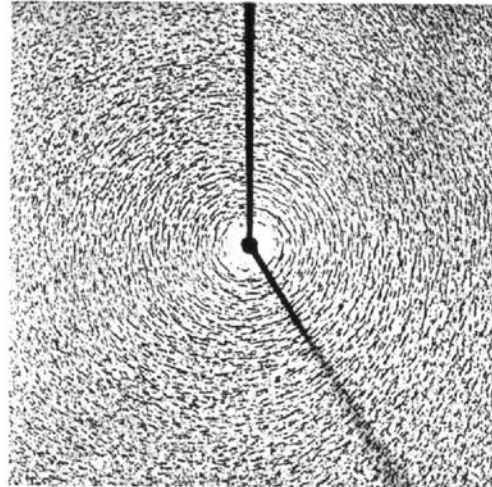
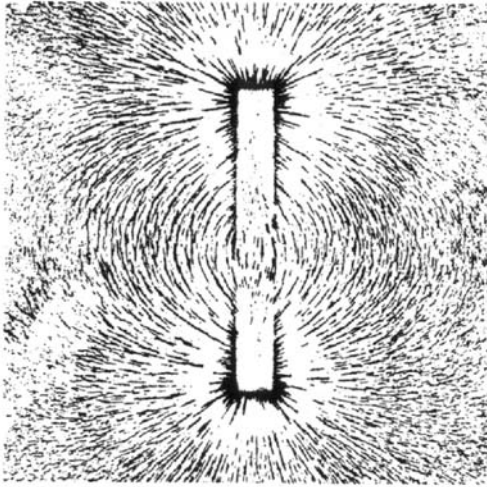


Section 3: Magnetism Surveying

Magnetic Fields

Magnetic fields exist around magnets and electric currents

- Iron filings spread above bar magnet or around wire carrying electric current experience a force that orients them in direction of magnetic field.



- Strength of magnetic force is represented by the concentration of field lines and is called **Magnetic Flux**
- Magnetic force is greatest near poles of a bar magnetic where flux is greatest

Magnetic Force

- Magnetic force is defined as force that would act on a unit positive pole placed in field:

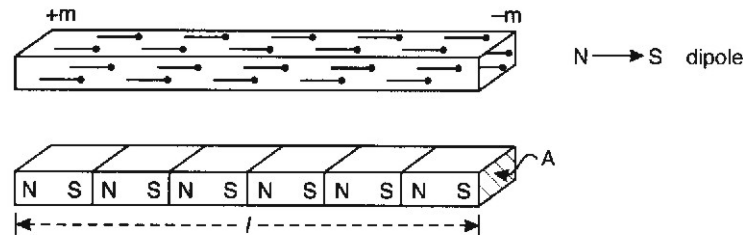
$$H = \frac{m}{4\pi\mu r^2}$$

where m is the strength of the magnetic pole creating the force, r is distance from the pole, and μ is permeability of medium.

- If m positive implies attraction, m negative is repulsion

Induced Magnetisation and Magnetic Susceptibility

An object placed in a magnetic field becomes magnetised as atoms are aligned by the external magnetic field



Atoms behave as bar magnets placed end to end, and create a net magnetic field inside and outside the object.

Intensity of Induced Magnetisation **J** (or Magnetic Polarisation)

In low magnetic fields, intensity of induced magnetisation **J** is proportional to the magnetising force **H**:

$$\mathbf{J} = \kappa \mathbf{H}$$

Constant of proportionality κ is called the **magnetic susceptibility**.

- Susceptibility is the fundamental rock parameter of magnetics prospecting.
- Different minerals have different magnetic susceptibilities
- Susceptibility of a rock depends on its constituent minerals.

Total Magnetic Field **B** (or Magnetic Flux Density)

We don't measure **H** directly. Rather we measure the magnetic flux density or total magnetic field **B**.

Inside an object, the total magnetic field is the sum of the external and internal components:

$$\mathbf{B} = \mu_0(\mathbf{H} + \mathbf{J}) = \mu_0(\mathbf{H} + \kappa \mathbf{H}) = \mu_r \mu_0 \mathbf{H} = \mu \mathbf{H}$$

where μ_0 is magnetic permeability of free space ($4\pi \times 10^{-7}$ H/m), μ_r is relative magnetic permeability, and μ is absolute magnetic permeability.

Clearly, $\kappa = \mu / \mu_0 - 1$

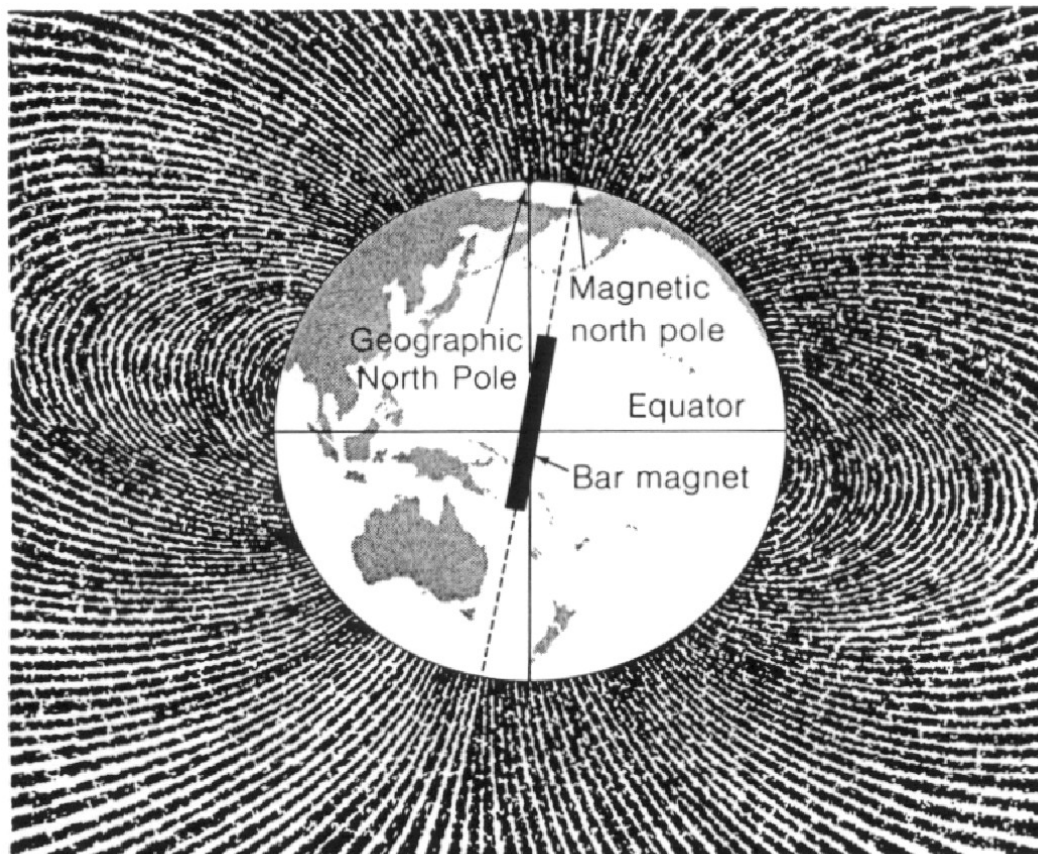
which represents the additional contribution to the magnetic field from the object.

- Magnitude of **B** represents “closeness” of field lines. Direction of **B** is along field lines.
- In SI system, units of magnetic field are volt. s /m² = Teslas (T)
- In c.g.s system, magnetic field measured in gauss or gamma
 $1 \gamma = 10^{-5}$ gauss = 1 nT.
- In geophysics, magnetic fields are small and measured in nT.

Earth's Dipole Field

Earth possesses a magnetic field whose strength varies from 20,000 to 60,000 nT.

Earth's magnetic field roughly appears as if it originates from a large bar magnet located at the centre of the Earth oriented at 11.5° to the axis of rotation.



- Suspended magnet aligns itself along the lines of Earth's magnetic field.
- [North-seeking \(positive\) pole](#) of magnet will point towards Earth's north pole.
- So Earth's north pole is same polarity as south pole of bar magnet!!!

Applications of Magnetism Surveying

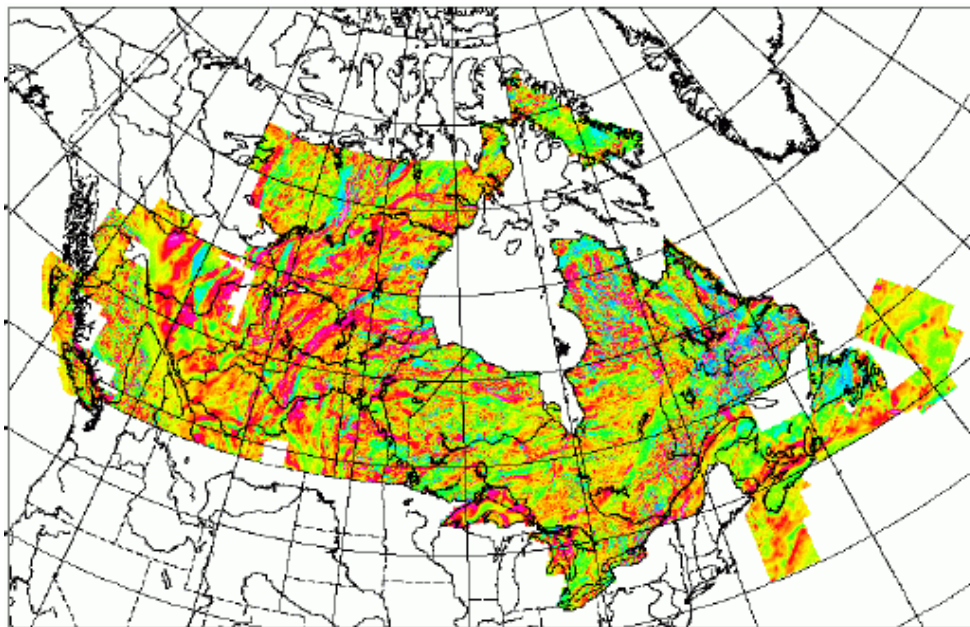
Objects placed in Earth's magnetic primary field, called the Core Field, produce their own induced magnetic fields

Magnetic surveys measure the magnitude and orientation of the Earth's total magnetic field: the core field plus contributions from induced fields in near-surface

Rocks or buried objects with a strong induced field due to high magnetic susceptibility, κ , stand out strongly in magnetic maps

Applications

- ❖ **Location of metal objects:** Pipes, cables, military ordnance.
- ❖ **Mineral Exploration:** Identification of metalliferous deposits, for example massive sulphides
- ❖ **Geological Bedrock Mapping:** Identification of faults and geological boundaries, especially beneath sediment cover.



Diamagnetism and Paramagnetism

- Atoms in a solid behave as small magnets due to orbiting electrons
- Unpaired electrons cause stronger magnetic behaviour
- In most materials, no overall magnetisation exists in absence of external field, because the magnetic moments of adjacent atoms are randomly distributed and cancel.

Diamagnetism

- ❖ In minerals such as **halite** and **quartz**, all electron shells are complete and no unpaired electrons exist.
- ❖ In an external magnetic field, electrons orbit to produce a very weak magnetic field that opposes applied field.
- ❖ Magnetic susceptibility is small and negative, e.g. -10×10^{-6}

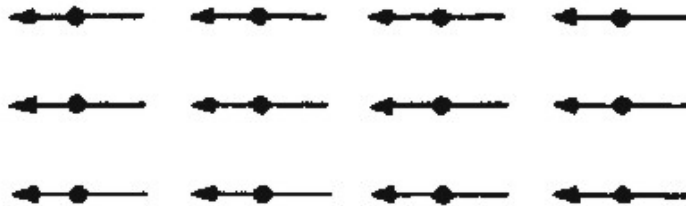
Paramagnetism

- ❖ In minerals such as **graphite** and **olivine**, unpaired produce weak magnetisation aligned with external field
- ❖ Magnetic susceptibility is weak and positive, but usually an order of magnitude stronger than in diamagnetic materials, e.g. 200×10^{-6}

Ferromagnetism

In metals such as **cobalt**, **nickel** and **iron**, unpaired electrons are coupled between adjacent atoms creating magnetic domains

- ❖ Magnetic domains are around 1 micron in size.
- ❖ Magnetic domains can be permanently reoriented to produce a permanent magnetic field in absence of external field.
- ❖ All are domains oriented in direction of external field, producing extremely large magnetic susceptibility, e.g. 10



External field oriented right to left

- ❖ Ferromagnetism disappears if material heated to Curie Temperature, T_C , as inter-atomic coupling restricted and domains cannot exist.
- ❖ Behaves as paramagnetic above Curie temperature.
- ❖ These native metals are almost never found in nature

Magnetic Domains

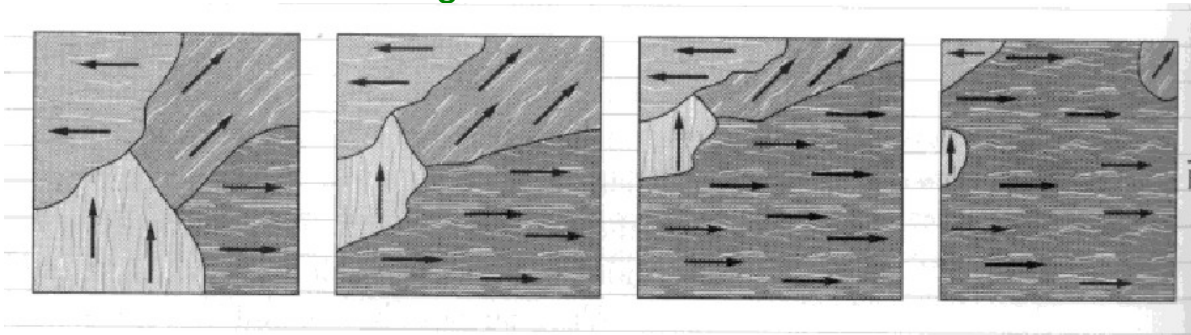
Unmagnetised Domains

- Each domain possesses a random magnetic field orientation.



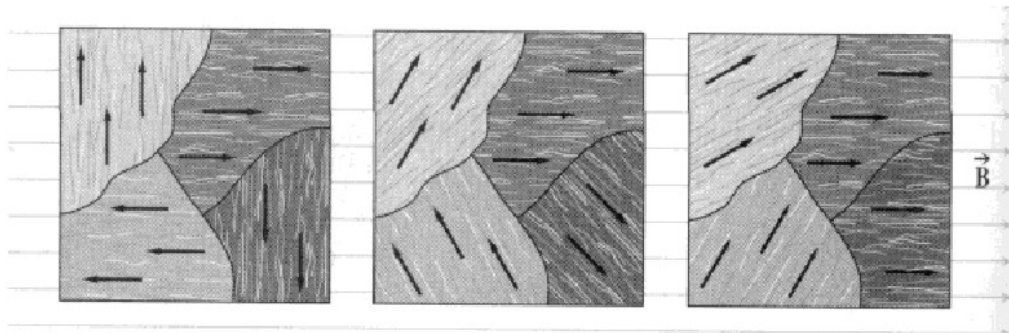
Induced Non-Permanent Ferromagnetism

- Some domains aligned with external field grow at expense of others as external magnetic field increases.



Induced Permanent Ferromagnetism

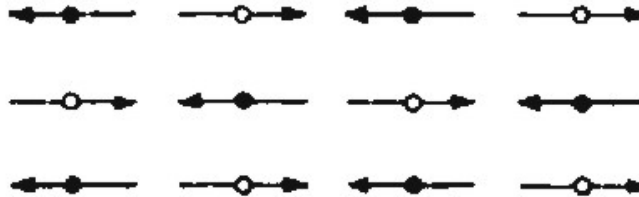
- Electrons in some domains rotate to align with external field as it increases.



Antiferromagnetism and Ferrimagnetism

Antiferromagnetism

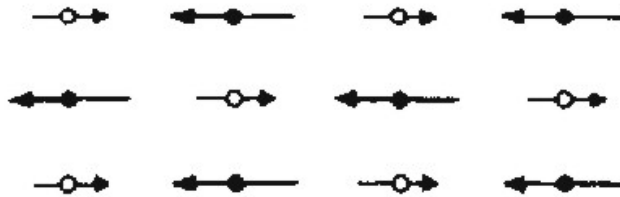
- ❖ In minerals such as **hematite** and **chromite**, magnetic domains form, but are aligned in antiparallel fashion.



- ❖ Magnetic fields cancel out, but crystal lattice defects cause small net field aligned with external field.
- ❖ Magnetic susceptibilities are large and positive, e.g. 7000×10^{-6}

Ferrimagnetism

- ❖ In minerals such as **magnetite**, **titanomagnetite**, and **ilmenite**, magnetic domains are antiparallel, but of unequal magnitude.



- ❖ Strong magnetisation that is aligned with external field.
- ❖ Magnetic susceptibilities are very large and positive, e.g. 6
- ❖ Domains can be permanently aligned, producing spontaneous magnetisation that exists after removal of external field.
- ❖ Ferrimagnetism disappears above Curie temperature.

Curie Temperature

Curie temperature is temperature at which mineral loses its ferromagnetic behaviour, and any permanent magnetisation is lost.

❖ Curie temperature varies with mineral:

Titanomagnetite	100-200° C
Titanomaghemite	150-450° C
Magnetite	550-580° C
Hematite	650-680° C

❖ Curie temperature is **below** melting point of rock.

❖ In rock such as granite, there will be multiple Curie temperatures for the different minerals present.

Low-Temperature Oxidation

❖ Oxidation at less than 300° C, tends to increase Curie temperature, as titanomagnetite oxidises towards hematite.

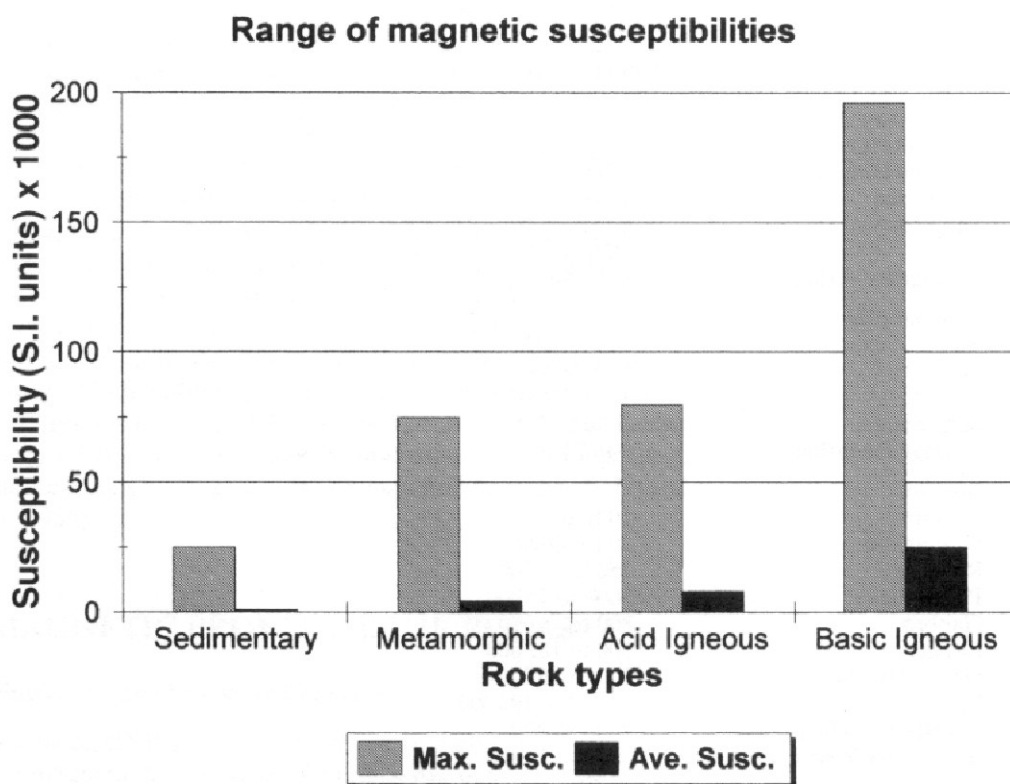
❖ Intensity of magnetisation also reduced.

❖ Oxidation can affect expected magnetic response of certain rocks.

Magnetic Susceptibilities of Rocks and Minerals

Rocks with significant concentrations of ferri/ferro-magnetic minerals have highest susceptibilities:

		$\times 10^{-6}$
Ultramafic rocks	highest	95,000 – 200,000
Mafic rocks	high	550 – 122,000
Felsic rocks	low	40-52,000
Metamorphic	low	0-73,000
Sedimentary	very low	0-360



Measured Values of Magnetic Susceptibility

Mineral or rock type	Susceptibility*
<i>Sedimentary</i>	
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
<i>Metamorphic</i>	
Schist	315 to 3000
Slate	0 to 38 000
Gneiss	125 to 25 000
Serpentine	3100 to 75 000
Average for various	0 to 73 000
<i>Igneous</i>	
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
<i>Minerals</i>	
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
Ilmenite (o)	314 000 to 3.8×10^6
Magnetite (o)	70 000 to 2×10^7

(d) = diamagnetic material; (o) = ore; (m) = with magnetic
 * $\kappa \times 10^6$ rationalised SI units; to convert to the unrationalised c.g.s. units, divide by 4π

Data from Parasnis (1986), Sharma (1986), Telford *et al.* (1990)

Primary Remnant Magnetisation

Rocks can become permanently magnetised in the Earth's magnetic field as they are formed

Remnant magnetisation is preserved if a rock is not heated above its Curie temperature, allowing past plate motions to be identified

Thermal Remnant Magnetisation (TRM)

- ❖ TRM acquired when a solid rock cools through the Curie temperature, e.g. cooling of pillow basalt at midocean ridge
- ❖ At Curie temperature, ferro/ferri-magnetic minerals become magnetised in direction of Earth's magnetic field **at that time**.
- ❖ TRM usually greater than induced magnetisation from present day field.

Detrital Remnant Magnetisation (DRM)

- ❖ DRM acquired when fine magnetic particles settle during formation of sedimentary rock, e.g. formation of clays
- ❖ Settling particles are oriented by Earth's magnetic field **at that time**.
- ❖ DRM << TRM

Secondary Remnant Magnetisation

Secondary remnant magnetisation is magnetisation acquired later in a rock's history by alteration processes.

Chemical Remnant Magnetisation (CRM)

- ❖ CRM acquired in situ when magnetic minerals grow or are chemically altered to another form below Curie temperature, e.g. growth of iron oxide in sandstone.
- ❖ Most common in sedimentary and metamorphic rocks.

Viscous Remnant Magnetisation (VRM)

- ❖ VRM produced by long exposure to ambient field in uniform environment.
- ❖ Buildup of VRM logarithmic with time.

Induced and Remnant Magnetisation

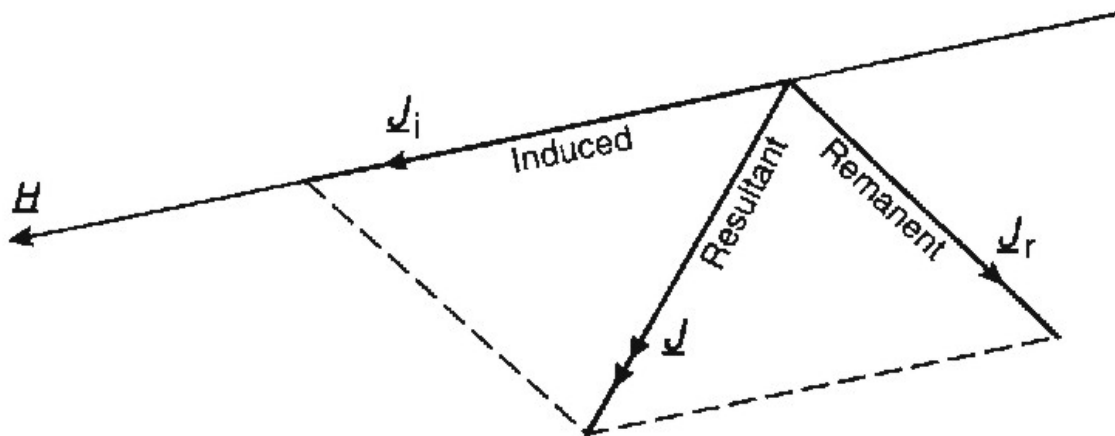
Induced Magnetisation

Induced Magnetisation $\mathbf{J}_i$ is produced within a rock in response to present day core field of the Earth.

Remnant Magnetisation

Magnetic field may exist within rock even in absence of external field due to permanently magnetised particles. This is remnant or permanent magnetisation.

Interpretation of magnetic data complicated as magnetic field due to a subsurface body results from combined effect of two vector magnetisations that may have different magnitudes and directions.



Königsberger Ratio

Remnant magnetisation may be much greater than that induced by Earth's field today, e.g. with TRM.

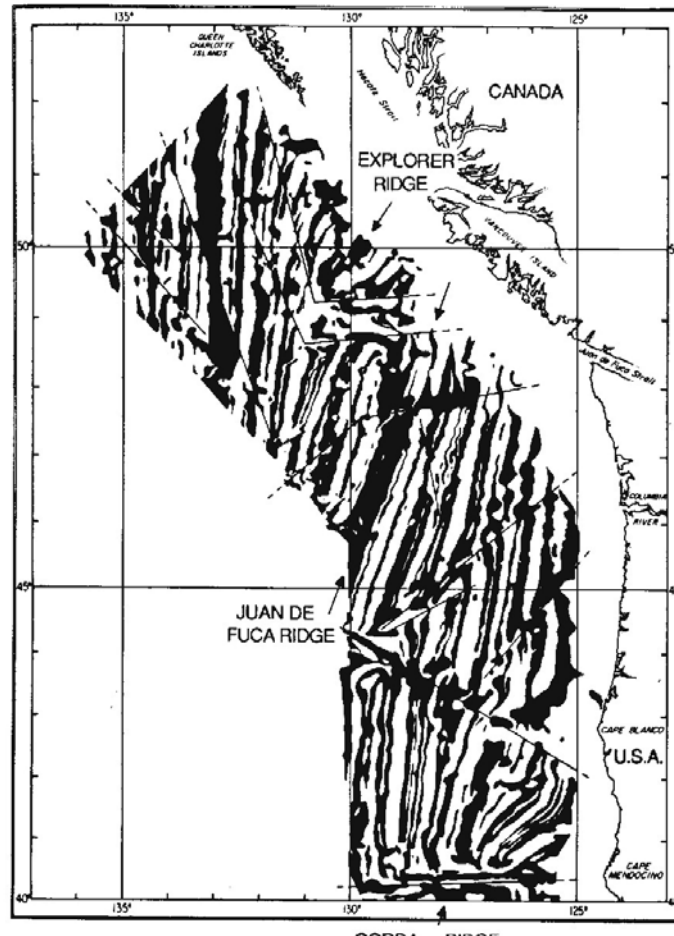
Königsberger Ratio Q is measure of ratio of intensity of remnant to induced magnetisation:

$$Q = \frac{J_r}{J_i}$$

- ❖ $Q \sim 30-50$ for rapidly quenched volcanic rocks, e.g. pillow basalts
- ❖ $Q \sim 10$ for volcanic rocks in general
- ❖ $Q \sim 1$ for slowly crystallised igneous and thermally metamorphosed continental rocks
- ❖ $Q < 1$ in sedimentary and metamorphic rocks when iron minerals not present

Magnetic Striping of the Ocean Floor

Magnetic anomaly map from west coast of N. America shows positive (black) and negative (white) values

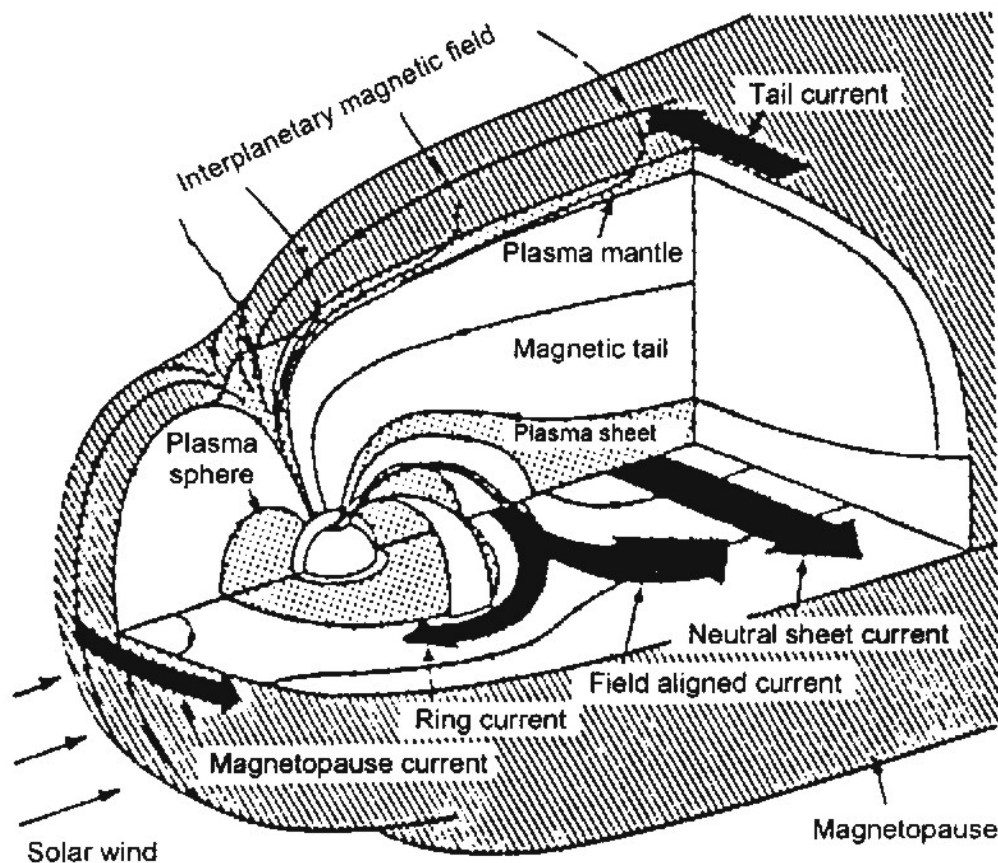


- Magnetic striping is typical of oceanic basins
- Stripes run parallel to and are usually symmetric about ocean ridges, but offset by fracture zones, transform faults between ridge spreading segments
- Stripes are ± 500 nT in magnitude, and a few 10s km in width

Earth's Distant Magnetic Field

Near the Earth's surface: magnetic field originates largely from currents flowing in the liquid outer core, and the magnetisation of surface rocks.

Away from the surface: magnetic field is affected by currents caused by the movement of charged particles associated with Van Allen radiation belts.



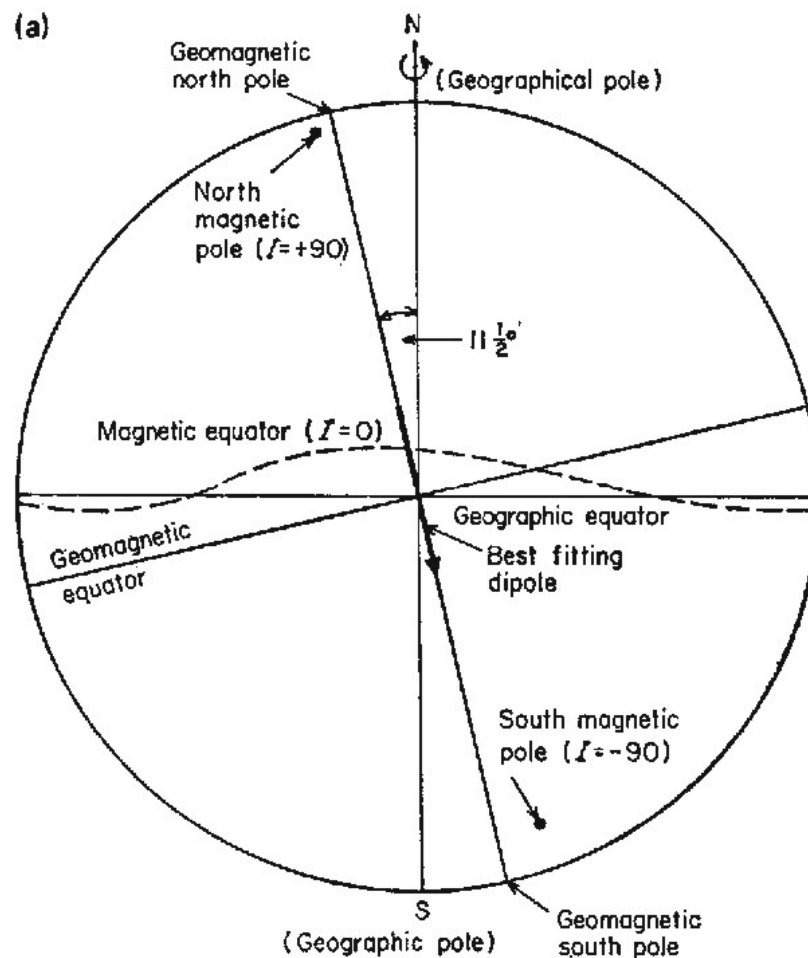
Some of these charged particles are responsible for the Aurora Borealis near the poles.

At great distance: the magnetic field is due to charged particles from the sun, the solar wind.

Earth's Magnetic Field

Geomagnetic Pole: the position on Earth's surface intersected by the axis of the dipole that fits best the Earth's magnetic field.

- ❖ **North:** Hayes Peninsula in northern Greenland
- ❖ **South:** Vostock research station in Antarctica



Magnetic Pole (or Dip Pole): the position where the magnetic field is vertical

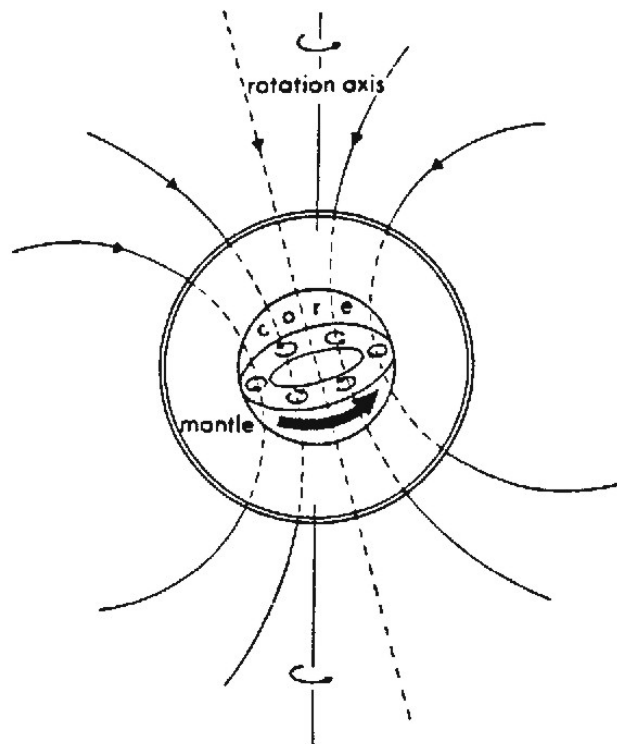
- ❖ **North:** North of Bathurst Island in Canadian Arctic
- ❖ **South:** 150 km offshore off Adelie coast of Antarctica

Geomagnetic and Magnetic Poles differ slightly because Earth's magnetic field is not quite a dipole.

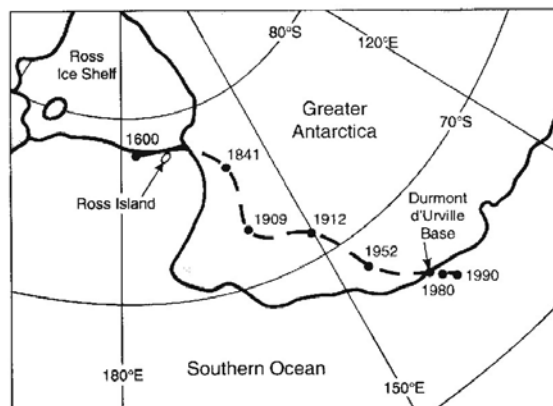
Generation of Earth's Core Magnetic Field

Exact mechanism responsible for generation of Earth's magnetic field is not known, but known to occur in Earth's liquid iron outer core

Slow convection within liquid outer core produces electrical eddy currents, which generate the magnetic field

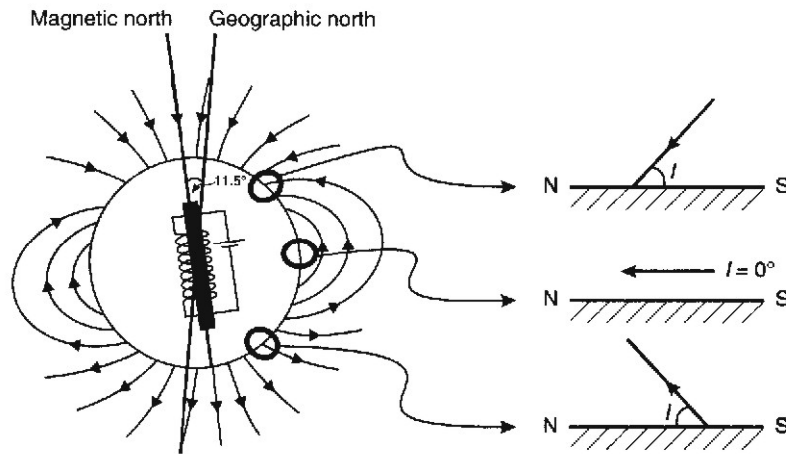


Secular Variation: Earth's magnetic field is slowly changing due to core processes, e.g. migration of magnetic south pole

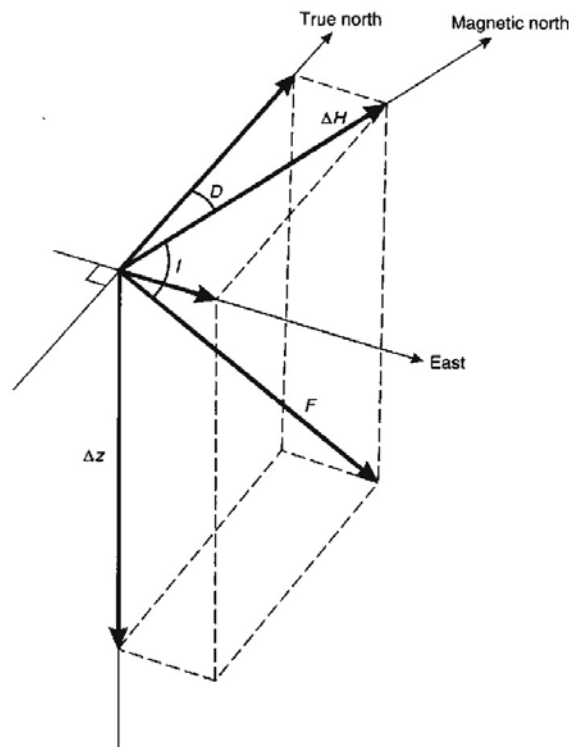


Description of Earth's Magnetic Field

A compass needle free to move in 3-D will point along the magnetic field, i.e. it will point down where field points into Earth.



Geomagnetic field can be described by the declination D , the inclination I , and total field vector F .



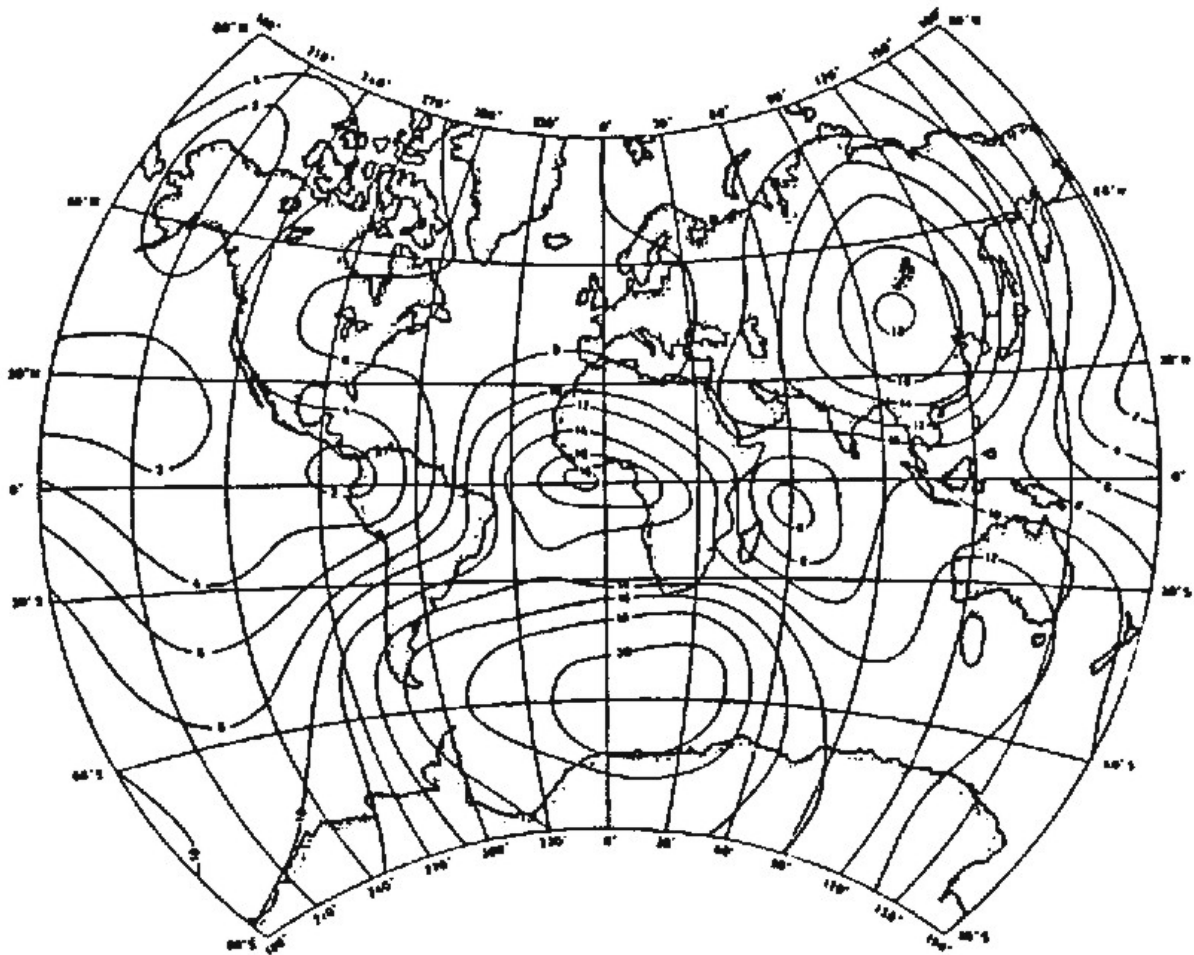
Can calculate magnetic latitude, λ , from inclination:

$$\tan I = 2 \tan \lambda$$

Earth's Non-Dipolar Field

90% of Earth's magnetic field can be represented by a dipole.

Difference between the actual magnetic field and that of the best-fitting dipole is called the **non-dipolar field**, i.e. Earth's field minus the contribution from the "bar magnet"



Features with magnitudes of 20,000 nT extending for 1000s km exist in the non-dipolar field

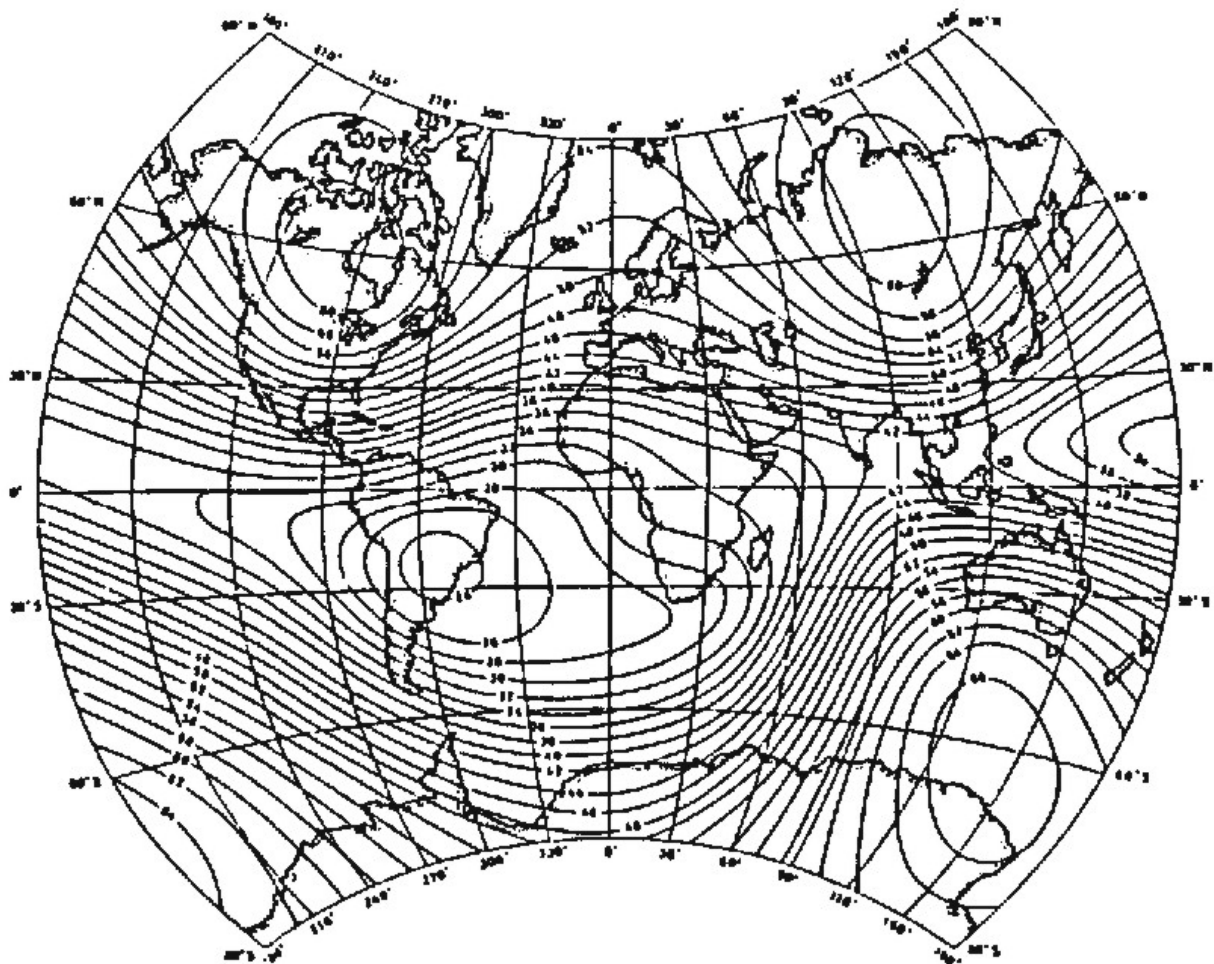
Non-dipolar field can be represented as 8-12 small dipoles oriented radially close to liquid core, simulates core eddy currents.

International Geomagnetic Reference Field

Geomagnetic field can be represented mathematically, and international standard is called [International Geomagnetic Reference Field \(IGRF\)](#).

Total field is recalculated every 5 years because of secular variation. Year of calculation is called the [epoch](#).

Total field intensity of the IGRF epoch 1980:



- ❖ A true dipole field would have two maxima, but Earth's magnetic field actually has four.
- ❖ IGRF excludes effects of near-surface rocks.

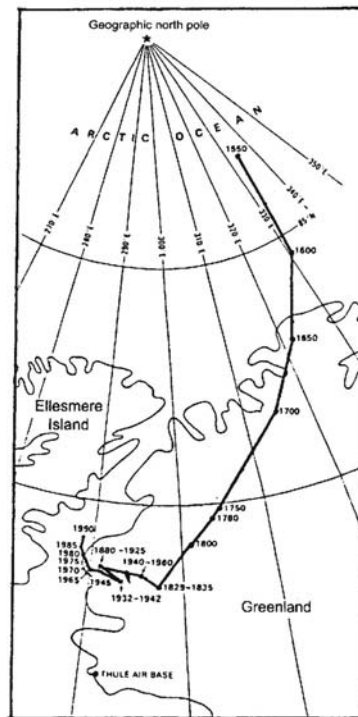
Variations in Earth's Magnetic Field

Geomagnetic Reversals

Earth's magnetic field flips polarity unpredictably on geological time scale due to sudden changes in fluid motions in core.

Secular Variations

- ❖ Observations of Earth's magnetic field made over 400 years show a gradual change in position of the magnetic pole.



- ❖ Due to slow movement of eddy currents in Earth's core.

Diurnal Variations

- ❖ Daily changes in field due to changes in currents of charged particles in ionosphere.
- ❖ Changes are smooth and average around 50 nT.

Magnetic Storms

- ❖ Short term disturbances in magnetic field associated with sun spot activity and streams of charged particles from sun.
- ❖ Can be up to 1000 nT in magnitude, and make magnetic surveying impossible.

Torsion and Balance Magnetometers (Obsolete)

Magnetometers measure the **total magnetic field** F_T or the **horizontal and/or vertical components of magnetic field**, F_H and F_Z respectively.

First magnetometers devised in 1640 essentially comprised:

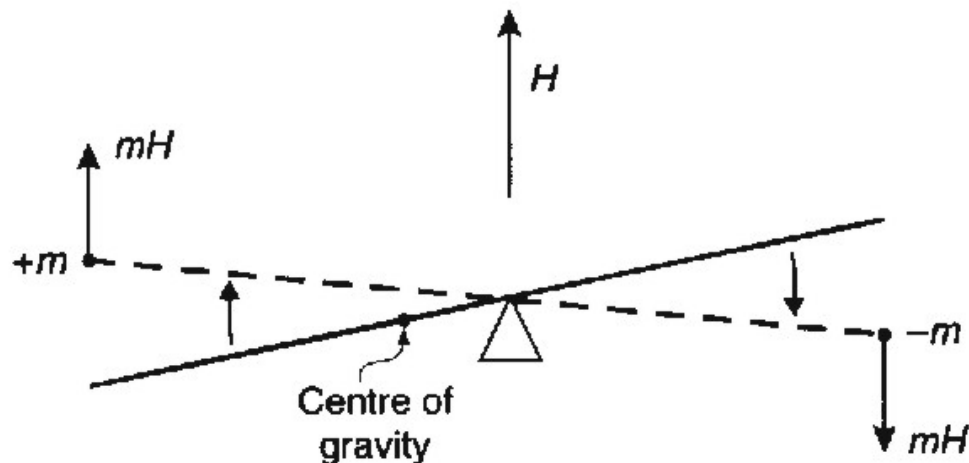
- ❖ a magnetic needle suspended on a wire (**Torsion type**), or
- ❖ a magnetic needle balanced on a pivot (**Balance type**)

Needle oriented in direction of magnetic field at station location.

Adolf Schmidt Variometer

Magnetic beam asymmetrically balanced on a knife edge, and zeroed at base station.

- ❖ Different magnetic field at another station caused displacement of beam, which was measured using collimating telescope.



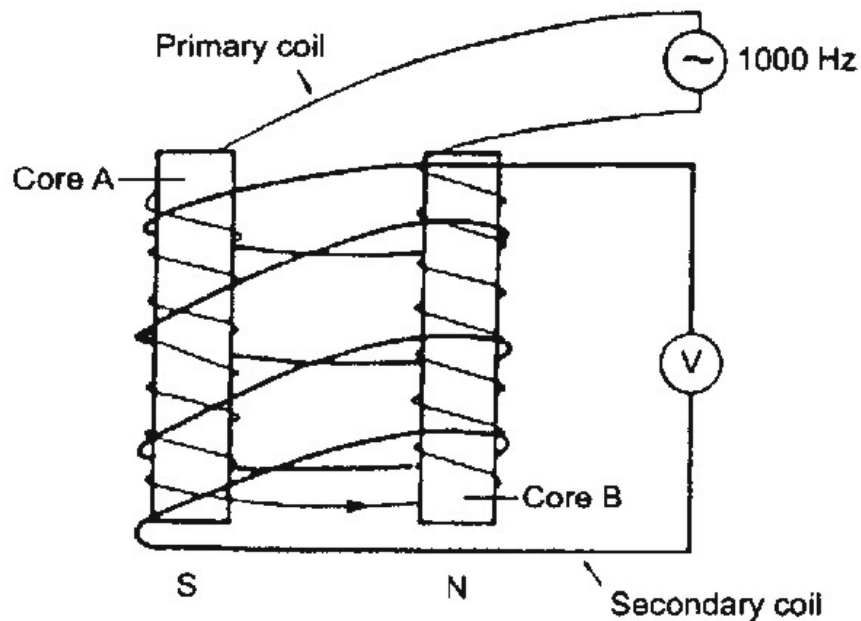
- ❖ Had to be oriented perpendicular to magnetic meridian to remove horizontal component of Earth's field. (Use compass?)
- ❖ Calibrated to read vertical magnetic field component.

Fluxgate Magnetometer

Measures component of magnetic field parallel to cores with accuracy of 1-10 nT.

Comprises two parallel cores of high μ ferromagnetic material.

Primary coil wound on two cores in series in opposite directions. Secondary coils also wound, but in opposite direction to primary.

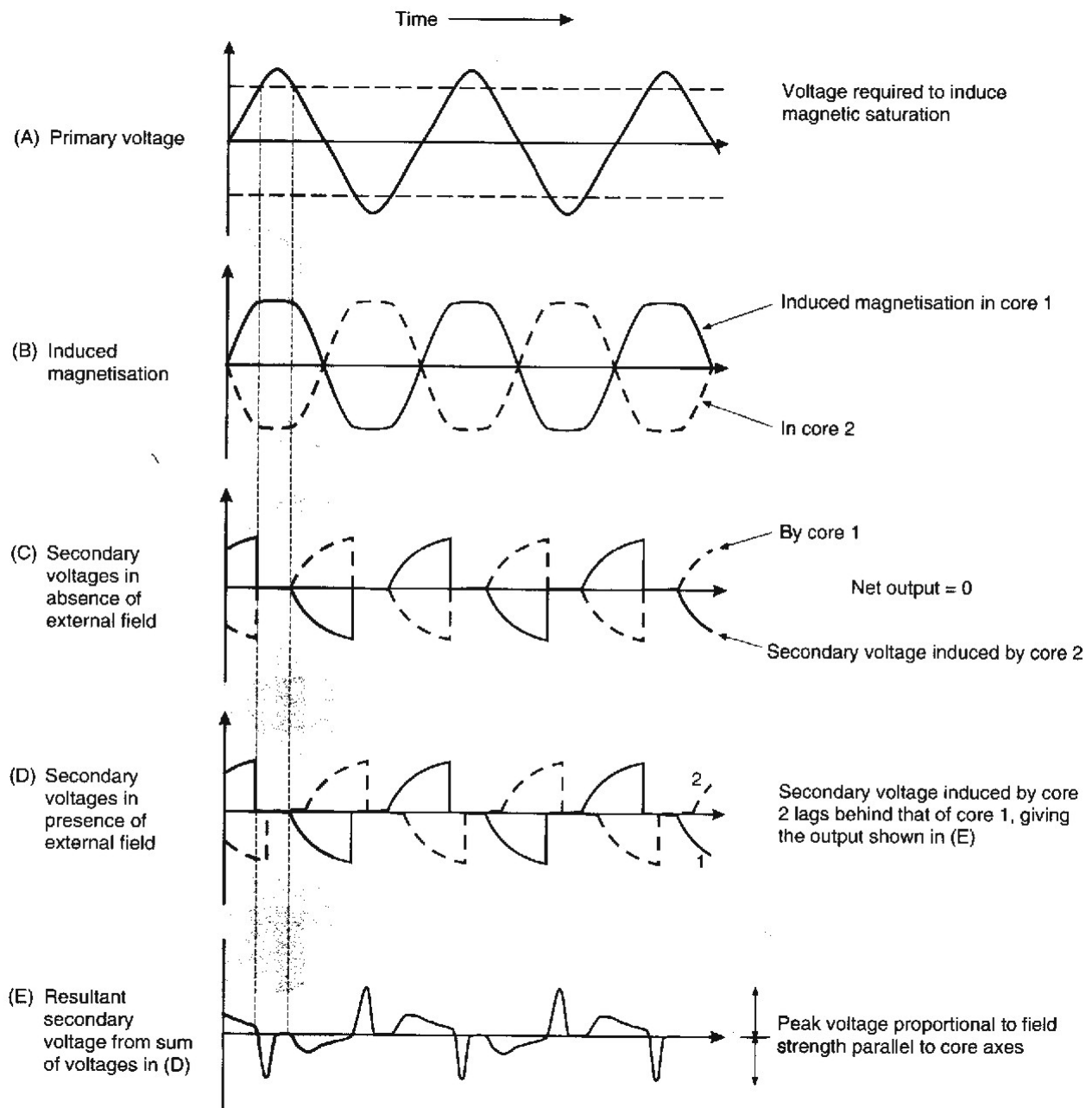


Operation of Fluxgate Magnetometer

- ❖ An alternating current at 50-1000 Hz is passed through primary coils, producing magnetic field that drives each core to saturation through a magnetisation hysteresis loop.
- ❖ With no external magnetic field, cores saturate every half cycle.
- ❖ Voltages induced in secondary coils have opposite polarity as coils wound in opposite directions. So zero net voltage.
- ❖ In Earth's magnetic field, component of field parallel to cores causes one core to saturate before the other, and voltages in secondary coils do not cancel.

Principle of Operation of Fluxgate Magnetometer

- ❖ Principle behind operation is **Faraday's Law of Induction** (twice)
- ❖ Voltage induced in secondary coil proportional to magnetic field generated in ferromagnetic core.
- ❖ When core saturated, magnetic field does not change, and no voltage is induced in secondary coil.



Proton Precession Magnetometer

Uses sensor consisting of bottle of proton-rich liquid, usually water or kerosene, wrapped with wire coil.

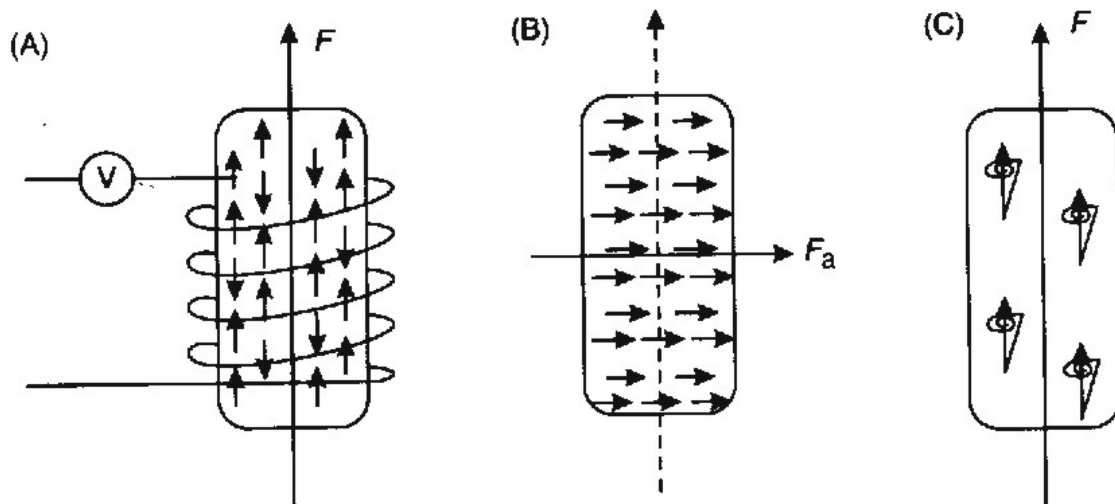
Two sensors indicates a gradiometer



- ❖ Protons have a net magnetic moment, and so are oriented by Earth's magnetic field or an applied field.
- ❖ Measures precession as protons reorient to Earth's field.
- ❖ Precession frequency proportional to total field strength.
- ❖ As sensor bottle 15 cm long, accuracy of measurement is reduced in areas of high magnetic field gradient.
- ❖ Measures total field strength, so instrument orientation not important, unlike fluxgate.
- ❖ Overhauser Effect adds electron-rich fluid to enhance polarisation effect, and increase accuracy.

Principle of Operation of Proton Magnetometer

A) In ambient field, majority of protons aligned parallel to field, remainder antiparallel.



B) Current in coil generates strong magnetic field at right angles to Earth's field, causing all protons to align.

C) When current turned off protons precess back to orientation of Earth's field.

- ❖ Protons are charged particles, and create magnetic field, which alternates as proton precesses.
- ❖ Current induces alternating voltage in coil at precession frequency.

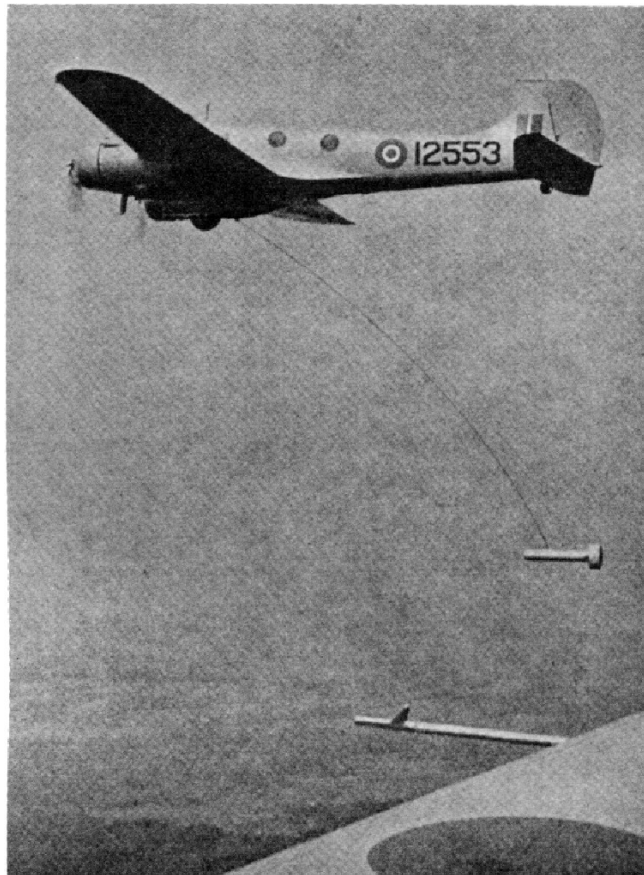
D) Measuring frequency of current in coil gives magnitude of Earth's total magnetic field as it is proportional to precession frequency.

E) Measuring current frequency to 0.004 Hz gives field to $\pm 0.1 \text{ nT}$.

Airborne and Seaborne Magnetometers

Proton precession magnetometers are used extensively in marine and airborne surveys:

- ❖ **At sea:** sensor bottle is towed in a “fish” 2-3 ship’s length astern to remove it from magnetic field of ship
- ❖ **In air:** sensor is towed 30 m behind aircraft or placed in a “stinger” on nose, tail or wingtip.



Often active compensation for magnetic effect of aircraft is calculated. Effectiveness of compensation is **called Figure of Merit (FOM)**.

Advantage:

Aeromag is rapid, cost-effective method for covering large areas.

Magnetic Gradiometers

Gradiometers use two sensors separated by fixed distance to measure gradient of the Earth's magnetic field:

- ❖ In airborne work, separation is 2-5 m for stinger, up to 30 m for bird.
- ❖ In ground work, separations of 0.5 m are common.

Example of 3-axis gradiometer system:



Advantages:

- ❖ No correction for diurnal variation required as measurement is difference off two magnetic sensors.
- ❖ Vertical gradient measurements emphasise shallow anomalies and suppress long wavelength features.

Magnetic Surveying

Ground Surveys

- ❖ Ideally lines should be perpendicular to strike, with a few along strike tie-lines.
- ❖ Establish base-station to monitor diurnal variations every 0.5-1.0 hours.
- ❖ Avoid readings near metal objects such as railway tracks, cars...
- ❖ Avoid wearing metal objects, such as watch, geological hammer.

Airborne Surveys

- ❖ Estimate line spacing to avoid significant signal aliasing for aircraft height.
- ❖ Approximate rule of thumb for maximum line spacing for particular application:

Survey type	Intended use	$\delta x_{\max}$
Total field	Contour map	$2h$
Total field	Computation of gradient, etc., maps	h
Vertical gradient	Gradient contour maps	h
Total field	Modelling of single anomalies	$h/2$

Note that h is flight height above magnetic basement, not Earth's surface.

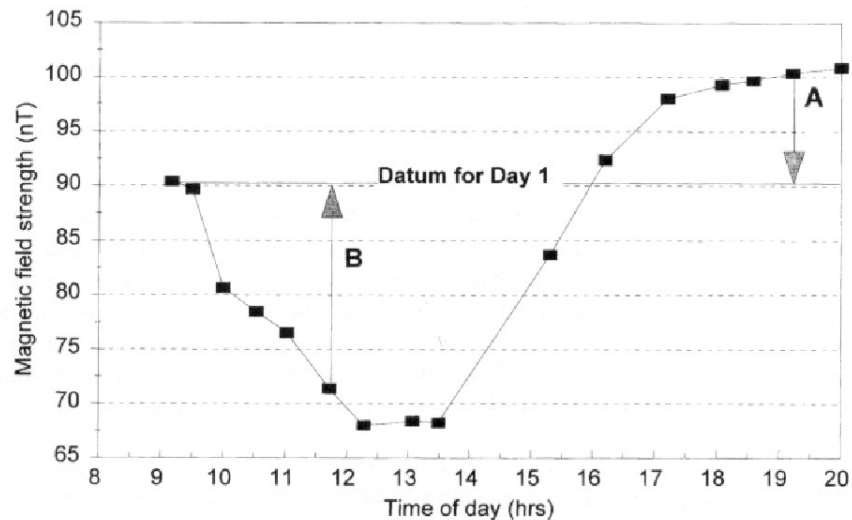
Reduction of Magnetic Survey Data 1

Magnetics data reduction is usually simpler than with gravity, comprising:

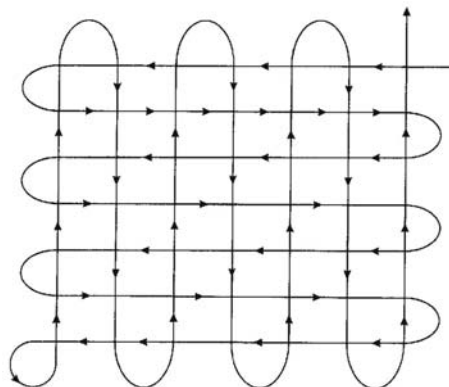
- 1) Diurnal Correction
- 2) Geomagnetic Correction
- 3) Elevation/Terrain Correction (occasionally)

Diurnal Variation

- ❖ Similar to tidal correction in gravity
- ❖ Reading is recorded at base station during survey, and then corrections applied to survey data.



- ❖ Difficult to return to base station in airborne work: possible to estimate diurnal correction from line intersections especially with additional tie lines



Reduction of Magnetic Survey Data 2

Geomagnetic Correction

Similar to latitude correction in gravity: produces “anomaly” data

Earth's total magnetic field varies from 25,000 nT at equator to 69,000 nT at poles

Three possible correction methods:

- 1) **Subtraction of IGRF**: Earth's theoretical magnetic field is removed from survey data by subtracting IGRF
- 2) **Linear approximation to IGRF**: Earth's field is approximated by linear variation across survey area, and subtracted:

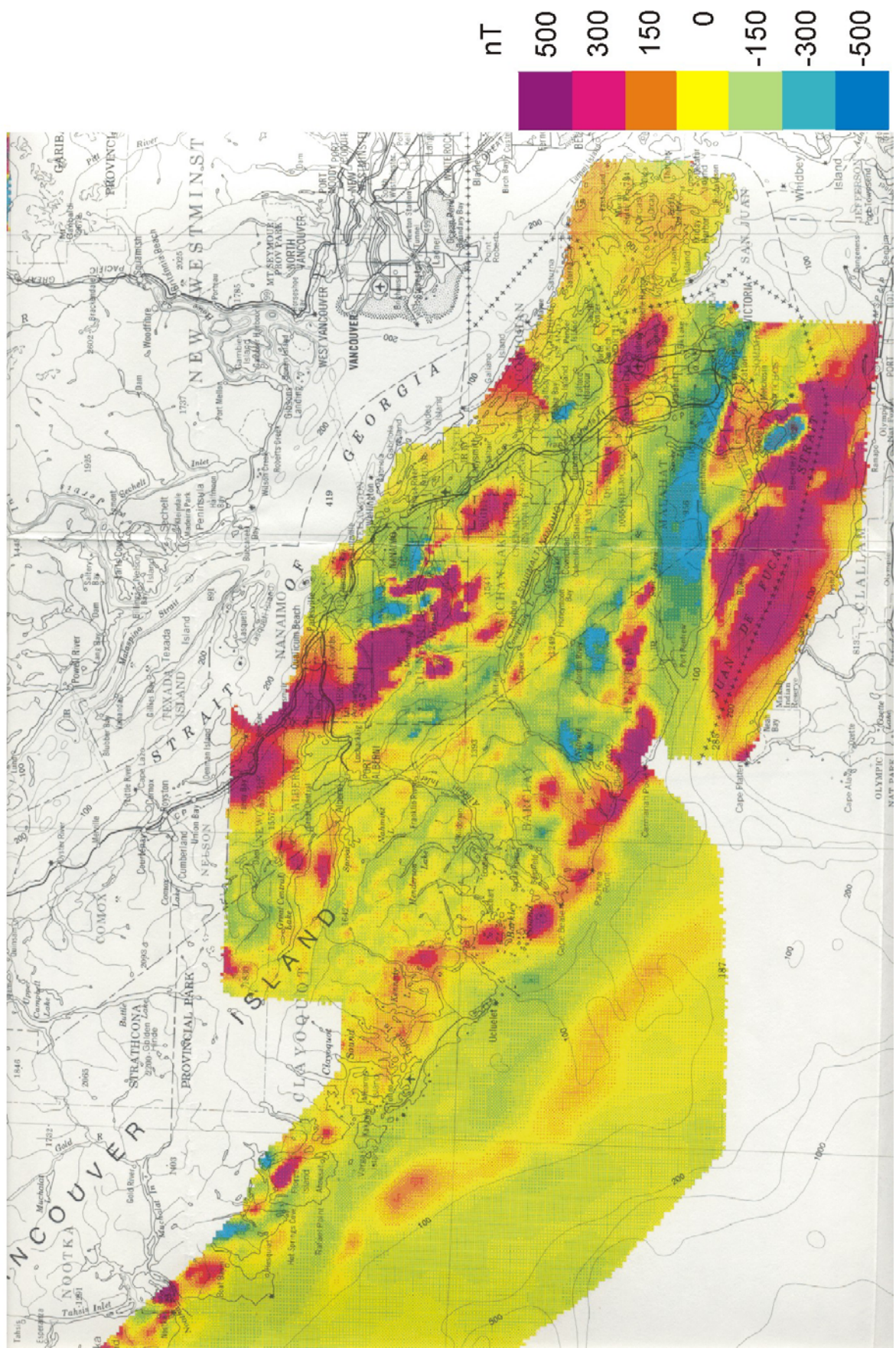
For example, in UK IGRF is approximated by 2.13 nT/km north, and 0.26 nT/km west.

- 3) **Regional correction**: With large surveys, regional trend can be estimated and removed to leave residual anomaly, as with gravity data.

Terrain Correction

- ❖ There are no elevation corrections (equivalent to Free-air and Bouguer corrections) with magnetic data as gradient is only 0.035 nT/m at poles, 0.015 nT/m at equator.
- ❖ Terrain corrections can be applied, but are complicated. Require estimate of ground susceptibility, and topography.

Total Magnetic Feild Anomaly Map of SW British Columbia



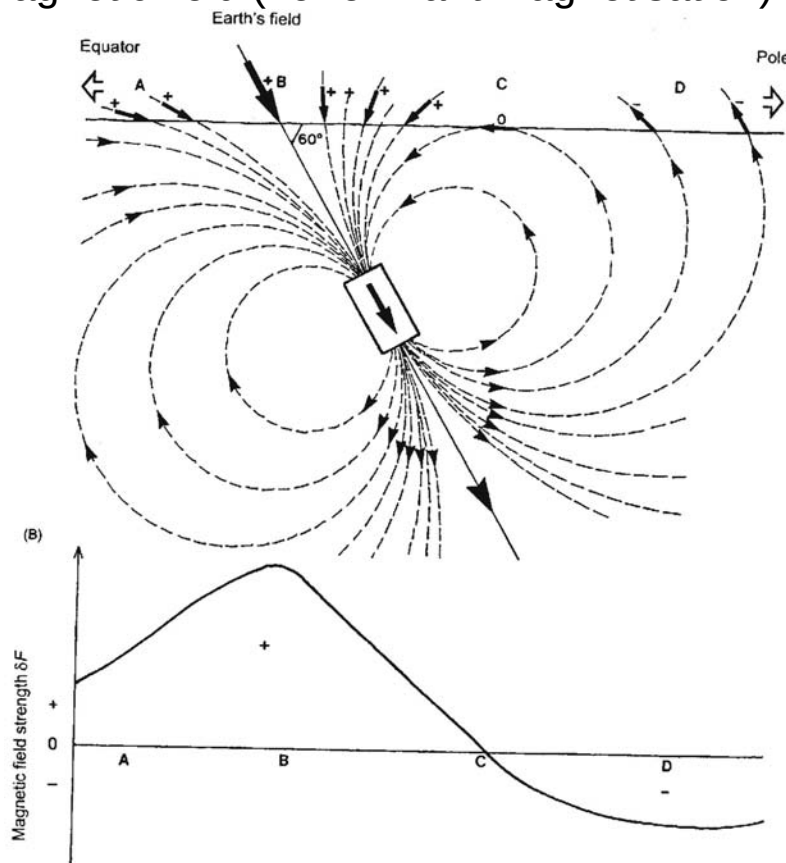
Shape of Magnetic Anomalies

Interpretation more complicated than gravity data because:

- 1) **Earth's magnetic field is dipolar:** single body can appear as peak and trough

Example

Total magnetic field induced in body inclined at 60° parallel to Earth's magnetic field (no remnant magnetisation)

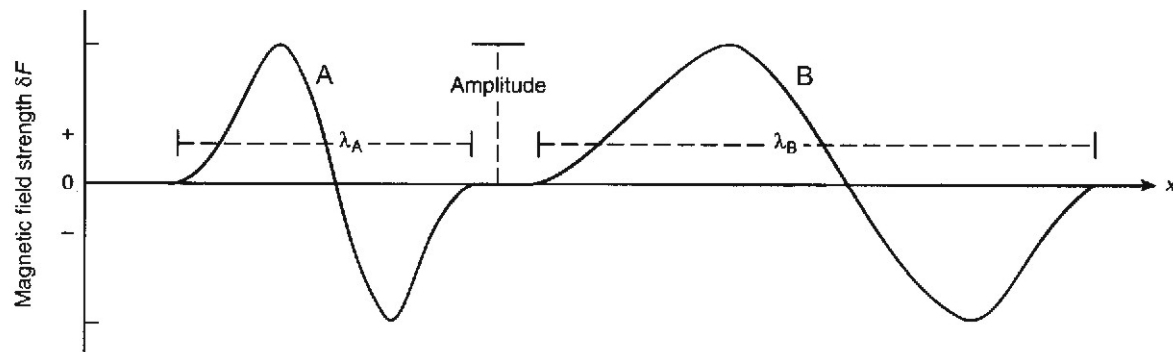


- ❖ Earth's field removed by IGRF correction.
 - ❖ Induced field strength maximum in direction of Earth's field.
 - ❖ Sign convention: downwards is positive, negative upwards.
 - ❖ Negative trough on side towards north pole
- 2) **Remnant magnetisation unknown:** strength and direction $\mathbf{J}_r$ can distort anomaly shape

Qualitative Interpretation of Magnetic Anomalies

General inferences can be made from magnetic anomaly shapes

Example



- ❖ Anomaly B is same form as A, but has longer wavelength, so must be deeper.
- ❖ Amplitude of B greater than A, so B has greater magnetisation.

Summary

Applies to:	Magnetic character	Possible cause
Segments of a profile and areas of maps	Magnetically quiet Magnetically noisy	Low κ rocks near surface Moderate–high κ rocks near surface
Anomaly	Wavelength $\pm$ amplitude	Short $\Rightarrow$ near-surface feature Long $\Rightarrow$ deep-seated feature Indicative of intensity of magnetisation
Profile*	Anomaly structure [†] and shape	Indicates possible dip and dip direction Induced magnetisation indicated by negative to north and positive to south in northern hemisphere and vice versa in southern hemisphere; if the guideline does not hold, it implies significant remanent magnetisation present
Profile and maps	Magnetic gradient	Possible contrast in κ and/or magnetisation direction
Maps	Linearity in anomaly	Indicates possible strike of magnetic feature
Maps	Dislocation of contours	Lateral offset by fault
Maps	Broadening of contour interval	Downthrow of magnetic rocks

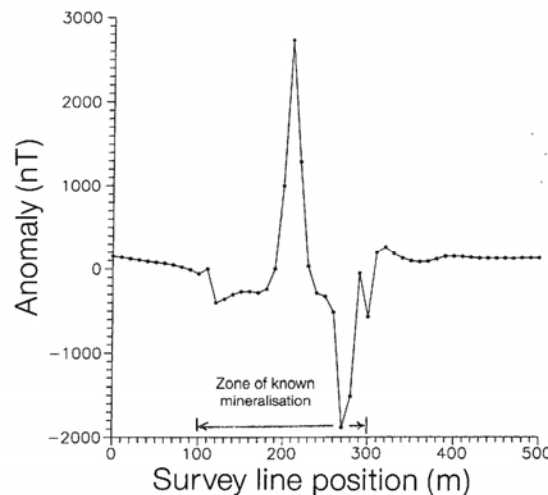
* Can be determined from maps also; [†] Structure = composition of anomaly, i.e. positive peak only, negative peak only or doublet of positive and negative peaks; κ = magnetic susceptibility

Qualitative Profile Interpretation

Identify zones with different magnetic properties:

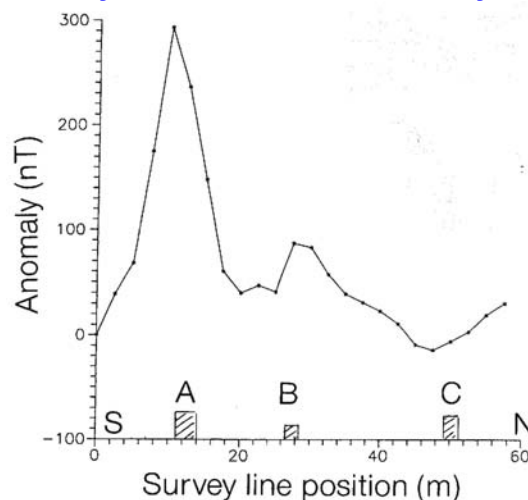
- ❖ Zones with little variation, “**magnetically quiet**”, associated with rocks of low susceptibility
- ❖ Sources in subsurface in “**magnetically noisy**” areas.

Example: Mineralisation in granite (Dartmoor, UK)



- ❖ Profile quiet except around mineralised zone.
- ❖ Negative on north side indicates direction $\mathbf{J}_i \gg \mathbf{J}_r$ as anomaly not distorted

Example: Geochemically identical dolerite dykes (Arran, Scotland)

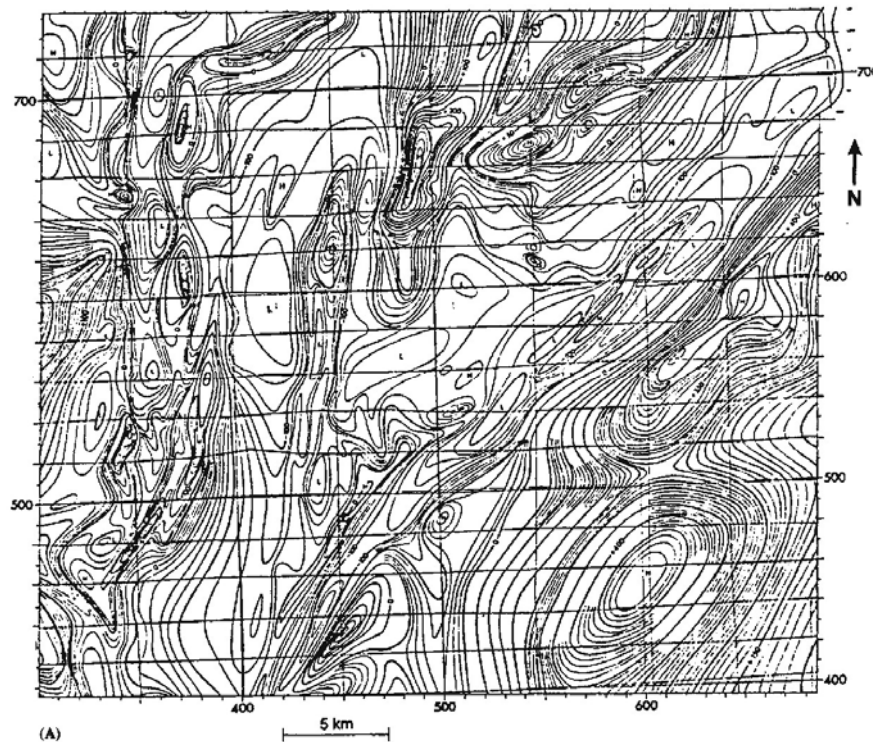


- ❖ $\mathbf{J}_r$ high as no dipolar anomaly shape
- ❖ Two peaks and trough, intruded after magnetic reversal

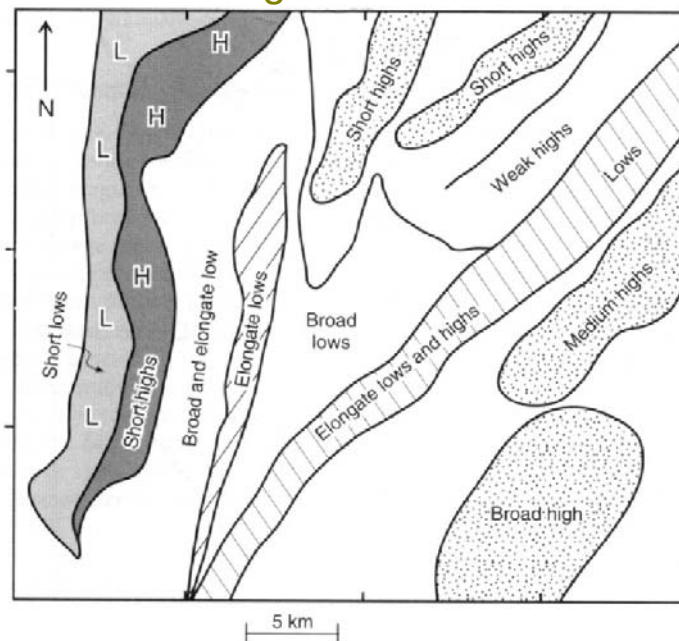
Qualitative Map Interpretation

Magnetic data acquired on ugrids can be displayed as maps

Example: Shetland Islands, Scotland



Interpretation in terms of magnetic characteristics:



- ❖ Elongate lows correspond to gneissified semipelites
- ❖ Can also identify fault at discontinuity

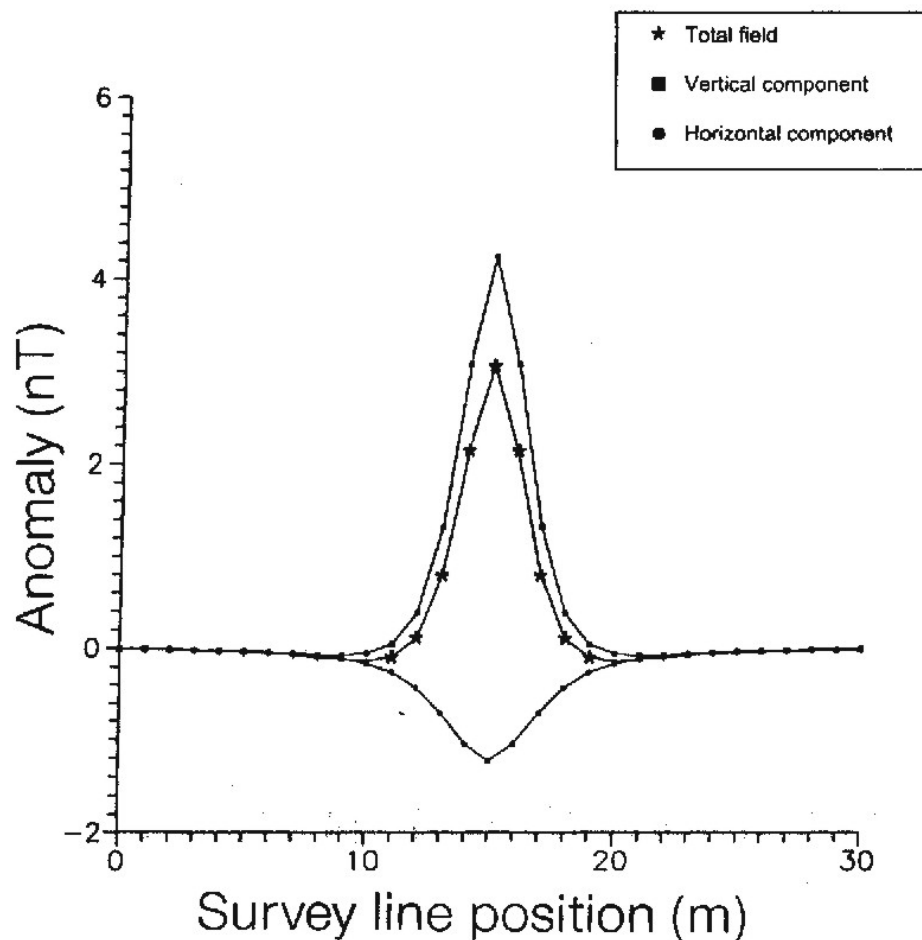
Magnetic Profile Across Buried Sphere

Magnetic data are often interpreted in terms of specific geometric forms that approximate subsurface bodies.

Sphere or dipping sheet most common and no remnance assumed

Sphere

Example with $F = 50000 \text{ nT}$, $I=60^\circ$, $D=0^\circ$, $\kappa=0.05$ for E-W profile across sphere radius 1 m at 3 m depth located at $x=15 \text{ m}$.

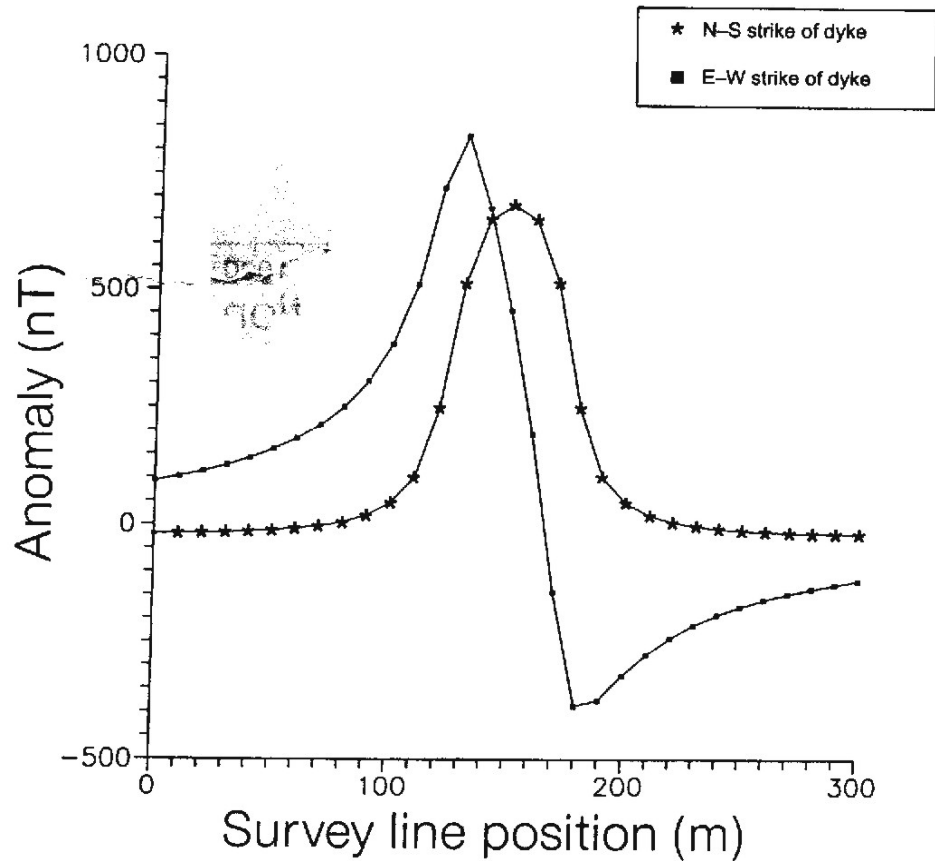


- ❖ Vertical and Horizontal components also shown in addition to total field

Magnetic Profile Across Vertical Dyke

Example

Total field over 50 m thick vertical dyke with $F = 50000 \text{ nT}$, $I = 60^\circ$, $D = 0^\circ$, $\kappa = 0.05$

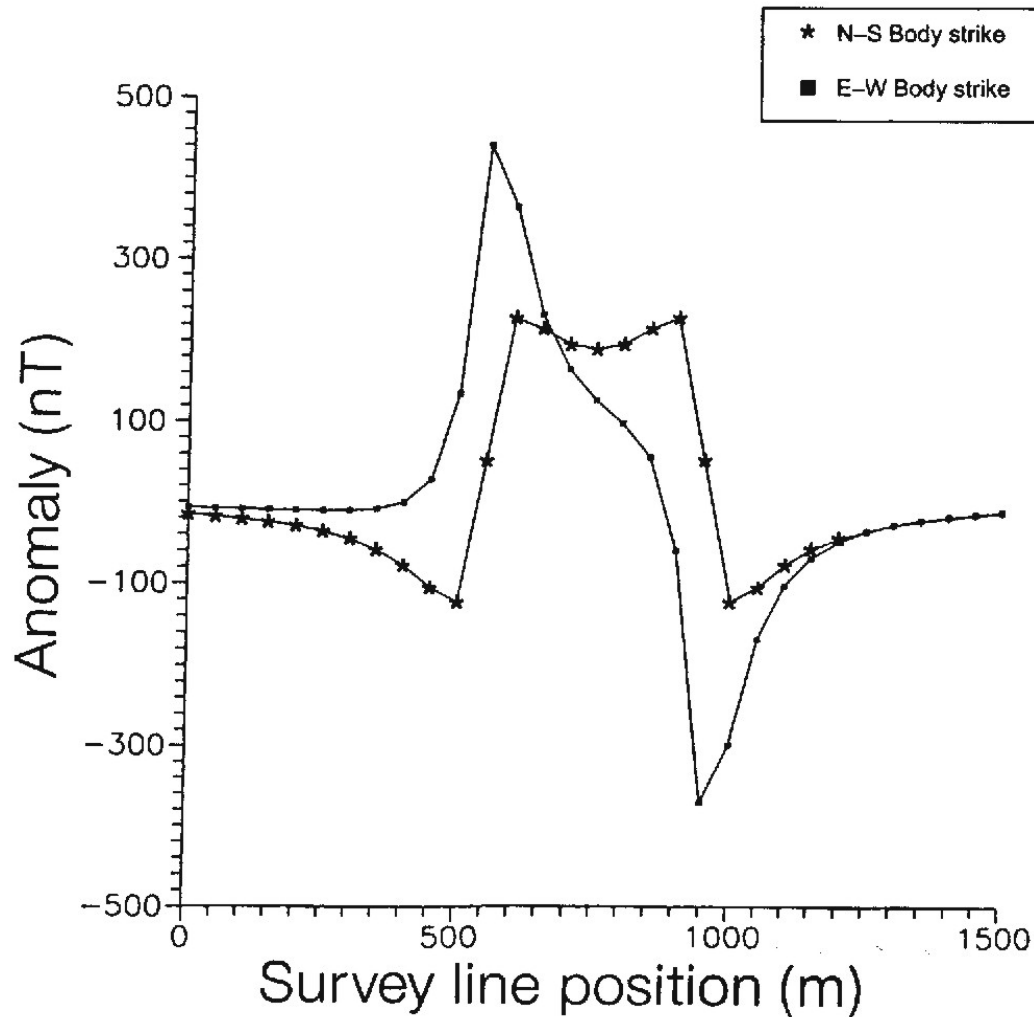


- ❖ Typical peak-trough anomaly arises when dyke strikes E-W
- ❖ Anomaly is symmetric when strike is N-S. True for all regular bodies.

Magnetic Profile Across Flat Slab

Example

Total field over 70 m thick, 400 m long flat slab located 30 m below surface with $F = 50000$ nT, $I = 60^\circ$, $D = 0^\circ$, $\kappa = 0.05$

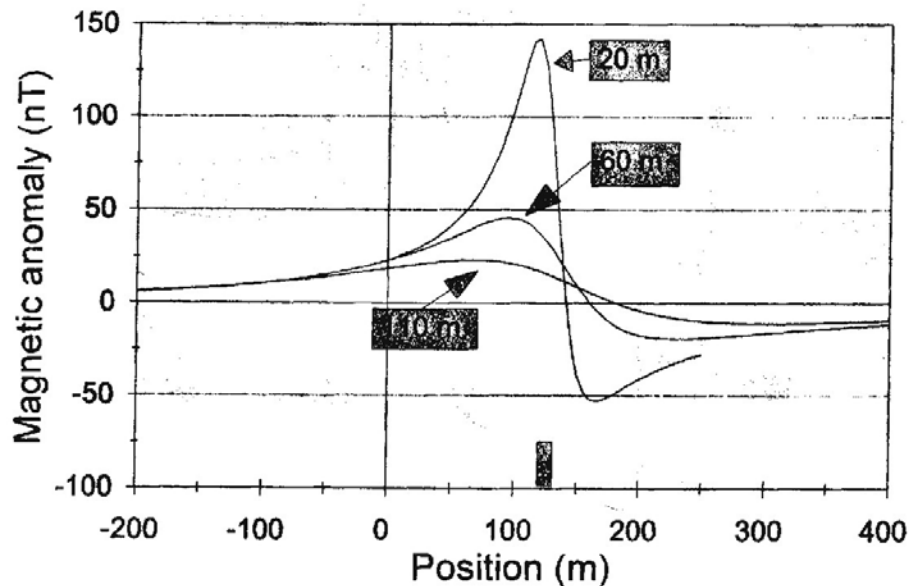


- ❖ Slab striking N-S has symmetric anomaly
- ❖ Anomaly is broader than for thinner vertical dyke

Effect of Change of Position on Magnetic Profile

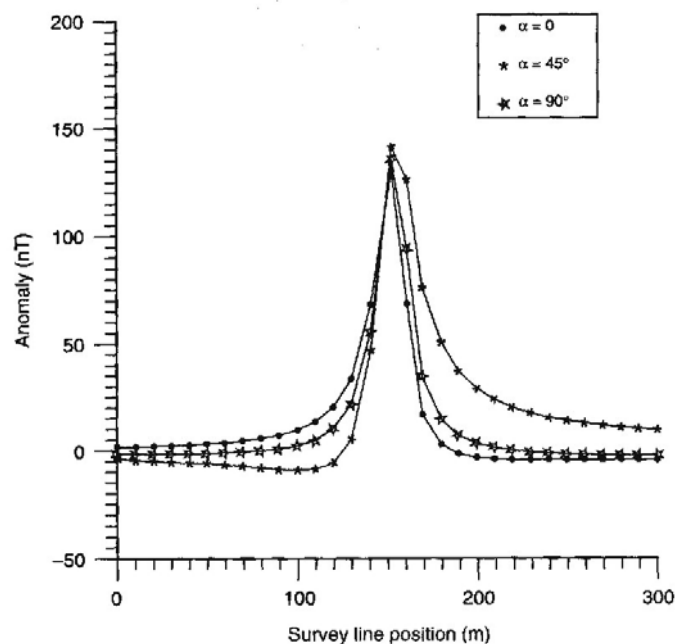
- ❖ **Change in Depth:** Anomaly will broaden and decrease in amplitude with increases in depth.

Total field over 10 m wide vertical dyke oriented E-W



- ❖ **Change in Dip:** Shape of anomaly is altered

Total field over 5 m wide dyke with varying dips



Effect of Change of Latitude

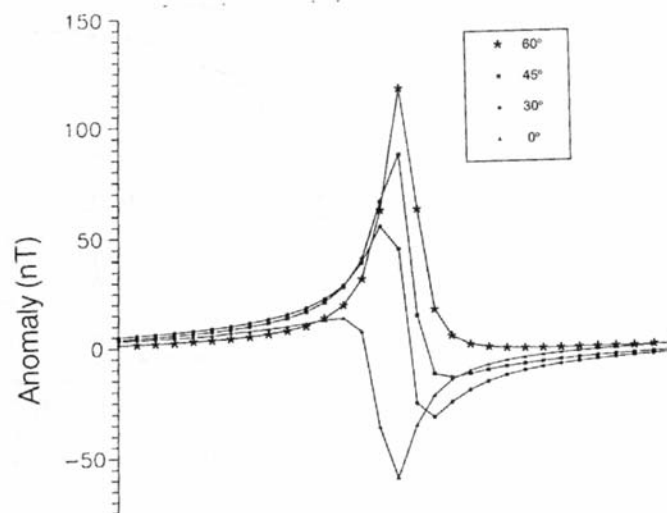
Unlike gravity, magnetic anomaly shape changes with latitude, because orientation and magnitude of Earth's total field varies.

Changes induced magnetisation.

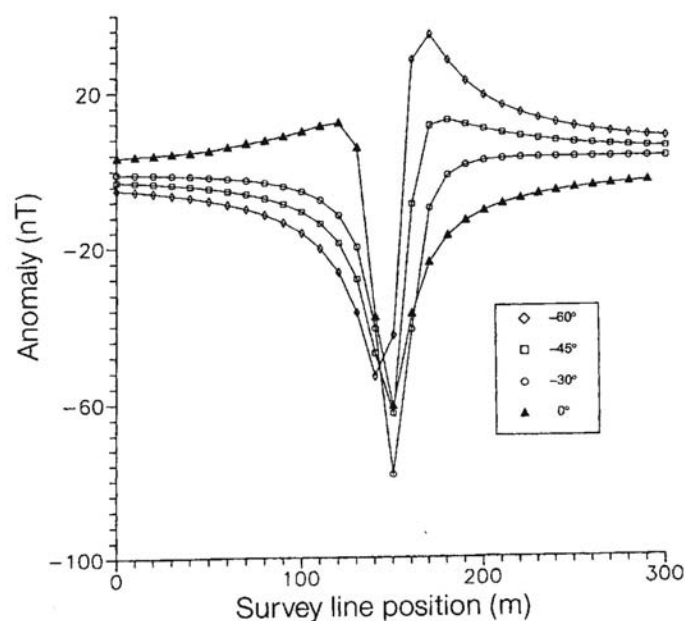
Example

5 m thick dyke dipping at 45 degrees to north with E-W strike with different magnetic inclinations

In Northern Hemisphere:



In Southern Hemisphere:

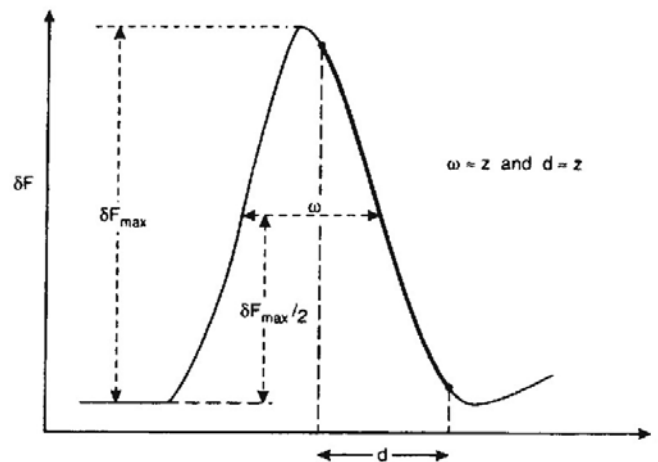


Depth Determination

Can get very approximate depth from magnetic anomalies

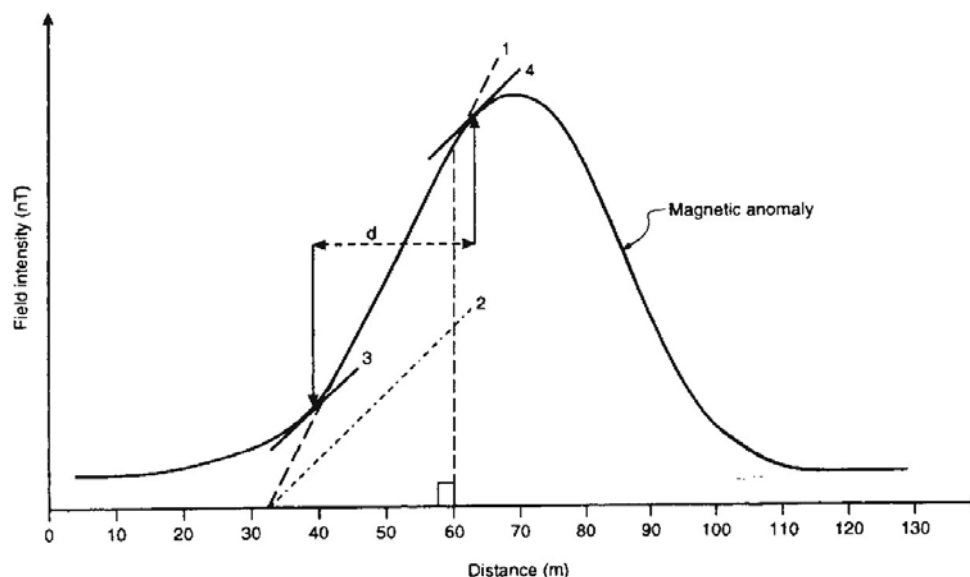
Sphere or half-cylinder: Depth to centre of body ω is roughly equal to width of anomaly peak at half its maximum value $\delta F_{\max}/2$.

Dipping Sheet or Prism: Depth to centre of body is roughly width of linear segment of anomaly d .



Peter's Half-Slope Method (~theoretically-based)

- ❖ Draw tangent at point of maximum slope (line 1)
- ❖ Find two tangents to curve with half maximum slope (lines 3, 4)



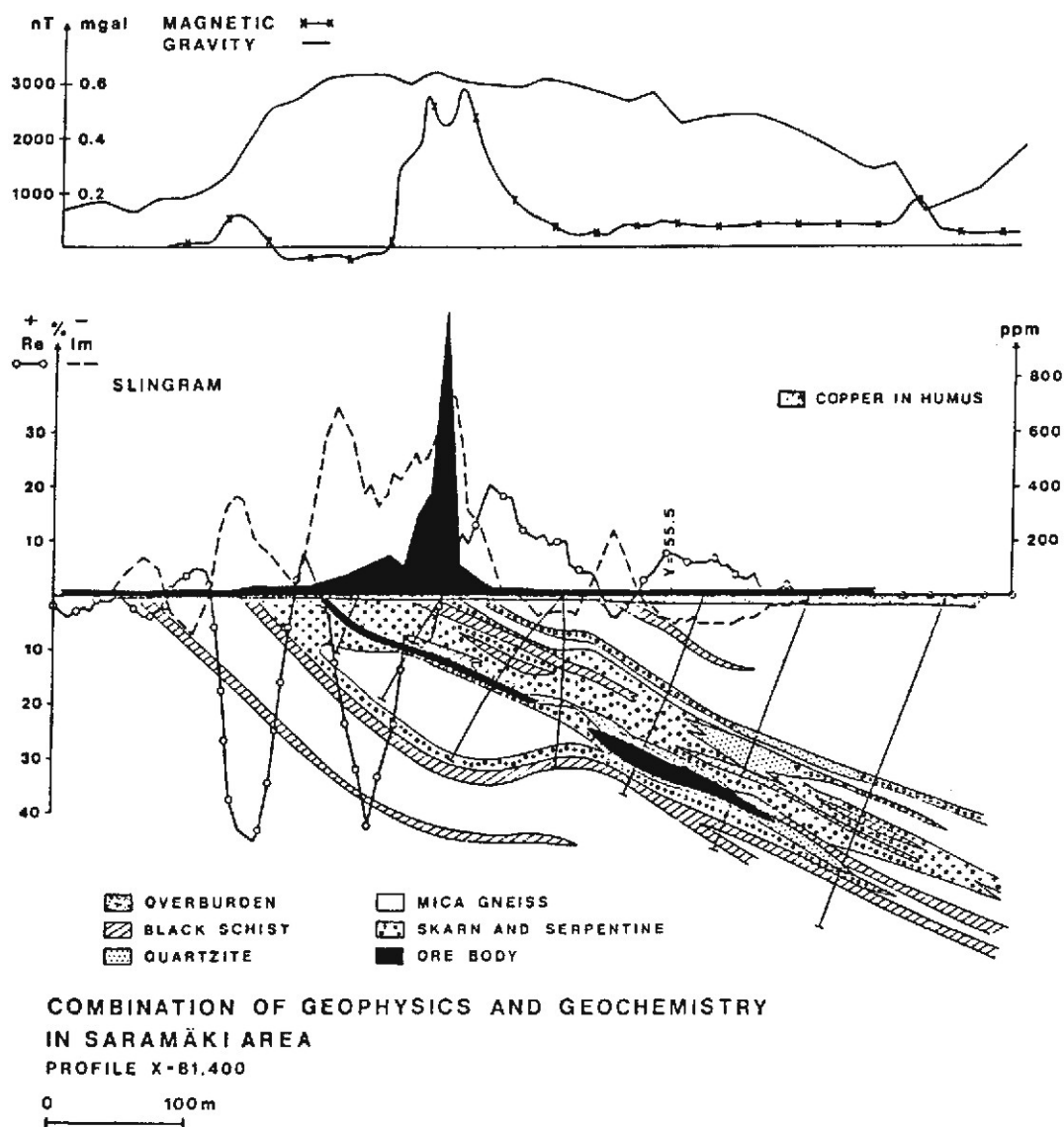
- ❖ Depth to top of body is distance between tangent points

Application to Mineral Exploration

Example from Saramäki deposit, Finland

Target is massive copper in mineralised black schists, beneath 30 m glacial overburden.

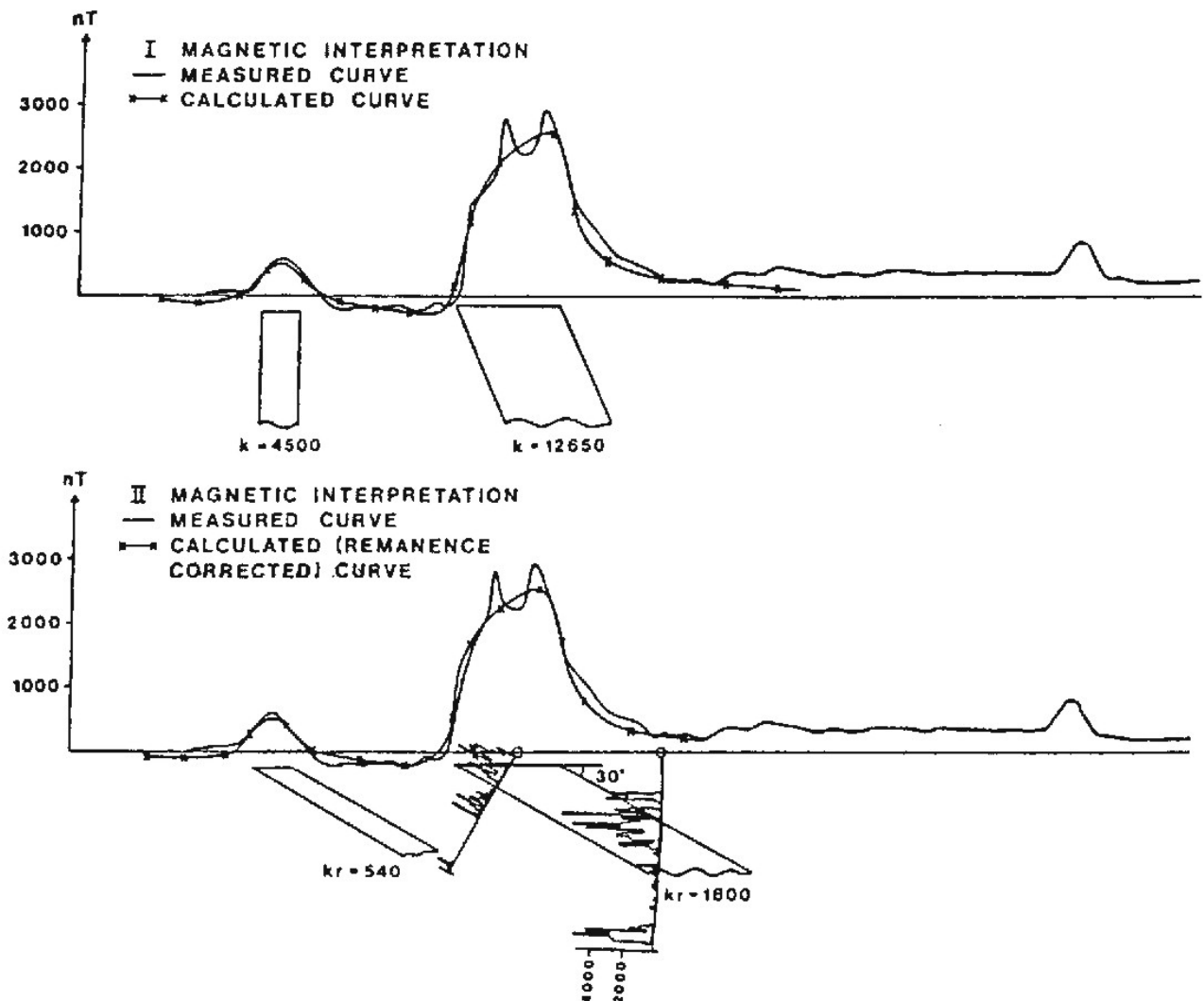
- ❖ Resistivity anomalies due to black (carbon-rich) schists, not Cu
- ❖ Entire skarn zone has high density, not just Cu, so cannot see subunits



- ❖ Shows up well in magnetics

Modelling of Saramäki ore body

- ❖ Drill information suggested that magnetisation of body heterogeneous, and upper part dominated anomaly.
- ❖ 2-D magnetics modelling could reproduce anomaly across body, but with incorrect dip if no remanence assumed



- ❖ Including remanence with 45° inclination and 90° declination in model allowed same match, but with correct dip.

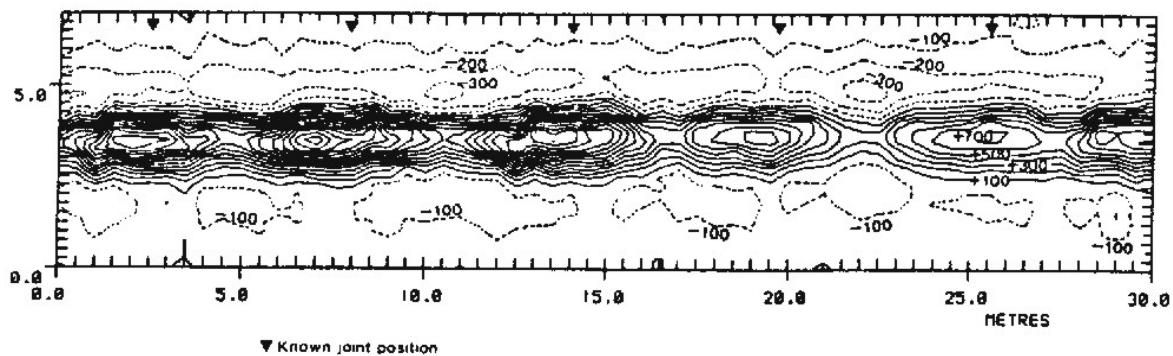
Detection of Underground Iron Pipes

Possible to identify underground pipes, and sometimes joints between sections, reducing excavation required for repairs.

Each individually cast segment behaves as dipole, causing repetition of anomalies along length

Example 1: E-W oriented pipe composed of 6.3 m segments with diameter 0.5 m at 0.5 m depth

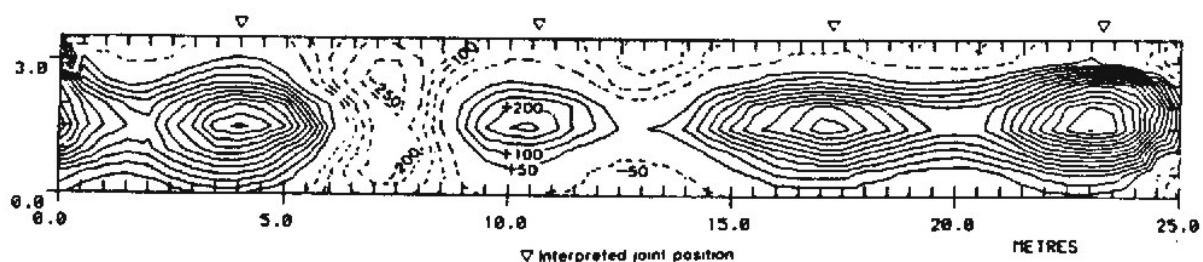
Gradiometer Data contoured at 200 nT/m



- ❖ Magnetic highs offset 0.5-1.0 m from joints along pipe
- ❖ Get typical peak-trough anomaly for E-Q oriented feature

Example 2: N-S oriented pipe with 7.6 cm diameter

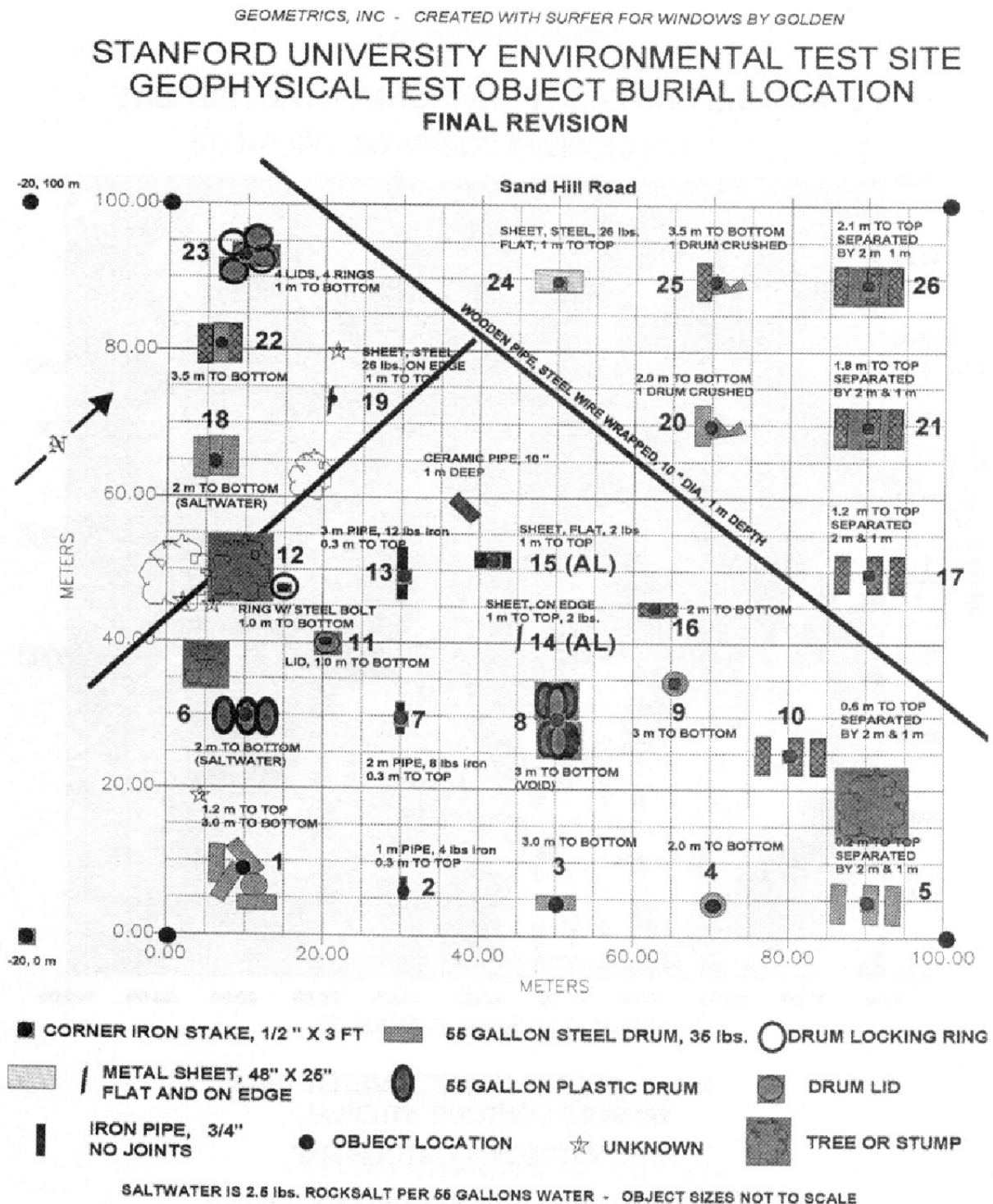
Gradiometer data contoured at 50 nT/m



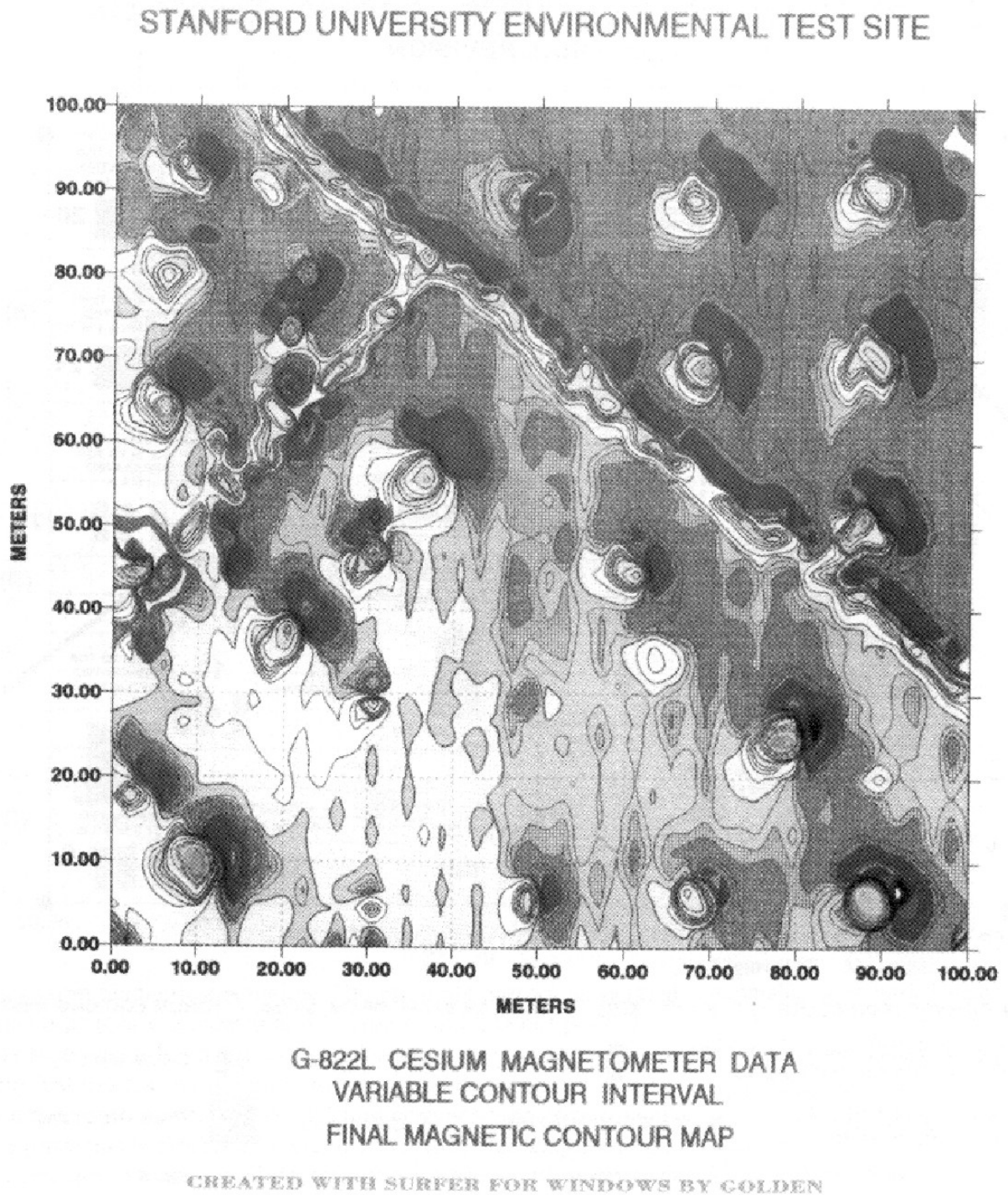
- ❖ More symmetric anomaly due to N-S orientation of pipe

Stanford Environmental Test Site Layout

Number of objects typical found in near surface buried in test site, which was surveyed



Magnetics Survey of Stanford Test Site



- ❖ Pipes stand out clearly due to linear trend
- ❖ Non-magnetic objects such as plastic drums or tree stumps have minimal anomaly