

# D

## DATING, MAGNETOSTRATIGRAPHY

### Introduction

Magnetostratigraphy refers to the application of the well-known principles of stratigraphy to the observed reversal pattern of the geomagnetic polarity recorded in rock sequences. This recording of the ancient geomagnetic field reveals successive intervals with alternating normal and reversed polarity in lava piles and sedimentary sequences. Normal means parallel to the present-day magnetic field (north-directed), while reversed refers to an antipodal south-directed field (Figure D20). As a rule, it appears that these successive intervals of different polarity show an irregular thickness pattern, caused by the irregular duration of the successive polarity zones. This produces a “bar code” in the rock record, which often is distinctive. Polarity intervals have a mean duration of some 250,000 years during the last 35 Myr, but large variations have occurred, ranging from 20,000 yr to several Myr. Once a calibrated “standard” or a so-called “geomagnetic polarity timescale” (GPTS) is constructed, dated by radiometric methods and/or by orbital tuning, one

can match the observed pattern with this standard and hence derive the age of the sediments. Magnetostratigraphy and correlation to the GPTS has become a standard tool in Earth sciences, especially because it can be applied to a wide variety of rock types (volcanic, sedimentary) and in different kinds of environment (continental, lacustrine, marine, etc.) (Opdyke and Channell, 1996; Tauxe, 1998).

### Historical background

In 1269, Petrus Peregrinus carried out a remarkable series of experiments with a spherical lodestone from which he deduced the dipolar nature of the magnet, and he reported his conclusions in his famous “*Epistola de Magnete*,” which is regarded as the first scientific treatise ever written. He also found that the magnetic force is both strongest and vertical at the poles, and became the first person to formulate the law that like poles repel and opposite poles attract. William Gilbert in 1600 published the results of his experimental studies in magnetism in “*De Magnete*.” He investigated the variation in inclination over the surface of a spherical lodestone and concluded for the first time that “*magnus magnes ipse est globus terrestris*” (the Earth itself is a great magnet). Apart from the spherical form of the



**Figure D20** Schematic representation of the geomagnetic field of a geocentric axial dipole (“bar magnet”). During normal polarity of the field, the average magnetic north pole is at the geographic north pole, and a compass aligns along magnetic field lines, the inclination being positive (downward-directed) in the northern hemisphere and negative (upward-directed) in the southern hemisphere. Conversely, during reversed polarity, the compass needle points to the south, and the inclination is negative in the northern and positive in the southern hemisphere. In the GPTS, periods of normal and reversed polarity are represented by black and white colored intervals, respectively.

Earth, magnetism was the first physical property to be attributed to the body of the Earth as a whole. The physical property of gravitation came 87 years later with the publication of Newton's "*Principia*."

Paleomagnetic studies of igneous rocks provided the first reliable information on reversals. In 1906, Brunhes observed lava flows magnetized in a direction approximately anti-parallel to the present geomagnetic field, and suggested that this was caused by a reversal of the field itself, rather than by some physicochemical property ("self-reversal" mechanism) of the rock. Matuyama (1929) demonstrated that young Quaternary lavas were magnetized in the same direction as the present field (normal polarity), whereas older lavas were consistently magnetized in the opposite direction. In the earliest 1950s, Jan Hospers and his supervisors were the first to realize that the polarity of lava flows could be a powerful stratigraphic correlation tool (Irving, 1988). Improved techniques and the undertaking of extensive investigations in many parts of the world have drastically increased the amount of paleomagnetic information and have now provided us with a very detailed GPTS (e.g., Berggren et al., 1995).

**The geomagnetic polarity time scale**

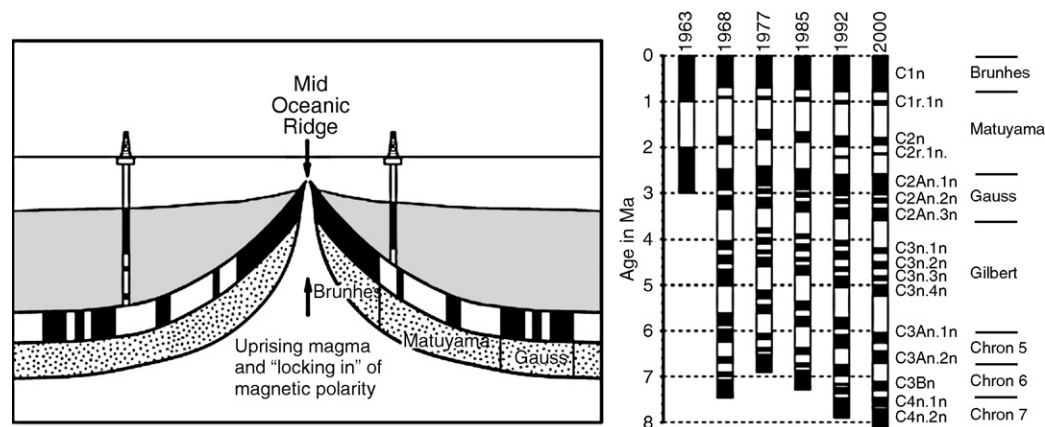
For the construction of the "bar code" pattern of magnetic polarity intervals, scientists rely on two fundamentally different records of geomagnetic polarity history: the marine magnetic anomaly record and the magnetostratigraphic record. Surveys over the ocean basins carried out from the 1950s onward found linear magnetic anomalies, parallel to mid-oceanic ridges, using magnetometers towed behind research vessels. During the early 1960s, it was suggested and soon confirmed that these anomalies resulted from the remanent magnetization of the oceanic crust. This remanence is acquired during the process of seafloor spreading, when uprising magma beneath the axis of the mid-oceanic ridges cools through its Curie temperature (The temperature at which thermal vibrations overcome the tendency toward magnetization. The curie temperature of magnetite is 575°C) in the ambient geomagnetic field, thus acquiring its

direction and polarity (Figure D21). The continuous process of rising and cooling magma at the ridge results in magnetized crust of alternating normal and reversed polarity, which produces a slight increase or decrease of the measured field: the marine magnetic anomalies. It was also found that the magnetic anomaly pattern is generally symmetric on both sides of the ridge, and, most importantly, that it provides a wonderfully continuous tape recording of the geomagnetic reversal sequence.

The template of magnetic anomaly patterns from the ocean floor has remained central for constructing the GPTS from the late Cretaceous onward (110–0 Ma). In addition, combined magnetostratigraphic, biostratigraphic and radiometric results of deep-sea sediments (see *Deep Sea Drilling Project (DSDP)*) and land-based sections have confirmed and refined the general validity and accuracy of the GPTS.

The development of the GPTS continuously shows increasing detail and gradually improved age control through time (Figure D21). Periods of a predominant (normal or reversed) polarity are called chrons, and the four youngest ones are named after persons: Brunhes (normal) who suggested field reversal, Matuyama (reversed) who proved this, Gauss (normal) who mathematically described the field, and Gilbert (reversed) who discovered that the Earth itself is a big magnet. Chrons may contain short intervals of opposite polarity called subchrons, which are named after the locality where they were discovered, e.g., the normal Olduvai subchron within the Matuyama reversed chron is named after Olduvai Gorge in Tanzania, and the Kaena reversed subchron within the Gauss normal chron after Kaena Point on Hawaii. Older periods of the GPTS have been subdivided into polarity chrons designated by the numbers correlated to oceanic magnetic anomalies (e.g., C3An). The polarity chron nomenclature has evolved progressively to accommodate additional polarity chrons (C3An.1n; C3An.2n) according to the chron nomenclature described in Cande and Kent (1992).

The oldest substantial parts of oceanic crust remaining in ocean basins are late Jurassic in age. The determination of the GPTS for older intervals must therefore be done by



**Figure D21** Formation of marine magnetic anomalies during seafloor spreading (*left*). The oceanic crust is formed at the ridge crest, and while spreading away from the ridge it is covered by an increasing thickness of oceanic sediments. The black (white) blocks of oceanic crust represent the original normal (reversed) polarity thermoremanent magnetization (TRM) acquired upon cooling at the ridge. The black and white blocks in the drill holes represent normal and reversed polarity depositional remanent magnetization (DRM) acquired during deposition of the marine sediments. Development of the geomagnetic polarity time scale (GPTS) through time (*right*) shows that the initial assumption of periodic behavior (in 1963) was soon abandoned as new data became available. The first modern GPTS based on marine magnetic anomaly patterns was established in 1968. Subsequent revisions show improved age control and increased resolution.

paleomagnetic studies of exposed stratigraphic sections on land. The best age control for Mesozoic sequences is in the late Triassic, where magnetostratigraphy in combination with cyclostratigraphy on long scientific drill cores in the continental sequences of the Newark basin (NE America) provided a high-resolution, astronomically calibrated GPTS (Kent and Olsen, 1999). For other Mesozoic and older periods, our knowledge of the polarity time scale is much less refined and various intervals are still subject to lack of data and often to serious controversies.

The latest development in constructing a GPTS comes from orbital tuning of the sediment record (see *SPECMAP*). It differs essentially from the conventional GPTS where reversal ages are interpolated between a limited number of (radiometric) calibration points, essentially assuming constant sea-floor spreading between these calibration points. In the astronomically tuned time scale, each reversal boundary – or any other geological boundary for that matter, e.g., biostratigraphic datum levels or stage and epoch boundaries – is dated individually (Hilgen et al., 1997). This directly determines the age of each reversal and has important consequences for (changes in) spreading rates of plate pairs. Instead of having to assume constant spreading rates between calibration points, one can now accurately determine these rates and changes therein. The astronomical polarity time scale (APTS) has provided a breakthrough in dating of the geological record and has significantly increased our understanding of, for example, the (paleo)climate system, since astronomical tuning relies on deciphering and understanding environmental changes driven by climate change, which in turn is orbitally forced (see *Cyclic sedimentation (cyclothem)*s).

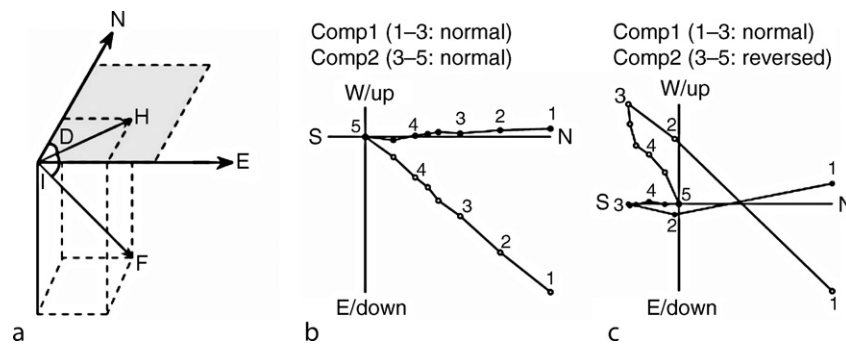
### The paleomagnetic signal in rocks

The ancient geomagnetic field can be reconstructed from its recording in rocks during the geological past (Figure D22). Almost every type of rock contains magnetic minerals, usually iron (hydr)oxides or iron sulfides. During the formation of rocks, these magnetic minerals (or more accurately: their

magnetic domains) statistically align with the then ambient field, and will subsequently be “locked in,” preserving the direction of the field as a natural remanent magnetization (NRM): the paleomagnetic signal.

The type of NRM depends on the mechanism of recording the geomagnetic signal, and we distinguish three basic types: TRM, CRM and DRM. A thermoremanent magnetization (TRM) is the magnetization acquired when a rock cools below the Curie temperature of its magnetic minerals, thereby “locking” the magnetic domains to be statistically aligned along the ambient field. A chemical remanent magnetization (CRM) is the magnetization acquired when a magnetic mineral grows through a critical “blocking diameter” or grain size. Below this critical grain size, the magnetic domains align along the ambient field, while above it the field will be locked and the acquired remanence may again be stable over billions of years. A depositional remanent magnetization (DRM) is the magnetization acquired when magnetic grains, either of detrital origin or formed in situ, and thus already carrying a TRM or CRM, are deposited. The grains statistically align with the ambient field as long as they are in the water column or in the soft water-saturated topmost layer of the sediment. Upon compaction and dewatering, the grains are mechanically locked – somewhere in a “lock-in depth zone” – and will preserve the direction of the ambient field.

As a rule, the total NRM is composed of different components. Ideally, the primary NRM, i.e., originating from the time of rock formation, has been conserved, but often this original signal is contaminated with or even completely overprinted by remanence components acquired later in its geological history, e.g., through weathering, metamorphism or tectonics. A parasitic component or partial overprint can be removed through “magnetic cleaning” or demagnetization procedure. This implies that rock samples must be subjected to various methods to remove stepwise any unwanted or non-original magnetization component, either by increased temperatures or alternating magnetic fields. Such experiments are routine paleomagnetic lab procedures, aimed at retrieving the original acquired magnetization that has recorded the ancient geomagnetic field.



**Figure D22** (a) The magnetic field on any point on the Earth’s surface is a vector ( $F$ ) that possesses a component in the horizontal plane called the horizontal component ( $H$ ), which makes an angle ( $D$ ) with the geographical meridian. The declination ( $D$ ) is an angle from north measured eastward ranging from  $0^\circ$  to  $360^\circ$ . The inclination ( $I$ ) is the angle made by the magnetic vector with the horizontal. By convention, it is positive if the north-seeking vector points downward and negative if it points upward. (b,c) To resolve the different magnetic components that can be acquired in a rock during its geological history, rock samples are subjected to a process of stepwise demagnetization. The standard method for presentation and analysis of the results of demagnetization are called Zijderveld diagrams (after Zijderveld, 1967). changes in vector magnetization during demagnetization involve both its direction and its intensity. The orthogonal vector Zijderveld diagrams show both the changes in intensity and direction. The endpoint of the vector measured after each demagnetization step is then projected both onto the horizontal plane (*closed symbols*) and onto the vertical plane (*open symbols*). Difference vectors (*lines between end points*) then show the behavior of the total vector upon stepwise removal (see text for details).

## Applications

Once the originally recorded geomagnetic field has been retrieved with sufficient accuracy and resolution, the successive intervals of normal and reversed polarity can be faithfully determined. Still, there are several prerequisites for a successful application of magnetostratigraphy as a dating technique for sedimentary sequences. First, one needs to have some approximate (biostratigraphic or radiometric) age control. In addition, the studied sequences must represent a sufficiently long period to reveal a characteristic pattern of reversals (generally >1 Myr during the Cenozoic) to be unambiguously correlated with the standard (GPTS or APTS). Naturally, hiatuses and major changes in sedimentation rate may obscure this “fingerprint” pattern, requiring careful field observations, while sampling resolution must ideally be several times higher than the shortest duration of (sub)chrons (20–30 kyr).

Often, these prerequisites can be met, enabling magnetostratigraphy to be used as a high-resolution age control, which has several fundamental advantages over other dating techniques. Contrary to biostratigraphic datum levels, reversals of the geomagnetic field are fundamentally globally-synchronous events, within sampling resolution, allowing precise correlations between different parts of the world and between different environments (marine vs. continental), regardless of their fossil content or radiometric suitability. Hence, it can be used to study the paleogeographic evolution and paleoclimatic history of different regions over long periods. This enables, for example, detailed continental-marine correlations and hence the determination of synchrony or diachrony of regional or even global paleoclimatic or tectonic events. A successful correlation of the recorded polarity pattern to the GPTS provides accurate ages of every recognized reversal boundary, allowing establishment of rates and rates of change.

Finally, it is very compelling to combine magnetostratigraphy with astrochronology, because (a) it can be used to improve the age control of the standard GPTS (since individual reversals can be directly dated), and (b) it can help increase the resolution of the standard GPTS, since subchrons shorter than 30 kyr are generally not resolved from the ocean floor anomaly patterns. The reliability and completeness of the

GPTS is not only crucial for geochronological purposes, but also for understanding the long-term statistical properties of the geomagnetic field.

Wout Krijgsman and C. G. Langereis

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## Cross references

Cyclic Sedimentation (Cyclothem)  
Dating, Biostratigraphic Methods  
Dating, Radiometric Methods  
Deep Sea Drilling Project (DSDP)  
Mineral Indicators of Past Climates  
SPECMAP

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