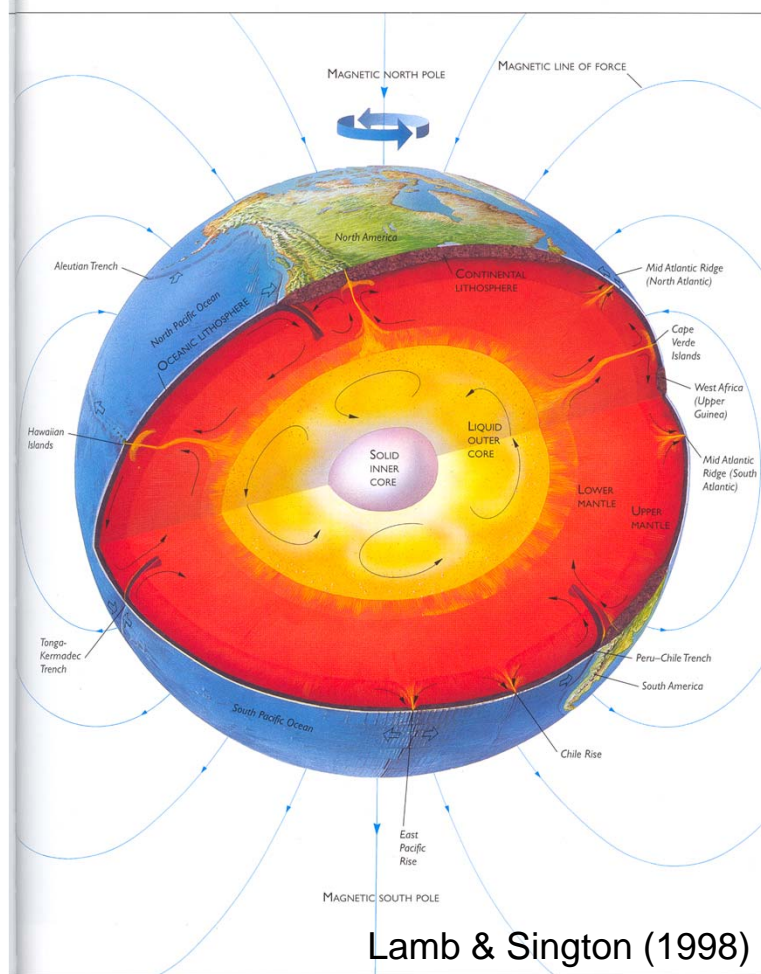


## 3.1 Introduction

# 3. Magnetostratigraphy

### Origin of the Earth's geomagnetic field

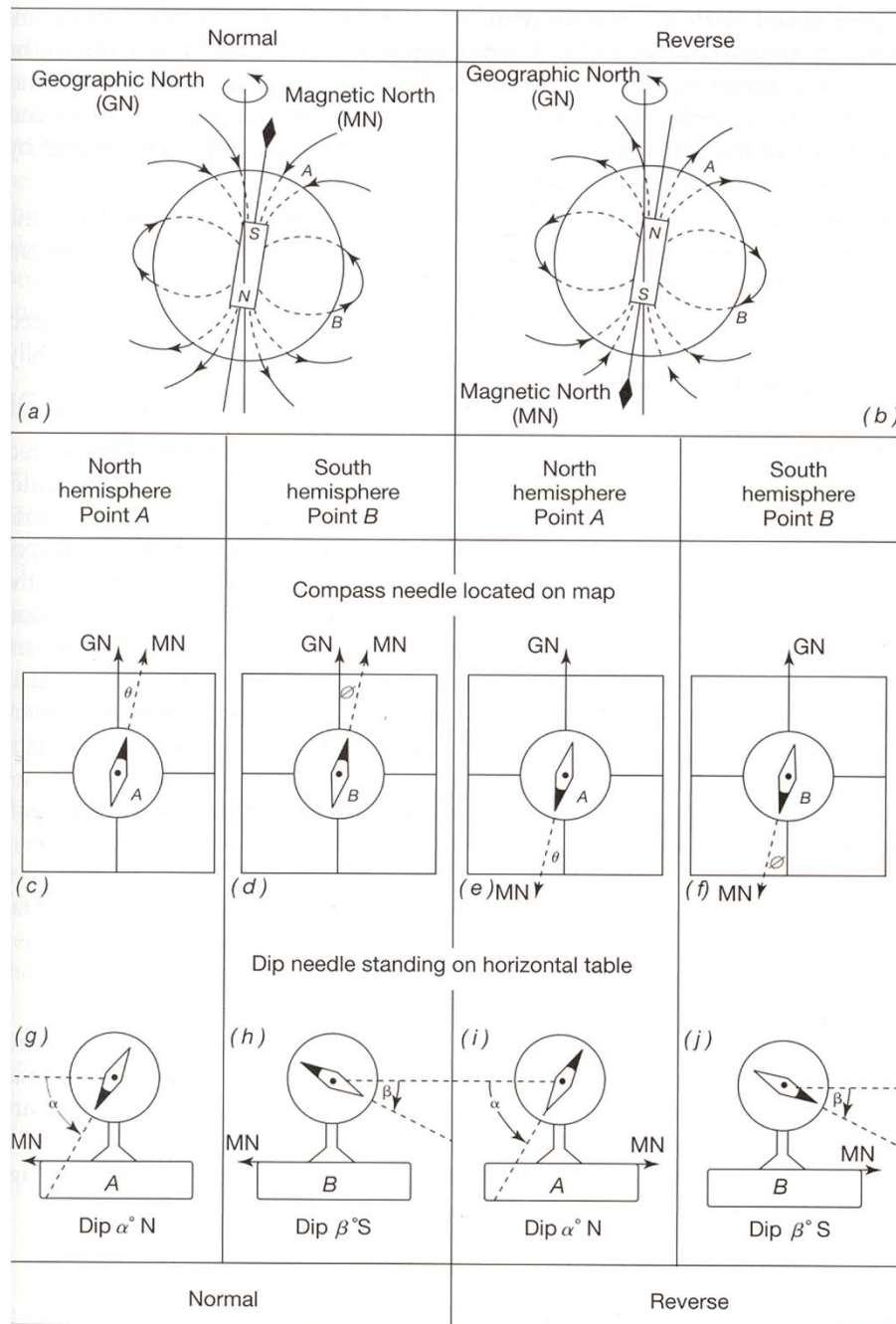
The geomagnetic field is generated in some poorly understood way by the motion of highly conducting nickel-iron (Ni-Fe) fluids in the outer part of Earth's core; this motion is assumed to be controlled by thermal convection and by the Coriolis force generated by Earth's rotation, constituting what is called a **self-exciting dynamo**.



### The Earth's magnetic field

When Earth's magnetic field has the present orientation, it is said to have **normal polarity**. When this orientation changes  $180^\circ$ , it has **reversed polarity**. Studies of the remanent magnetism in igneous and sedimentary rocks show that the dipole (main) component of Earth's magnetic field has reversed its polarity at irregular intervals from Precambrian time onward, apparently owing to instabilities in outer-core convection.

Reversals of Earth's magnetic field are recorded in sediments and igneous rocks by patterns of normal and reversed remanent magnetism. These geomagnetic reversals are contemporaneous worldwide phenomena. Thus, they provide unique stratigraphic markers in igneous and sedimentary rocks. The reversal process is thought to take place over a period of 1,000 – 10,000 years.



**Declination:** The angle between geographic north and magnetic north.

**Inclination:** The angle between the horizontal and a magnetic vector. Conventionally, a vector with a magnetic north pole dipping below the horizontal is considered positive, and an upward vector is negative. Positive inclination in the Northern Hemisphere indicates normal polarity; negative inclination means reversed polarity.

Boggs (2001)

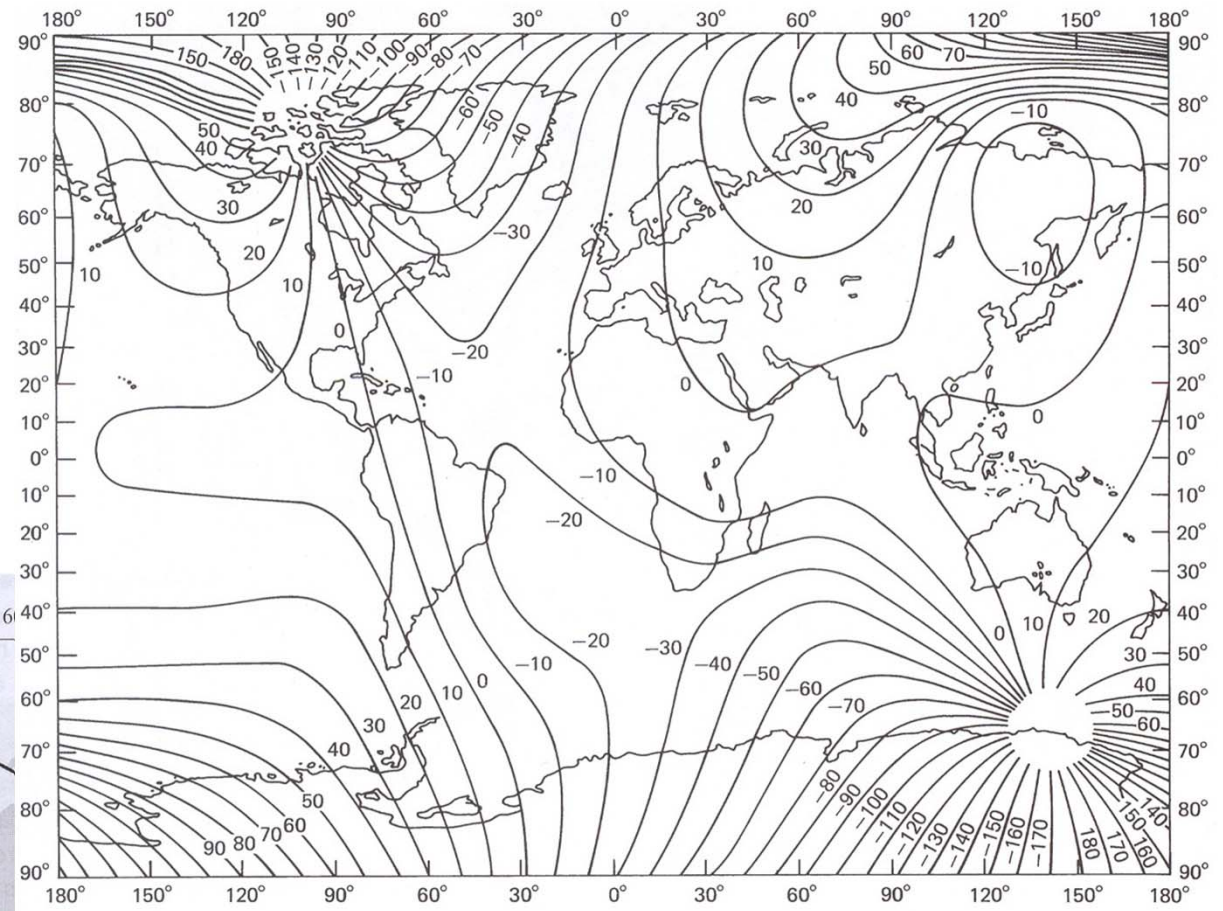
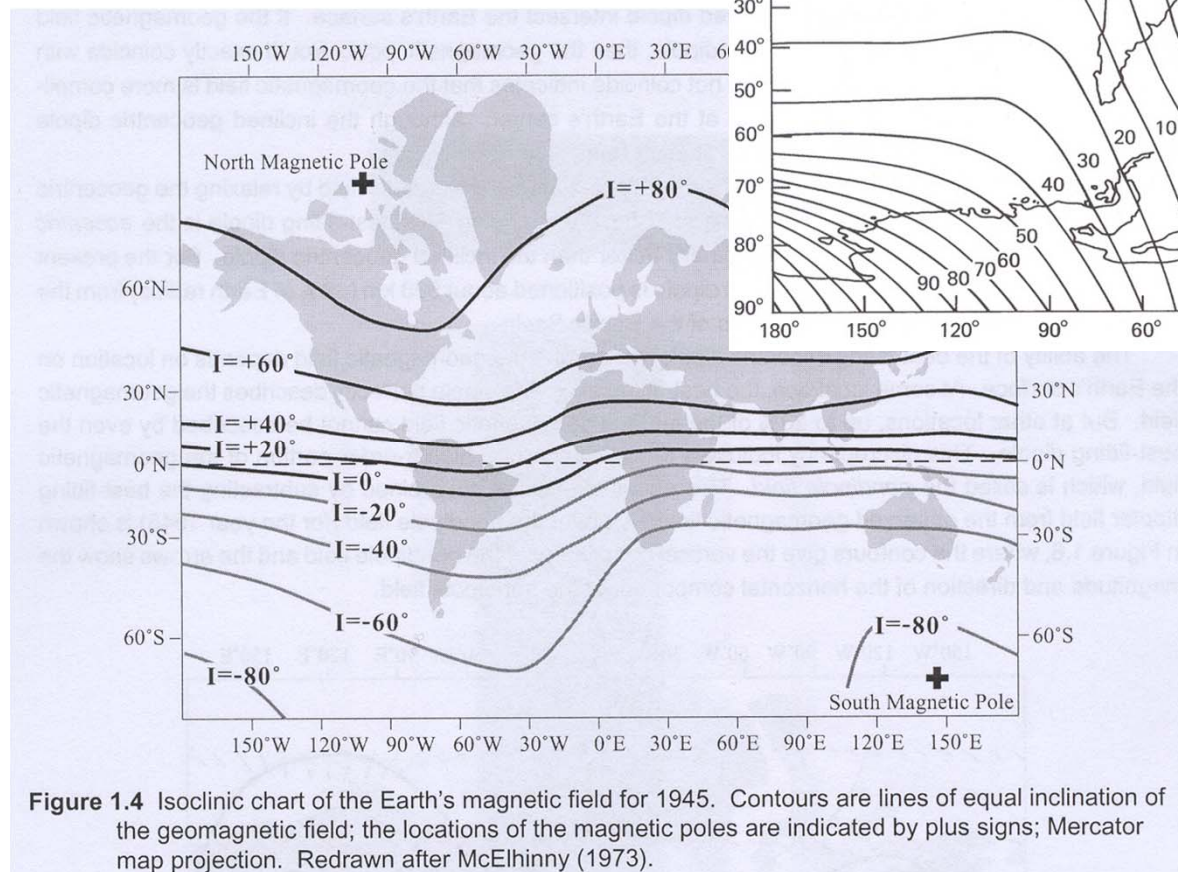
**Figure 16.1**

Schematic representation of Earth's magnetic field during episodes of (a) normal and (b) reversed polarity. The diagram also shows behavior during these episodes of a horizontal compass needle (c–f) and a vertical compass needle (g–j) at two different points (A and B) on Earth. [From Wylie, P. J., 1976, *The way the Earth works*: John Wiley and Sons, Inc., Fig. 9.1, p. 120, reprinted by permission.]



Present-day declination

Present-day inclination



Butler (1992)

## 3.2 Remnant magnetism in rocks

Remnant magnetism (殘磁性)

The magnetization remaining after the removal of an externally applied field, and exhibited by ferromagnetic materials.

**Curie temperature or point ( $T_c$ , 居禮溫度):** The temperature at which thermal vibration prevent quantum-mechanical coupling between atoms, thereby destroying any ferromagnetism.

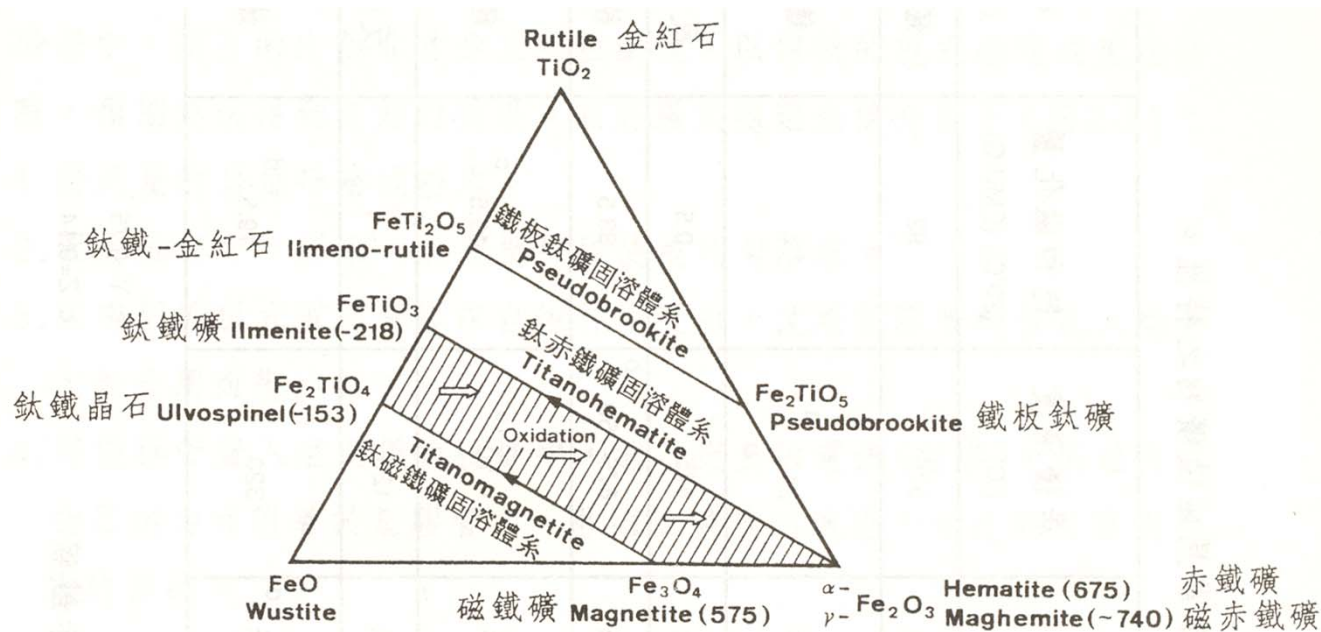


圖 2-1 鈦鐵氧化物三相圖。斜線區域為磁性礦物的成份分佈。主要磁性礦物的居禮溫度 ( $^{\circ}\text{C}$ ) 示於括弧中。細箭頭為鈦磁鐵礦與鈦赤鐵礦兩固溶體系居禮溫度遞減的方向，空心箭頭為氧化作用時成份改變的方向。

洪崇勝 (1991)

**Magnetic minerals (磁性礦物)**

Common magnetic minerals belong to two solid-solution series: the **titanomagnetites** (鈦磁鐵礦固溶體系), for which  $T_c$  ranges from about  $200^{\circ}\text{C}$  to  $575^{\circ}\text{C}$ , e.g. magnetite (磁鐵礦),  $575^{\circ}\text{C}$ ; and the **titanohematites** (鈦赤鐵礦固溶體系), with values of  $T_c$  up to  $675^{\circ}\text{C}$ , e.g. hematite (赤鐵礦),  $675^{\circ}\text{C}$ .

## **Natural remnant magnetism (NRM, 自然殘磁性)**

NRM is remnant magnetization present in a rock sample prior to laboratory treatment. NRM depends on the geomagnetic field and geological processes during rock formation and during the history of the rock. NRM typically is composed of more than one component. The NRM component acquired during rock formation is referred to as **primary NRM** and is the component sought in most paleomagnetic investigations. However, **secondary NRM** components can be acquired subsequent to rock formation and can alter or obscure primary NRM.

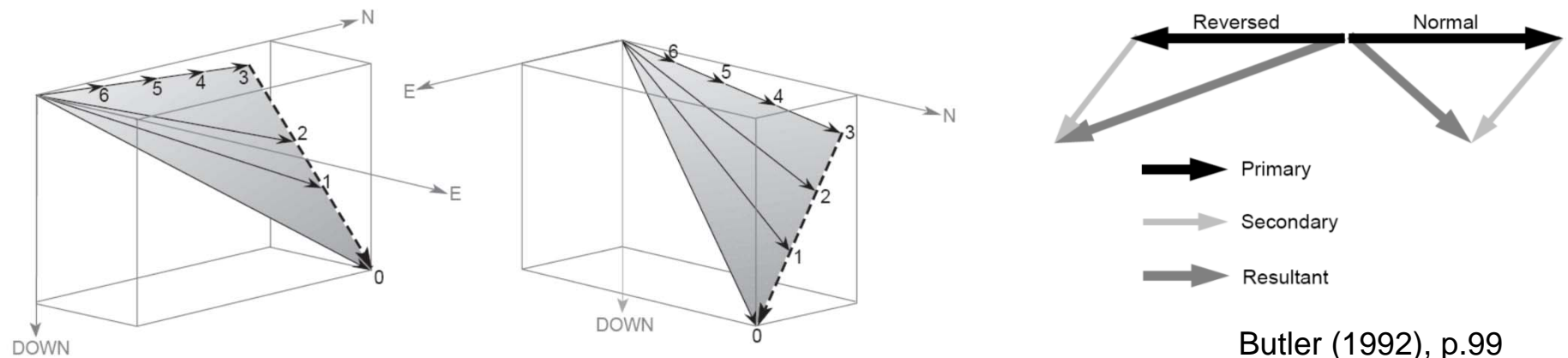
$$\text{NRM} = \text{primary (原生) NRM} + \text{secondary (次生) NRM}$$

The three basic forms of **primary NRM** are:

1. **Thermal remnant magnetization (TRM)**: acquired during cooling from high temperature. Thermal remnant magnetism is produced by cooling from above the Curie temperature ( $T_c$ ) in the presence of a magnetic field.
2. **Chemical remnant magnetization (CRM)**: formed by growth of ferromagnetic grains below Curie temperature. Chemical reactions involving ferromagnetic minerals include (a) alteration of a preexisting mineral to a ferromagnetic mineral or (b) precipitation of a ferromagnetic mineral from solution, e.g. hematite formed during diagenesis of “Red Sandstone”.

**3. Detrital remnant magnetization**, acquired during accumulation of sedimentary rocks containing detrital ferromagnetic minerals. During deposition of sediments, small magnetic mineral grains are able to rotate in the loose, unconsolidated sediment on the depositional surface and thus align themselves mechanically with Earth's magnetic field. This (statistically) preferred orientation of magnetic minerals in sedimentary rocks imparts bulk magnetic properties to the rocks, referred to as depositional, or **detrital remnant magnetism**.

**Secondary NRM** can result from chemical changes affecting ferromagnetic minerals (e.g. alteration of one magnetic mineral to another), exposure to nearby lightning strikes, or long-term exposure to the geomagnetic field subsequent to rock formation. Demagnetization techniques (two methods: 1. alternating field demagnetization --交流磁場去磁; and 2. thermal demagnetization – 熱去磁) are available for destroying this secondary magnetic effect in the lab so that the primary magnetization can be measured.



Butler (1992), p.99

**Figure 5.3** Perspective diagram of NRM vector during progressive demagnetization. Geographic axes are shown; solid arrows show the NRM vector during demagnetization at levels 0 through 6; the dashed arrow is the low-stability NRM component removed during demagnetization at levels 1 through 3; during demagnetization at levels 4 through 6, the high-stability NRM component decreases in intensity but does not change in direction.



# Measuring, and displaying remnant magnetism

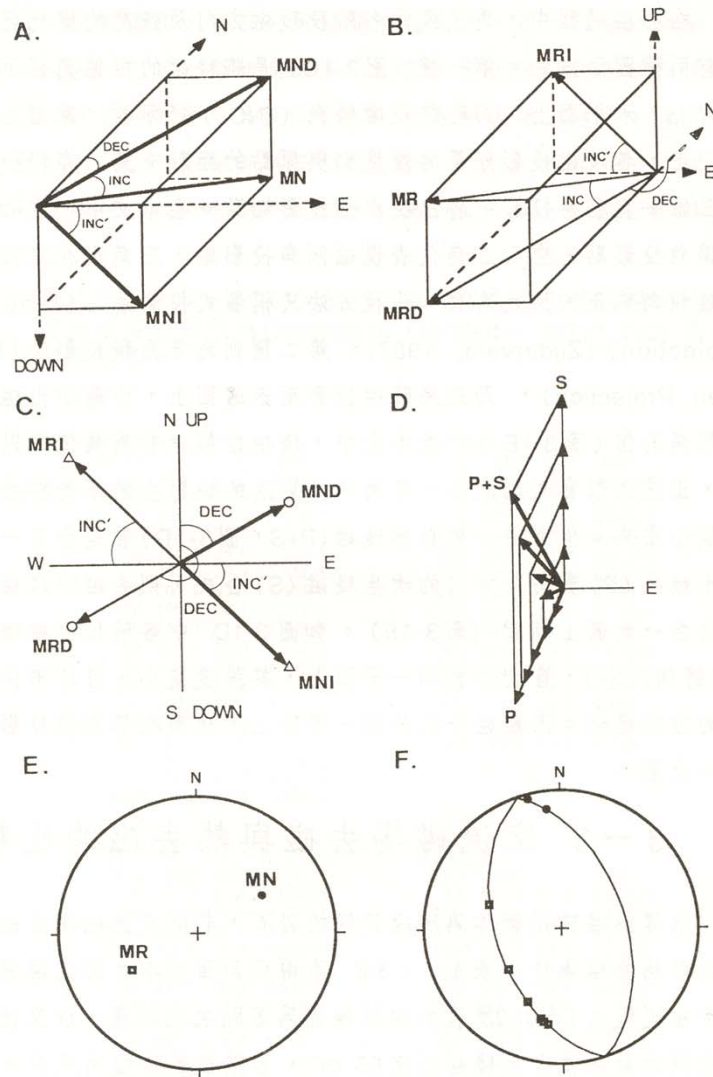


圖3-1 殘磁向量的表示。A. 正向殘磁MN。B. 反向殘磁MR。C. 正反向殘磁的翟氏投影。D. 自然殘磁(P+S)由原生殘磁(P)與另一次生殘磁(S)合成，其去磁時的殘磁變化如粗箭頭所示。E. 正反向殘磁的等面積投影。F. 為D.圖殘磁方向的等面積投影。

Inclination and declination together define the geomagnetic field vector. Inclination is a function of the latitude at which the rock specimens formed and declination shows the deviation of the ancient paleomagnetic pole from the geographic pole. A remanent magnetic vector (MN in the following figure A) can be represented by two components: (1) horizontal component (MND); and (2) vertical component (MNI).

Figure D shows that the NRM has two components: primary (P) and secondary (S) NRM. Applying demagnetization techniques on samples will progressively remove the secondary NRM and retain the primary NRM. This progressive process can be displayed by two methods:

- (1) **Construction of vector component diagram** (Figure C in the following figure): (1) project the MN vector on a horizontal (N-S-E-W) plane (MND), using the angle of declination (DEC) and the intensity of the MND vector; (2) project the MN vector on a vertical (up-down-E-W) plane (MNI).
- (2) **Equal-area projection** (the Lambert or Schmidt projection) (Figures E and F)

### 3.3 Development of the magnetic polarity time scale (GPTS)

Magnetostratigraphy is the application of the chronology of reversals in polarity of the geomagnetic field to the study of the stratigraphy of layered materials (i.e. sedimentary and volcanic rocks).

An essential criterion for accurate magnetostratigraphic work is a reliable timescale for the reversal chronology of the Earth's magnetic field: hence the development of the **geomagnetic polarity time scale (GPTS)**.

A story on the development of magnetostratigraphy and GPTS:

© Motonari Matuyama (a Japanese) first found in 1929 that some volcanic rocks record reverse south-pointing magnetism. But this idea received no attention until 1960s.

First magnetic survey on ocean floor supervised by Arthur Raff was carried out off the west coast of the North America in 1958. This survey found that the magnetic map of the ocean floor is characterized by stripes of highs and lows of the magnetic anomaly. But nobody knows why.

Fred Vine (a Cambridge Ph.D. student) and his supervisor Drummond Matthews, using magnetic stripes near Carlsberg Ridge (Indian Ocean) and Harry Hess's idea of "sea-floor spreading", proposed in 1963 that the alternately magnetized stripes are the result of sea-floor spreading.

The first convincing proof of Vine's idea was obtained in 1966. Tuzo Wilson surveyed the magnetic anomalies **either side** of the mid-ocean ridge (*Eltanin* profile) in the Pacific Ocean, south of Easter Island. The *Eltanin* magnetic profile shows remarkable symmetry of the magnetic anomalies about the mid-ocean ridge. These observations led to the plate tectonics paradigm.

© Magnetostratigraphy developed since mid-1960s.

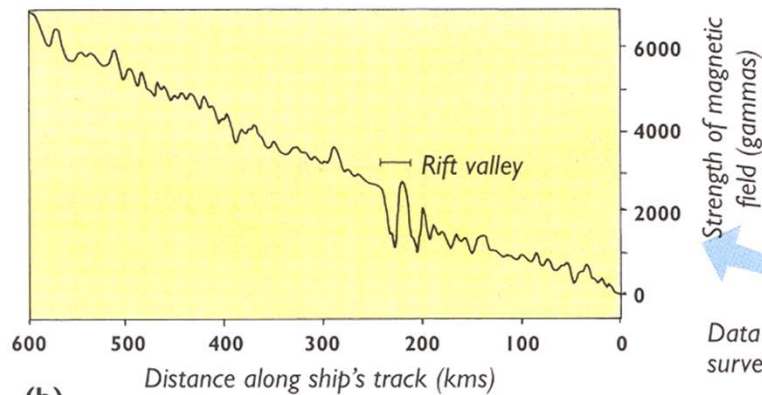
© Initially applied to volcanic rocks and young (<5 Ma) sediments.

Detailed magnetostratigraphy has been extended to the Jurassic.

Recent combination of high-precision  $^{40}\text{Ar}/^{39}\text{Ar}$  isotope dating and magnetic polarity data for igneous rocks has led to improved estimates of ages of the GPTS, particularly for the Cenozoic.

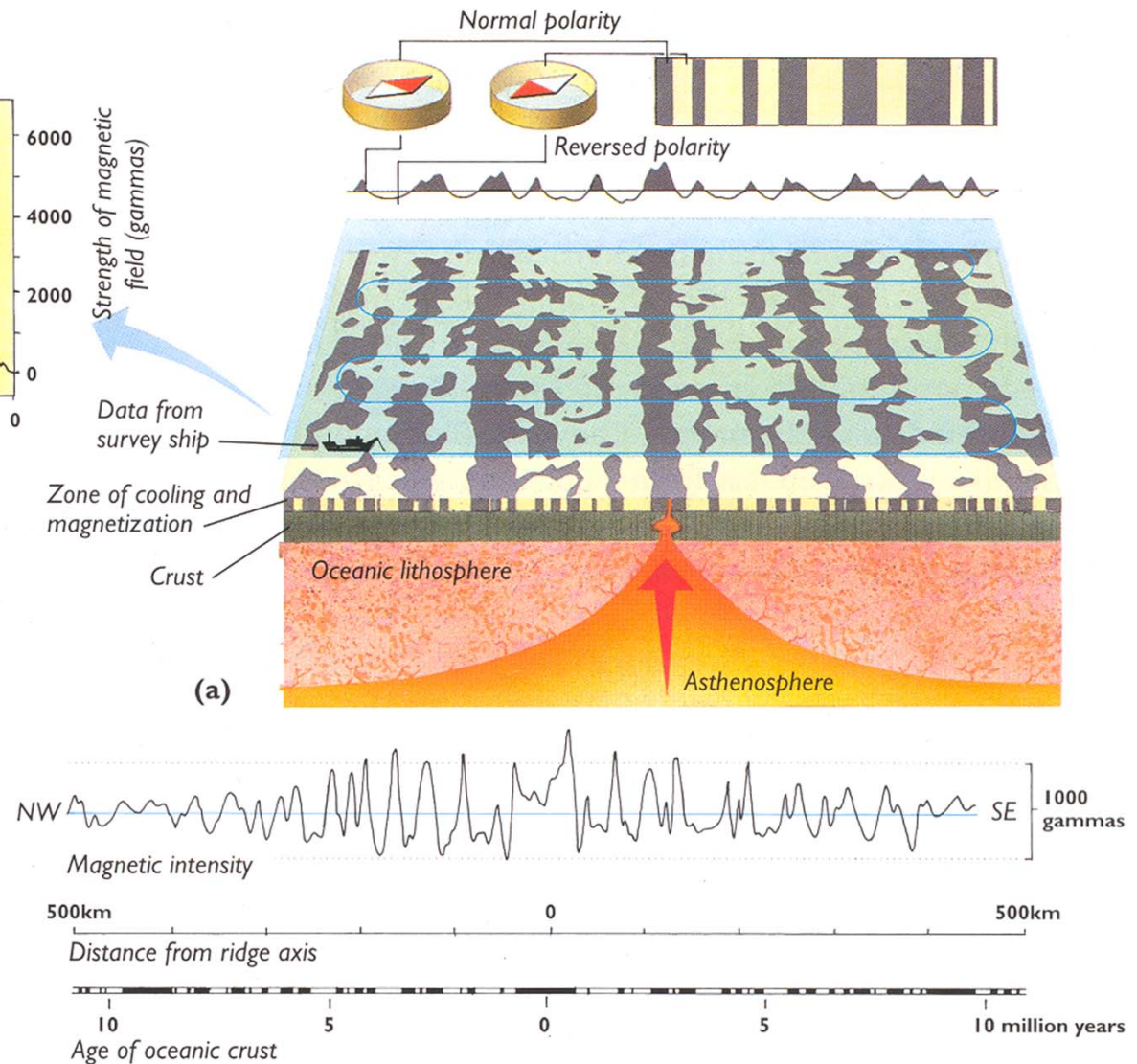


## OCEAN MAGNETIC ANOMALIES



(b)

Geophysicists tow magnetometers behind ships as they sail over the mid-ocean ridge (a). Instead of a smooth variation, the strength of the Earth's magnetic field fluctuates, giving rise to a series of anomalies (b). Anomalies detected on adjacent ships' tracks can be joined up to reveal a stripey pattern of magnetic anomalies in the oceans which are parallel to the mid-ocean ridge. When ocean crust is created along the axis of the mid-ocean ridge, it is magnetized by the Earth's magnetic field. However, because the polarity of the Earth's magnetic field has reversed from time to time, the direction of this magnetization has also reversed, creating the observed magnetic anomalies – the anomalies can be used to date the oceanic crust.



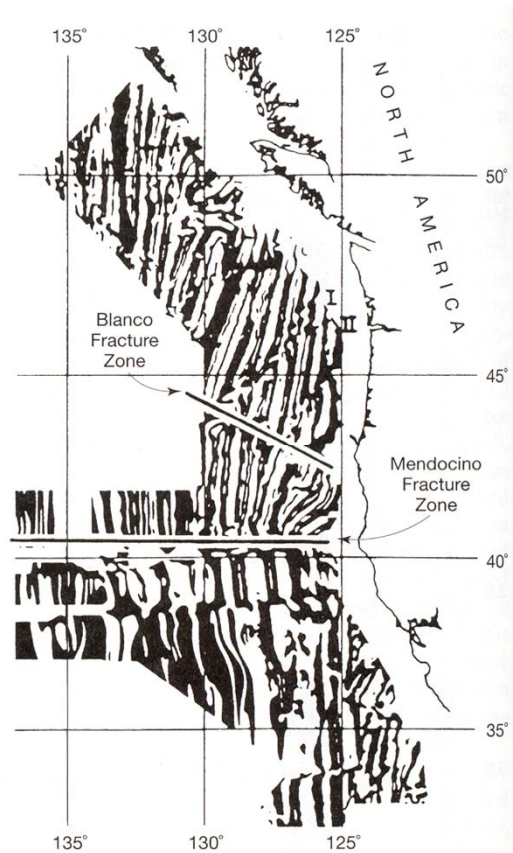
(c) Eltanin profile showing the symmetrical pattern of magnetic anomalies about the ridge axis (see p.53).

Eltanin Profile

## The first magnetic anomaly map

**Figure 16.5**

Linear magnetic anomaly pattern in the northeastern Pacific. Positive anomalies (normal polarity) are black. [After Mason, R. G., and A. D. Raff, 1961, Magnetic survey of the west coast of North America, 32°N. latitude to 42°N. latitude: *Geol. Soc. America Bull.*, v. 72, Fig. 1, p. 1260; and Raff, A. D., and R. G. Mason, 1961, Magnetic survey of the west coast of North America, 40°N. latitude to 52°N. latitude: *Geol. Soc. America Bull.*, v. 72, Fig. 1, p. 1268; as modified by Conde, K. C., 1982, *Plate tectonics and crustal evolution*, 2nd ed., Fig. 4.22, p. 65, reprinted by permission of Pergamon Press, New York.]



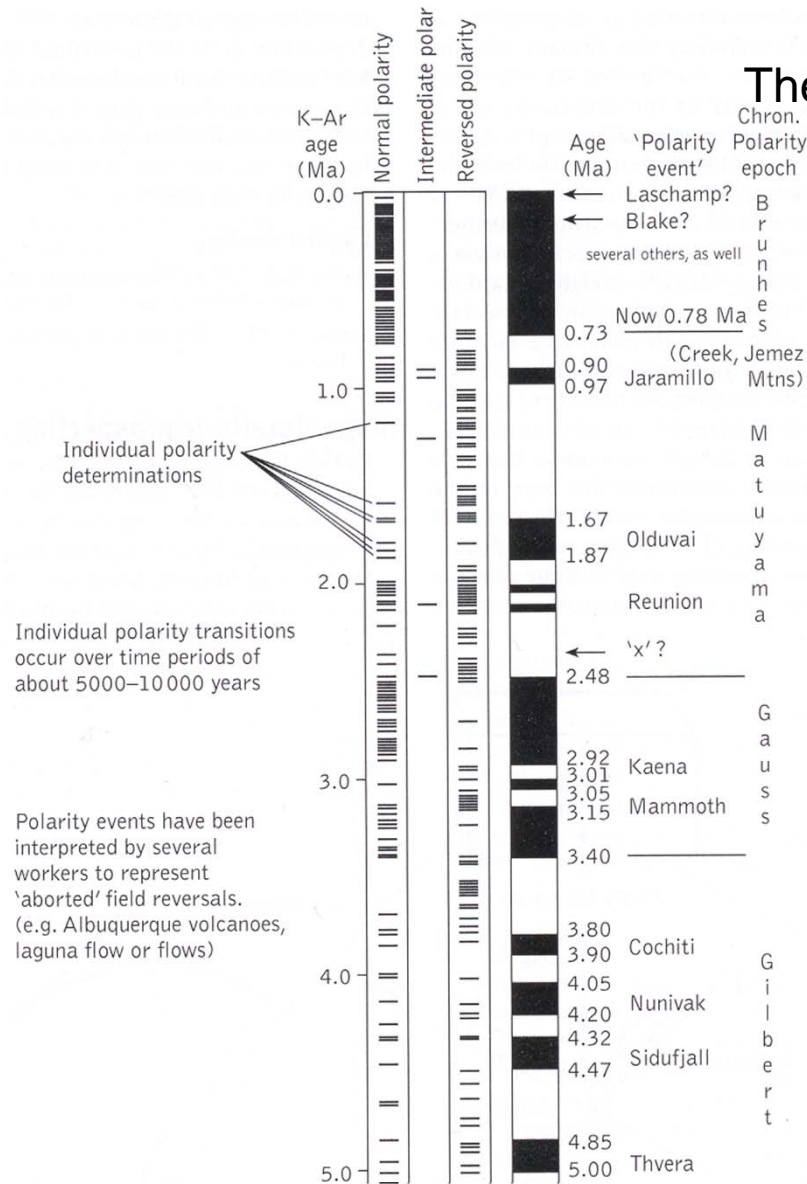
Boggs (2001)

Magnetostratigraphic studies have several goals, among which are:

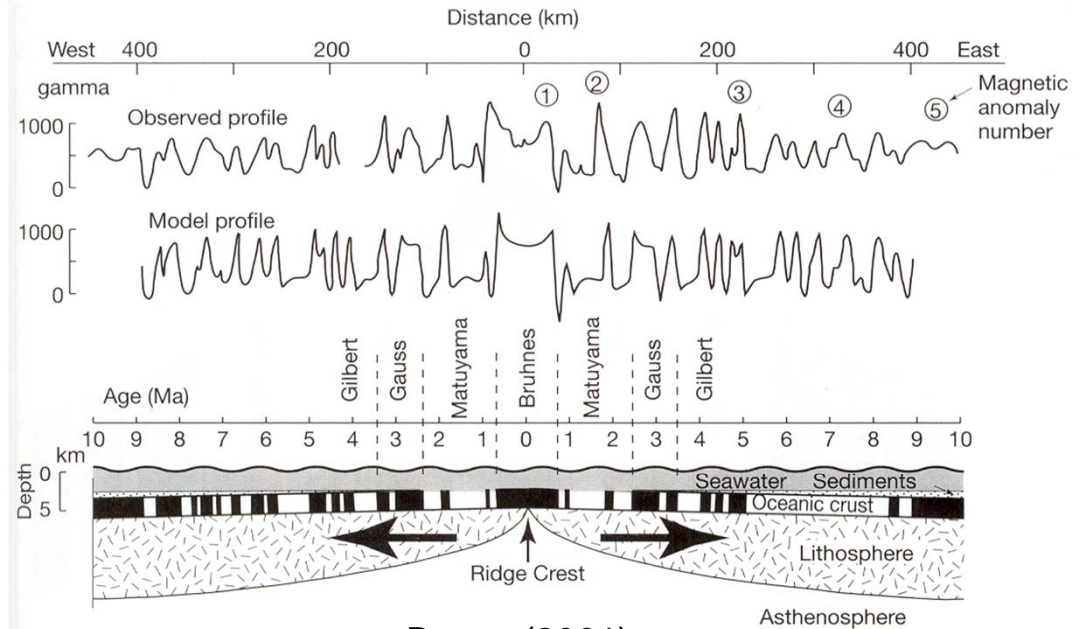
1. Defining the polarity history of the Earth, in particular prior to about 160 million years, the age of the oldest oceanic lithosphere yielding interpretable marine magnetic anomaly data;
2. Time correlation of different sections of strata; and
3. Determination of absolute ages of overall sections of strata where independent information (e.g. isotopic age data) is available.



## The GPTS for the past 5 m.y.



**Fig. 1.** Part of the geomagnetic polarity timescale (GPTS) for the latest Cenozoic. In the timescale, black refers to a period of time (magnetozone) where the Earth's field is dominantly normal polarity; white to a magnetozone where the field is dominantly of reverse polarity. At the present, that is, in the Brunhes normal polarity magnetozone, for example, there is evidence for at least five different and independent short-lived, unsuccessful field reversals, the most recent of which was



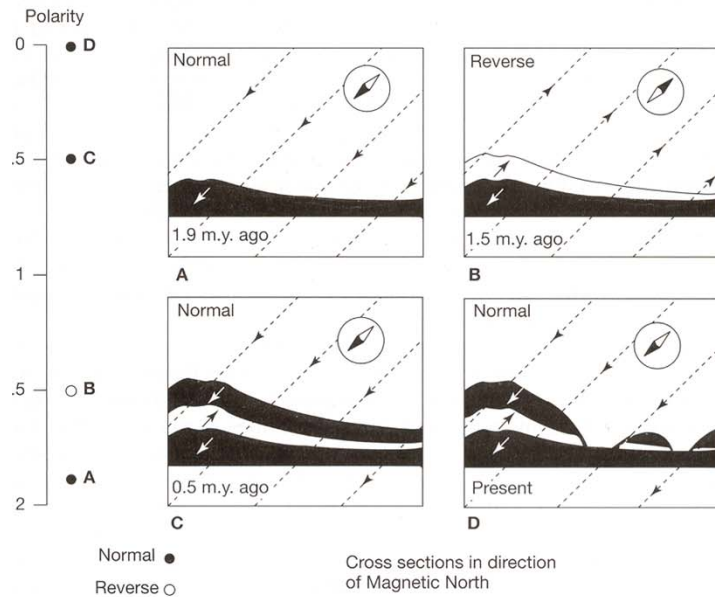
**Figure 16.6**

Boggs (2001)

Formation of marine magnetic anomalies at an oceanic ridge undergoing seafloor spreading. The oceanic crust is the upper part of the oceanic lithosphere forming at the ridge crest and being covered by oceanic sediments. The black blocks of oceanic crust represent normally polarized thermal remanent magnetism (TRM) and the white blocks indicate reversed polarity remanent magnetism. TRM was acquired during original cooling of the oceanic crust. [After Butler, R. F., 1992, *Paleomagnetism: Magmatic domains to geologic terranes*: Blackwell Scientific Publications, Fig. 9.4, p. 215. Based on data from Pitman and Heirtzler, 1966. Reproduced by permission of Blackwell Science Ltd.]

about 30 000–40 000 years ago. This geomagnetic polarity timescale was compiled by Ed Mankinen and G. Brent Dalrymple of the US Geological Survey in 1979. The ages of many of the magnetozone boundaries have been refined since this compilation. For example, the age of the Matuyama to Brunhes polarity reversal is now considered to be about 780 000 years.

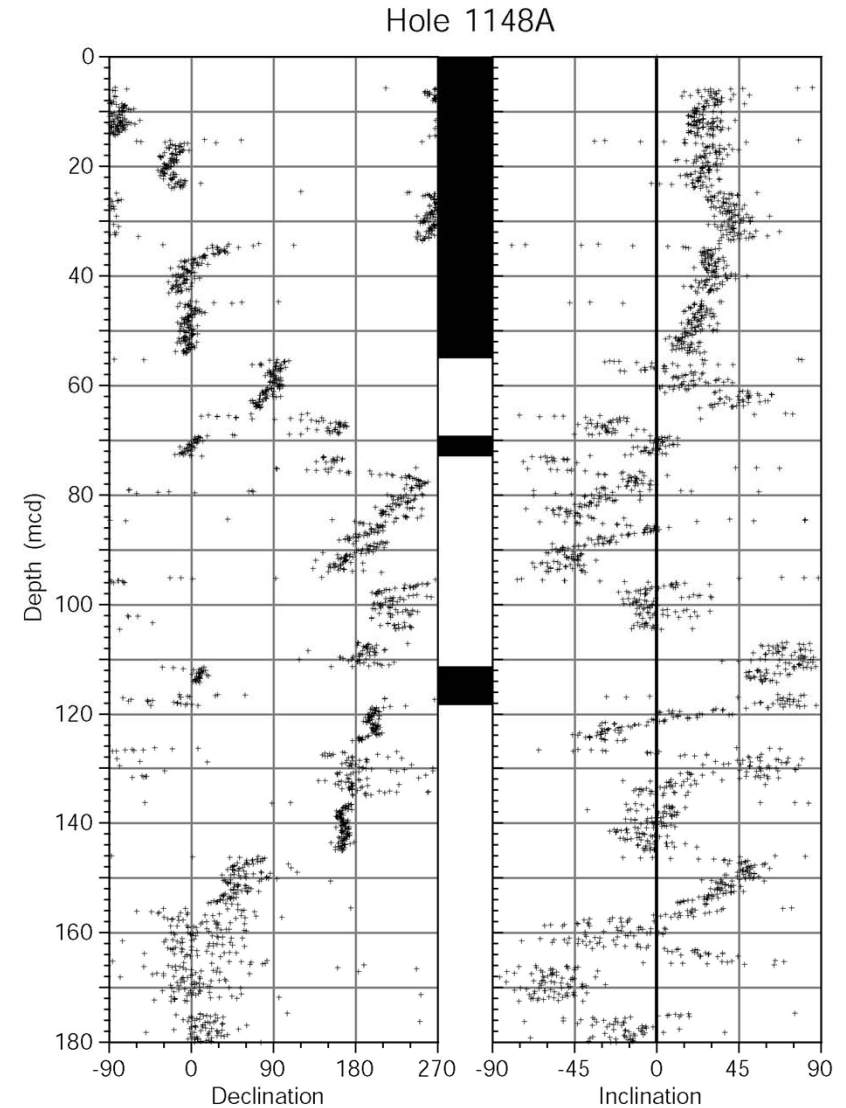
## Diagram showing the magnetic polarity developed in layered materials.



**Figure 16.3**  
A, B, C. Diagrammatic representations of the magnetic polarity developed in three lava flows that erupted during the last 2 million years. Each of these lavas became magnetized at the time of eruption, with the direction of magnetization oriented parallel to the magnetic lines of force (dashed arrows) around Earth. D. Present time, showing retention of magnetic polarity. By measuring the radiometric ages of the lavas, geologists can construct a polarity time scale (left). [From Wylie, P. J., 1976, *The way the Earth works*: John Wiley and Sons, Inc., Fig. 9.2, p. 122, reprinted by permission.]

Boggs (2001)

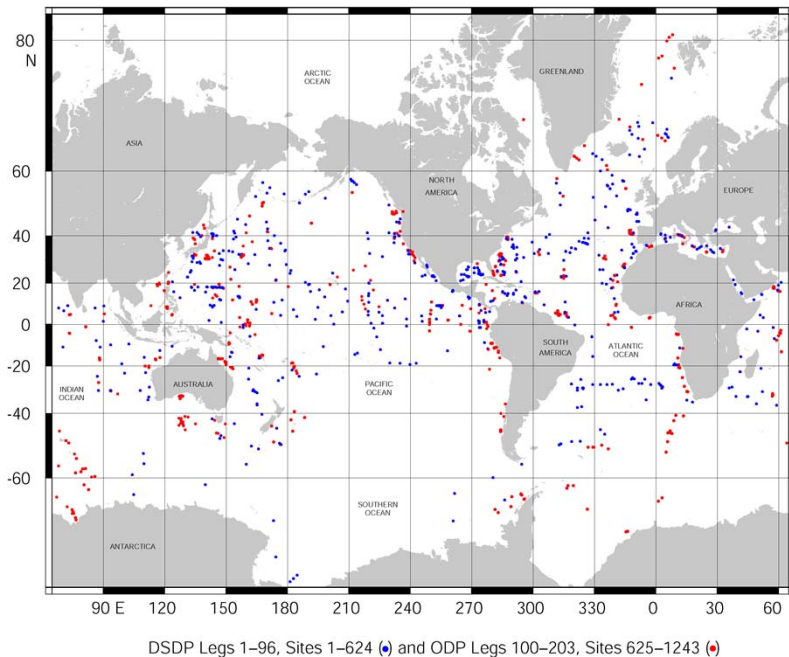
**An example of displaying declination and inclination of primary natural remnant magnetism (from ODP Leg 184 site 1148, South China Sea, Wang et al. 2000).**





## Establishing the Geomagnetic Polarity Time Scale

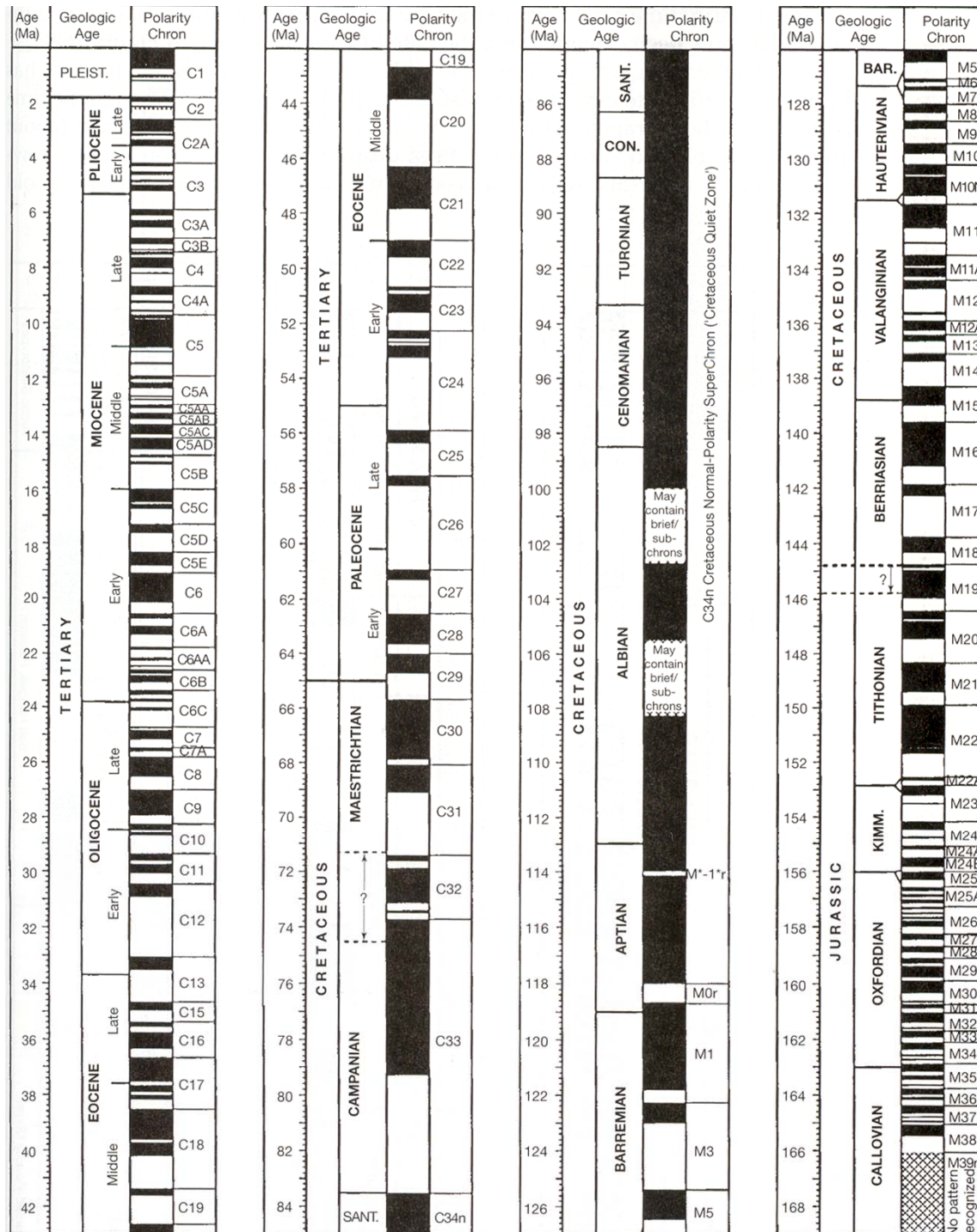
1. Measuring the magnetic polarity and dating the absolute ages of layered volcanic rocks (Cox, Doell, and Dalrymple, 1963). This approach initially applied to young ( $< 5$  Ma) volcanic rocks by using K-Ar techniques to estimate the ages of the rocks. The “young” rocks approach is because the precision of K-Ar dates is  $\pm 2\%$ . For rocks older than 5 Ma, the error is equivalent to  $\pm 0.1$  m.y., which is longer than the duration of many of the shorter polarity intervals.
2. Linear magnetic anomalies on the seafloor. Ages of older (e.g.  $> 5$  Ma) magnetic anomalies can be estimated by extrapolating ages on the basis of rates of seafloor spreading (c.f. Heirtzler et al. 1968 and Cande and Kent, 1992, Late Cretaceous to Cenozoic).



3. Sediments exposed on land or recovered by coring at the ocean floor (DSDP, ODP) have extended the GPTS into middle Jurassic as calibrated by biostratigraphic zonation and age dates.

4. Continuous land records with good paleontologic calibration allows extension of the GPTS for the Tertiary and late Mesozoic into the Palaeozoic.

Sites (until mid-2002) drilled by ODP (Ocean Drilling Program) and its predecessor DSDP (Deep Sea Drilling Program).



## Magnetic polarity time scale for the Cenozoic-late Mesozoic

Figure 16.8

Magnetic polarity time scale for the Cenozoic-late Mesozoic. Intervals of normal polarity are shown in black, reversed polarity in white. Intervals lacking magnetostratigraphic studies or having uncertain validity are cross-hatched. [Compiled by Ogg, J. G., 1995, Magnetic polarity time scale of the Phanerozoic, in Ahrens, T. J. (ed.), Global Earth physics—A handbook of physical constants: AGU Reference Shelf 1, American Geophysical Union, Washington, D.C., Fig. 2, p. 252, reproduced by permission.]

### 3.4 Nomenclature and classification of magnetostratigraphic units

A **magnetostratigraphic unit** is “a body of rock strata unified by similar magnetic characteristics (not only magnetic polarity) which allows it to be differentiated from adjacent strata”. The magnetic characteristics referred above include: **polarity**, **dipole-field-pole position** (including apparent polar wander), the **non-dipole component** (secular variation), and **field intensity**.

However, it is the magnetic **polarity** that is of use for stratigraphic classification. So, a rock unit defined specifically on the basis of its magnetic polarity is called a **magnetostratigraphic polarity unit**, which is “a body of rock characterized by its magnetic polarity that allows it to be differentiated from adjacent rocks”.

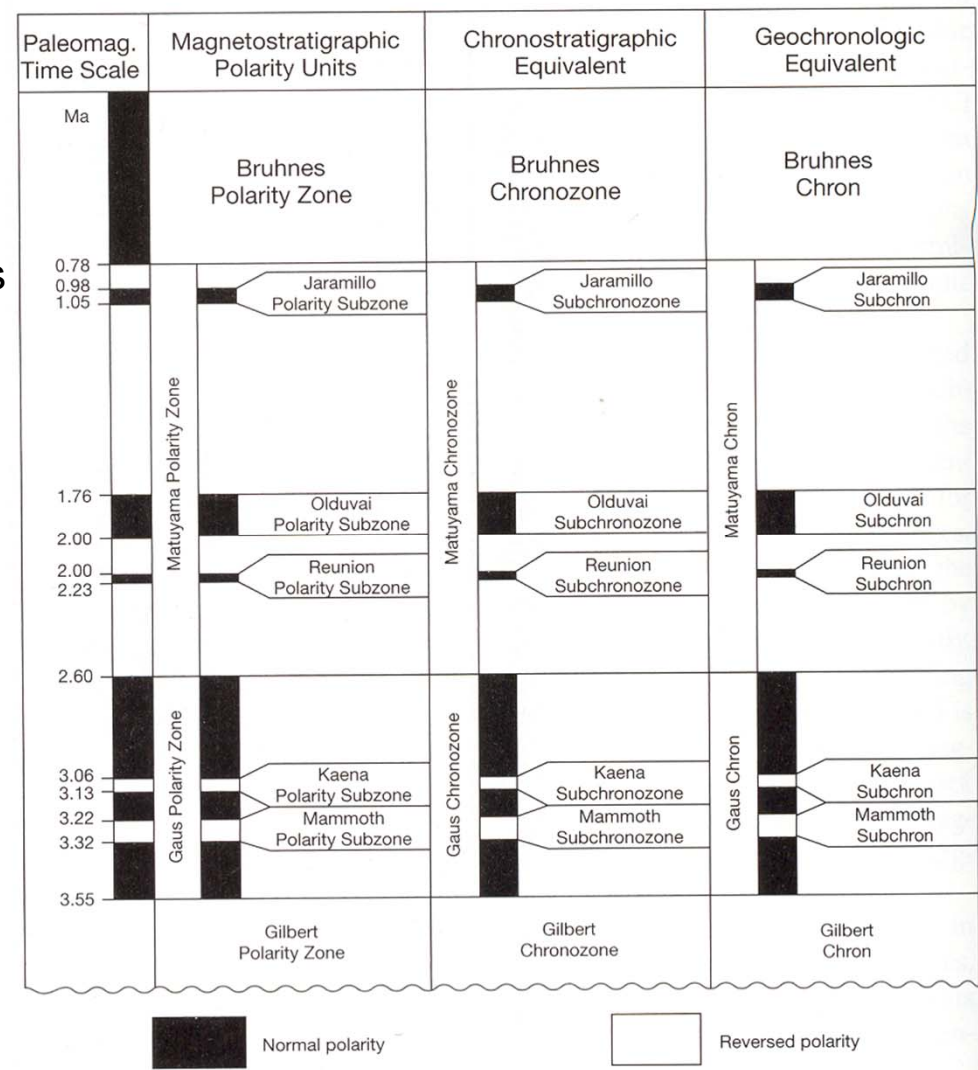
Magnetostratigraphic polarity units are subdivided into polarity superzones, polarity zones, polarity subzones.

The polarity zone is the fundamental polarity unit for subdivision of stratigraphic sections.

Boggs (2001)

**Figure 16.11**

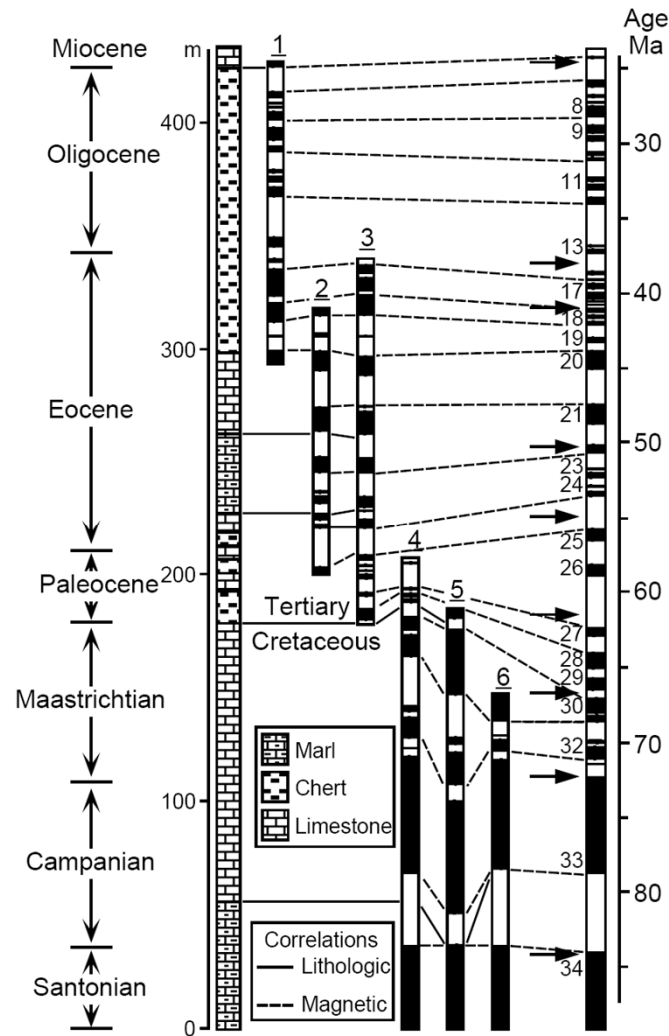
Example of terminology for magnetostratigraphic polarity units as applied to the last 3.5 million years of Earth's history. [After Salvador, A. (ed.), 1994, International stratigraphic guide, International Union of Geological Sciences and Geological Society of America, Inc., Fig. 12, p. 75. Reproduced by permission.]





## 3.5 Applications of magnetostratigraphy and paleomagnetism

### 1. Global or local stratigraphic correlation



Butler (1992)

### 2 Geochronology on nonfossiliferous stratigraphic sections

For examples: Chinese loess (eolian) deposits. Fluvial sediments, etc.

### 3. Plate reconstructions and regional tectonics

Figure

**Figure 9.8** Correlations of Late Cretaceous through Cenozoic magnetostratigraphic sections in the Umbrian Apennines with the marine magnetic anomaly sequence. Age from foraminiferal zonation is shown at left; the dominant lithology is noted on the stratigraphic column (scaled in meters); polarity zones in individual columns are correlated with each other and with the marine magnetic anomaly sequence shown by polarity column at the right (magnetic anomaly numbers and paleontological calibration points (shown by the arrows) are noted at the left side of this column); the section numbers noted at the top of the columns are as follows: 1 Contessa quarry; 2 Contessa road; 3 Contessa highway; 4 Bottaccione; 5 Moria; 6 Furlo upper road. Adapted from Lowrie and Alvarez (1981)