The magnetic Field of the Earth

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Importance of Earth's Magnetic Field

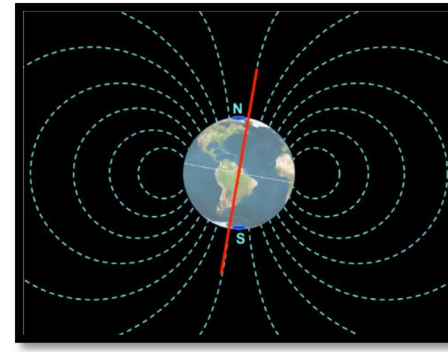
– *Earth's magnetic field is necessary for life on Earth.*

+ The magnetic field protects us against the flow of charged particles from the sun and acts a kind of shield.
+ Some researchers believe that evolution of life is accelerated during periods of weak magnetic fields, because this would enhance genetic changes – mutations.

Importance of Earth's Magnetic Field

- *The magnetic field on the continents and their shelves is used for prospecting for oil, gas and mineral deposits.*
- *The interpretation of the magnetic field on the oceans had a major impact on the development of plate tectonics.*

The Earth's Magnetic Field Introduction



-The Earth itself is a magnet.

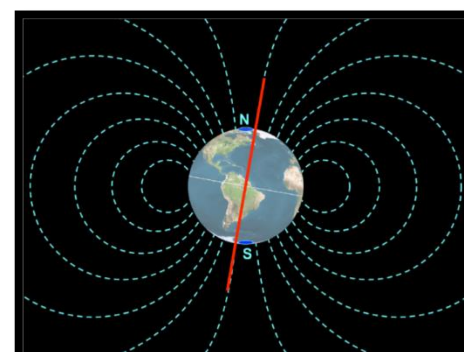
- It has a magnetic field sort of like a bar magnet (but not really like a bar magnet).

- The poles of the Earth's magnetic field are not aligned with the Earth's geographic poles defined as the endpoints of the axis of the Earth's rotation.

The Earth's Magnetic Field Introduction

- –The Earth's magnetic field is not as simple as drawn here because it is distorted by the solar wind (*Protons from the Sun moving at 400 km/s*)

– The field inside the Earth is very complex.

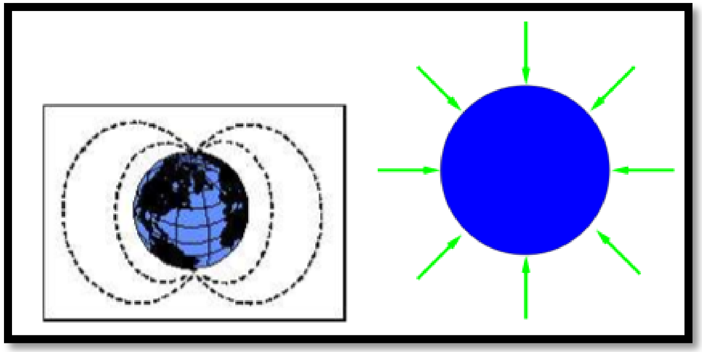


Similarities between geomagnetic and gravity

- *Passive measurement of a naturally occurring field of the earth.*
- *Potential fields – thus, the mathematics is similar.*
- *The interpretations are non-unique.*

Differences between geomagnetic and gravity

- *While the gravitational force is always attractive, the magnetic force can be either attractive or repulsive.*
- *While the gravitational field may be described as sum of monopoles (single point sources), the geomagnetic field is described as sum of positive and negative monopole*

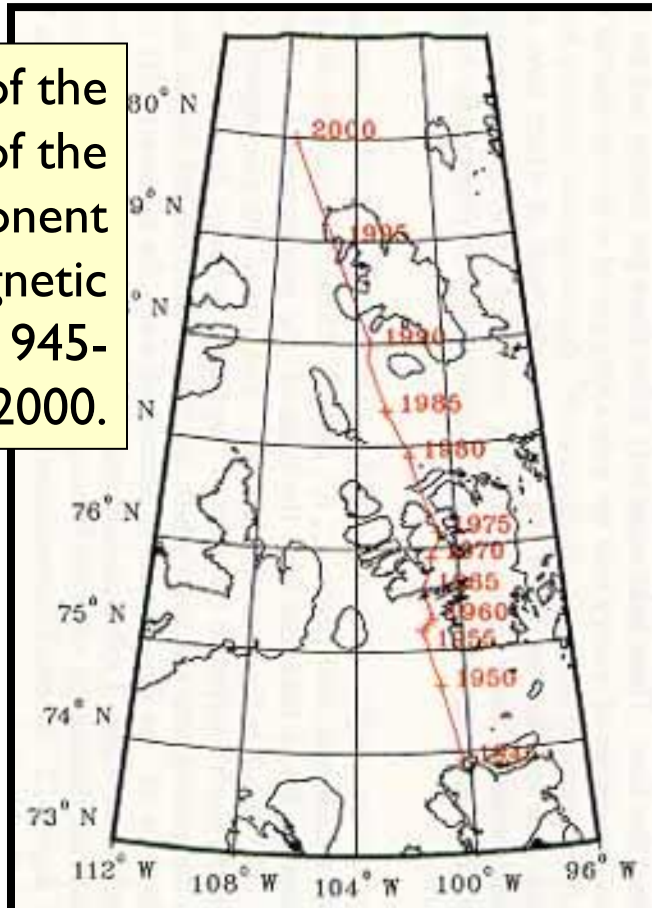


Earth’s Magnetic Poles

- *The north and south magnetic poles are not located at the north and south geographic poles*
  - The magnetic north pole is located in Canada
  - The magnetic south pole is located on the edge of Antarctica
- *The magnetic poles move around, at a rate of 40 km per year (polar Wondering)*
  - By the year 2500 the magnetic north pole will be located in Siberia
  - There are indications that the Earth’s magnetic field reverses (N ↔S) on the time scale of 1 million years or so.

Polar Wondering

Locations of the north pole of the dipole component of the geomagnetic field from 1945-2000.



Magnetic Declination

–A compass needle points toward the magnetic north pole rather than true north.

–The angle between the direction a compass needle points and true north is called the *magnetic declination.*

–The magnetic declination is defined to be

+ ***positive when magnetic north is east of true north***
+ ***negative when magnetic north is west of true north***

– The magnetic north pole currently resides on a line that passes through central Missouri, Eastern Illinois, Western Iowa, and Eastern Wisconsin

– Along this line the magnetic declination is zero.

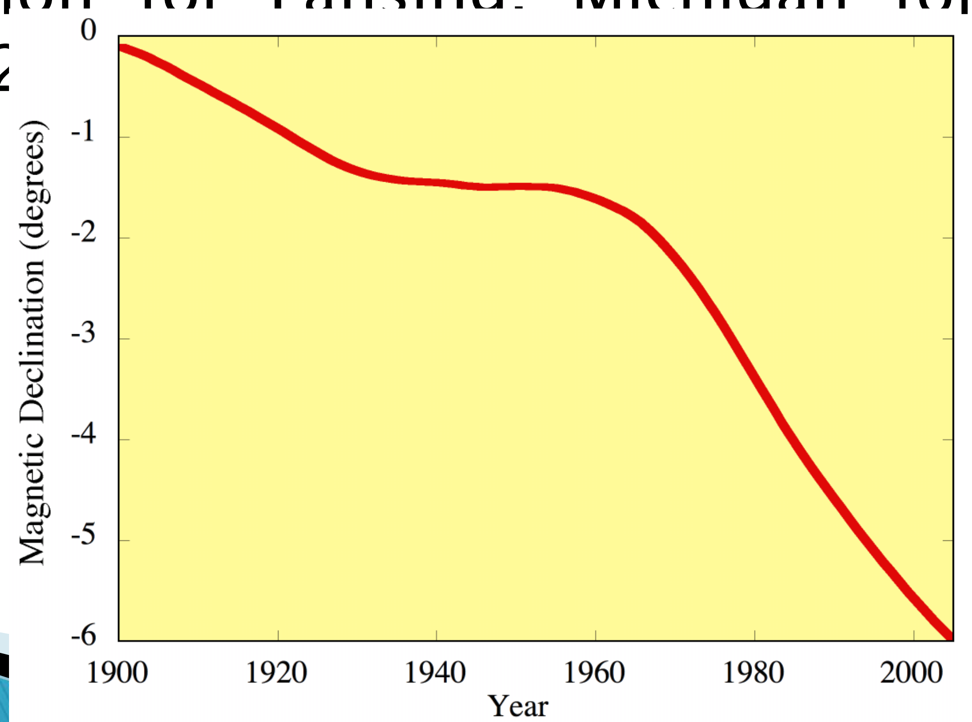
– West of this line the magnetic declination is positive and reaches 18° in Seattle.

– East of this line the declination is negative, up to −18° in Maine.

Magnetic Declination

–Because the positions of the Earth’s magnetic poles move with time, the magnetic declination is not constant.

–For example, here is the estimated magnetic declination for Lansing, Michigan for the period 1900 – 2



Magnetic field components

-The Earth's magnetic field is a vector quantity; at each point in space it has a strength and a direction. To completely describe it we need three quantities. These may be:

+ three orthogonal strength components (**X**, **Y**, and **Z**);

+ the total field strength and two angles (**F**, **D**, **I**); or

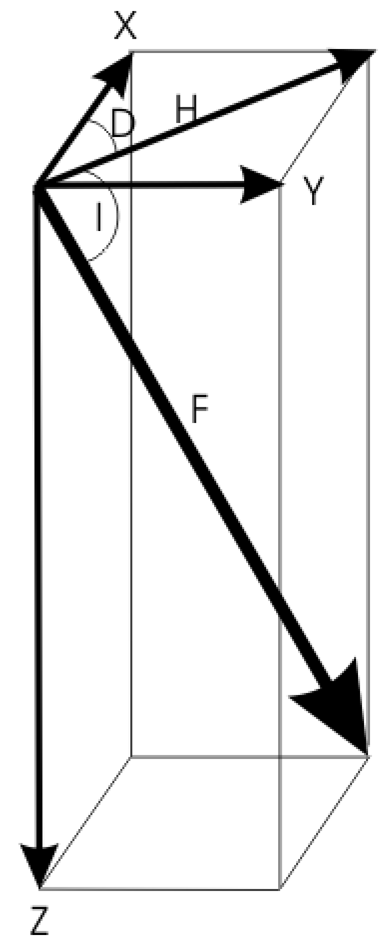
two strength components and an angle (**H**, **Z**, **D**)

+ The relationship between these 7 elements is shown in the diagram (Fig.1).

Magnetic field components

F =the total intensity of the magnetic field vector
H= the horizontal component of the magnetic field vector
Z = the vertical component of the magnetic field vector; by convention Z is positive downward
X= the north component of the magnetic field
Y = the east component of the magnetic field
D= magnetic declination, defined as the angle between true north and the horizontal component of the field measured eastward from true north
I=magnetic inclination, defined as the angle measured from the horizontal plane to the magnetic field vector;

downward is positive



Coulomb (Magnetic)Force

According to the Coulomb law, the magnetic force, F_m, acting between two magnetic monopoles is given by:

$$F_m = \frac{1}{\mu}\frac{p_1 p_2}{r^2},$$

Where:

μ is a constant of proportionality known as the magnetic permeability.

p_1 and p_2 are the charges of the two magnetic monopoles.

r is the distance between the two poles.

Coulomb(Magnetic)Force : the units

The units in SI are:

- F_m is in Newton [N]
- r is in meters [m].
- p_1 and p_2 are in Ampere times meter [Amp m].

In other words, if the force is equal 1 Newton and the two magnetic poles are separated by 1 meter, the poles charge is equal to 1 Ampere meter.

The Coulomb (magnetic) force: related notes

- Note the similarities to the gravitational force, i.e., the $1/r^2$ dependence.
- Unlike the gravitational constant, the magnetic permeability, μ, is a material property.
- p_1 and p_2 can be either of a positive or a negative sign. If p_1 and p_2 are of the same sign, the Coulomb force is repulsive, otherwise it is attractive.

The strength of the geomagnetic field

The ***magnetic field strength***, *H*, is defined as the force per unit pole exerted by a magnetic monopole, p_1:

$$H = \frac{F_m}{p_2} = \frac{1}{\mu}\frac{p_1}{r^2}.$$

- -Note that the magnetic field strength is the magnetic analog to the gravitational acceleration.

-*H* is measured in units of **Tesla** ,T, where: 1 T = N Amp^{-1} m^{-1}.

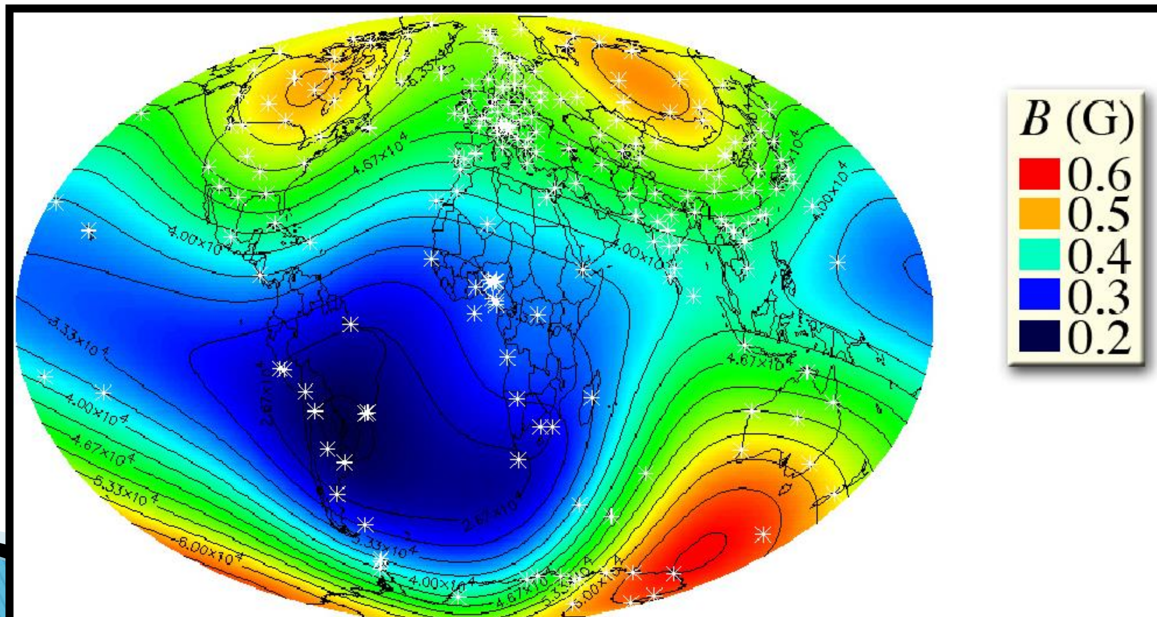
-When describing the magnetic field strength of the earth, it is more common to use units of nano Teslas, nT. The average strength of the Earth's magnetic field is about 50,000 nT.

Earth's Magnetic Field Strength

–The strength of the Earth's magnetic field at the surface of Earth is on the order of 1 G

–The strength varies between 0.25 G and 0.65 G

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



Induced magnetization and magnetic susceptibility

When a magnetic material is placed within a magnetic field, *H*, the magnetic material will produce its own magnetization.

The ***intensity of the induced magnetization***, J_i, is given by:

$$J_i = \chi H,$$

where χ, the ***magnetic susceptibility***, is a unitless number, property of the material

Induced magnetization and magnetic susceptibility

-The values given here are for SI, International System Units.

– *While the spatial variation in density are relatively small (between 1 and 3 Kg m^{-3}, magnetic susceptibility can vary as much as four to five orders of magnitude.*

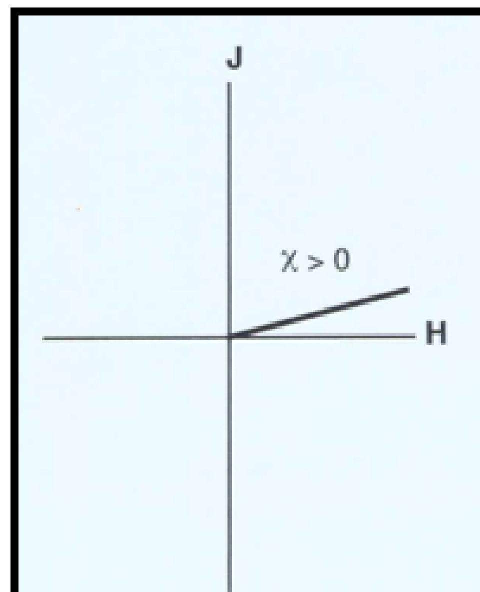
– ***Wide variations in susceptibility occur within a given rock type. Thus, it will be extremely difficult to determine rock types based on magnetic prospecting***

material	Susceptibility* $\times 10^3$
Air	0.
Quartz	-0.01
Salt	-0.01
Calcite	-0.001 – 0.01
Pyrite	0.05 – 5
Magnetite	1200 – 19,200
Limestone	0 – 3
Sandstone	0 – 20
Granite	0 – 50
Gabbro	1 –90
Basalt	0.2 – 175

Induced magnetization and magnetic susceptibility

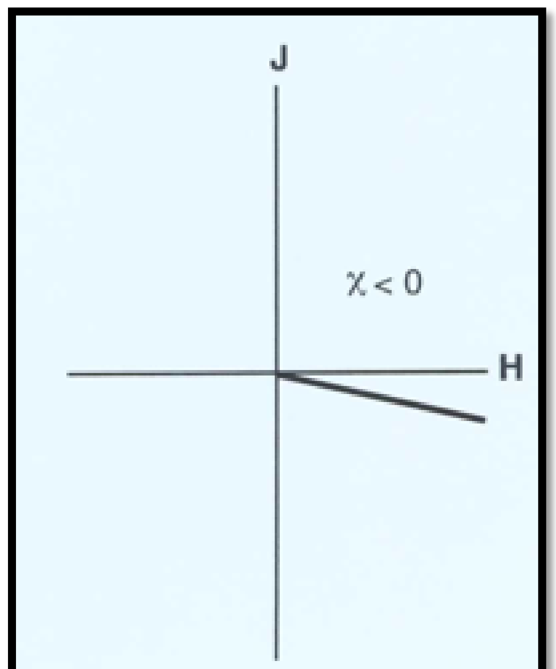
-The value of the magnetic susceptibility can take on either positive or negative values.

- Positive value means that the induced magnetic field is in the same direction as the inducing field, H.



Induced magnetization and magnetic susceptibility

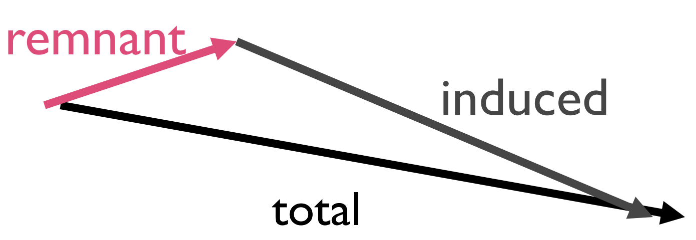
Negative value means that the induced magnetic field is in the opposite direction as the inducing field.



Remnant magnetization

- –If the magnetic material has relatively large *susceptibilities*, or if the inducing field is strong, the magnetic material will retain a portion of its induced magnetization even after the inducing field disappears. This remaining magnetization is called *remnant magnetization.*

– *The total magnetic field is a sum of the main magnetic field produced in the Earth's core, and the remnant field within the material.*



Secular Variation of the Geomagnetic Fields

-The Earth's magnetic field is slowly changing on time scales that range from years to millennia.

- Such changes are referred to as secular variation.

- Secular variation was first recognized in 1634 when Gellibrand compared *magnetic declination* observations he had made at London with earlier observations.

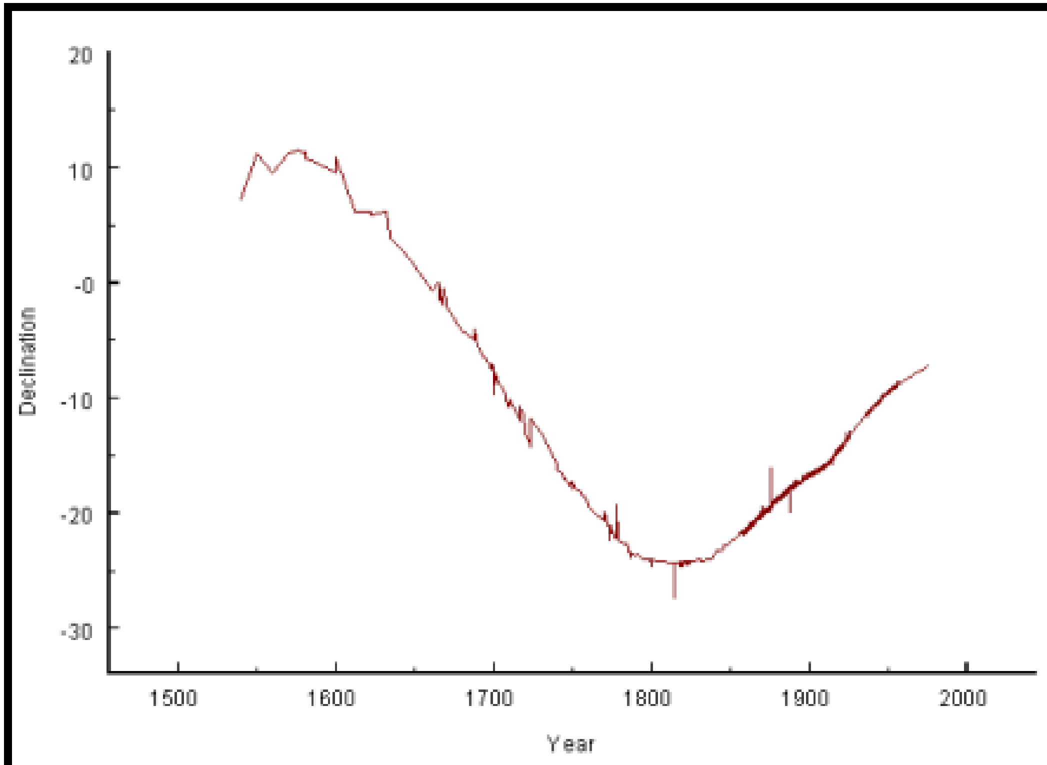
Secular Variation of the Geomagnetic Fields

-The observations of declination made at London over the years constitute one of the best records of secular variation.

- The figure(2) shows that declination has changed from approximately 10˚ E in the late 16th century to 25˚ W in the early 19th century before returning to a current value of about 3˚ W.

Secular Variation of the Geomagnetic Fields

Figure 2.

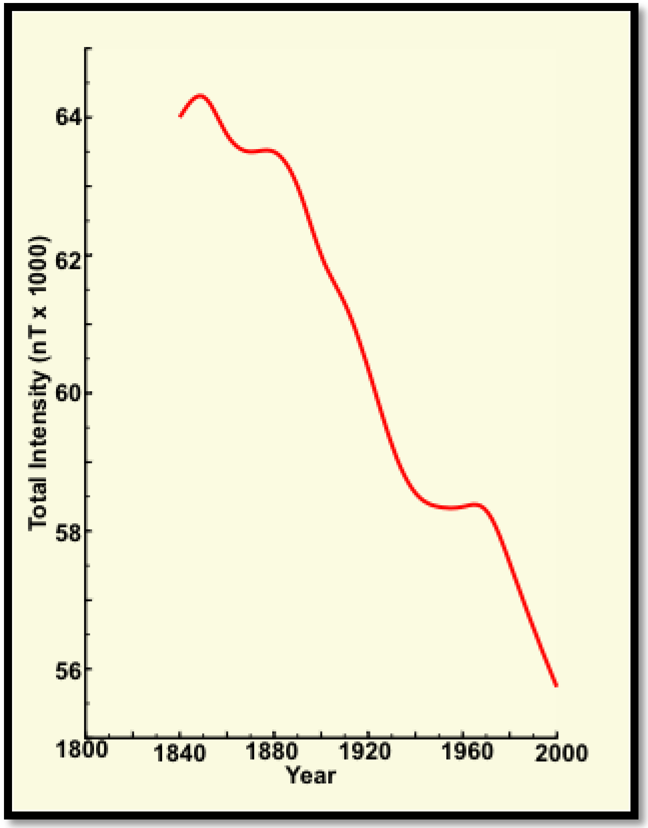


Secular Variation of the Geomagnetic Fields

–All elements of the magnetic field change with time – not just the declination. For example, the total intensity at Toronto has decreased 14%, from approximately 64,000 nT to 55,000 nT, during the last 160 years (Figure 3).

Secular Variation of the Geomagnetic Fields

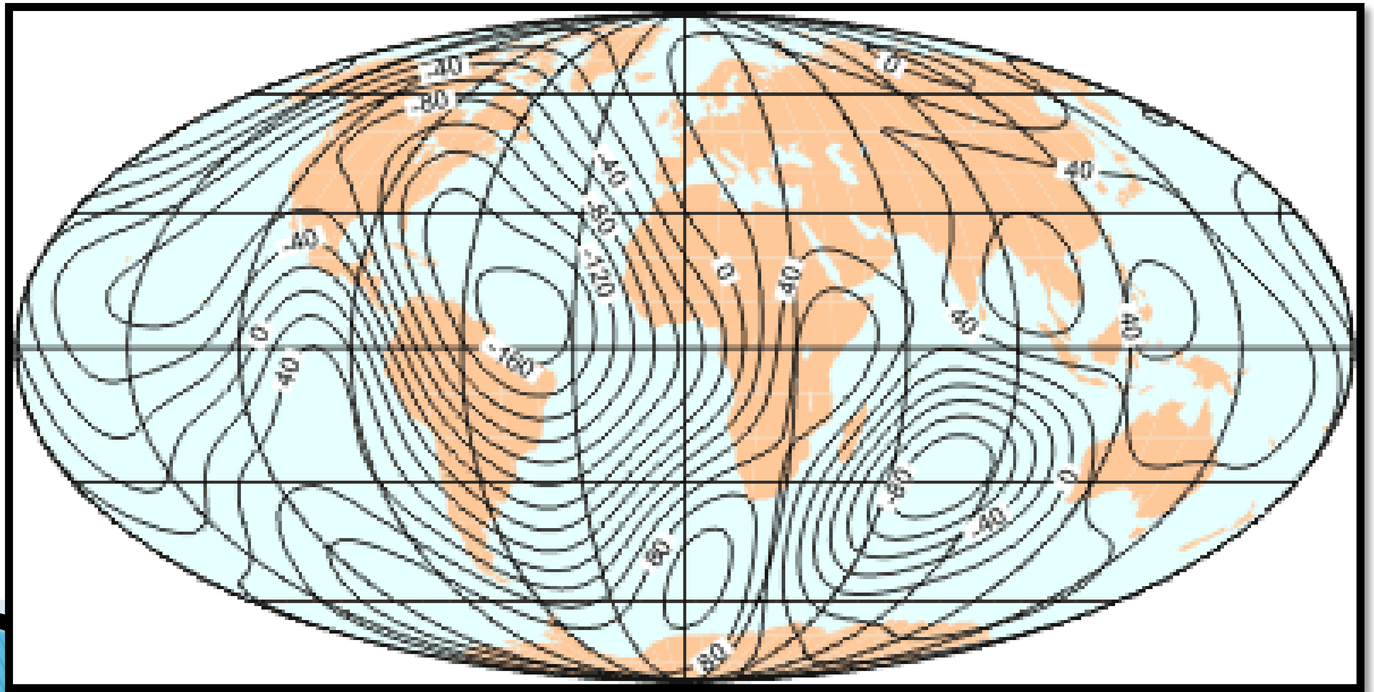
Figure 3. Change in F at Toronto.



Secular Variation of the Geomagnetic Fields

The map shows the annual change (the secular variation over one year) of the vertical component of the magnetic field (Figure 4).

Figure 4. Secular variation of the vertical component of the magnetic field.

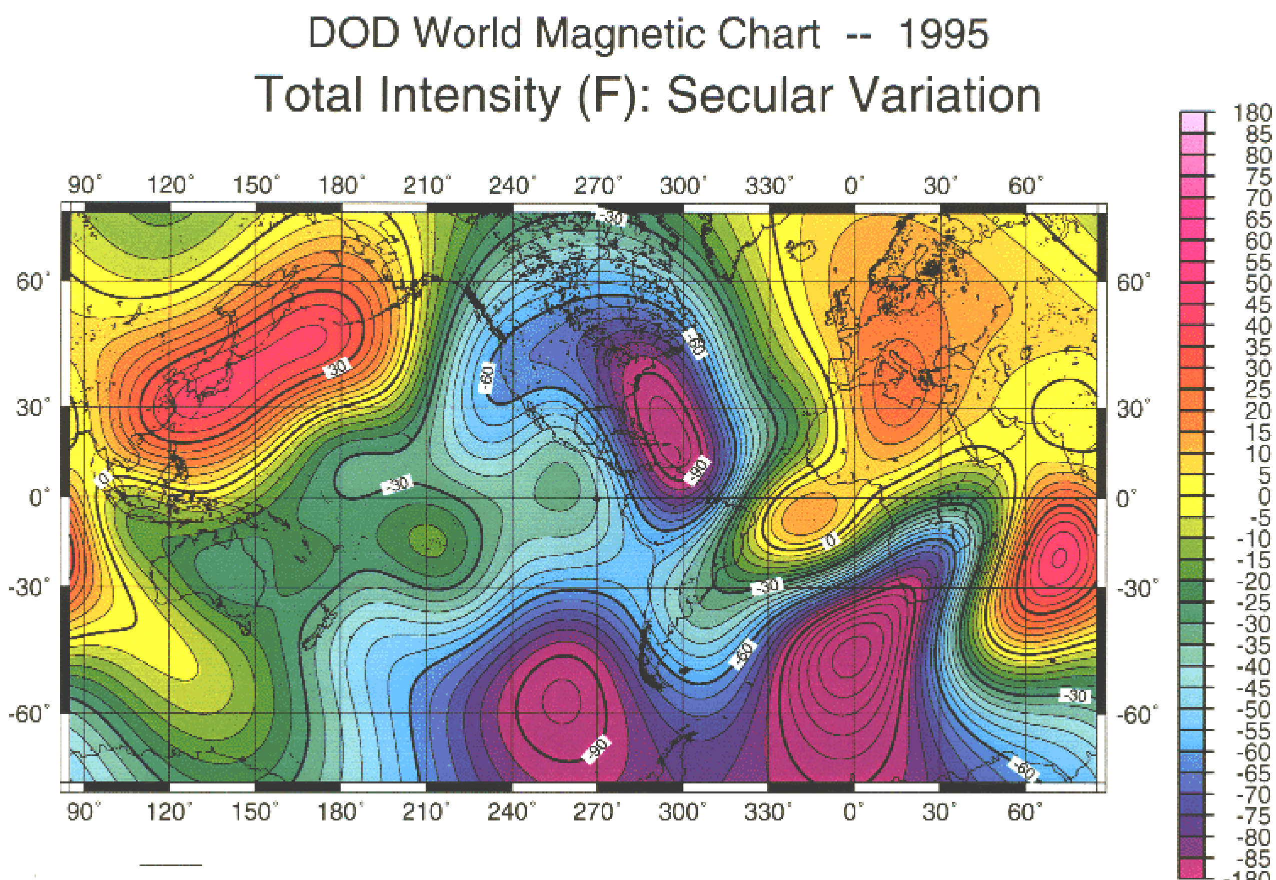


Secular Variation of the Geomagnetic Fields

-The previous three figures illustrate two important points about secular variation:

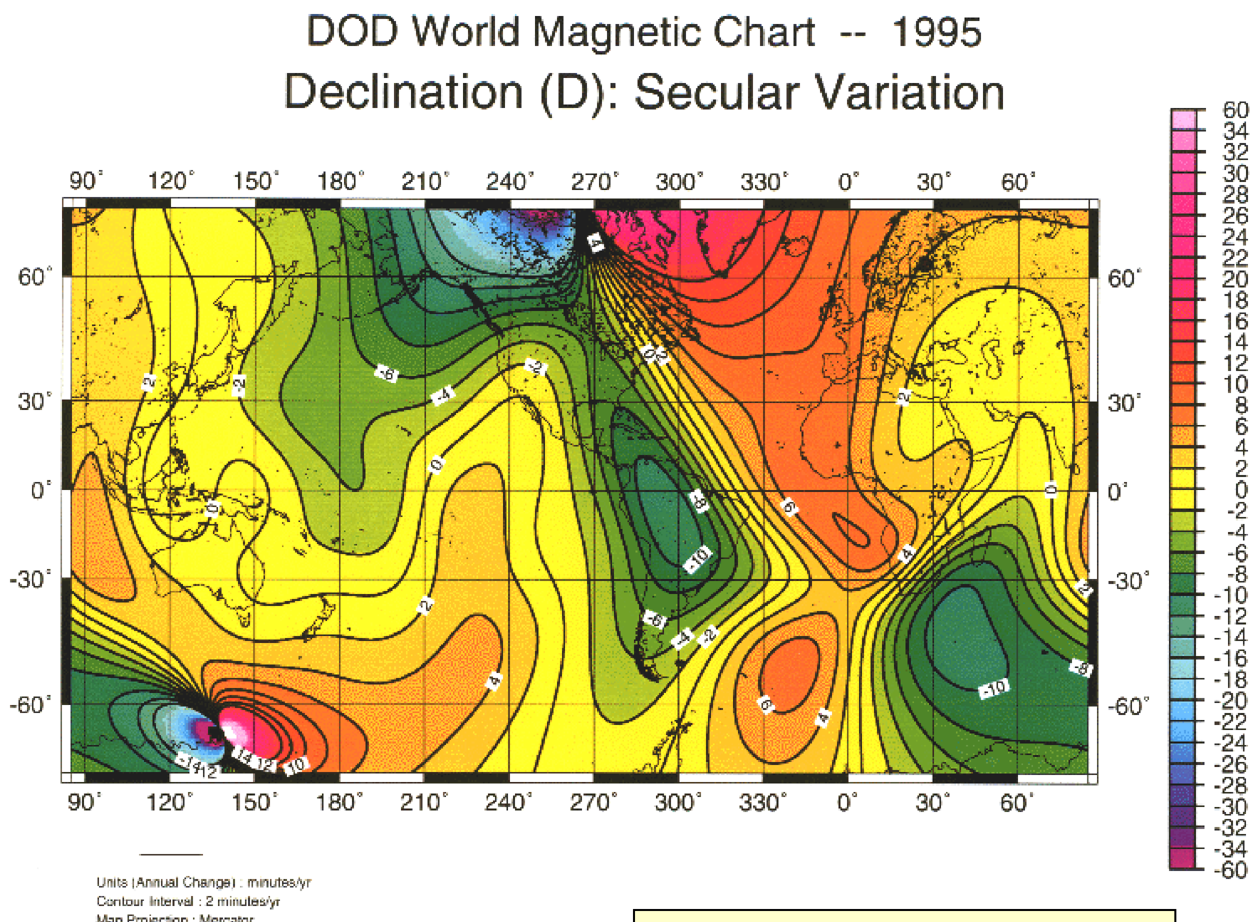
1. It is not constant in time.
2. It varies from place to place.

Secular Variation



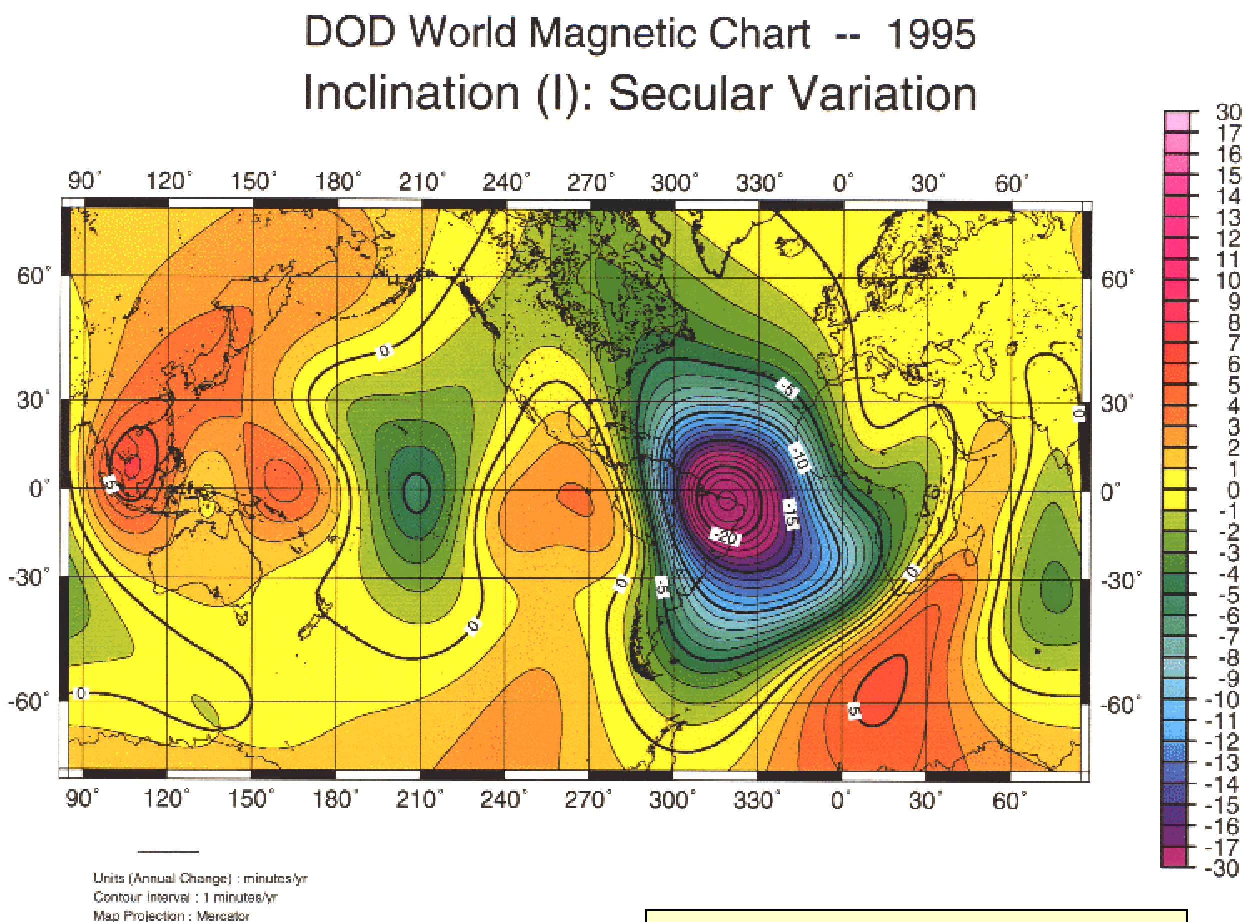
units: **nT/yr**
contour interval: 5 nT/yr
Main field: 30,000 to 60,000 nT

Secular Variation



units: **minutes/yr**
contour interval: 2 min/yr

Secular Variation



units: **minutes/yr**
contour interval: 1 min/yr

Generation of the Earth's magnetic field

- Although the Earth's magnetic field resembles that of a bar magnet we must find another explanation for the field's origin.
- Permanent magnets cannot exist at the temperatures found in the Earth's core. We also know that the Earth has had a magnetic field for hundreds of millions of years.
- We cannot, however, simply attribute the existence of the present geomagnetic field to some event in the distant past.

Generation of the Earth's magnetic field

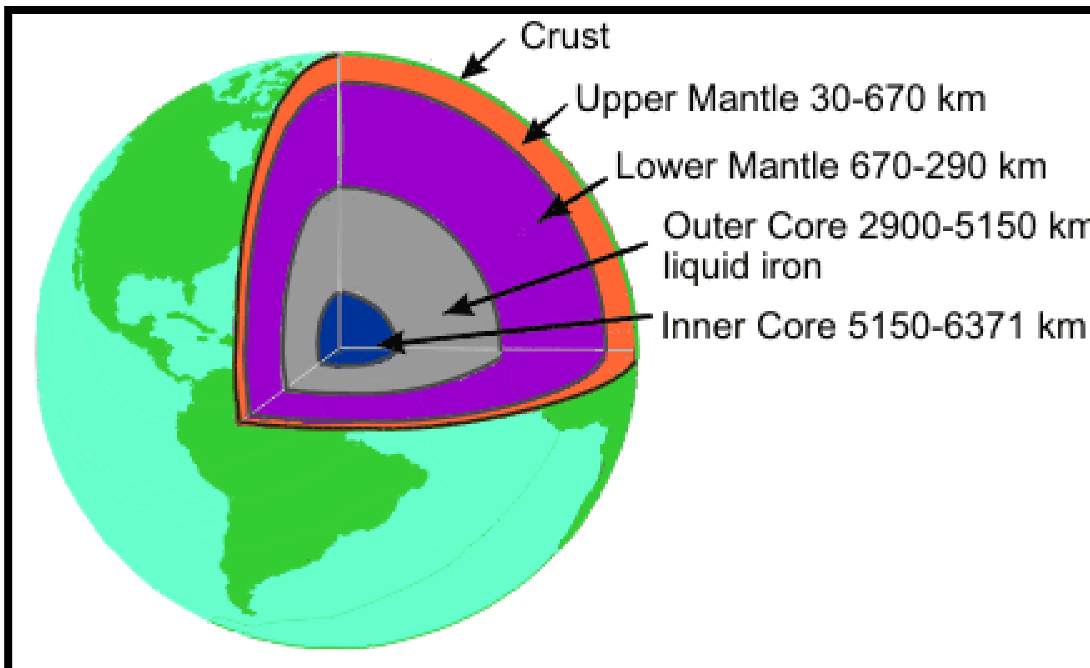
Many mechanisms have been postulated to explain how the magnetic field is generated, but the only one that is now considered plausible is analogous to a dynamo, or generator – a devise for converting mechanical energy to electrical energy. To understand how a dynamo would work in the context of the Earth, we need to understand the physical conditions in the Earth's interior.

Generation of the Earth's magnetic field

- *The Earth is composed of layers: a thin outer crust, a silicate mantle, an outer core and an inner core* ,Figure 9*.*
- Both temperature and pressure increase with depth within the Earth.
- *The temperature at the core mantle boundary is roughly 4800° C, hot enough for the outer core to exist in a liquid state.*
- The inner core, however, is solid because of increased pressure.
- *The core is composed primarily of iron, with a small percentage of lighter elements.*
- The outer core is in constant motion, due both to the Earth's rotation and to convection.
- *The convection is driven by the upward motion of the light elements as the heavier elements freeze onto the inner core.*

Generation of the Earth's magnetic field

Figure 9. Structure of Earth's Interior.



Generation of the Earth's magnetic field

For magnetic field generation to occur several conditions must be met:

1. There must be a conducting fluid;

2. There must be enough energy to cause the fluid to move with sufficient speed and with the appropriate flow pattern;

3. There must be a "seed" magnetic field.

Generation of the Earth's magnetic field

All these conditions are met in the outer core:

–Molten iron is a good conductor.

– There is sufficient energy to drive convection, and the convective motion, coupled with the Earth's rotation, produce the appropriate flow pattern.

– Even before the Earth's magnetic field was first formed magnetic fields were present in the form of the sun's magnetic field. Once the process is going, the existing field acts as the seed field.

Generation of the Earth's magnetic field

- As a stream of molten iron passes through the existing magnetic field, an electric current is generated through a process called magnetic induction. The newly created electric field will in turn create a magnetic field.
- Given the right relationship between the magnetic field and the fluid flow, the generated magnetic field can reinforces the initial magnetic field.
- As long as there is sufficient fluid motion in the outer core, the process will continue.

Paleomagnetism

-**Paleomagnetism** is the study of the record of the Earth's magnetic field in rocks.

-Certain minerals in rocks can record direction and intensity of the field as it has changed over geologic time.

-The record of these changes in rocks and sediments provides a time scale that is used in geochronology.

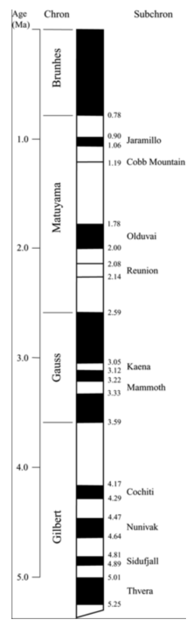
Fields of Paleomagnetism

Paleomagnetism is studied on a number of scales:

1. *Secular variation* ***studies*** look at small-scale changes in the direction and intensity of the Earth's magnetic field.
2. *Reversals* examines the periodic polarity reversion of the Earth's magnetic field. The reversals have occurred at irregular intervals throughout the Earth's history. The age and pattern of these reversals is known from the study of *sea floor spreading* zones and the dating of volcanic rocks , Figure 10.

Fields of Paleomagnetism

Figure 10.



Remnant magnetization

- The study of paleomagnetism is possible because *iron-bearing* minerals such as *magnetite* may record past directions of the Earth's magnetic field.
- Paleomagnetic signatures in rocks can be recorded by three different mechanisms.

1. **Thermal remnant magnetization**
2. **Detrital remnant magnetization**
3. **Chemical remnant magnetization**

Thermal remnant magnetization

- Iron-titanium oxide minerals in *basalt* and other *igneous rocks* may preserve the direction of the Earth's magnetic field when the rocks cool through the *Curie temperatures* of those minerals.
- The Curie temperature of *magnetite*, a *spinel*-group *iron oxide*, is about 580°C, whereas most *basalt* and *gabbro* are completely crystallized at temperatures above 900°C.

Thermal remnant magnetization

- Hence, the mineral grains are not rotated physically to align with the Earth's field, but rather they may record the orientation of that field.
- The record so preserved is called a *thermal remnant magnetization* (TRM).
- The record has been preserved well enough in basalts of the ocean crust to have been critical in the development of theories of sea floor spreading related to *plate tectonics*.

Detrital remnant magnetization

- In a completely different process, magnetic grains in sediments may align with the magnetic field during or soon after deposition; this is known as *detrital remnant magnetization* (DRM).
- If the magnetization is acquired as the grains are deposited, the result is a *depositional detrital remnant magnetization (dDRM);* if it is acquired soon after deposition, it is a *post-depositional detrital remnant magnetization (pDRM).*

Chemical remnant magnetization

- In this process, magnetic grains may be deposited from a circulating solution, or be formed during chemical reactions, and may record the direction of the magnetic field at the time of mineral formation.
- The field is said to be recorded by *chemical remnant magnetization* (CRM). The mineral recording the field commonly is hematite, another *iron oxide*. *Redbeds*, *clastic sedimentary rocks* (such as *sandstones*) that are red primarily because of hematite formation during or after sedimentary *diagenesis*, may have useful CRM signatures,

Geomagnetic reversal

- A *geomagnetic reversal* is a change in the orientation of Earth's magnetic field such that the positions of magnetic north and magnetic south become interchanged.
- The first examination of the timing of magnetic reversals was done by *Motonori Matuyama* in the 1920s , who observed that there were rocks in Japan whose magnetic fields were reversed and those were all of early *Pleistocene* age or older.

Geomagnetic reversal

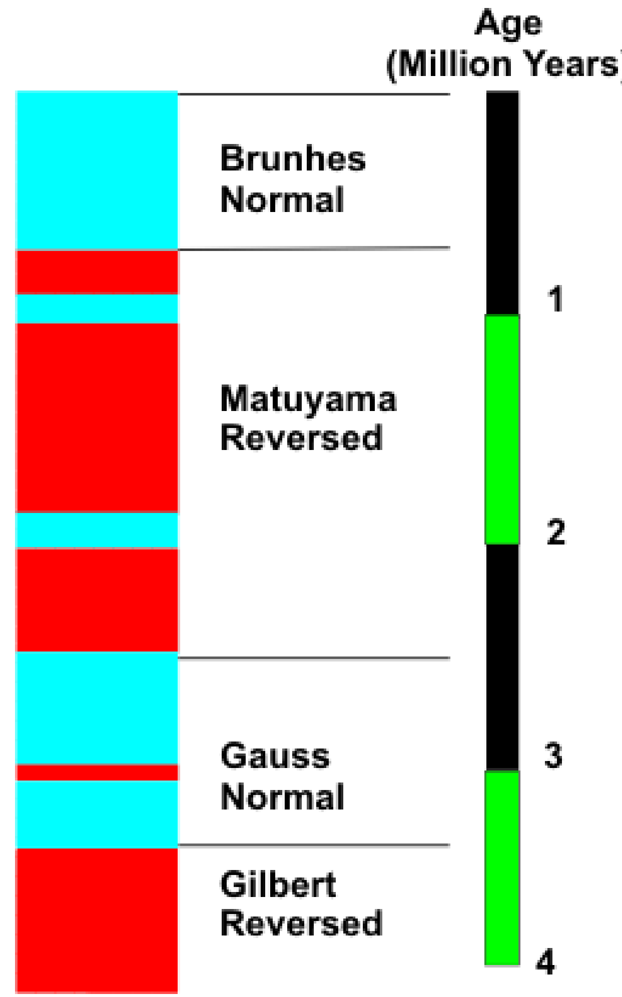
- Reversals have been documented as far back as 330 million years.
- During that time more than 400 reversals have taken place, one roughly every 700,000 years on average.
- The time between reversals is not constant, varying from less than 100,000 years, to tens of millions of years.

Geomagnetic reversal

- In recent geological times reversals have been occurring on average once every 200,000 years, but the last reversal occurred 780,000 years ago.
- At that time the magnetic field underwent a transition from a "reversed" state to its present "normal state“ (Figure .11).

Geomagnetic reversal

Figure 11. The last reversal of geomagnetic field



Mechanisms of geomagnetic reversal

- Although other mechanisms – *such as meteor impacts* – have been postulated, it is generally agreed that reversals occur because of some change in the dynamo process that generates the magnetic field.
- The simplest explanation is that convection in the outer core ceases, allowing the magnetic field to decay.
- Eventually, heat build up will start convection going again and a new field will form whose polarity will depend on the polarity of any residual field at the spot where convection restarts.

Mechanisms of geomagnetic reversal

- Ultimately, the occurrence of reversals must be related to changes in the fluid flow in the outer core.
- In fact, there is evidence, borne out by computer simulations, that fluid motions try to reverse the field every few thousand years, but that the inner core acts to prevent reversals because the field cannot diffuse as rapidly in the inner core as it can in the fluid outer core.

References

Stacey F. and Davis P., Physics of the Earth, Cambridge University Press, 2008.

- Lowrie, W., Fundamentals of Geophysics, Cambridge University Press, 2007.