are present, a magnetic moment at the atomic scale appears

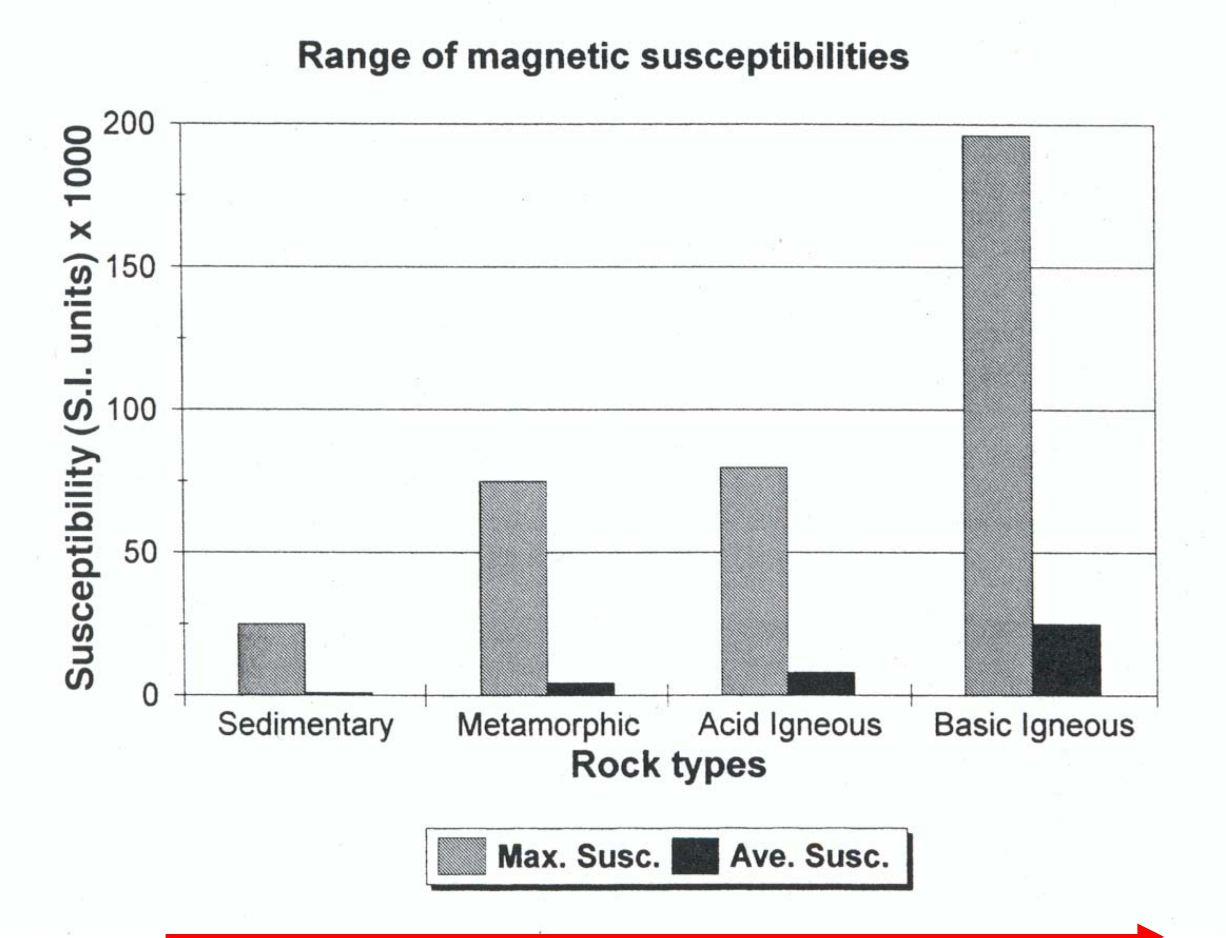
- Paired and unpaired electrons are mainly at the origin of the various magnetic rock properties

Rock magnetism

$$\vec{B} = \mu_0 \vec{H} + \mu_0 \vec{J}_i = (1 + k)\mu_0 \vec{H}$$

- Diamagnetic: $k<0$
- Paramagnetic: $k>0$
- Ferromagnetic (e.g. iron), ferrimagnetic (e.g. magnetite) and antiferromagnetic (e.g. haematite)

Magnetic properties of rocks



Magnetite content

$$\vec{B} = (1 + k)\mu_0 \vec{H}$$

Magnetic properties of rock depend mainly on the concentration size, shape and dispersion of magnetite

Remanent magnetization

The strength of the magnetization of ferro and ferrimagnetic material decreases with temperature and disappears at the Curie temperature (for most of the rocks about 500 ^oC, i.e. to a depth of 40 to 50 km).

Origin of remanent magnetization:

- Thermoremanent magnetization
- Detrital remanent magnetization
- Chemical remanent magnetization
- Viscous remanent magnetization

These notions were developed in last year lectures…

4. Survey strategies and interpretation

Magnetic surveys

How to proceed…

(1) Data measurements, basis measurements, data location
(2) Calculation of the theoretical field (IGRF)
(3) Calculation of the geomagnetic anomalies, reduction
(4) Removal of the regional trend
(5) Modeling, inversion
(6) Interpretation

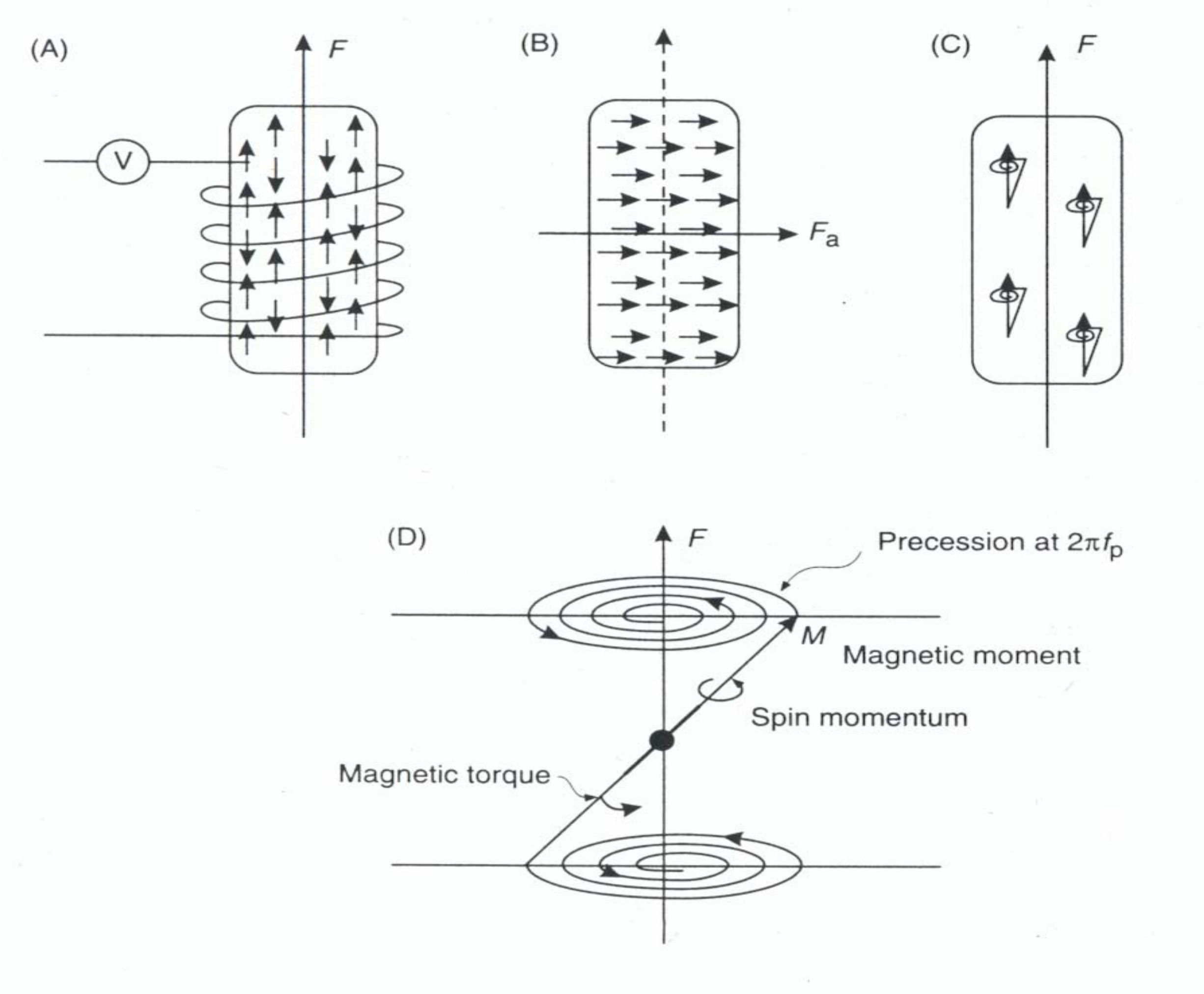
Magnetic surveying instruments

Two types of magnetometers are frequently used in magnetic surveying:

- Proton magnetometer
- Optically pumped magnetometer
- Other device: fluxgate magnetometer

Precision required: about ± 0.1 nT (about one part in 5×10^6 of the background field)

Proton magnetometer



Proton magnetometer

$$\omega = 2\pi f = \gamma_p H$$

γ_p is the gyromagnetic ratio of the proton (constant)

Precession frequency $f \cong 2000$ Hz

$$H_{total} = \frac{2\pi f}{\gamma_p} \cong 23.49 f$$

- Sensitivity about ± 0.1nT
- Frequency measurement 2-3 s

Optically pumped magnetometer

- A glass cell containing an evaporated alkali (e.g. Cesium) is energized by a light of particular wavelength.

- Measurement principle based on the partition of valence electrons into different energy levels.

- Very rapid and sensitive measurements: used in gradiometers

Sensitivity < 0.01nT

Frequency measurement 0.1 s

Magnetic gradiometers

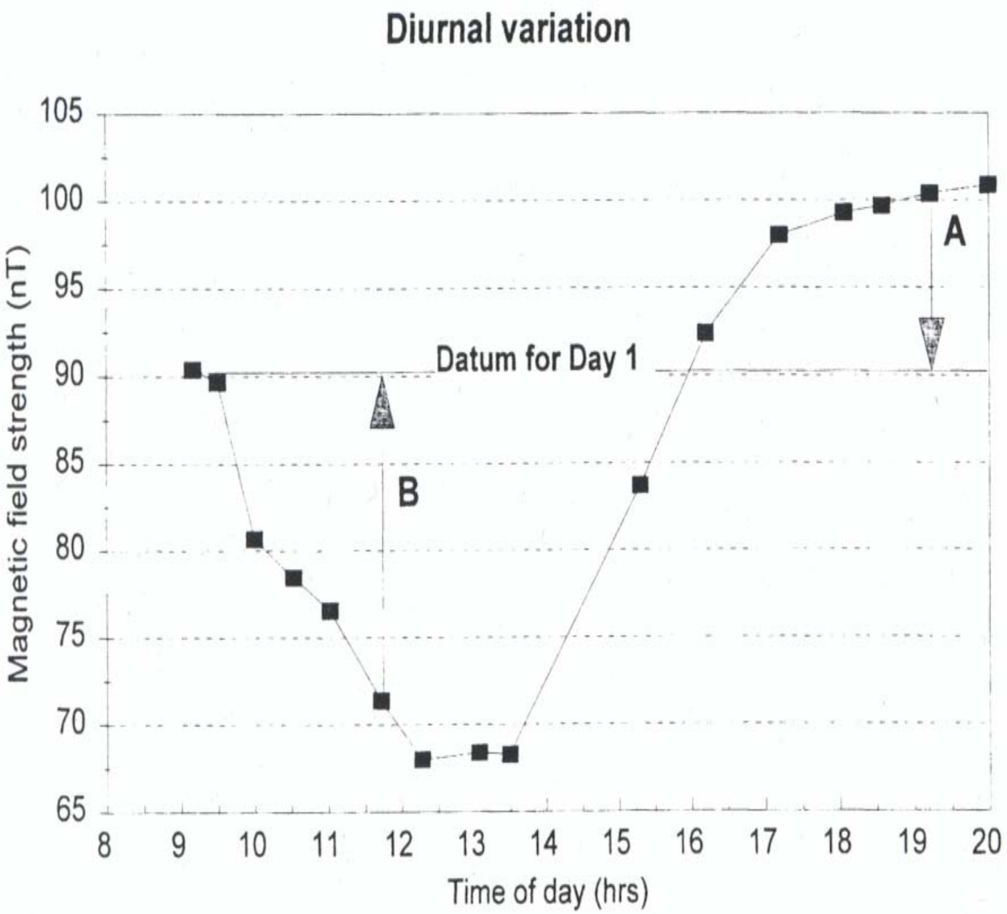
Meters are used in pairs to measure either horizontal or vertical magnetic gradients. Useful in shallow geophysics to resolve complex anomalies. Regional and temporal variations are automatically removed.

Reduction of magnetic data

The main corrections are…

- Diurnal variation correction
- Elevation and terrain correction
- Geomagnetic correction

Diurnal variation correction



- Loop to a reference basis (tedious…)
- Use a fixed magnetometer located at the basis to correct the data collected with a second magnetometer
- Use the record of a regional magnetic observatory

Using a basis: some considerations

Remember: for gravity, the basis readings are taken both to correct for the drift and the tidal effects.

In magnetic, only for the diurnal effect since magnetometers do not drift!

Elevation and terrain corrections

The gradient of the magnetic field is only some 0.03 nTm^{-1} the pole and -0.015 nTm^{-1} at the equator: no elevation correction is applied for ground surveys.

The terrain correction is very difficult to applied (generally rarely applied) since we need to know about the magnetic properties of the topographic features.

Corrections for aeromagnetic meas.

- To be considered in case of aeromagnetic measurements

- The reduction to a datum is applied for local measurements with steep topography. The measurement located at z=h is reduced to a datum z=0 using:

$$Z(x,y,0) = Z(x,y,h) - h\left.\frac{\delta Z}{\delta h}\right|_{z=h}$$

Drift, secular variations and storm

- Drift: fluxgate and proton magnetometers do not drift
- Secular variation are yearly variations. Too slow for a influencing a survey.
- Magnetic storm: stop the survey!

Moreover…

…do not carry out magnetic surveys in the vicinity of metallic objects such as railway lines, cars, fencing !!!

… as an operator, do not carry metallic objects!!!

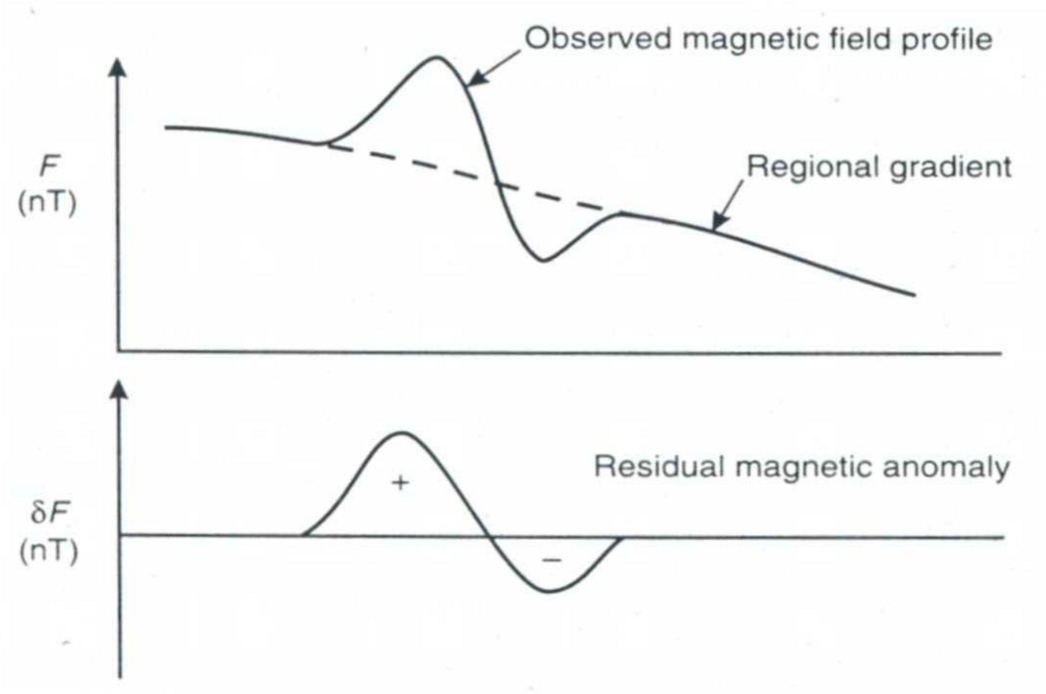
Latitude (geomagnetic) correction

- Equivalent of the latitude correction in gravimetry (reference ellipsoid)

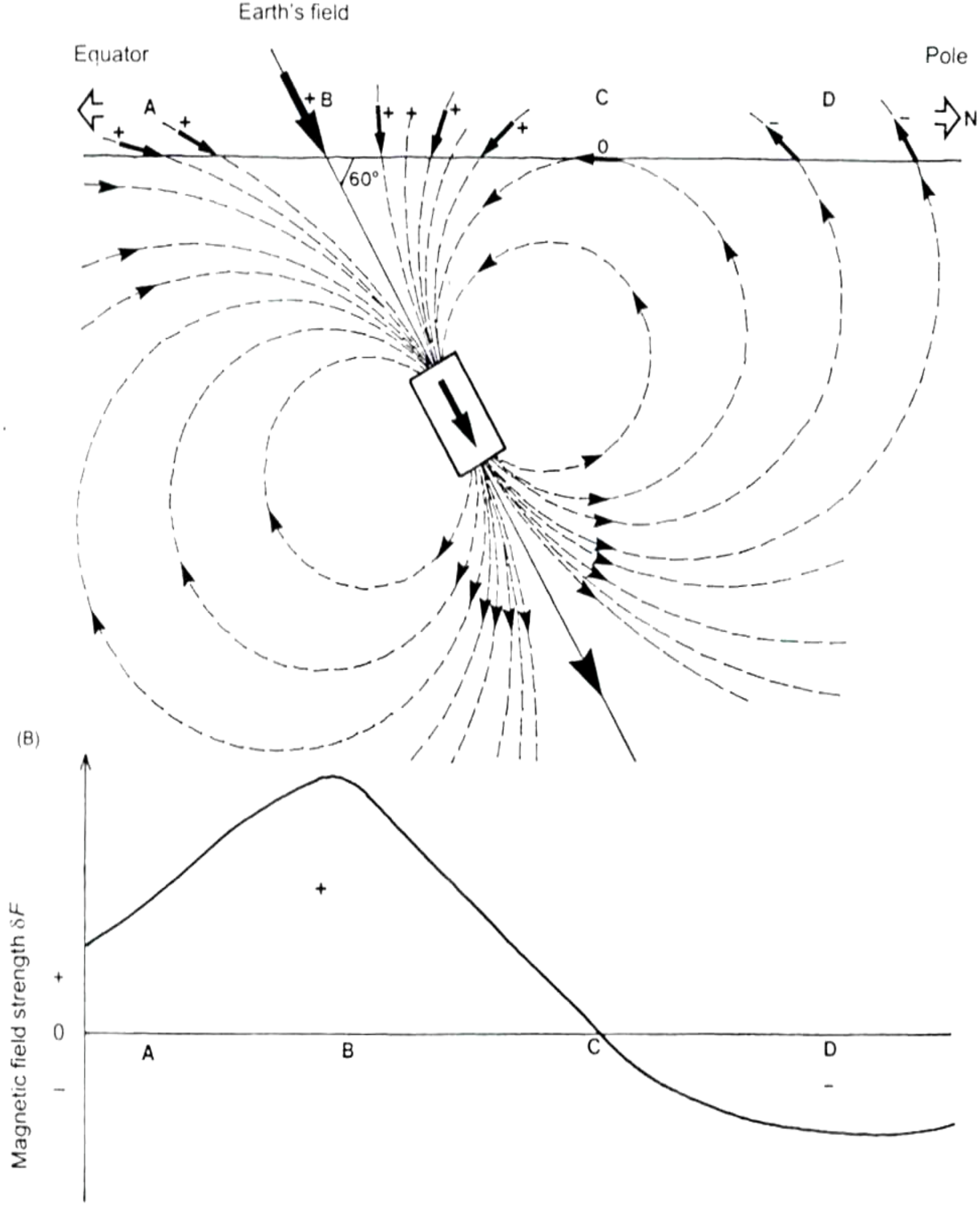
- We can use the International Geomagnetic Reference Field (IGRF), updated every 5 years, which defines the theoretical undisturbed magnetic field at any point of the Earth surface. Warning: the IGRF is imperfect and in areas remote from observatories can be substantially in error!

- Alterative method for small surveys: use a trend analysis, where the regional field is approximated by a linear trend

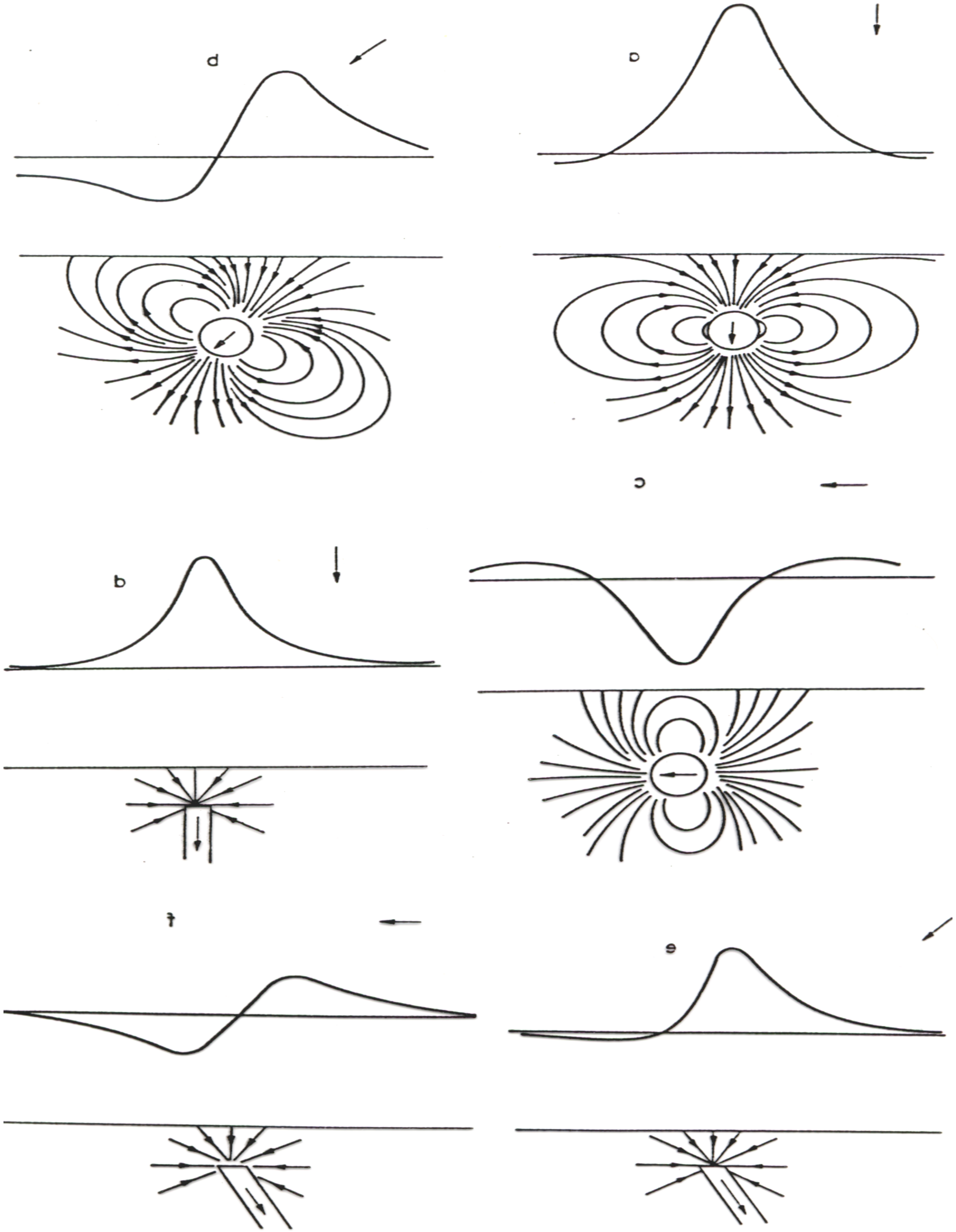
Residual magnetic anomaly



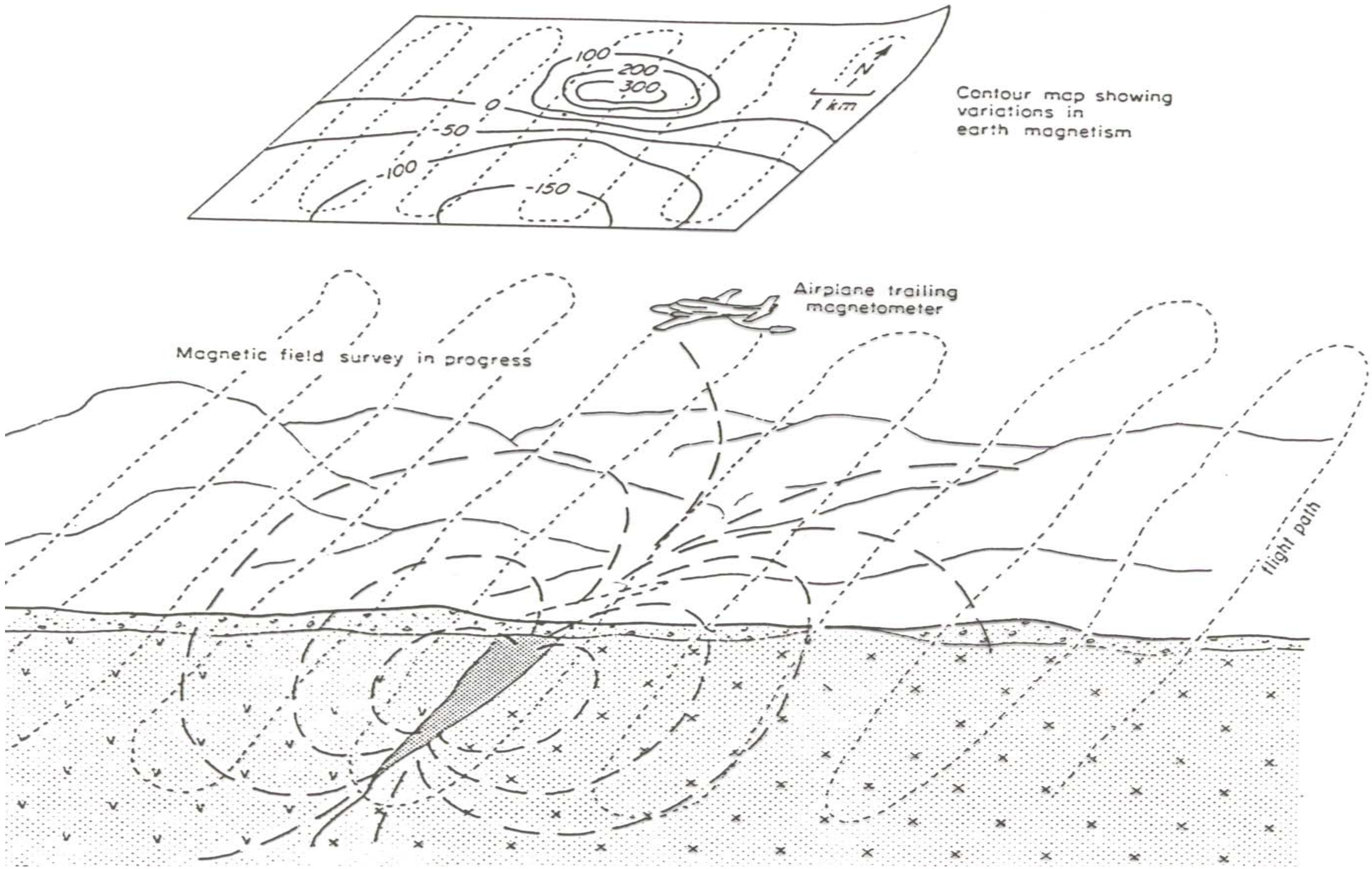
Complex shape: anomaly not only positive or negative like in gravity surveys!



More complex than gravity anomalies (vary not only in amplitude but also in direction)



Bodies with identical shapes and intensity of magnetization can give rise to very different magnetic anomalies depending their latitude



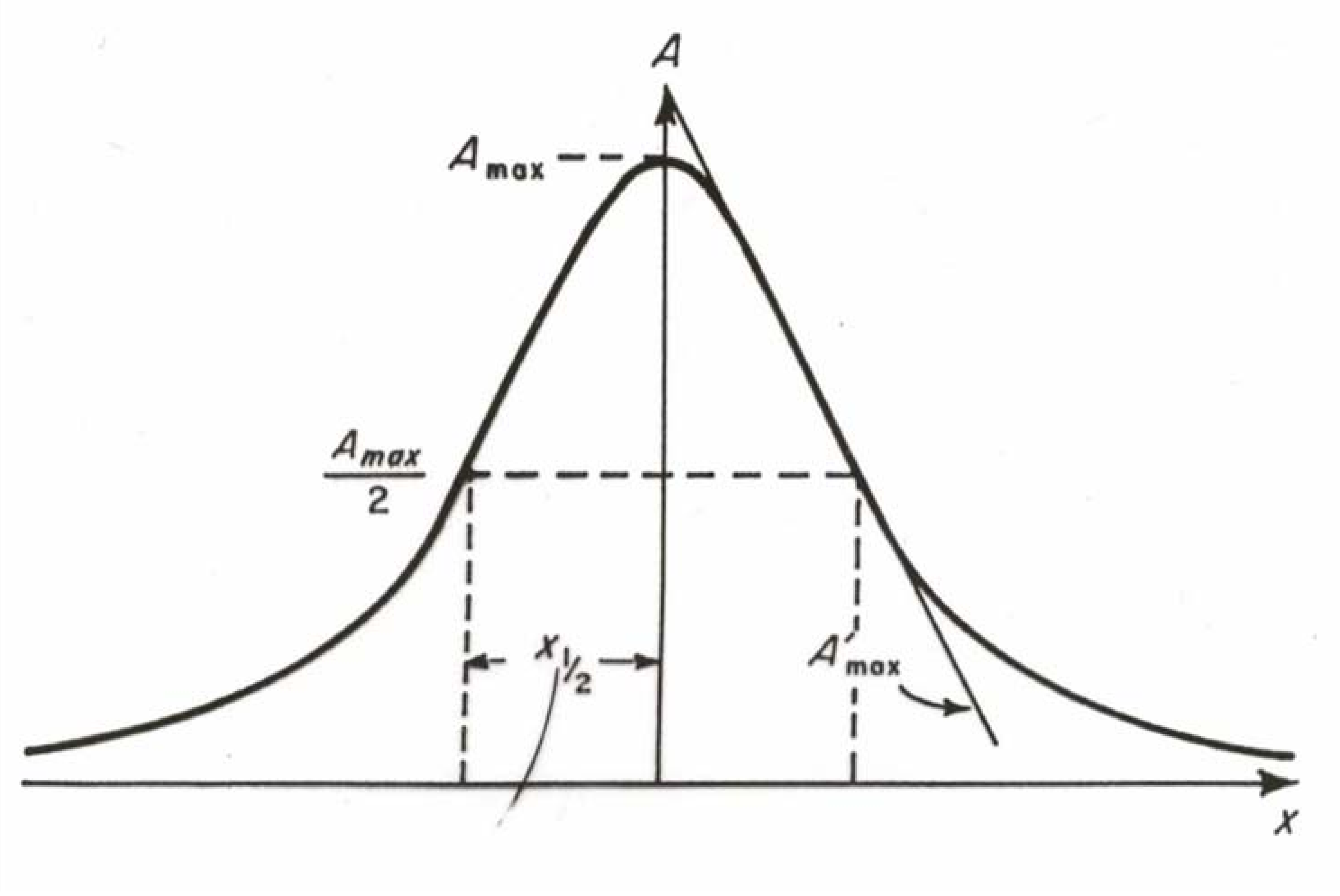
Interpretation of magnetic surveys is mainly qualitative (maps)

Interpretation

Like for gravity, we can use…

- Direct interpretation
- Indirect interpretation and automatic inversion

Direct interpretation



Simple geological structures

- *Ball:* Compact bodies (salt domes, karst)
- *Horizontal cylinder:* paleo-valleys, tunnel, karst, cables
- *Vertikale cylinder :* volcanic structures, karst

Body	Anomaly	Depth
Ball (magnetic dipole)	$F_z = 100\frac{4}{3}\pi R^3 \Delta J_z \left(2z^2 - x^2\right)\left(x^2 + z^2\right)^{5/2}$	$z = 2.00 x_{1/2}$
Horizontale cylinder (line of dipoles)	$F_z = 200\pi R^2 \Delta J_z \left(z^2 - x^2\right)\left(x^2 + z^2\right)^2$	$z = 1.75 x_{1/2}$
Vertical cylinder (magnetic monopole)	$F_z = 100\pi R^2 \Delta J_z \frac{1}{\left(x^2 + z^2\right)^{3/2}}$	$z = 1.30 x_{1/2}$

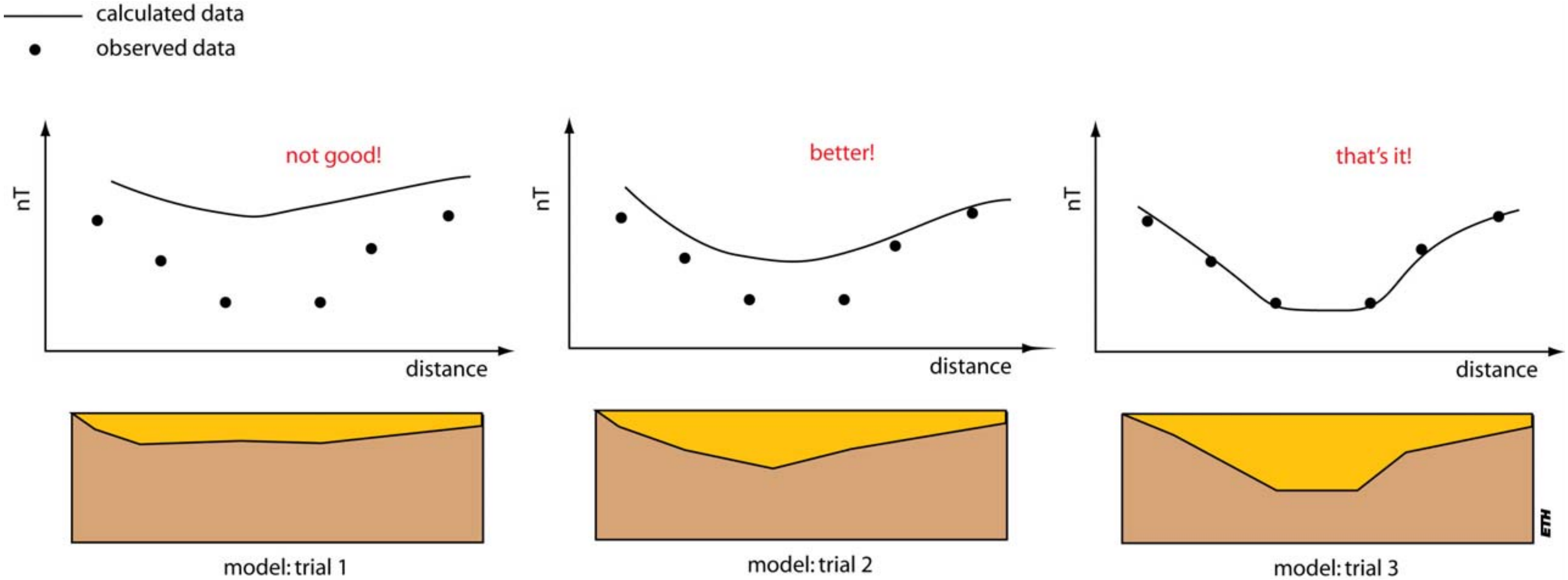
Other interpretation techniques

Other techniques:

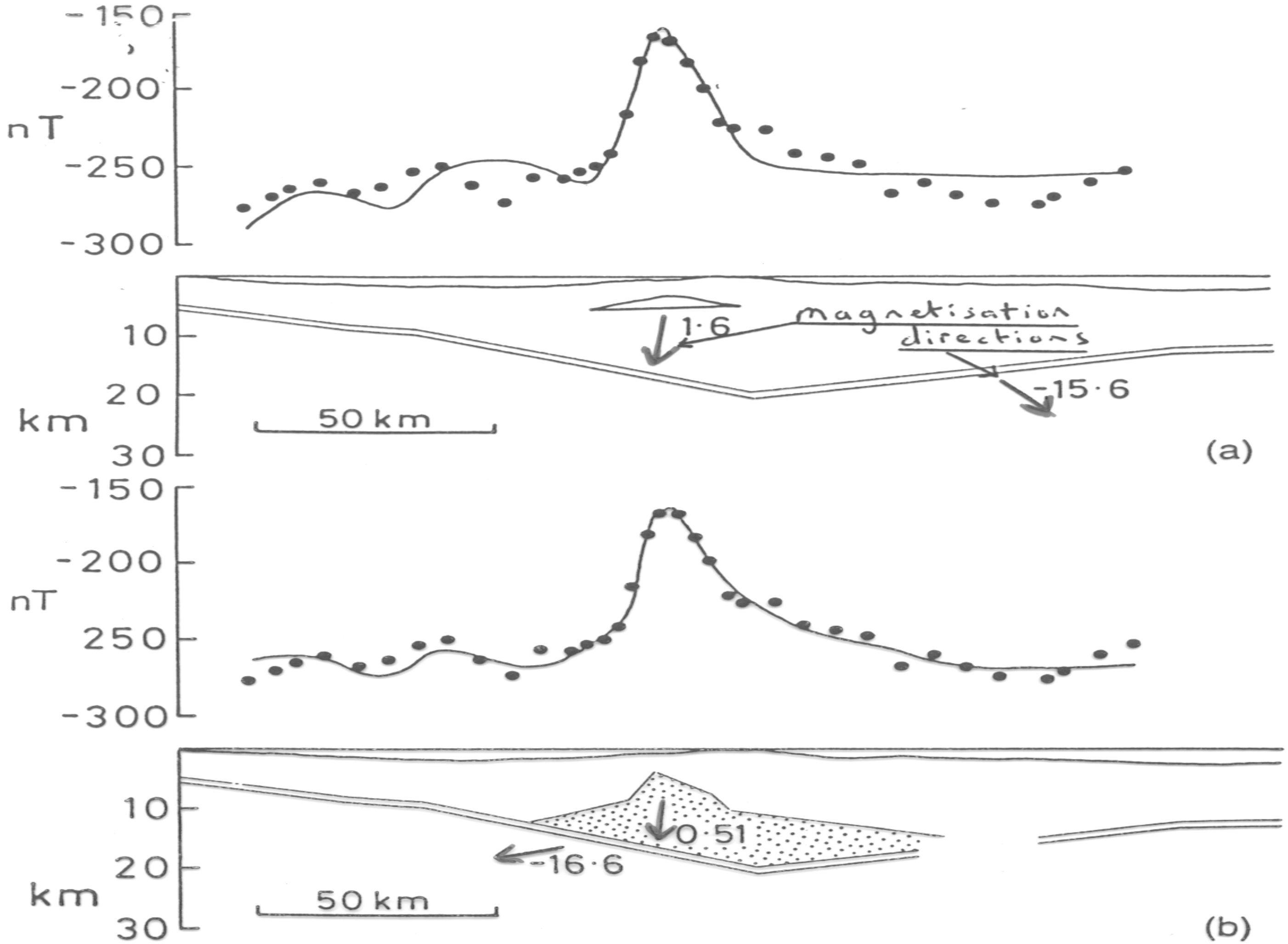
- Euler deconvolution: a complex but more rigorous method of determining depth to magnetic sources
- Reduction to the pole: simplify anomaly, produce anomaly that are axisymmetric

Indirect interpretation

- Same approach than in gravimetry (improvement of a initial model, see picture)
- Automatic inversion useful since anomalies are complex
- Model built using a series of dipoles (sum of positive and negative poles)



Ambiguity in interpretation



Comparison grav/mag 1

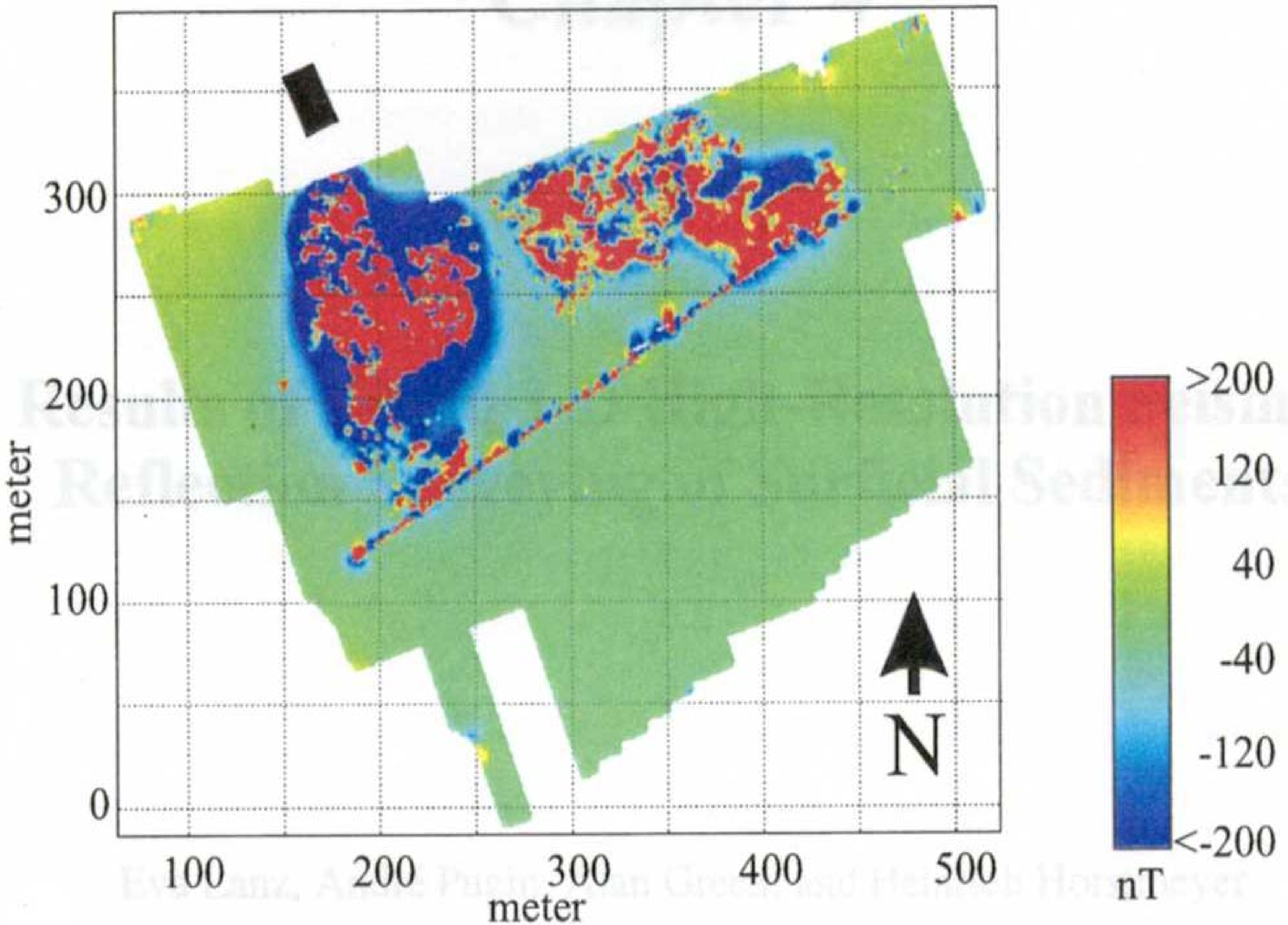
- Magnetic properties of the rocks disappear at about 20 to 40 km depth (Curie temperature)
- Variations of magnetic permeability over several orders of magnitude, density over only a range of 20-30%
- Density is a scalar, intensity of magnetization is a vector

Comparison grav/mag 2

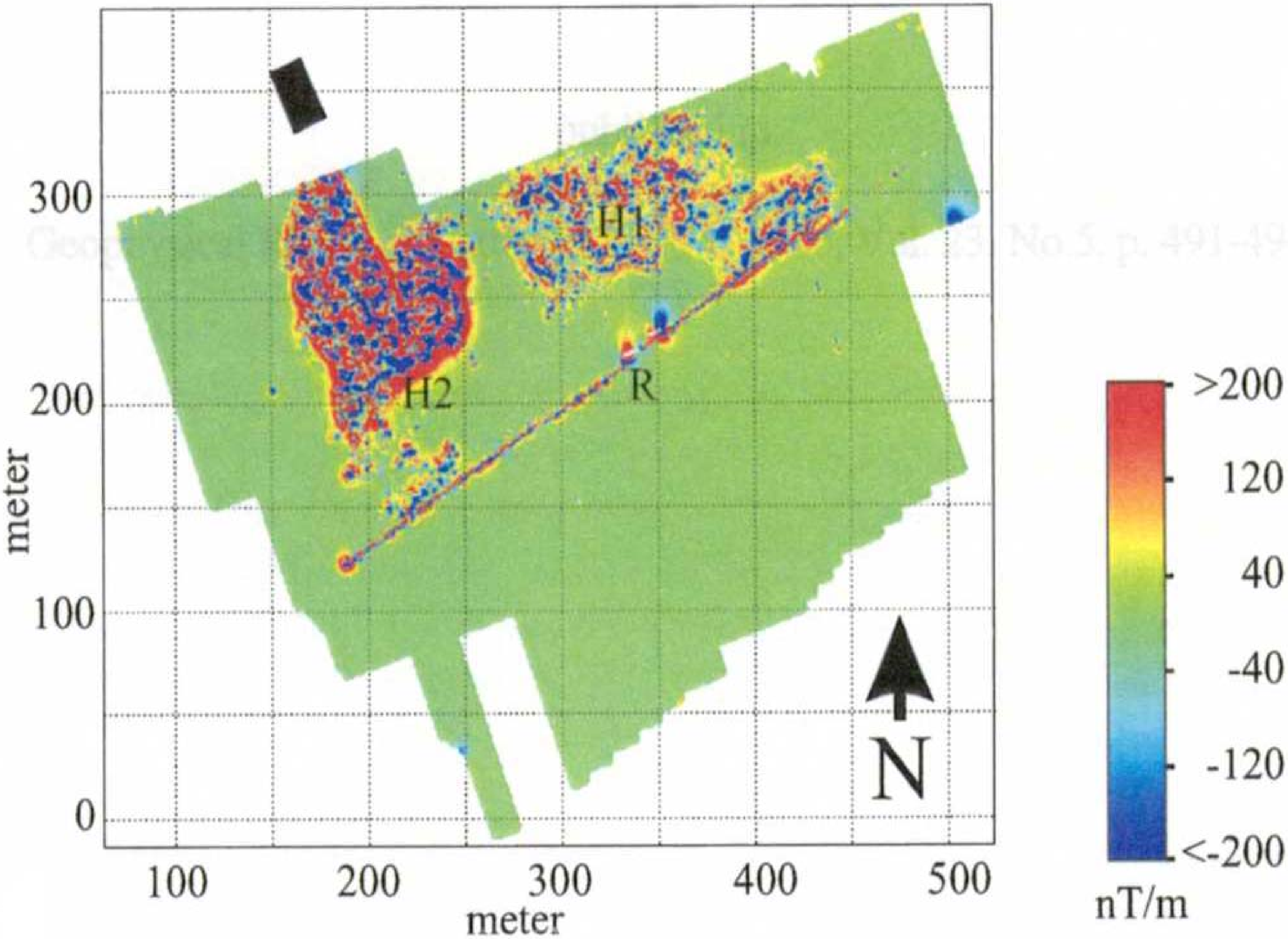
- 2:1 length-width ratio sufficient to validate 2D approximation in gravimetry, but 10:1 for magnetics!
- Survey faster and simpler than gravimetry, since no leveling required
- The magnetic anomalies are asymmetric depending on the latitude! The magnetic anomalies are more complex than the gravity anomalies

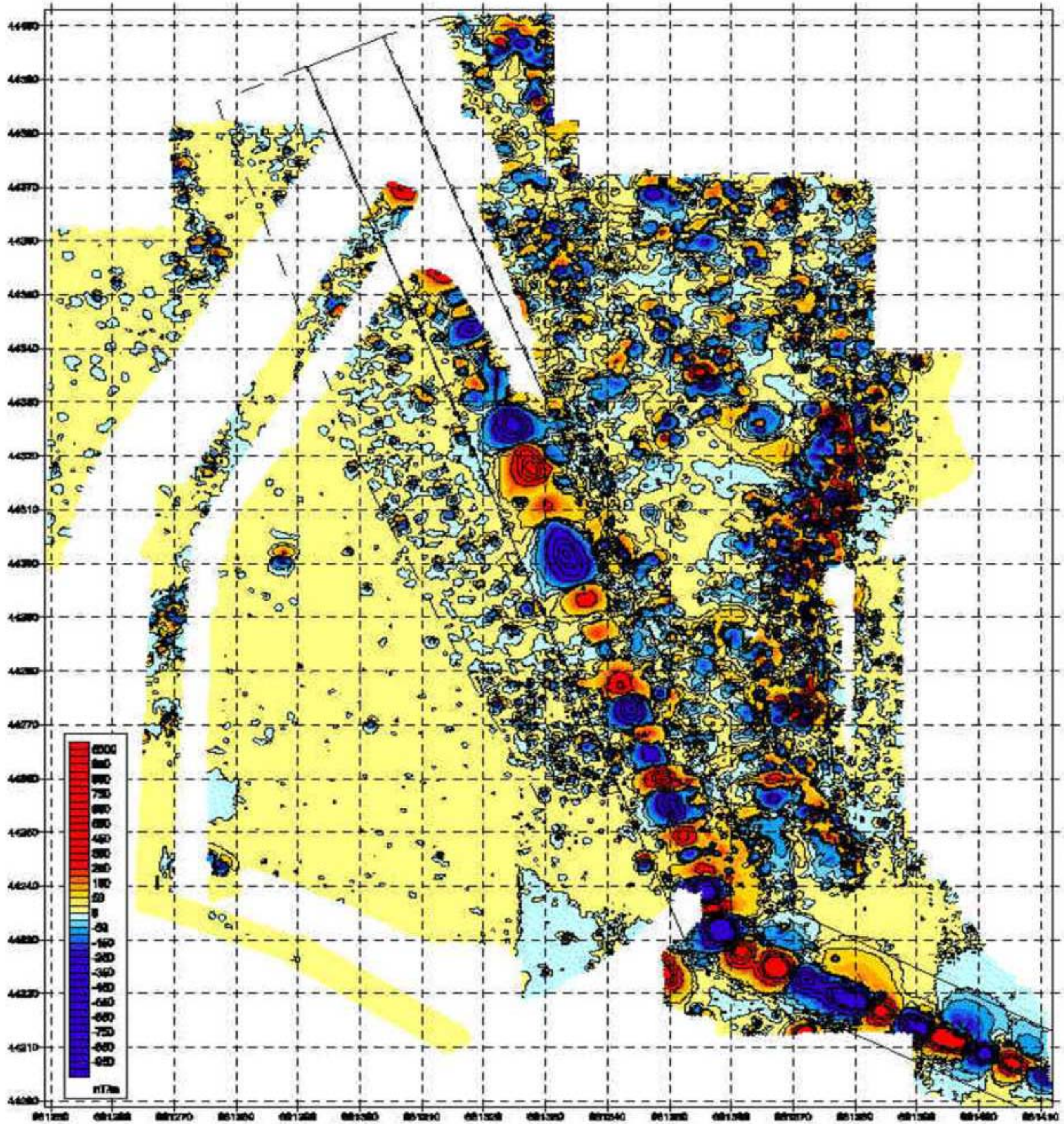
Examples

Bottom Sensor Total-Field Magnetic

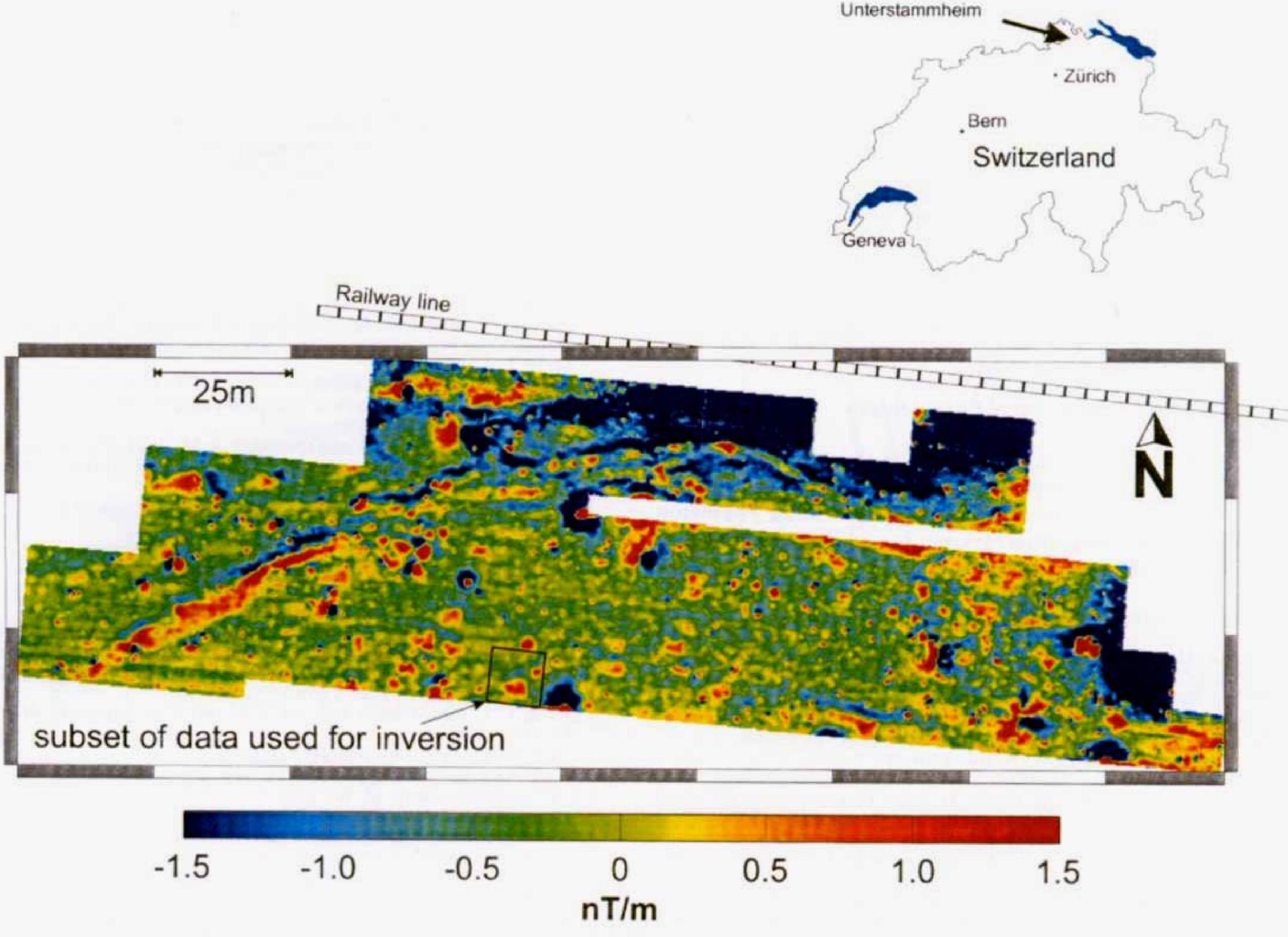


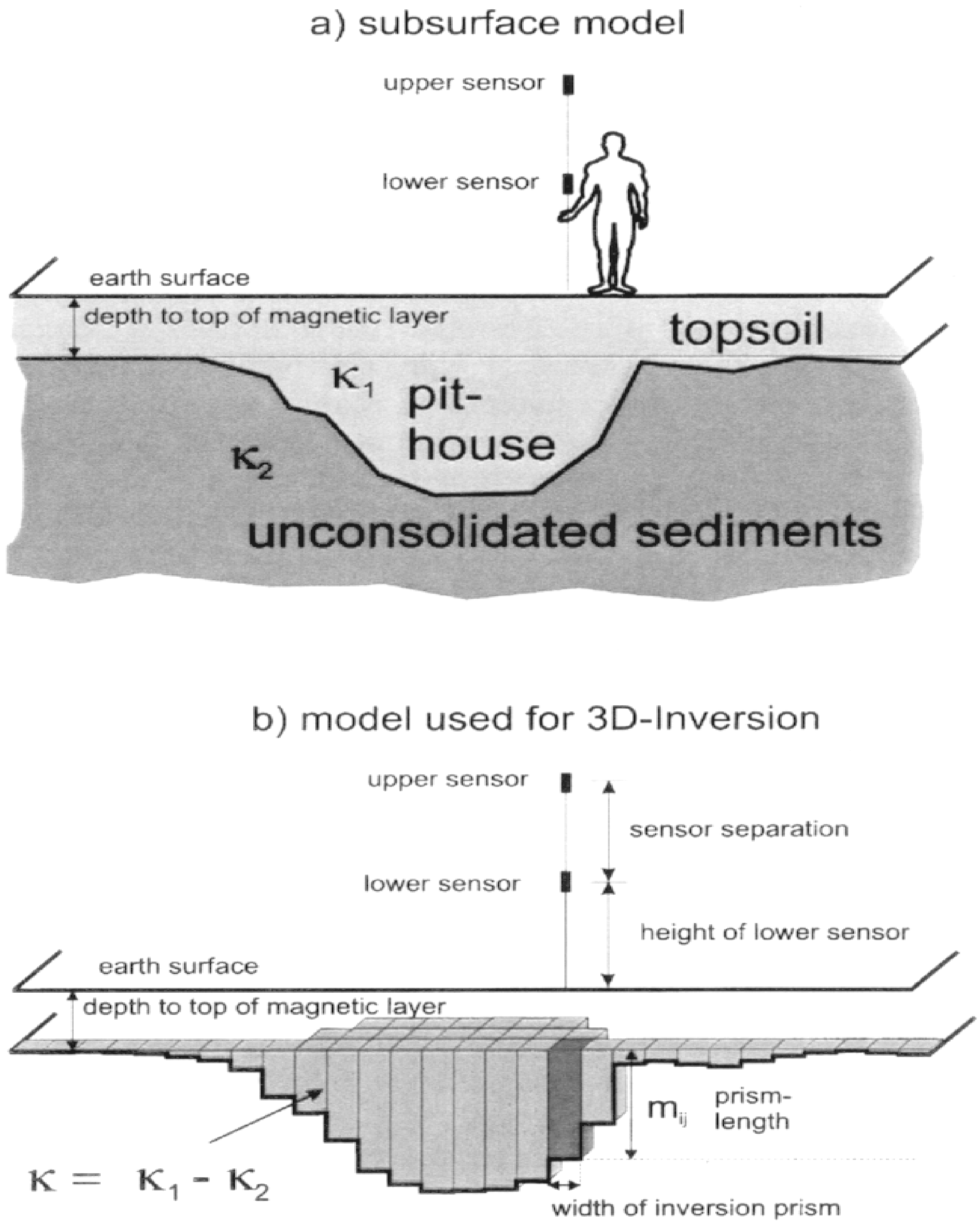
Vertical-Gradient Magnetic

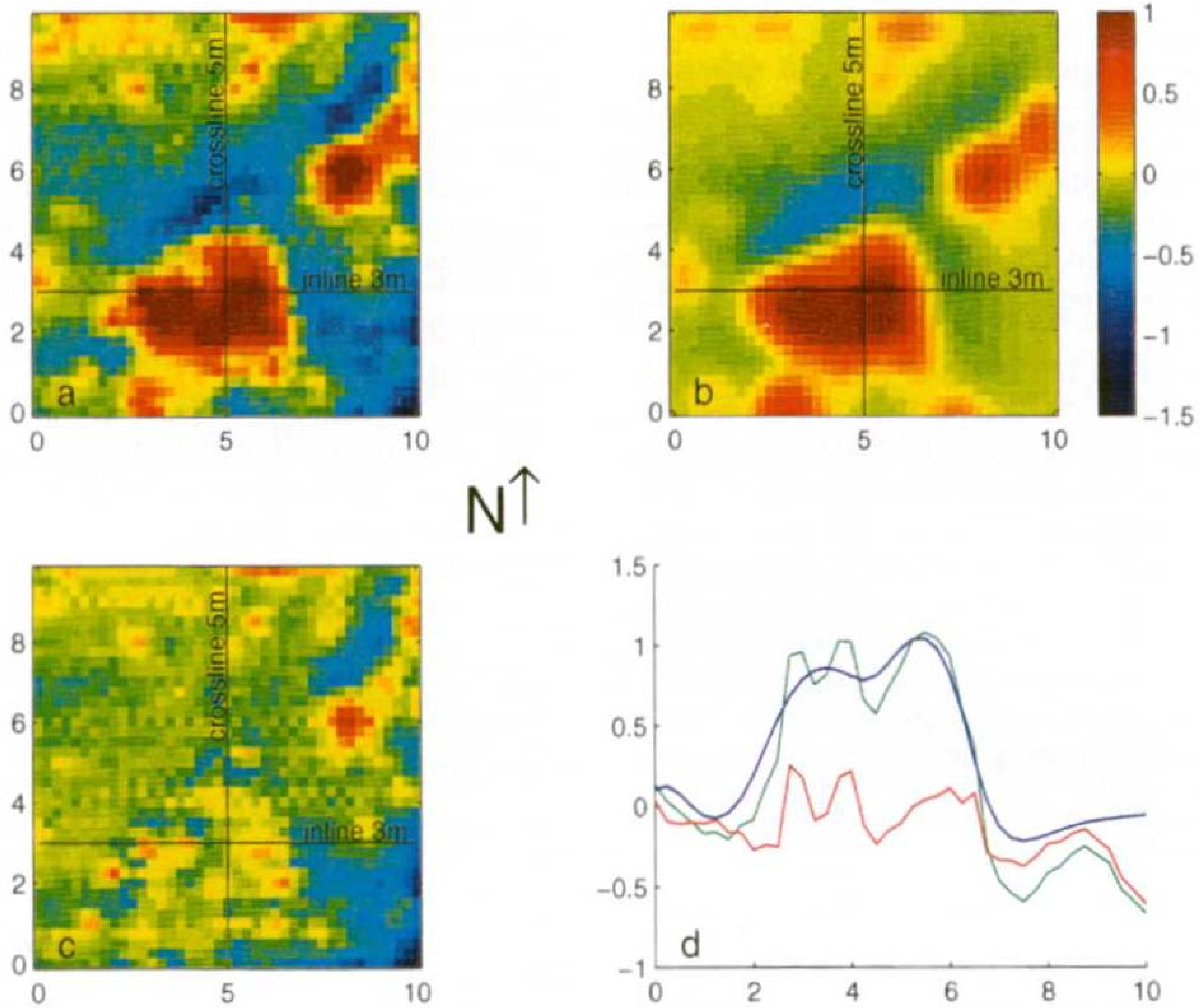




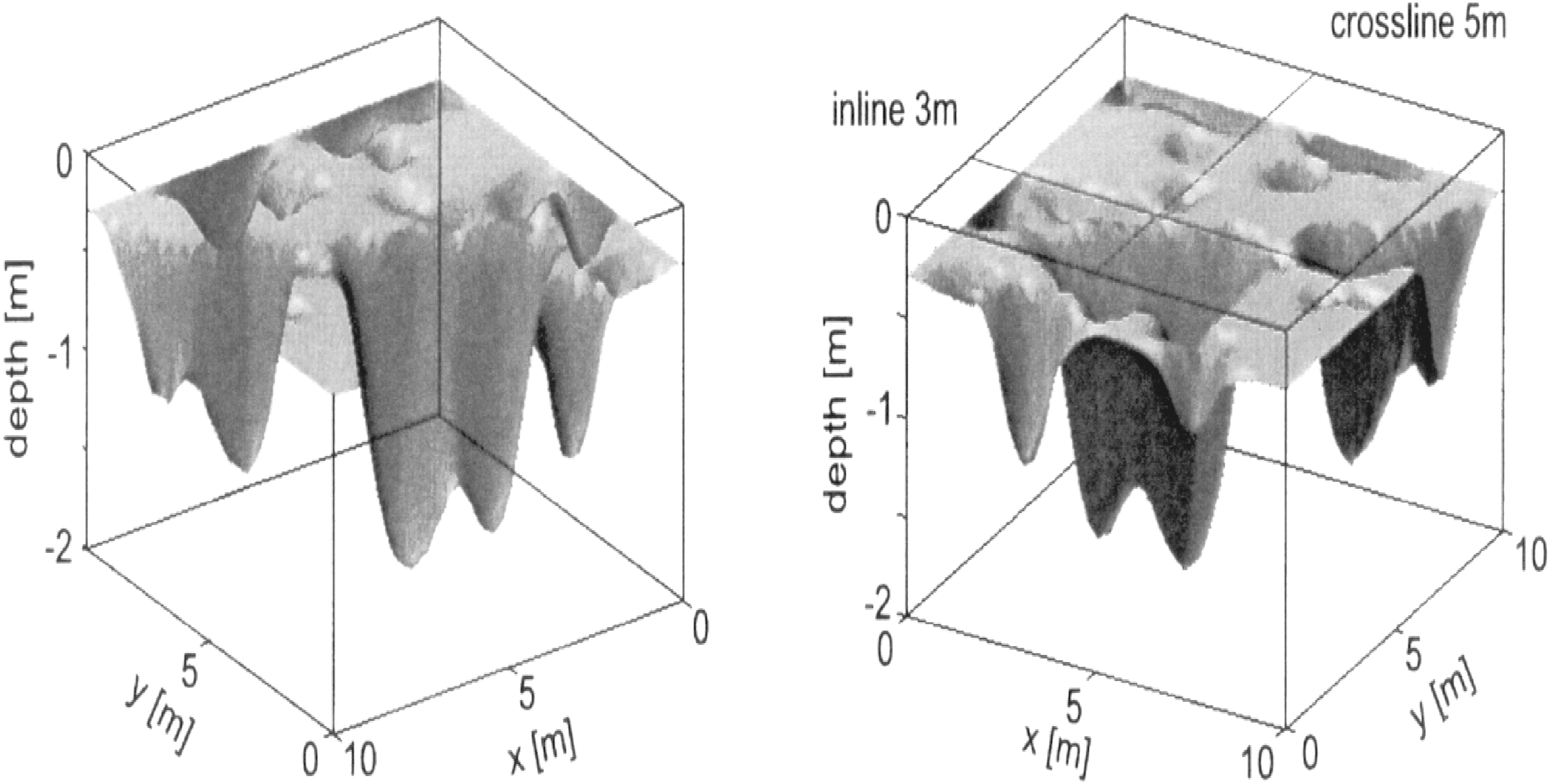

Scale 1:1 000
0 0.020 0.040 0.060
Kilometers


Unterstammheim
Zürich
Bern
Switzerland
Geneva
Railway line
25m
N
subset of data used for inversion
-1.5
-1.0
-0.5
0
0.5
1.0
1.5
nT/m


a) subsurface model
upper sensor
lower sensor
earth surface
depth to top of magnetic layer
topsoil
κ_1
pit-house
κ_2
unconsolidated sediments
b) model used for 3D-Inversion
upper sensor
sensor separation
lower sensor
height of lower sensor
earth surface
depth to top of magnetic layer
m_{ij} prism-length
$\kappa = \kappa_1 - \kappa_2$
width of inversion prism

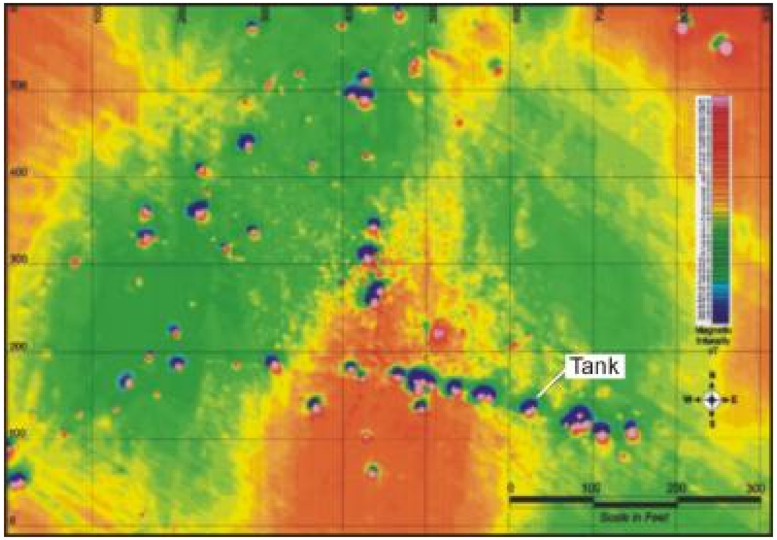


crossline 5m
inline 3m
a
b
c
d
N
1
0.5
0
−0.5
−1
−1.5



crossline 5m
inline 3m
depth [m]
0
-1
-2
y [m]
x [m]
5
10
0

Unexploded ordnance (UXO)



5. Conclusions

Advantages

- Simple
- Fast
- Cost effective
- No artificial source required
- Good qualitative tool for mapping

Drawbacks

- Very sensitive to non-unicity in the modeling solutions
- Mainly qualitative
- Very sensitive to metallic fences, rails (difficult to use in urbanized regions)