Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Geophysics: Gravity and Magnetic

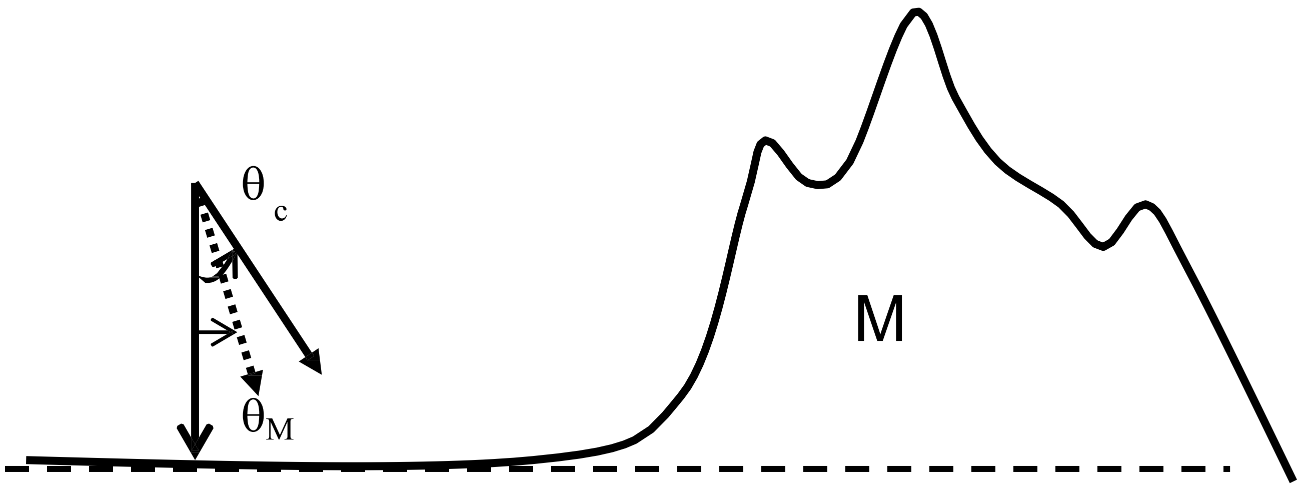
Previous Class: Gravity

Isostasy

•An explanation for the variation in topography on the Earth, either high mountains or deep ocean basins

•explanation originated from high-precision survey of India (mid-1800's) near the Himalayas

➢errors in survey due to deflection of the plumb line from vertical



But measured deflection θ_M is less than calculated deflection θ_c for the mass M

Suggests that excess mass M above the datum is somehow compensated by a reduced mass of underlying material

i.e. mass deficiency required to correct the deflection is approximately equal to mass M above ground.

This suggests a "balance" of masses above some compensation level. More precisely, a "balance" of pressures above the compensation level is the principle that controls how high a lower density object floats in a higher density fluid.

This suggests that entire crust is floating on an underlying fluid layer – mantle asthenosphere

Isostatic balance or isostatic compensation : Static pressure is equal everywhere at same depth of compensation

Two end-member cases :

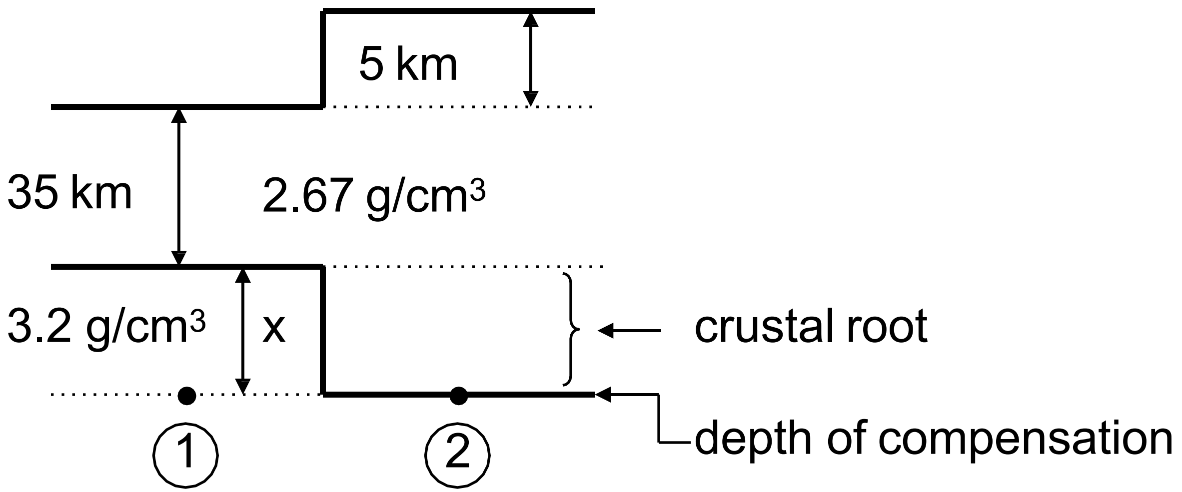
Airy : constant density crustal blocks, different thicknesses

Pratt : varying density crustal or mantle blocks, but flat base of crust (I.e. constant depth Moho)

Example 1 : Tibet plateau, 5 km average elevation. Assume normal crust thickess 35 km; crust density 2.67 g/cm^3;

mantle density 3.2 g/cm^3.

Airy - plateau supported by “crustal root”. Find thickness x.



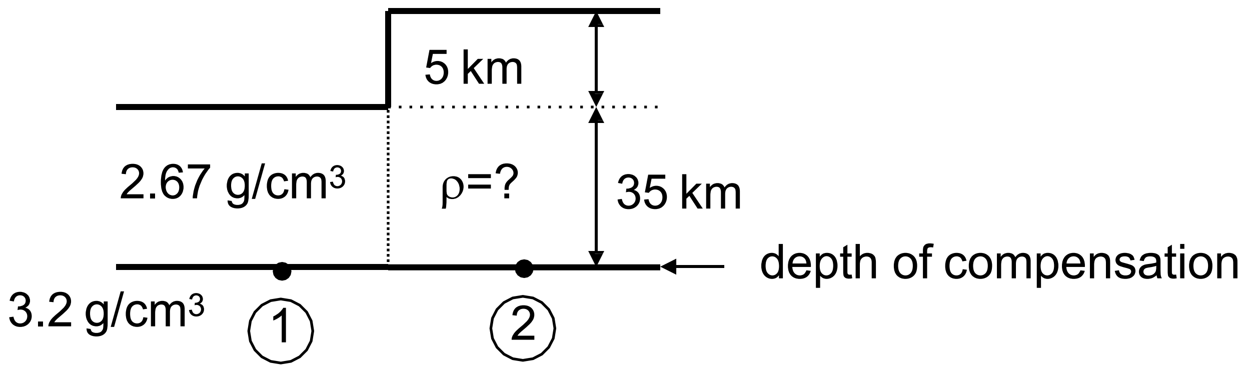
pressure at point 1 = pressure at point 2

(2.67) g (35 km) + (3.2) g (x) = g (2.67) (5+35+x)

x = [(40)(2.67) – (35)(2.67)] / [3.2 – 2.67] = 25.2 km

Total crustal thickness = 5+35+25.2 = 65.2 km

Pratt -no crustal root, but crust below plateau is lighter. Find density ρ.



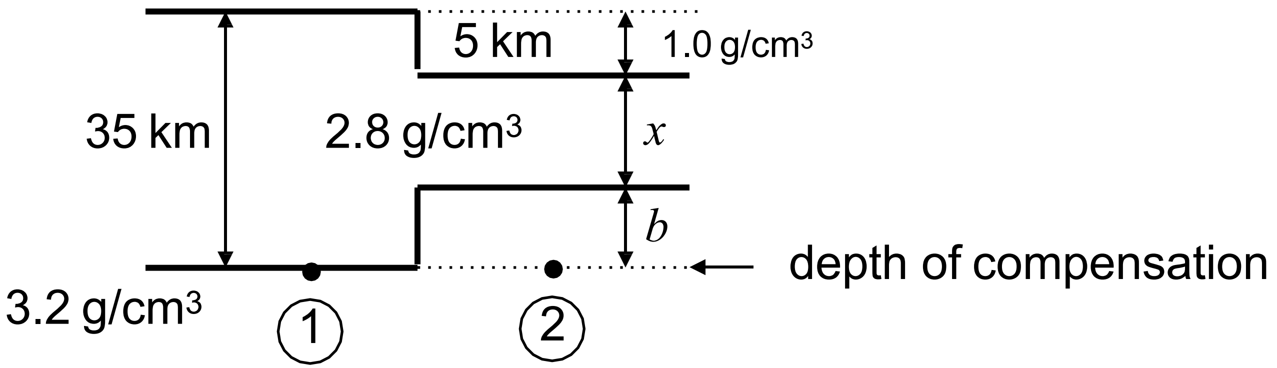
$$(2.67)\,(35) = \rho\,(5+35)$$

$$\rho = (2.67)\,(35)\,/\,(40) = 2.34\ \text{g/cm}^3$$

Is this a reasonable density for hard rock? NO

That is, compensation model beneath Tibet is most likely Airy

Example 2 : Crustal thickness beneath ocean basin (Airy comp)



There are 2 unknowns, x and b, but in general there are also two equations:

1)Total pressure (divided by g) for any vertical column is constant

2)Total thickness of any vertical column is known

For the model above :

1) $(35)(2.8) = (5)(1.0) + x(2.8) + b(3.2)$

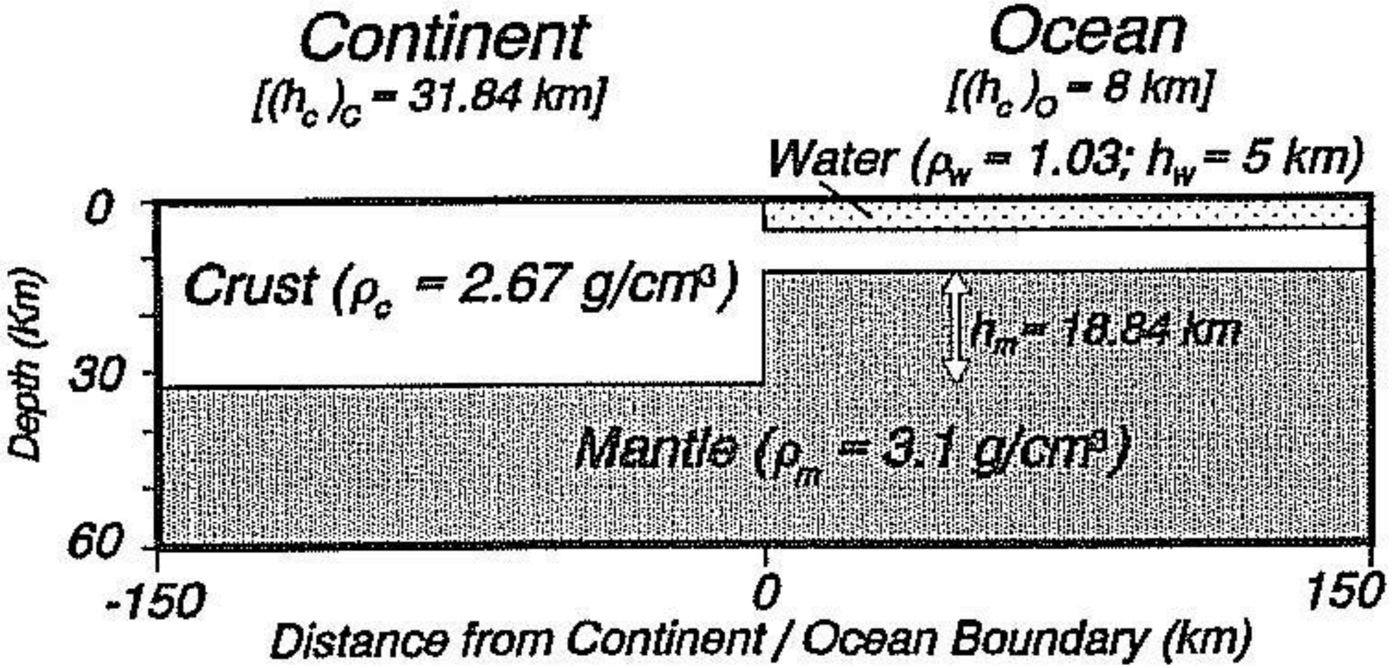
2) $35 = 5 + x + b$

Thus, $b = 30 - x$

and $98 = 5 + 2.8x + (30-x)(3.2)$ $\quad (3.2 - 2.8)x = 3$ or $x = 7.5$ km

Gravity Examples:Geological applications of semi-infinite slab model

1. Continent – ocean transition

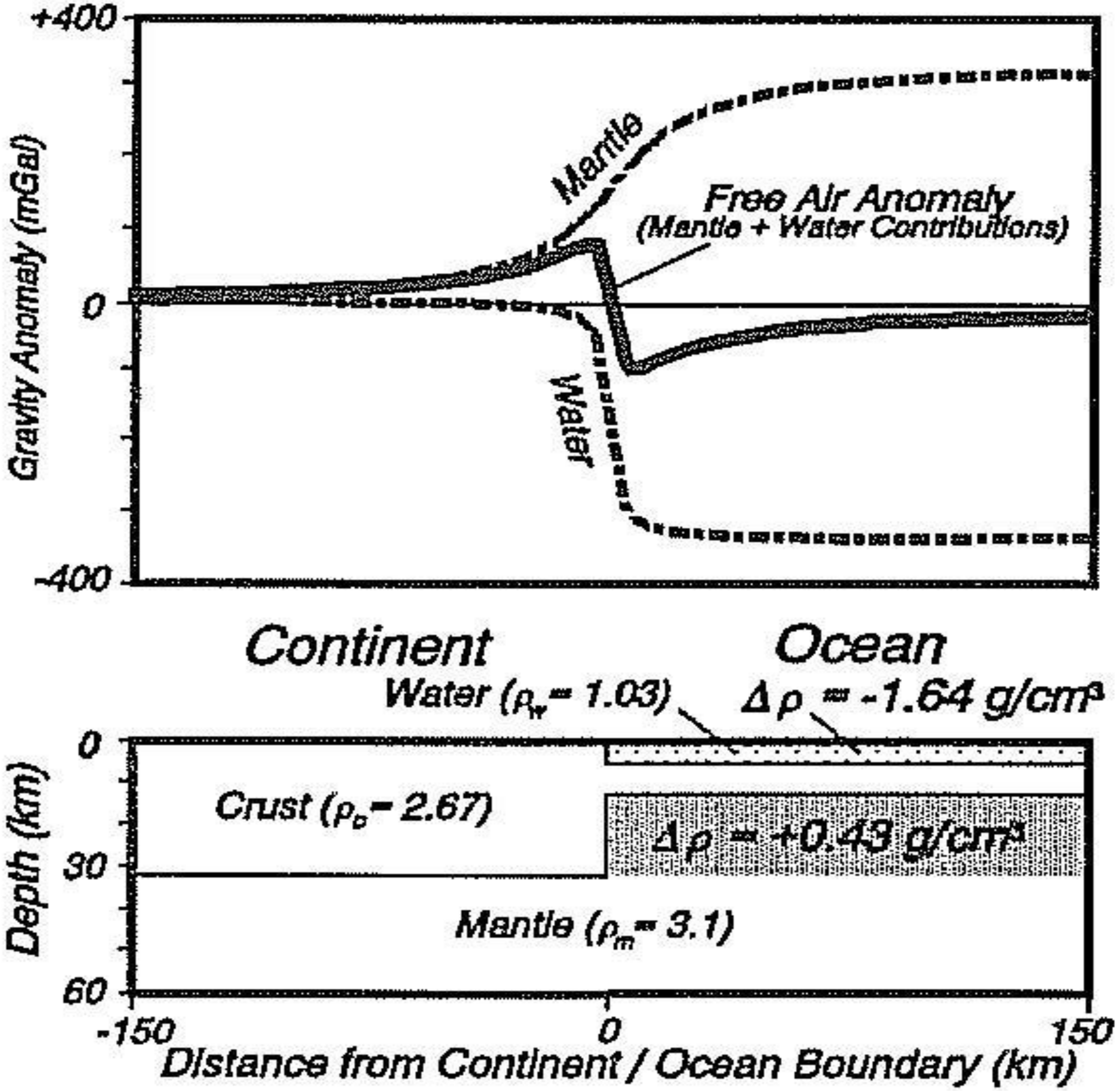


Assume ocean is a semi-infinite slab, with deficit mass; <u>negative</u> contribution, with steep gradient at edge since ocean is shallow

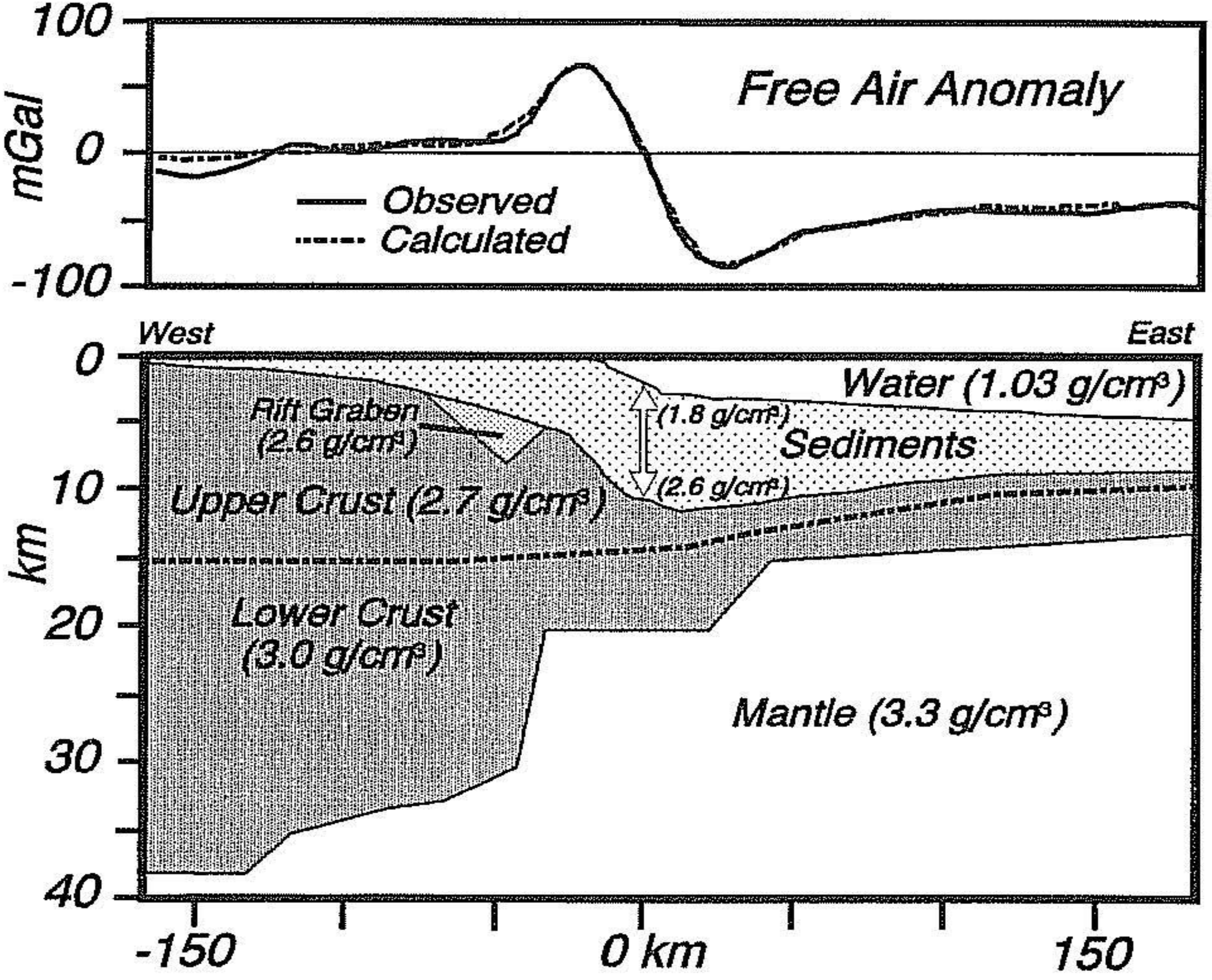
Assume mantle root is semi- infinite slab, with excess mass; <u>positive</u> contrib, with shallow gradient at edge because root is deep.

Net free-air gravity produces edge effect due to different gradients

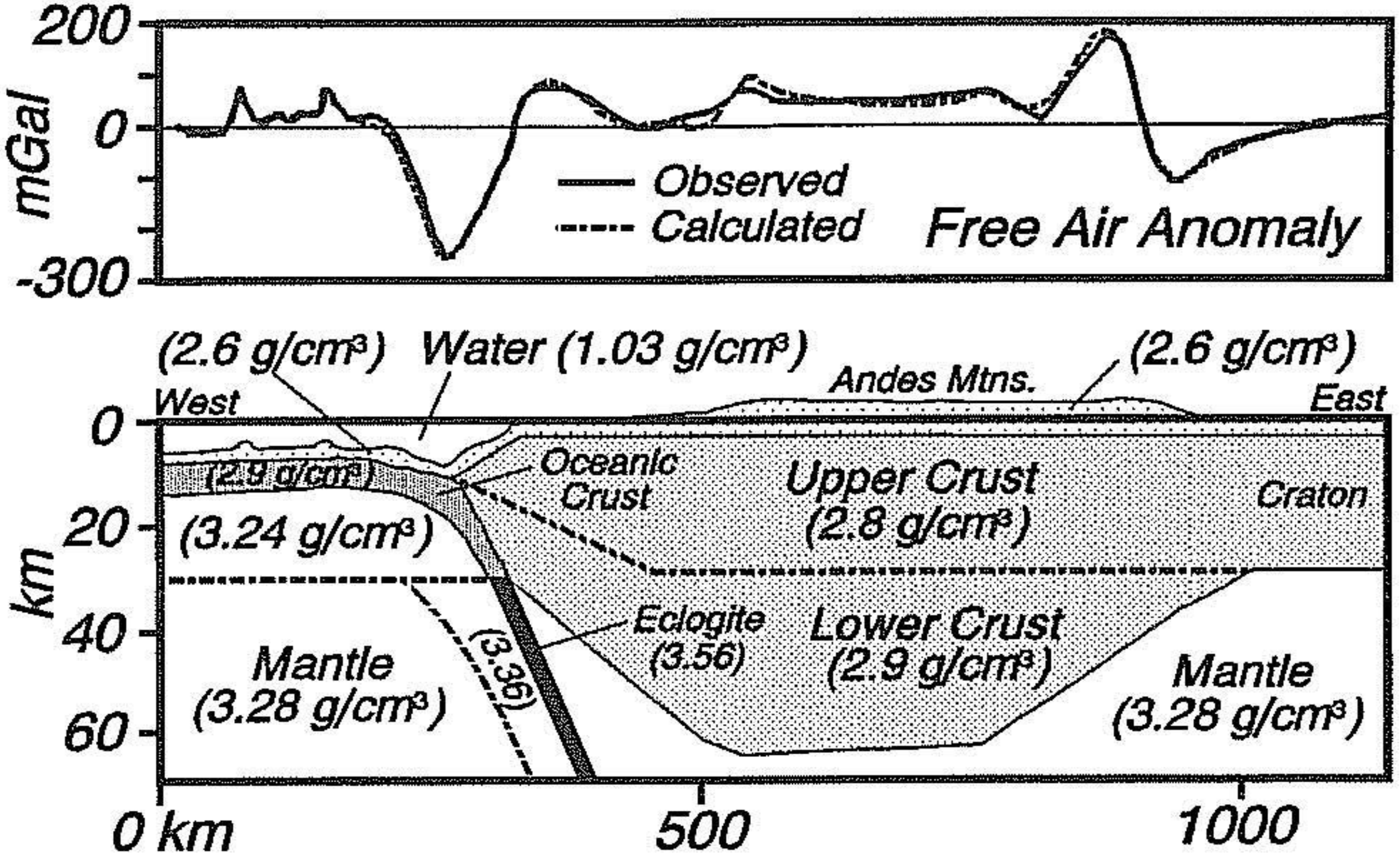
: far from edge, net gravity is zero since negative and positive contributions sum to 0



Atlantic margin : observed free-air gravity and model



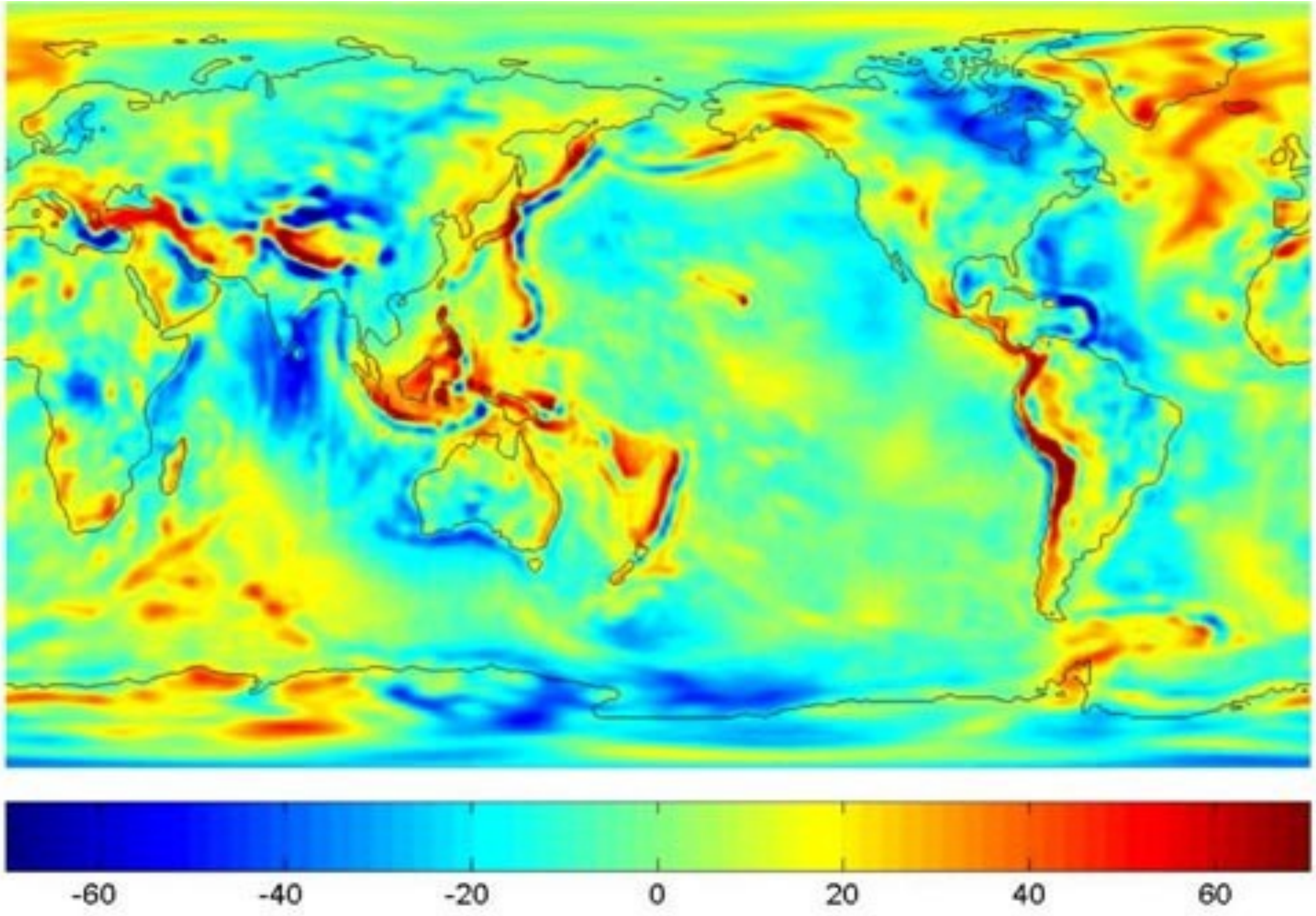
Andes subduction zone (free air anomaly)



Note positive "Batman" ears.
On west, edge effect low is exaggerated at trench (grav < -200 mGal), and slight positive over outer arc bulge

GRACE : Gravity Recovery and Climate Experiment

Gravity surveying measures variations in the Earth's gravitational field caused by differences in the density of subsurface rocks.



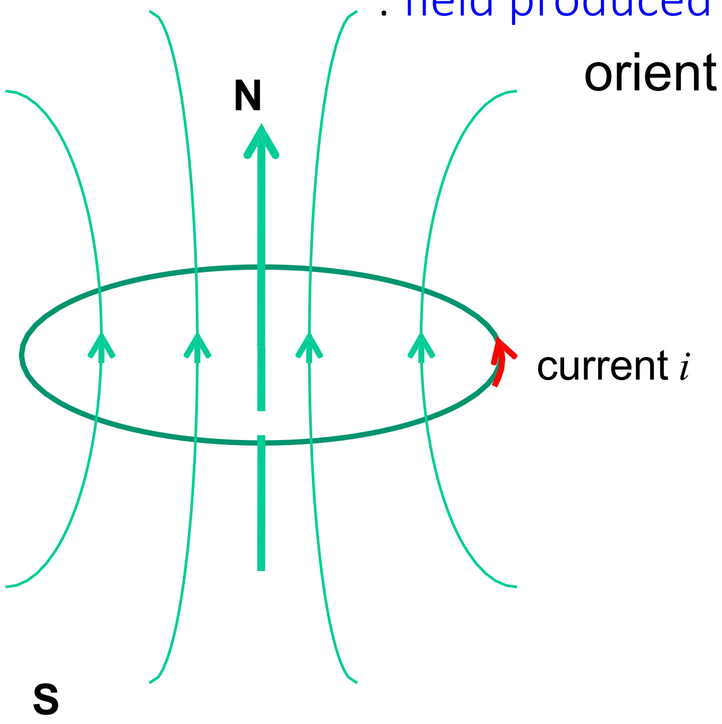
https://www.youtube.com/watch?v=9P6GEpxFtSY

Magnetic Prospecting: Magnetic basics

Magnetic field is actually produced by a current , or moving charge

: field produced by a loop with current i is like a dipole;

orient itself parallel to field line



Current loop is an electromagnet

Earth material which produces no permanent magnetic field by itself (e.g. a rock) will have a magnetic field induced in it by an external field

: the size of the induced field depends on the "magnetic susceptibility" χ (chi), which is a characteristic physical property of the material

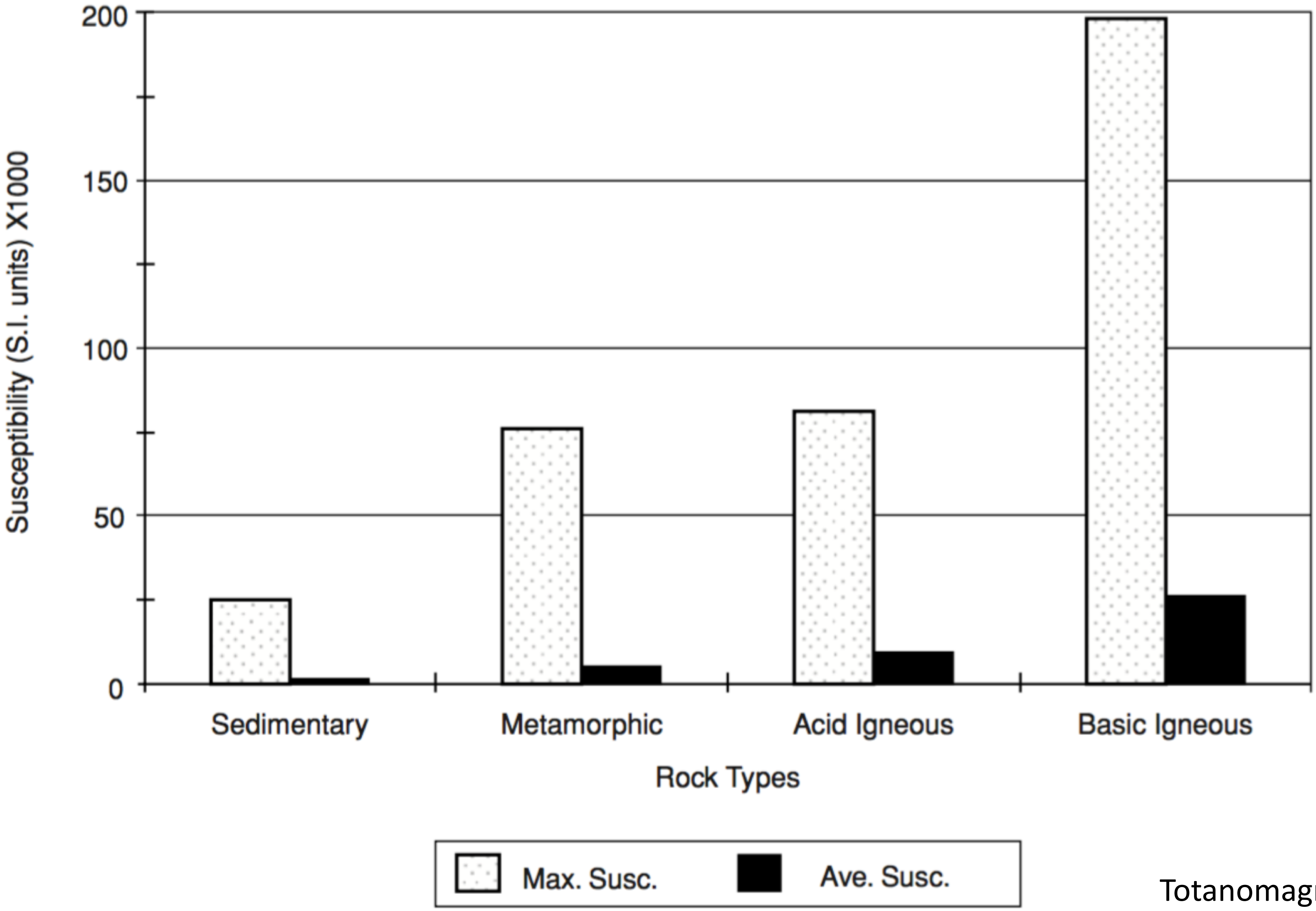
Magnetic units and formulae

B	magnetic field	weber/m^2, tesla	(Monopole) $B = \frac{\mu}{4\pi}\frac{m}{\mu_r r^2}$
μ_0	permeability of free space	henry/m $\mu_0 = 4\pi \times 10^{-7}$	$\mu_r = \frac{\mu}{\mu_0}$
H,	magnetizing field	ampere/m [Am^{-1}]	$H = i/r$ $B = \mu H$
m	magnetic pole strength	weber [also Am]	
M	dipole moment	ampere m^2	$M = m\,L$ $M = i\,A$
χ k	magnetic susceptibility	-	$\mu_r = 1 + \chi$
J_i	magnetization	ampere/m	$J_i = M/V$ $J_i = \chi H$

Material	Susceptibility x 10^3 (SI)
Air	~0
Quartz	-0.01
Rock salt	-0.01
Calcite	-0.001 - 0.01
Pyrite	0.05 – 5
Hematite	0.5 –35
Ilmenite	300 – 3500
Magnetite	1200 – 19,200
peridotite	90-200

Material	Susceptibility x 10^3 (SI)
Limestones	0 – 3
Sandstones	0 – 20
Shales	0.01 – 15
Schist	0.3 – 3
Gneiss	0.1 – 25
Slate	0 – 35
Granite	0 – 50
Gabbro	1 – 90
Basalt	0.2 - 175

Unlike density, notice the large range of susceptibilities not only between varying rocks and minerals but also within rocks of the same type. Susceptibility varies by a factor of 10^6

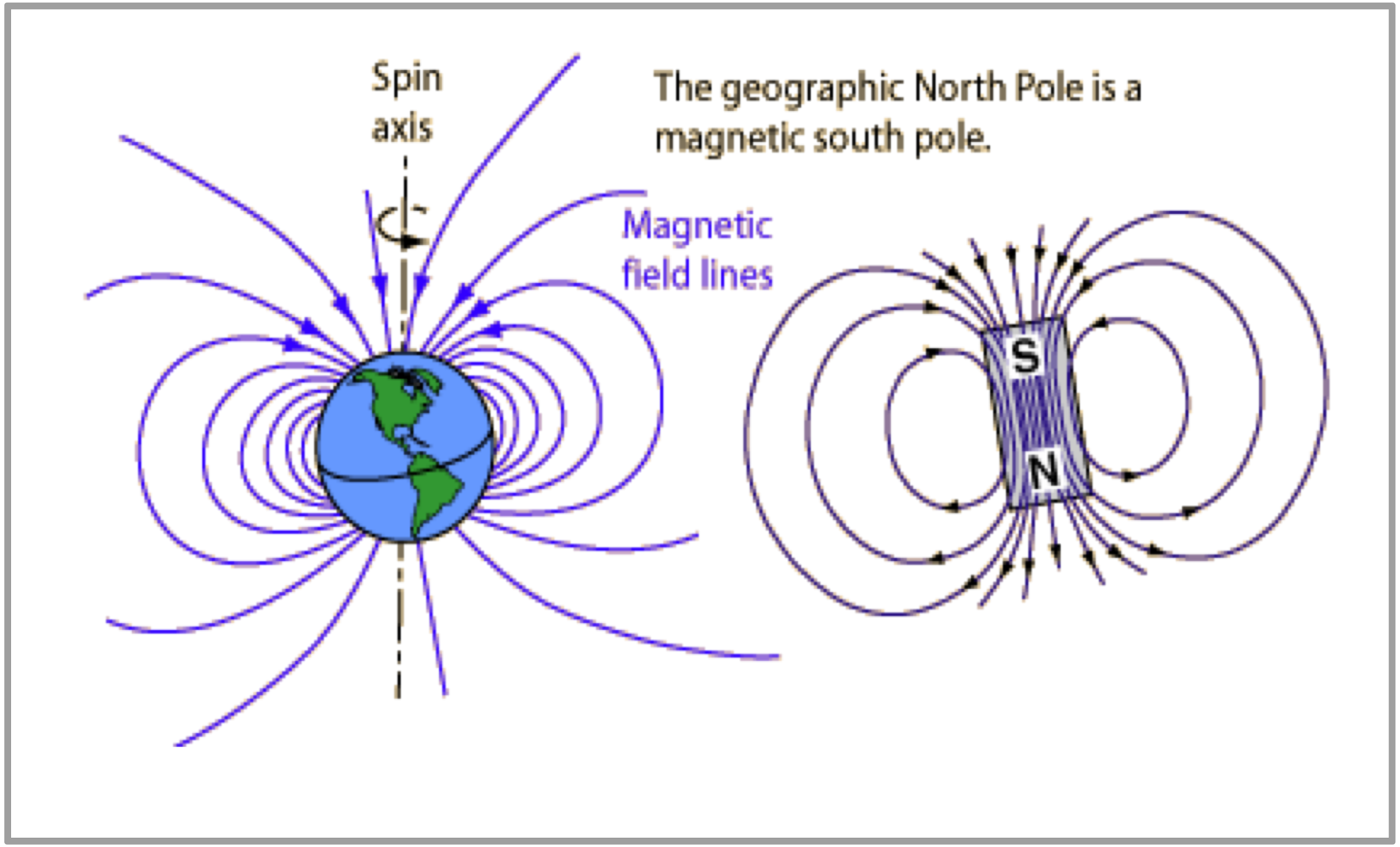


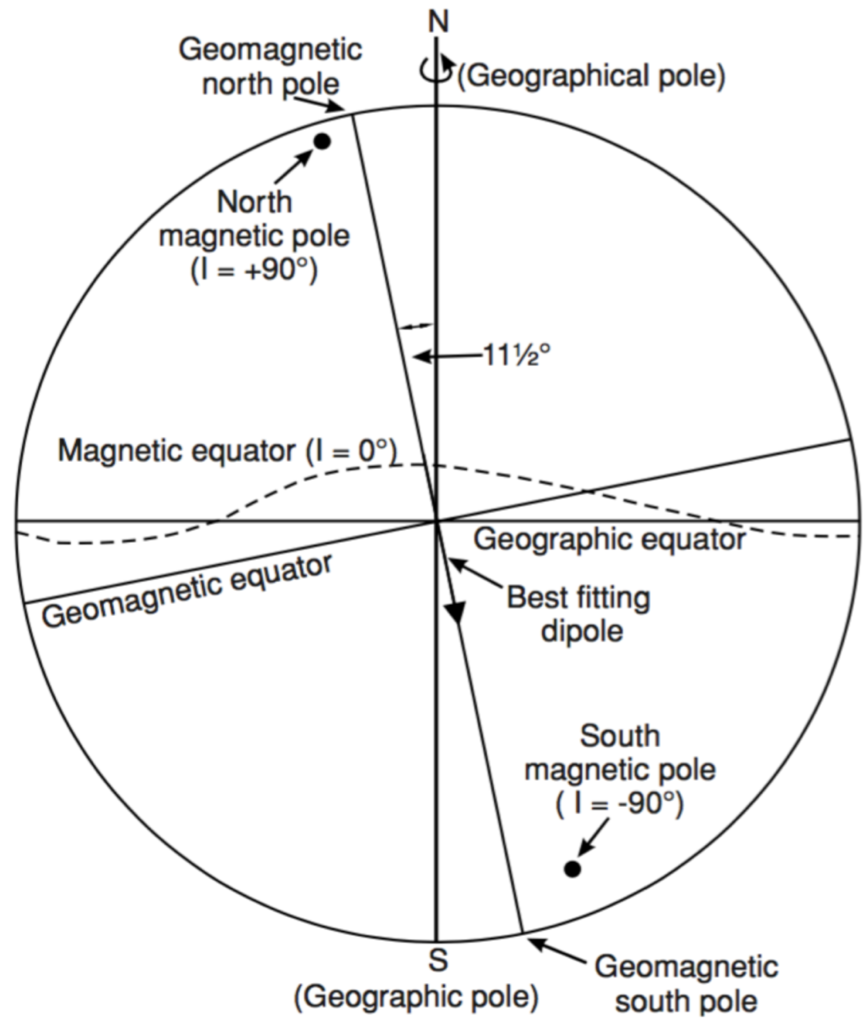
Magnetic anomalies are associated with magnetic minerals - primarily magnetite. As magnetite is common in sedimentary rocks, anomalies vary laterally with magnetite concentration.

Magnetite is even more common in metamorphic and igneous rocks, thus larger anomalies are observed in these rocks.

Totanomagnetite is common in Ocean floor

Earth's Magnetic Field

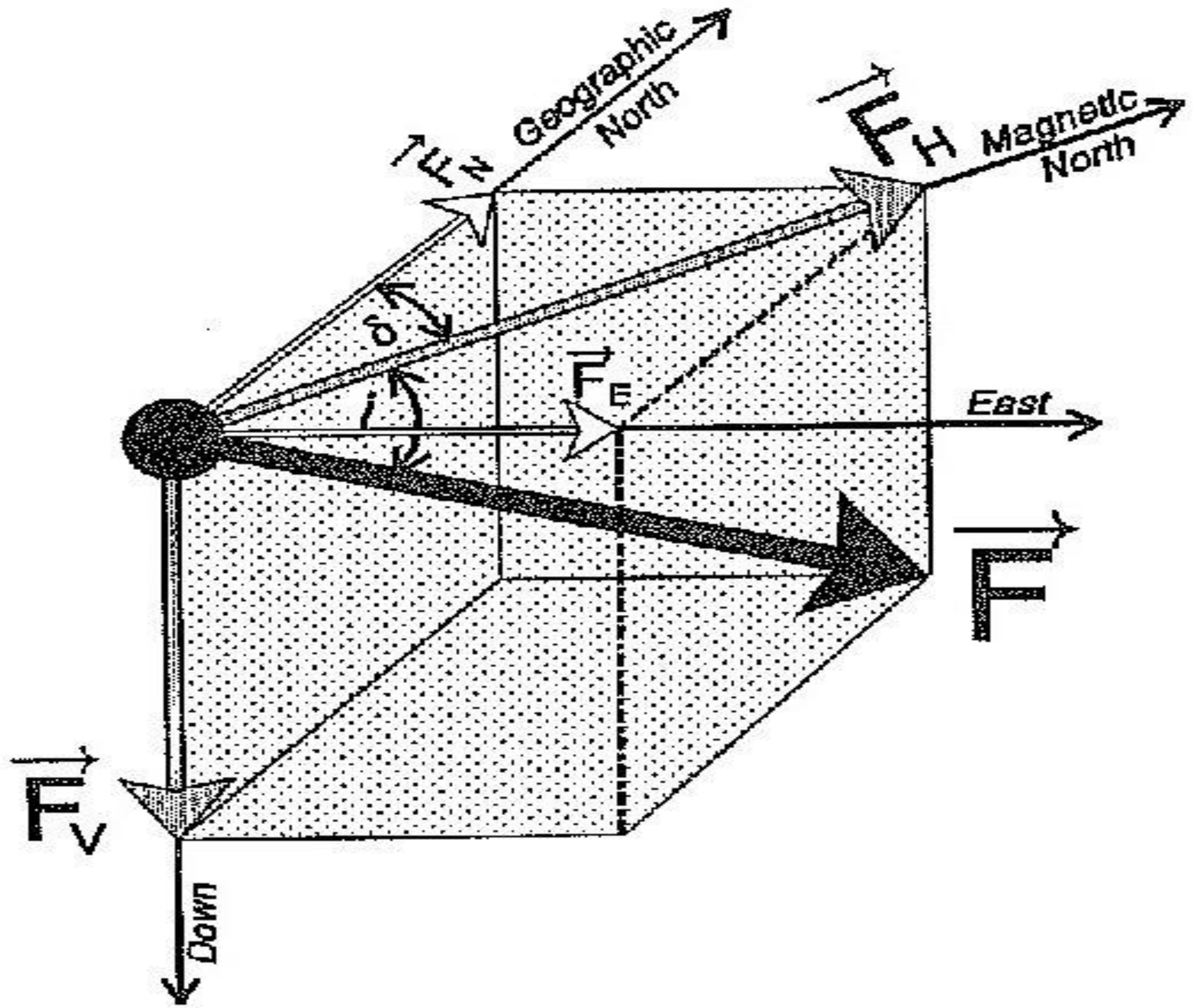




__Axial Dipole Model__ : dipole tilted at 10.9° to rotation axis

: explains 90% of Earth's external field; remainder is <u>non-dipole</u> component

Strength and Direction of Magnetic Field



Magnetic field is a vector

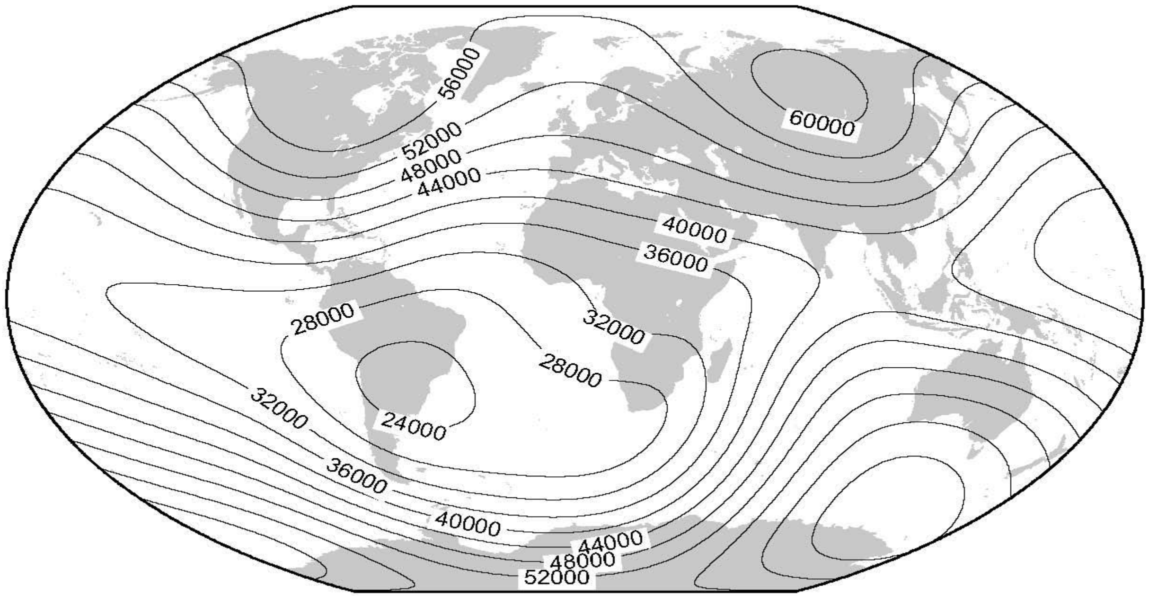
$\vec{F}_E, \vec{F}_N, \vec{F}_V$: 3 components

$\vec{F}_E$ and $\vec{F}_N$ form horizontal component $\vec{F}_H$

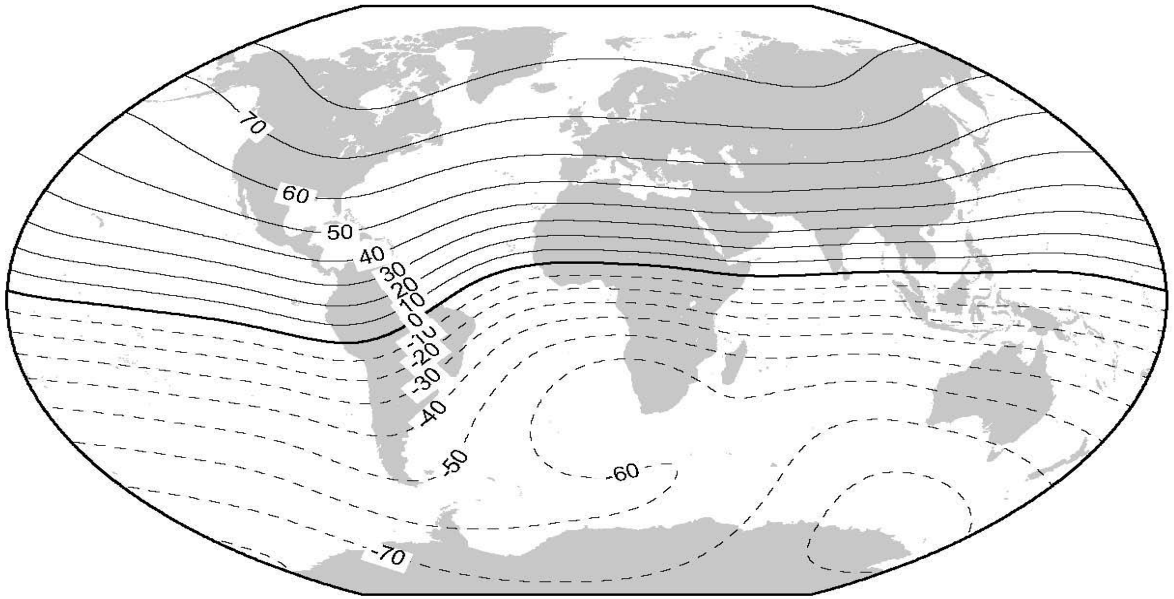
declination : angle of horizontal field with true north

inclination : angle of total magnetic field with horizontal

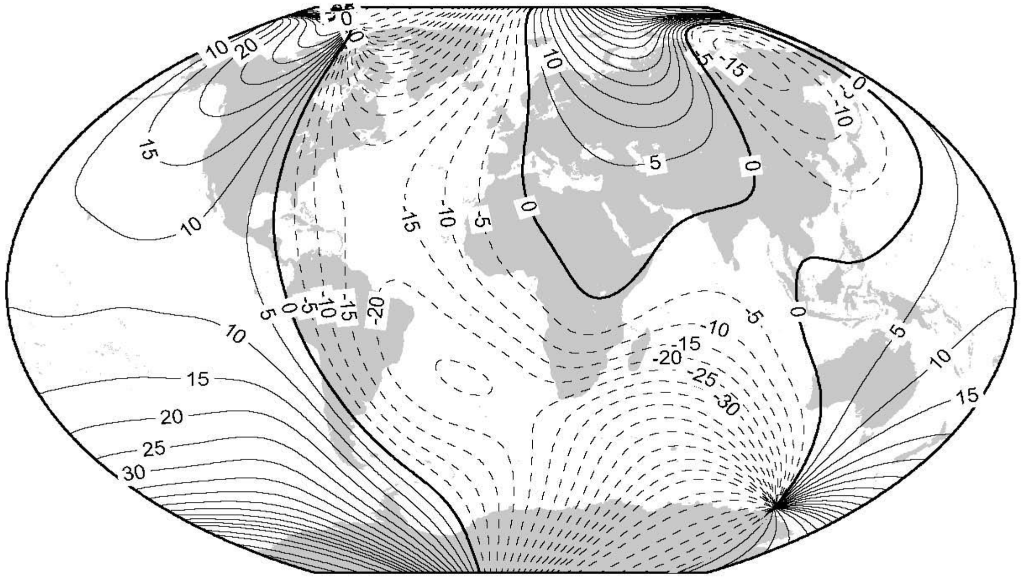
Total intensity (nT) at 2005.0.



Inclination (degrees) at 2005.0.



Declination (degrees) at 2005.0.



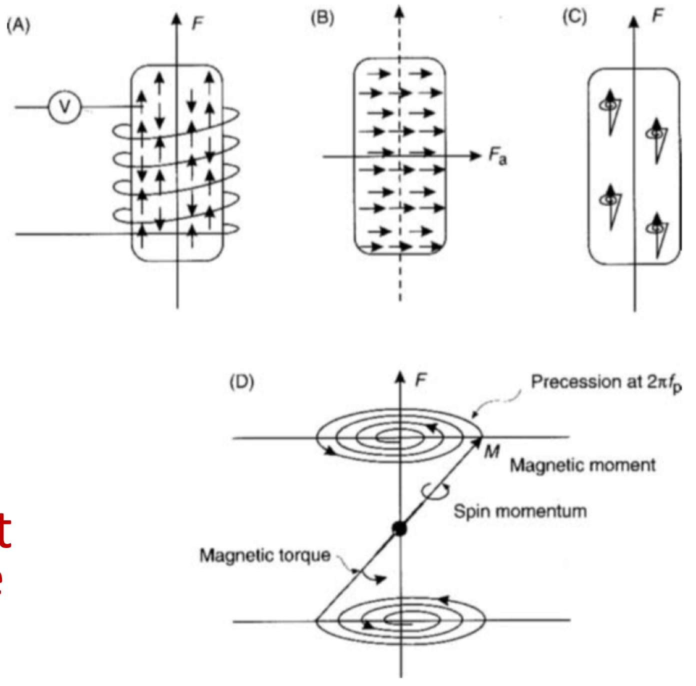
from British Geological Survey
http://www.geomag.bgs.ac.uk/earthmag.html

https://maps.ngdc.noaa.gov/viewers/historical_declination/

Proton Precession Magnetometer

The proton magnetometer has a sensor which consists of a bottle containing a proton-rich liquid, usually water or kerosene, around which a coil is wrapped, connected to the measuring apparatus. Each proton has a magnetic moment ***M*** and, as it is always in motion, it also possesses an angular momentum ***G***, rather like a spinning top. In an ambient magnetic field such as the Earth's (***F***), the majority of the protons align themselves parallel with this field, with the remainder orientated antiparallel. Consequently, the volume of proton-rich liquid acquires a net magnetic moment in the direction of the ambient field (***F***). A current is applied to the coil surrounding the liquid, generating a magnetic field about 50 to 100 times stronger than, and at right-angles to, the Earth's field. The protons align themselves to the new magnetic direction. When the applied field is switched off, the protons precess around the preexistent ambient field ***F*** at the *Larmor precession frequency* (*f* p) which is proportional to the magnetic field strength ***F.*** As protons are charged particles, as they precess they induce an alternating voltage at the same frequency as *f* p into the coil surrounding the sensor bottle. Interaction between adjacent protons causes the precession to decay within 2–3 seconds, which is sufficient time to measure the precession frequency. To obtain a value of ***F*** to within ± 0.1 nT, frequency must be measured to within ±0.004 Hz, which is quite easily achieved.

Other Magnetometers: Fluxgate and Alkali Vapour magnetometers



$$\boldsymbol{F} = 2\pi f_p/\gamma_p$$

where γ_p is the **gyromagnetic ratio of the proton**, which is the ratio of the magnetic moment and spin angular momentum;

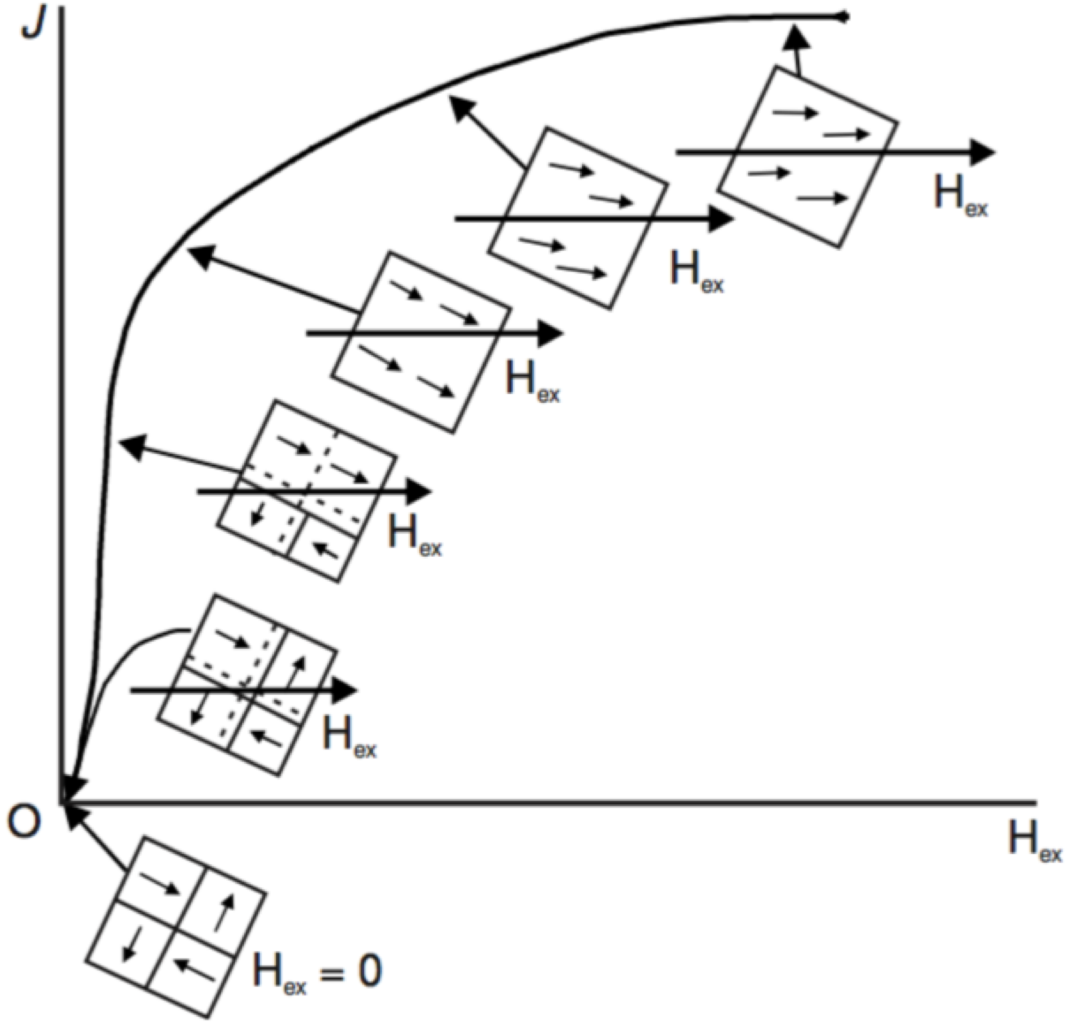
F= field strength; f_p = proton precession frequency.

γ_p=0.26753Hz/nT and $2\pi/\gamma_p$=23.4859nT/Hz. Thus:

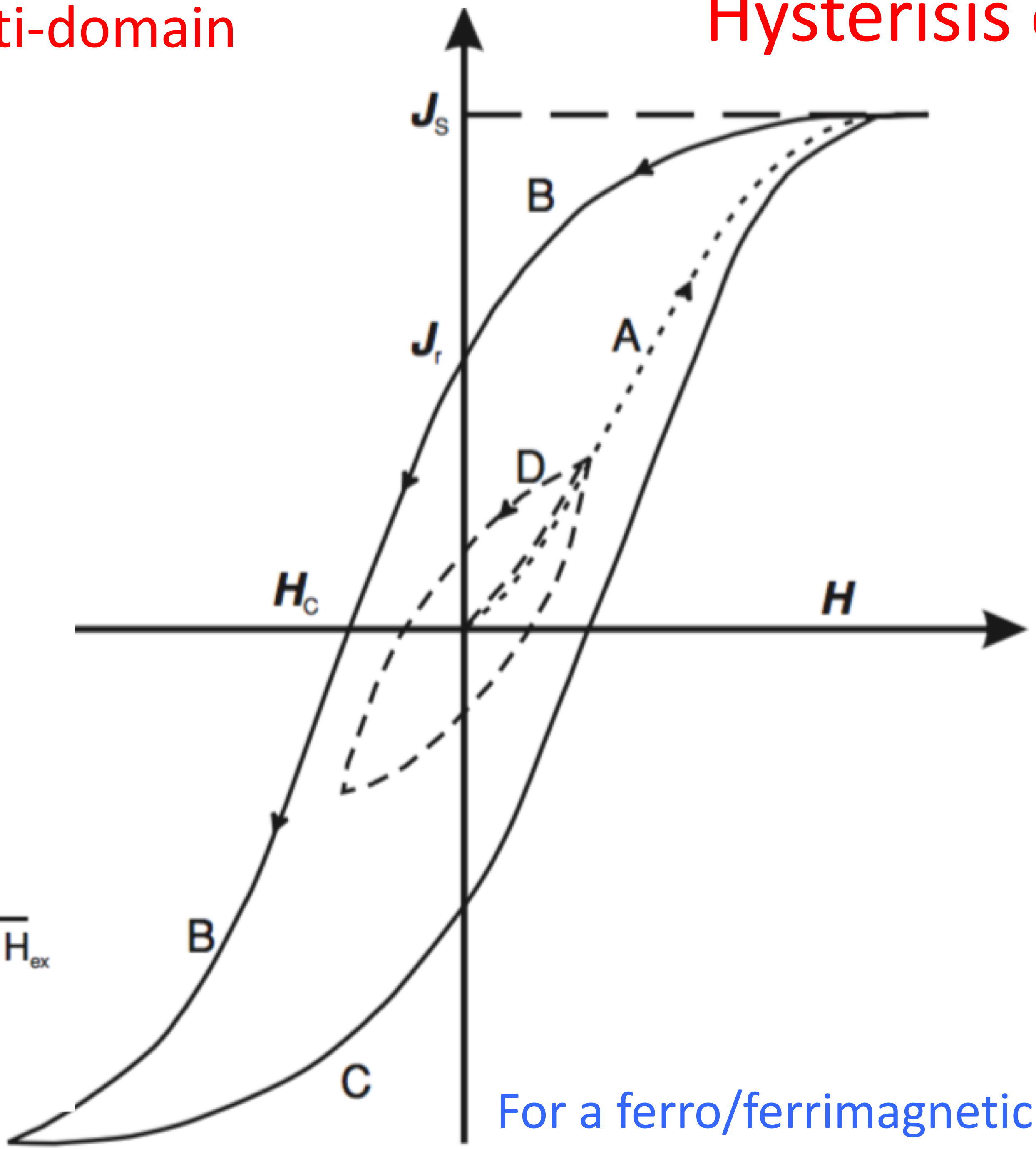
$\boldsymbol{F} = 23.4859 f_p$

For example, for $\boldsymbol{F}$ = 50,000 nT, f_p = 2128.94 Hz.

Process of magnetisation for a multi-domain Ferromagnetic material



Hysterisis curve

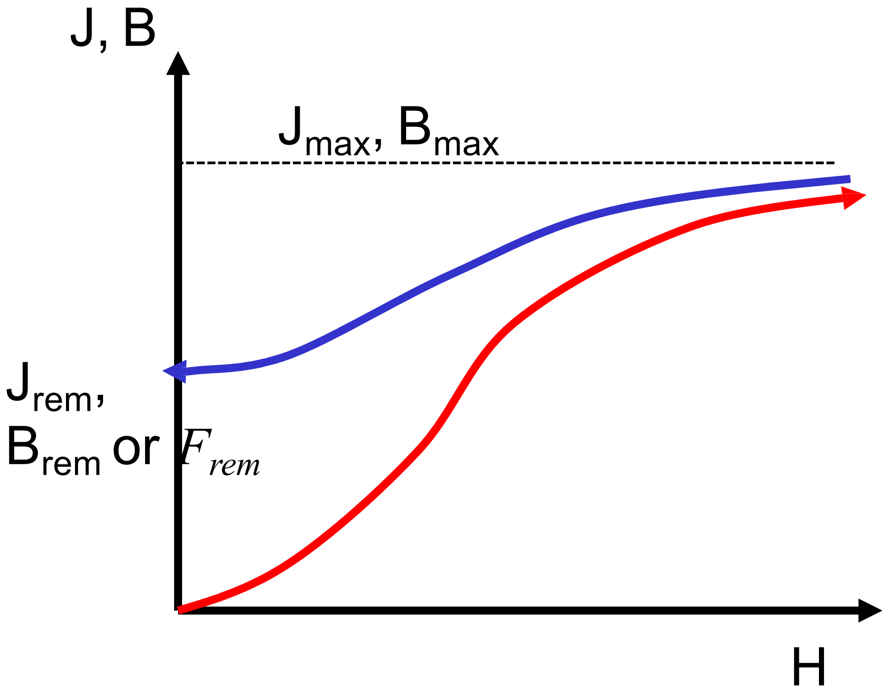


For a ferro/ferrimagnetic material

Remanent Magnetization

Ferrimagnetic materials retain a permanent magnetization even when the external field is removed.

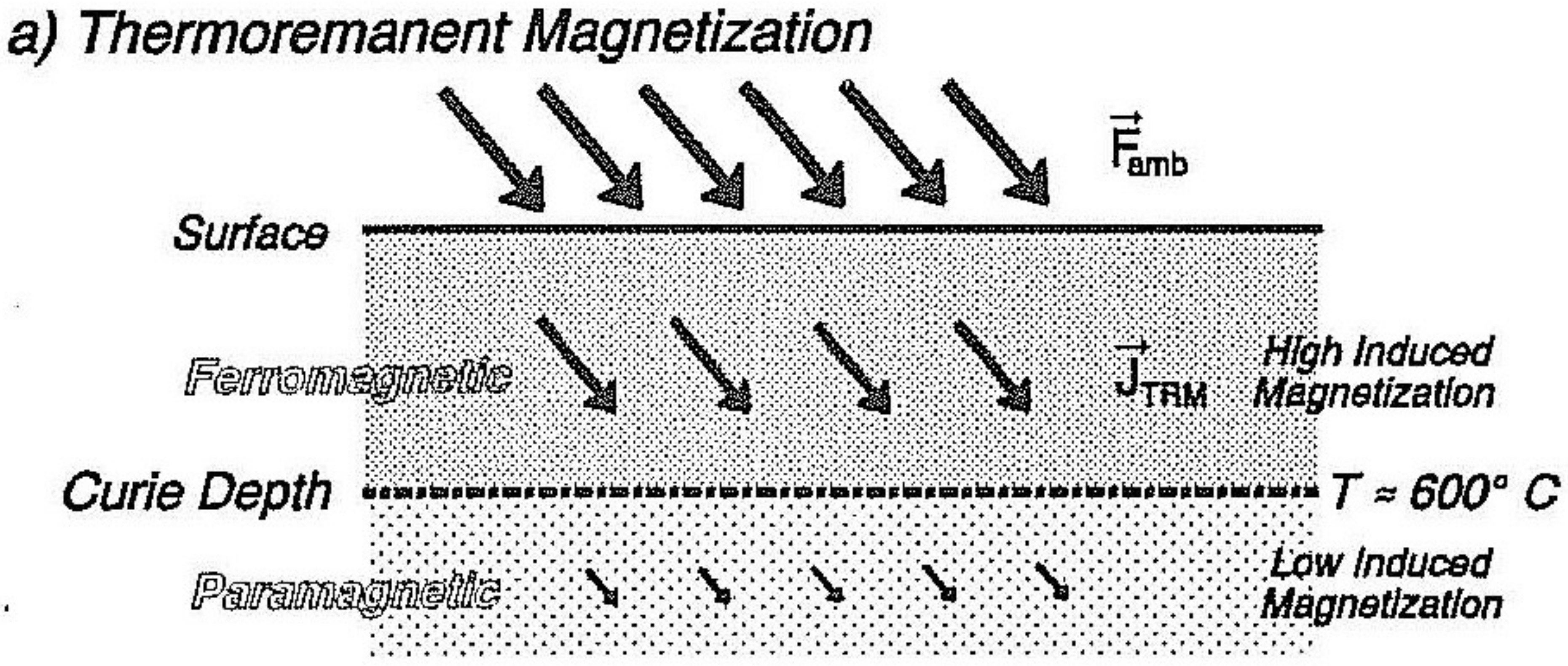
- As inducing field H increases from 0, there is a maximum induced field B for which all the domains are aligned, no matter



how big H is $\Rightarrow$ <u>saturation</u>

As domains grow to grain size, it is energetically favourable for alignment to remain even after inducing field H is removed.

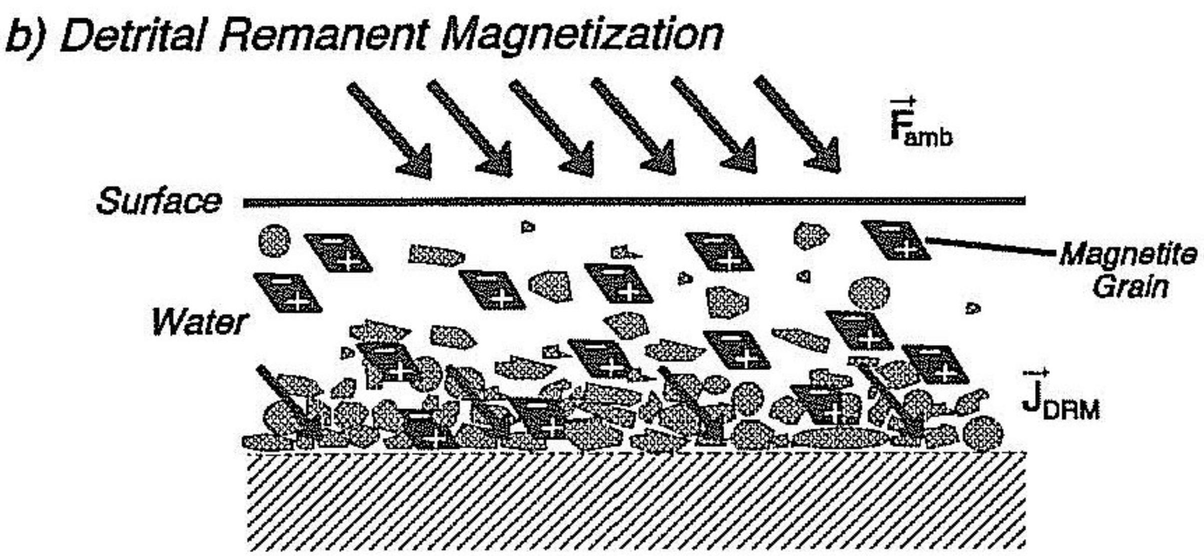
$$\vec{F}_{tot} = \vec{F}_{amb} + \vec{F}_{ind} + \vec{F}_{rem}$$

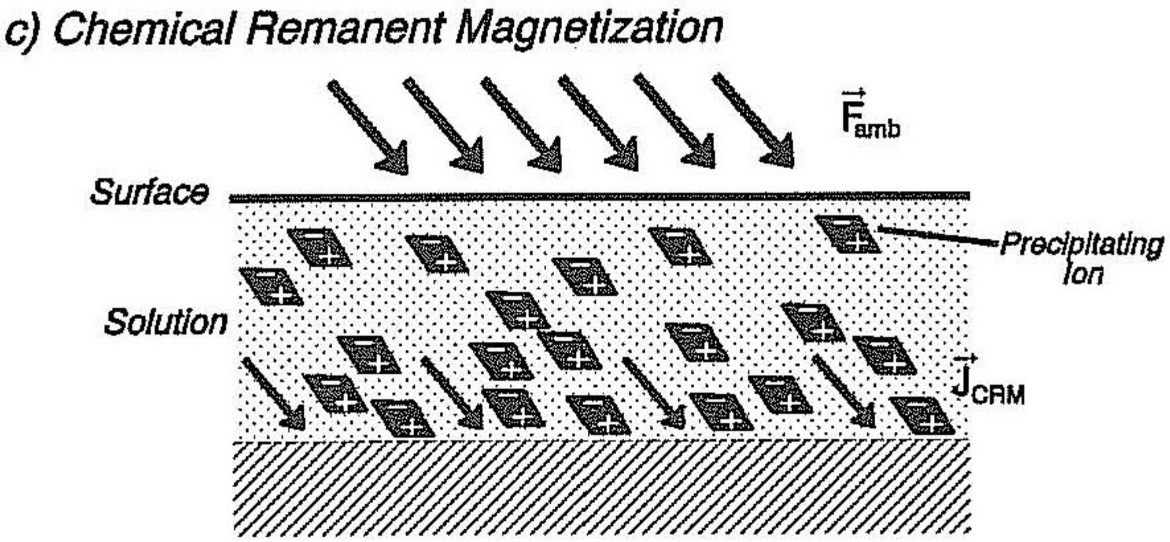


Primary remanent magnetisations are acquired by the cooling and solidification of an igneous rock from above the Curie temperature (of the constituent magnetic minerals) to normal surface temperature (TRM)

Curie temp : temp above which a ferrimagnetic material can no longer retain permanent magnetization
578°C magnetite; 770 ° C pure iron

- above Curie temp, material is only paramagnetic





As sediments settle in water, magnetic grains orient with the ambient field.

As <u>ions precipitate from solution to form magnetic minerals (during crystallization)</u>, magnetic domains in crystals align with ambient field

e.g., “red beds – iron-rich, red from hematite.

Remnant magnetization

Types of RM	Process
Natural (NRM)	Acquired by a rock or mineral under natural conditions.
Thermal (TRM)	Acquired by a material during cooling from a temperature greater than the Curie temperature to room temperature (e.g. molten lava cooling after a volcanic eruption).
Isothermal (IRM)	Acquired over a short time (of the order of seconds) in a strong magnetic field at a constant temperature (e.g. such as by a lightning strike).
Chemical (CRM)	Also crystallisation RM; acquired at the time of nucleation and growth or crystallisation of fine magnetic grains far below the Curie point in an ambient field.
Thermal-chemical (TCRM)	Acquired during chemical alteration and cooling.
Detrital (DRM)	Also depositional RM; acquired by the settling out of previously magnetised particles to form ultimately consolidated sediments which then have a weak net magnetisation, but prior to any chemical alteration through diagenetic processes.
Post-depositional (PDRM)	Acquired by a sediment by physical processes acting upon it after deposition (e.g. bioturbation and compaction).
Viscous (VMR)	Acquired after a lengthy exposure to an ambient field with all other factors being constant (e.g. chemistry and temperature).
Anhysteretic (ARM)	Acquired when a peak amplitude of an alternating magnetic field is decreased from a large value to zero in the presence of a weak but constant magnetic field.

Primary remanent magnetisations are acquired by the cooling and solidification of an igneous rock from above the Curie temperature (of the constituent magnetic minerals) to normal surface temperature (TRM) or by detrital remanent magnetisation (DRM).

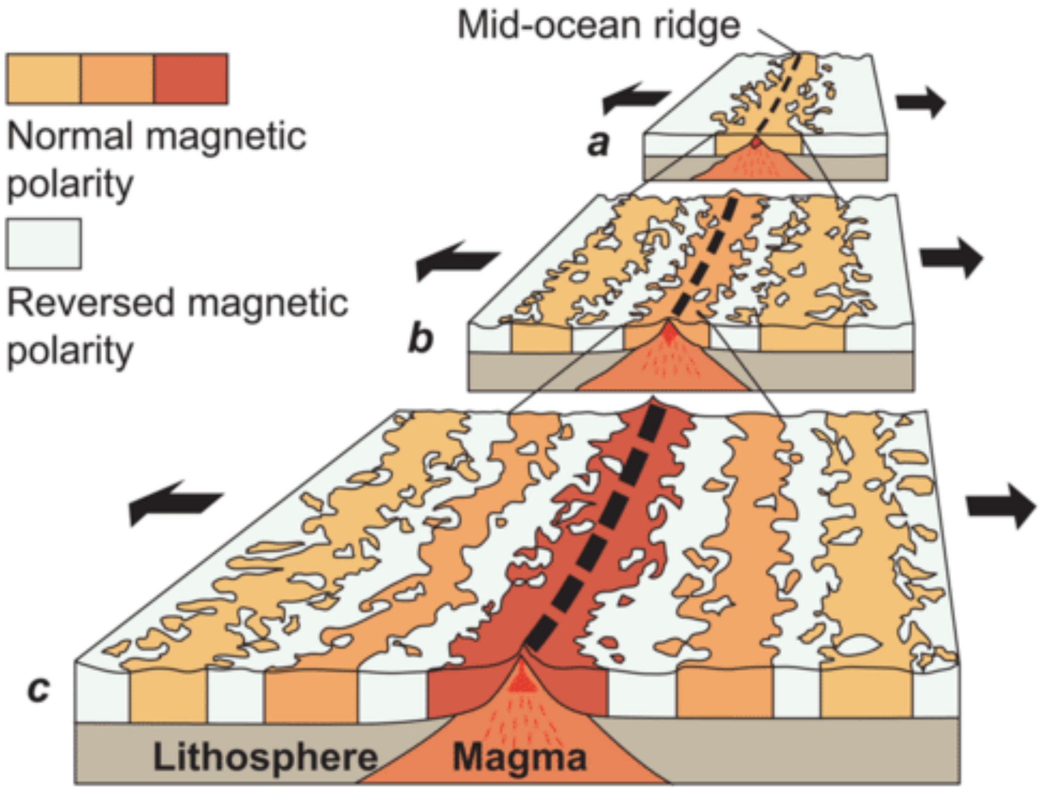
Secondary remanent magnetisations, such as chemical, viscous or post-depositional remanent magnetisations, may be acquired later on in the rock's history.

Magnetic polarity reversal

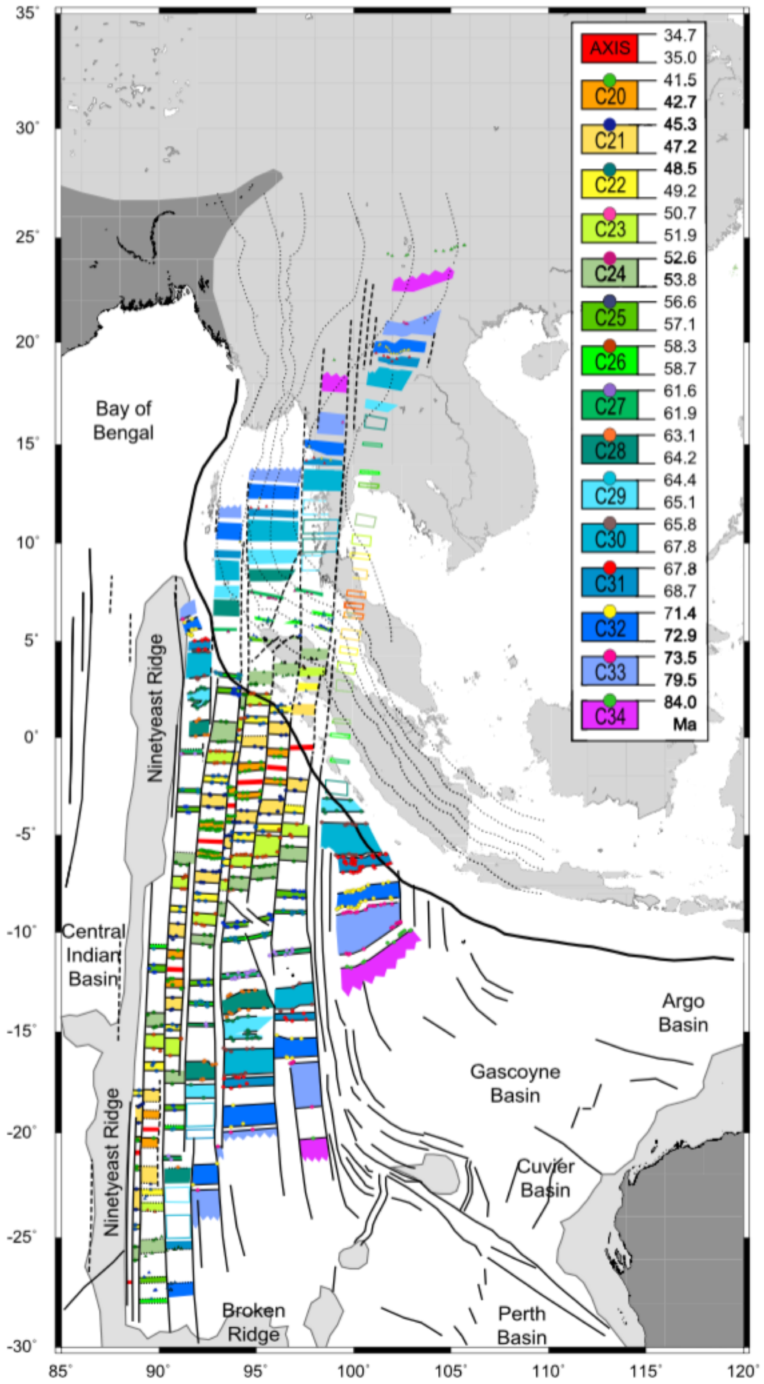
•Data from magnetometers dragged behind ships looking for enemy submarines in WWII discovered amazing magnetic patterns on the seafloor.

• Oceanic crust behaves like a magnetic tape.

• Rocks of normal and reversed polarity are found in stripes symmetrically about the mid-ocean ridge axis.



https://www.ck12.org/earth-science/Magnetic-Evidence-for-Seafloor-Spreading/lesson/Magnetic-Evidence-for-Seafloor-Spreading-HS-ES/

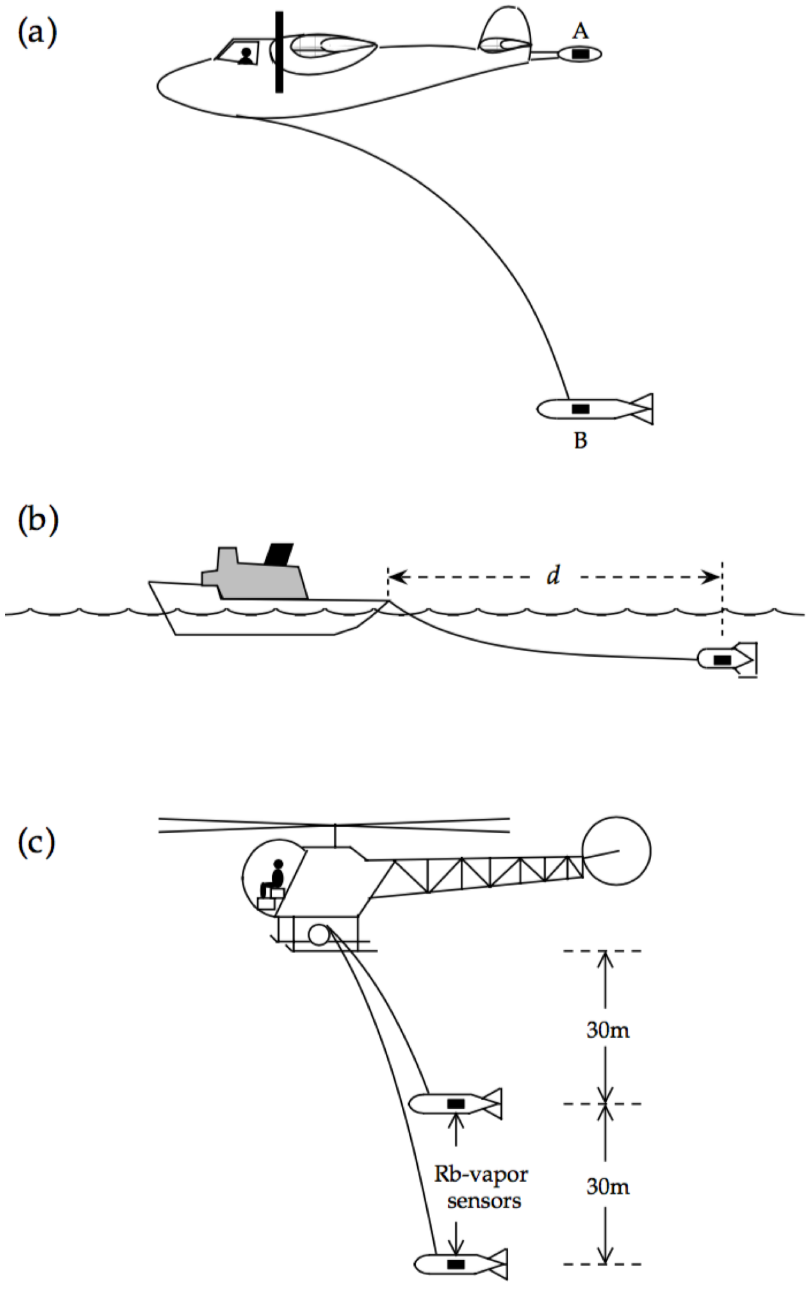


Subducted fossil spreading in Wharton basin In red

Jacob et al., 2013

Magnetic surveying

- Survey profiles should, where possible, be conducted across strike with tie-lines along strike
- In ground-based surveys, a local base station is required in an area away from suspected magnetic targets or magnetic noise and where the local field gradient is relatively flat.
- As the survey progresses, if a continuous-reading base-station magnetometer is used to measure the diurnal variation, it is still worth returning to base every 2–3 hours, just in case the base magnetometer fails.
- Regular checks on the recording of data are vital.
- For airborne survey, the larger the value of $h/\delta x$, the less aliasing will occur; a survey is considered reasonably designed if $h/\delta x \geq 0.5$.
- Correction should be applied as magnetic data often get contaminated by noise.
- <u>Magnetic sensors (Proton precession) should be kept away from any magnetic object like car, geological hammer, power lines, metal pipes, railway line and so on.</u>

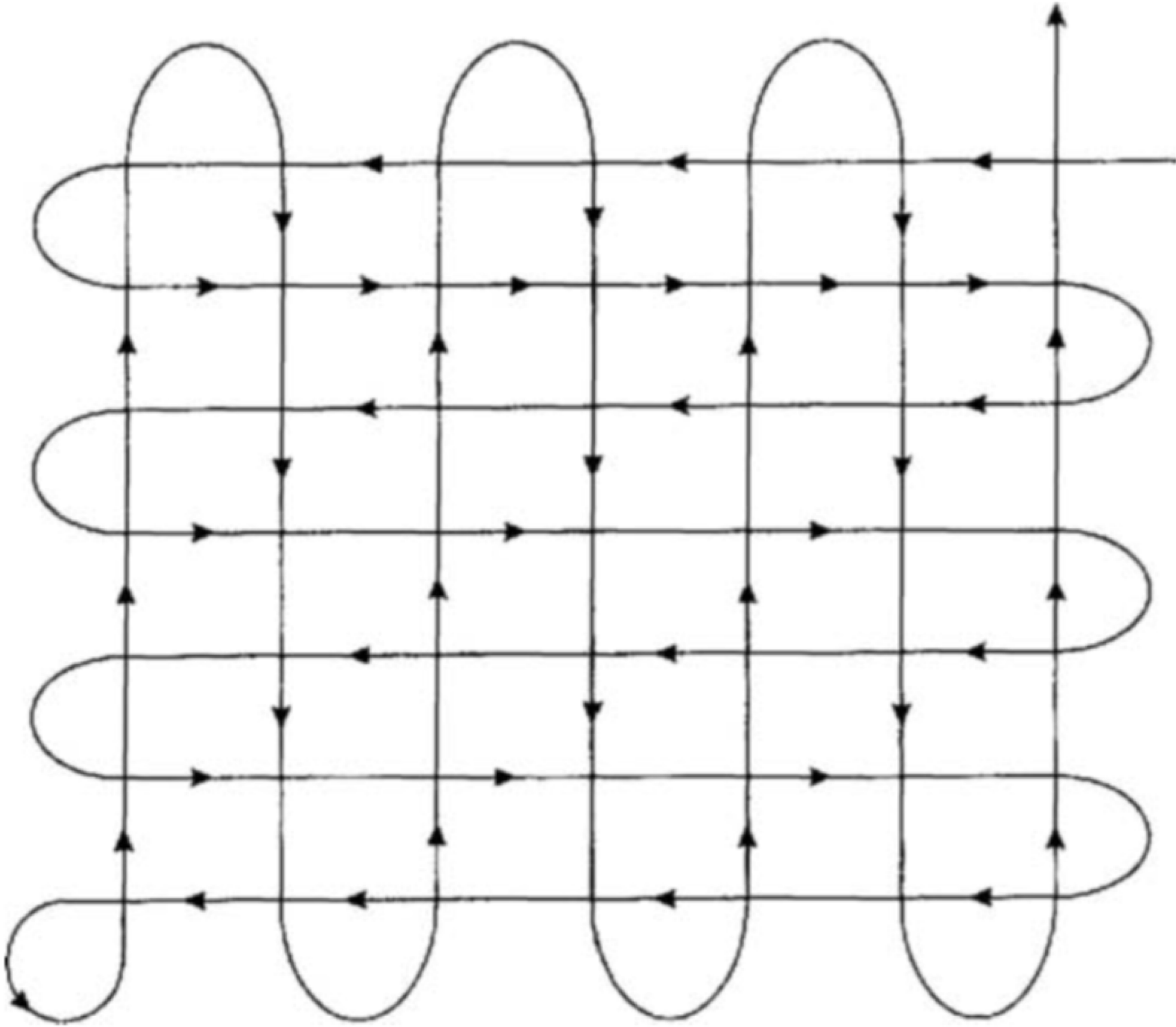


Aeromagnetic survey

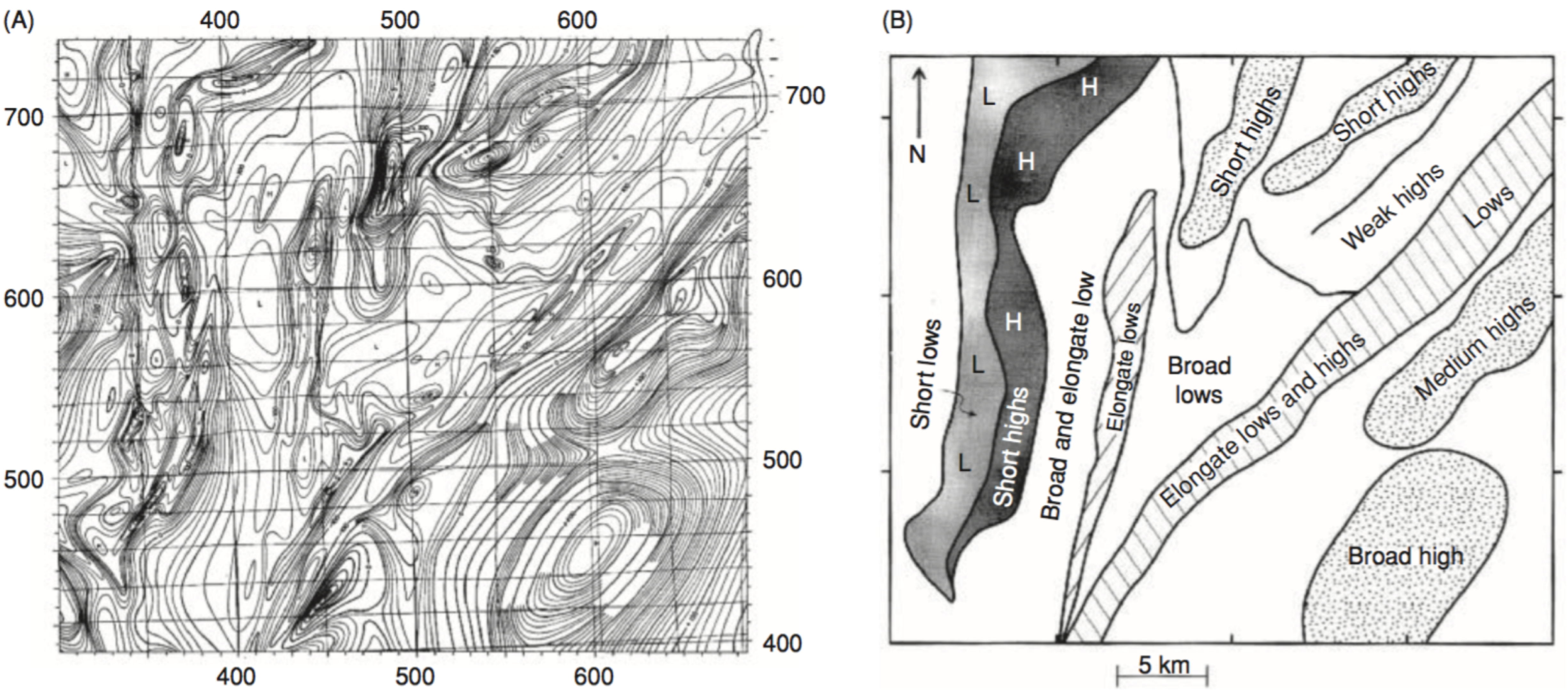
Alkali vapour magnetometer is used

Survey lines should intersects and the interval should not be kept very large to avoid spatial aliasing.

Very attractive method as it is cost effective and cover large area in very short period.

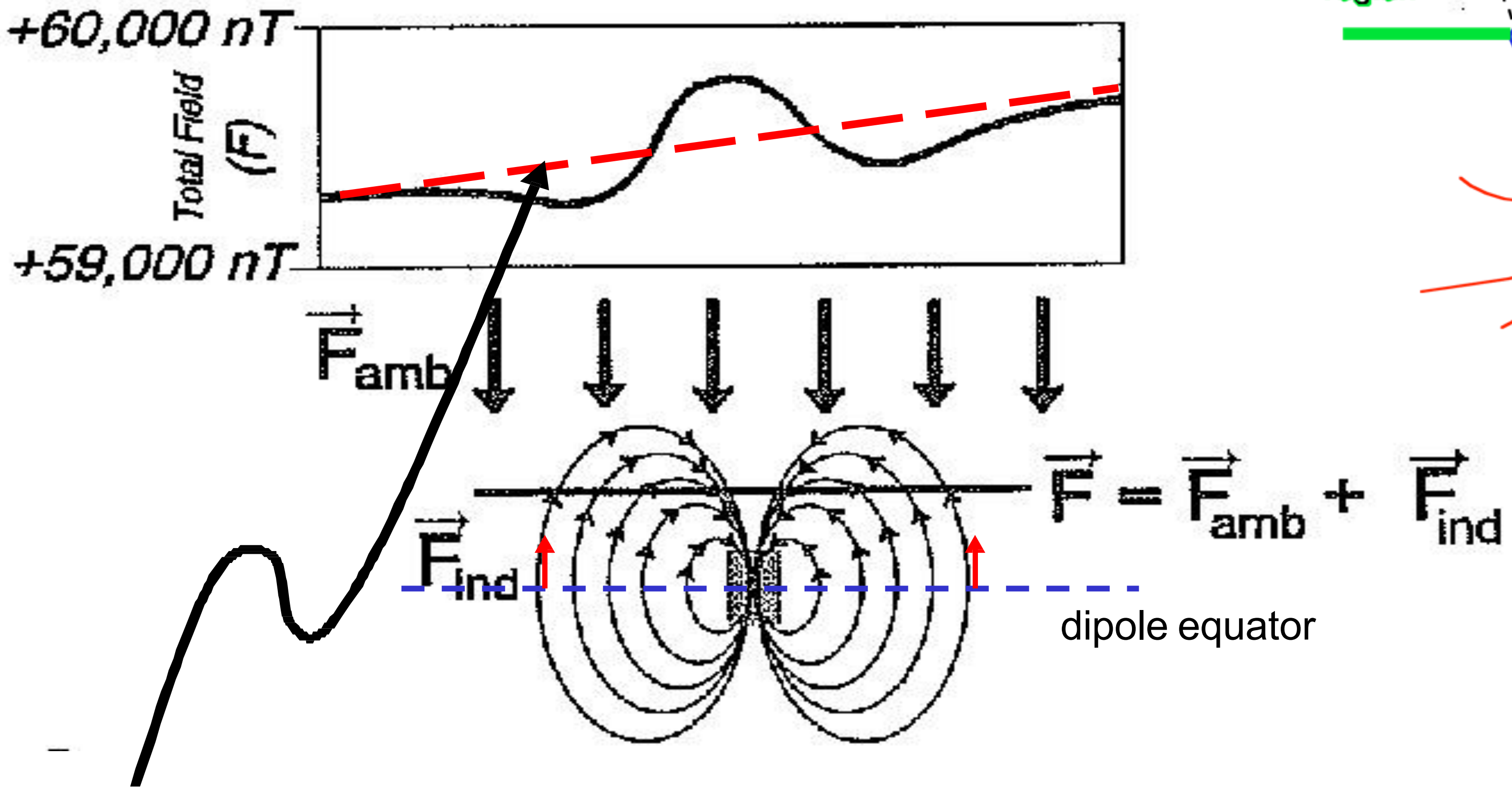


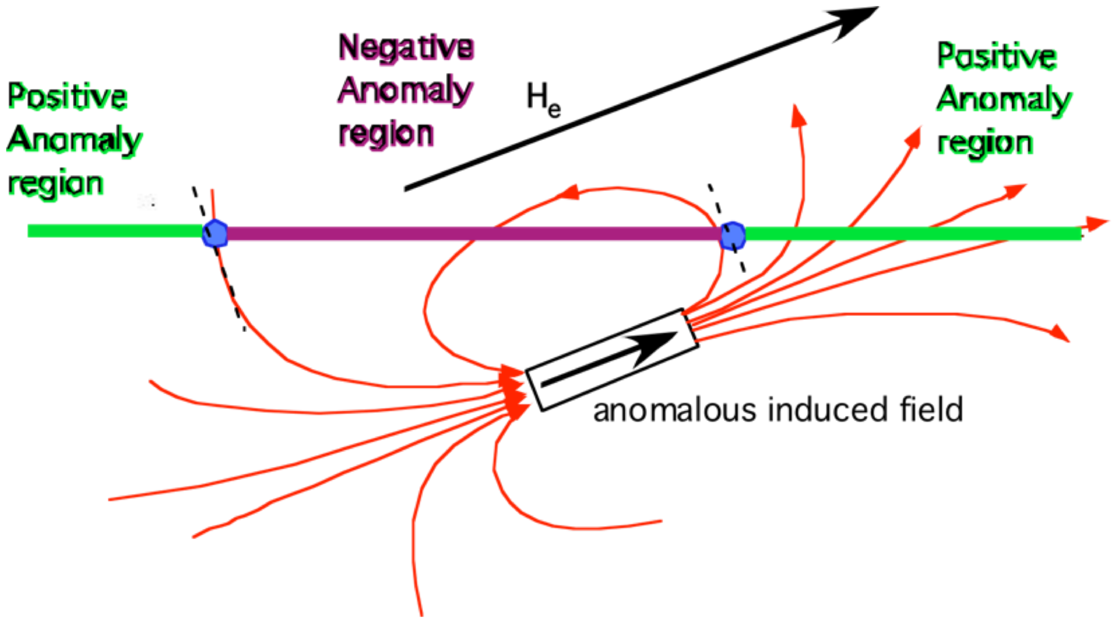
Example of aeromagnetic map



<u>Total field anomaly</u> : dependence on direction of ambient field

Magnetization induced by ambient field in a subsurface magnetic body can often be represented by a small dipole.
Note that at the magnetic equator of induced dipole, the induced field is <u>opposite</u> to the ambient field



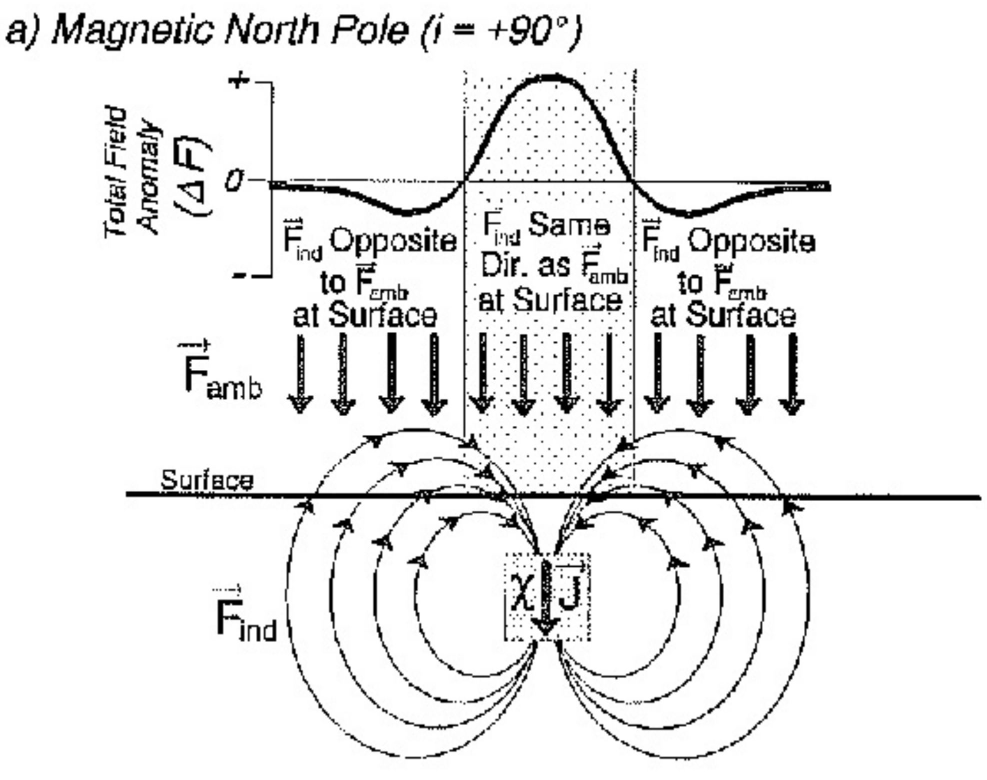


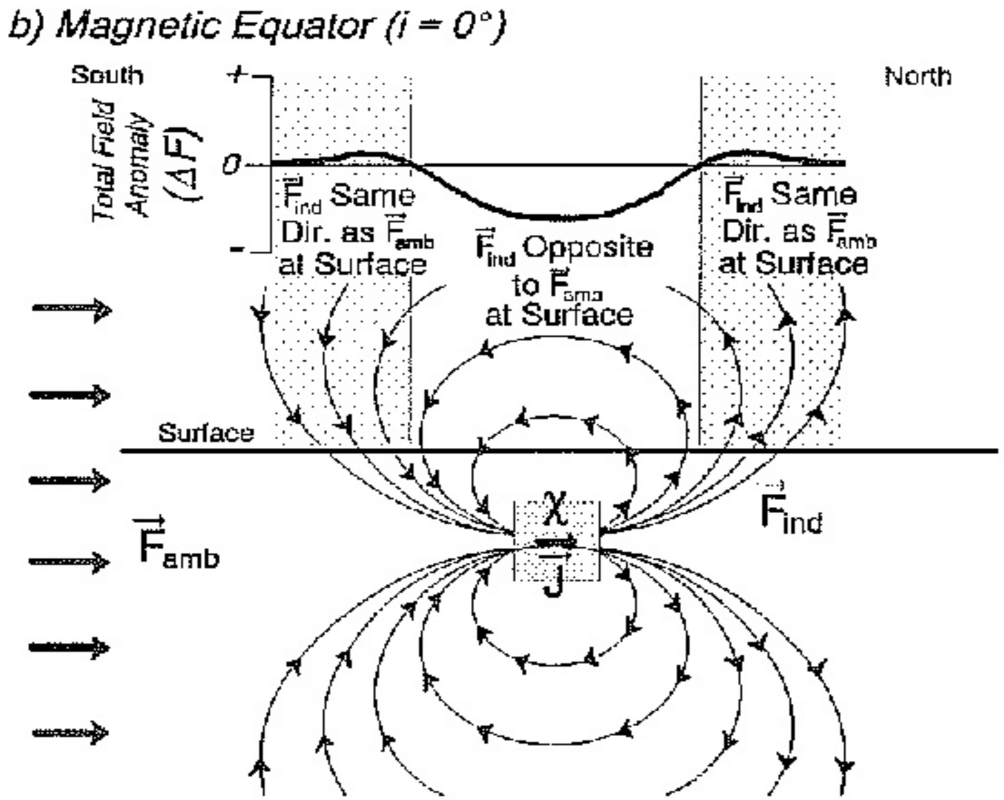
Variation of ΔF along a horizontal surface thus depends not only on magnetic susceptibility, but also on the direction of the ambient field.

ΔF positive : where induced field has a component in same direction as F_{amb}

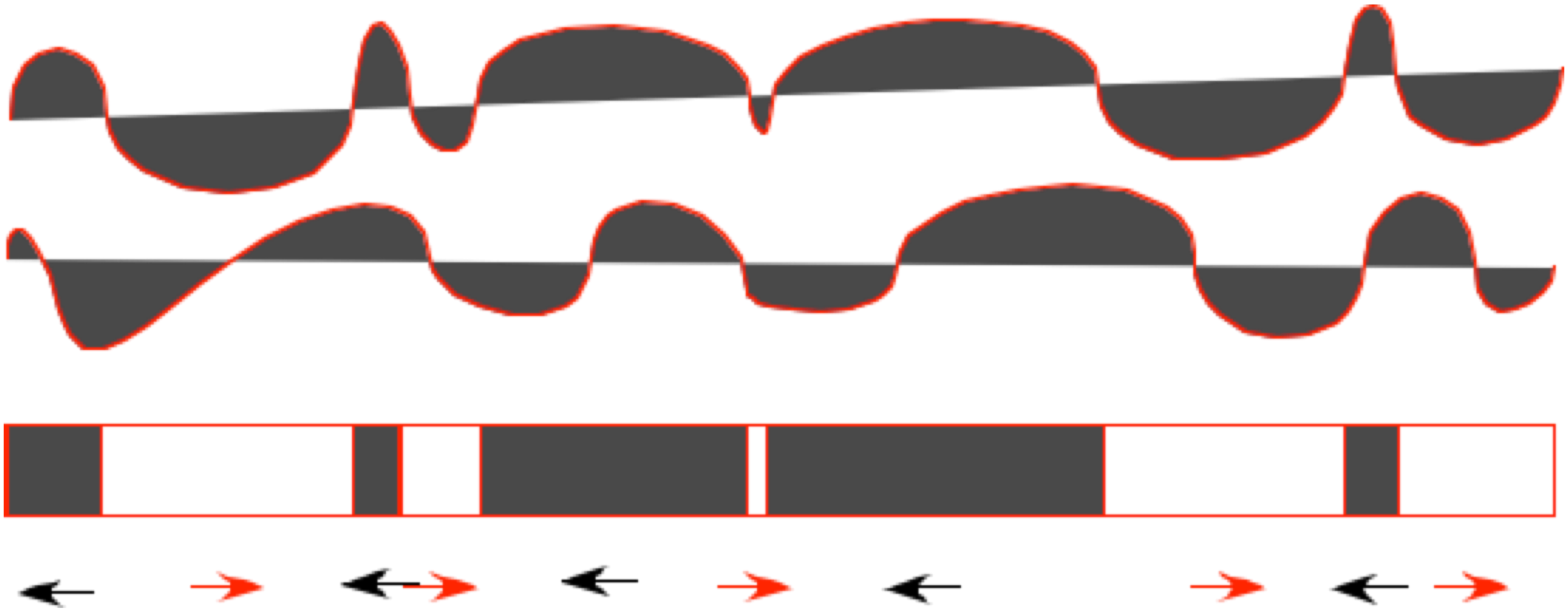
ΔF negative : where induced field has a component in opposite direction as F_{amb}

Thus, the same body will have quite a different magnetic signature when found near the equator, compared to its signature when located in more northerly regions.

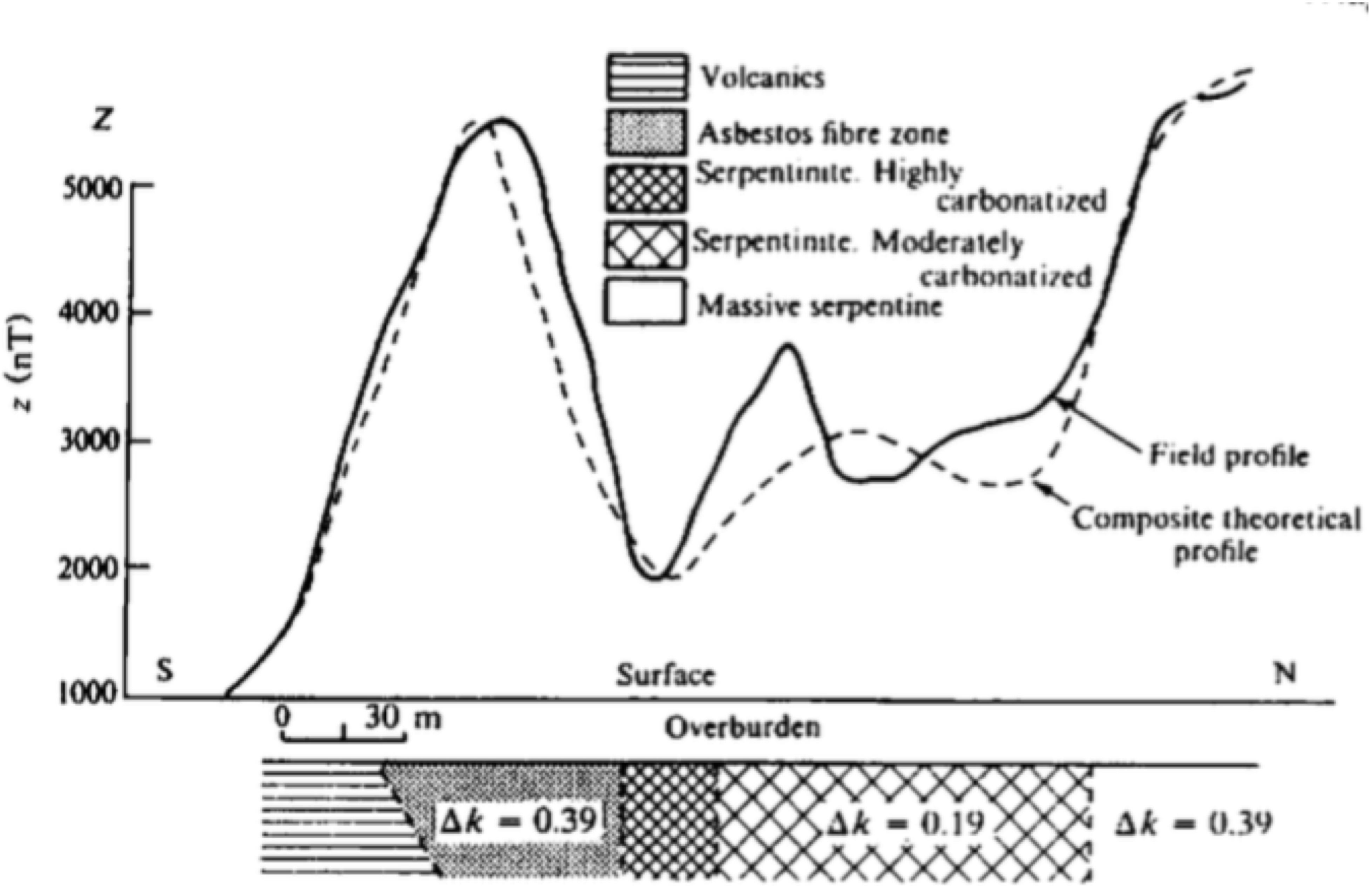




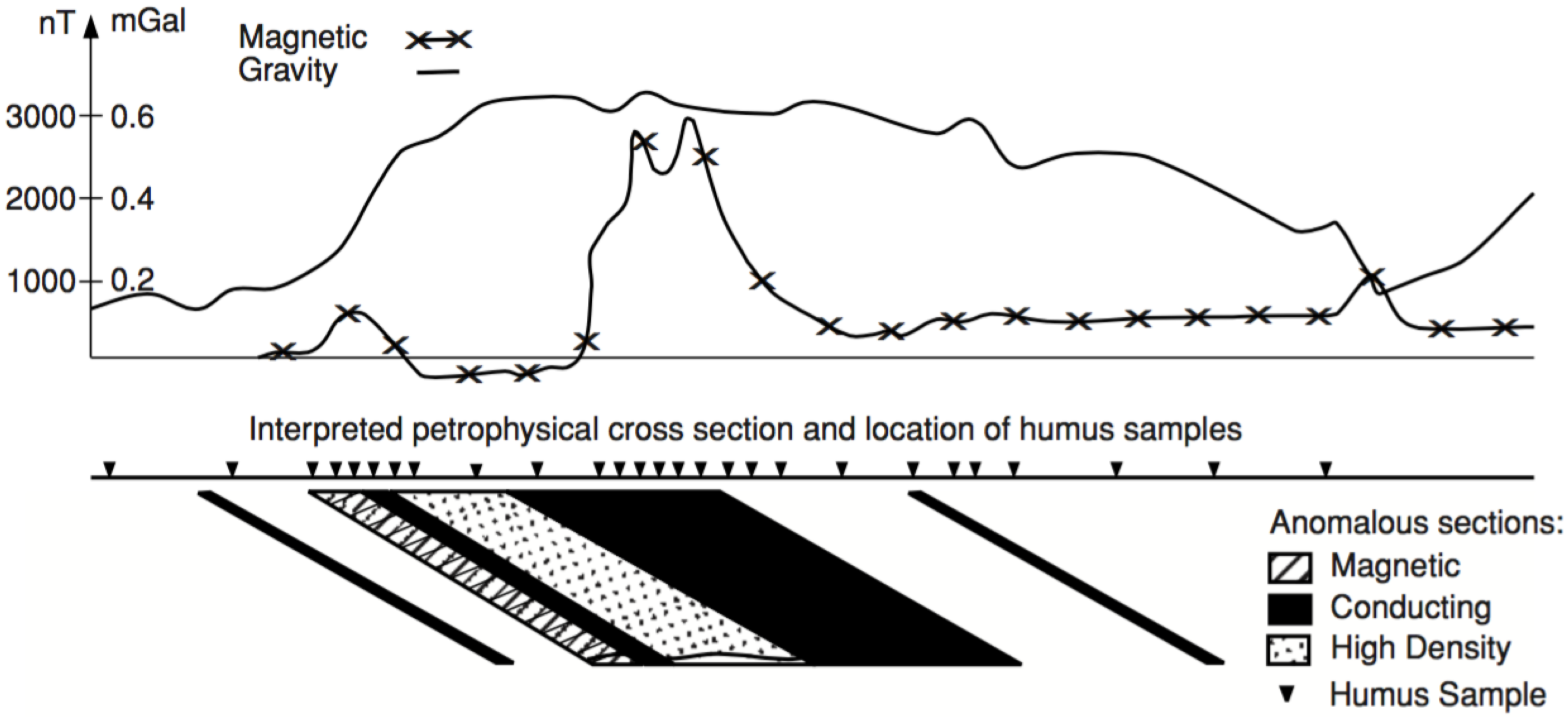
REDUCTION TO THE POLE: Because magnetic anomalies depend not only on the shape and orientation of the magnetic body in question, but on the magnetic latitude of the region, it is often desirable to apply a function that will change the anomalies so that they appear as though they were observed at the magnetic pole. In this way, skewed anomalies from symmetric bodies, become symmetric themselves.



Magnetic anomaly example



Gravity and magnetic comparisons



Magnetic survey interpretation

Magnetic anomalies are often very complex and difficult to interpret for the following reasons:

1) While we are usually after the shape and depth of an anomalous body, we also need to be concerned with

  the direction of the earth's field
  the strength of the earth's field
  the orientation of the body with respect to the earth's field

2) There are no unique answers:

  There are an infinite number of models that will satisfy the magnetic field, BUT the characteristics of the anomaly and constraints from other information can remove an infinite number of possibilities.

3) While we often assume that an anomaly is generated by induced magnetism, remanant magnetism can also contribute.

4) We also often assume that the susceptibility in a body is uniform, but that is also likely to be a poor assumption. Pockets of high susceptibility can greatly distort an anomaly.

USES:

Depth to basement/Ore bodies/Structural trends/Archeological surveys/Detection of voids/Well logging/Marine magnetics