Magnetic Anomalies

Definition

A magnetic anomaly is the magnetic field remaining after the Earth's magnetic field has been removed from the observed amplitude of the local magnetic field. The remanent magnetization of rocks records past variations of the geomagnetic field whereby spatial changes in their magnetization give rise to magnetic anomalies. We can date the oceanic crust by studying the unique pattern of lineated positive and negative magnetic anomalies that arise due to past reversals of the geomagnetic field with known age. Besides the primary signal that is related to past polarity reversals, the shape and tiny variations (wiggles) of the anomalies can be used to further constrain the age of the crust. Altogether, magnetic anomalies provide the main source of dating for the oceanic basins and lay the foundations for global plate reconstructions which place important constraints on the development of the lithosphere, biosphere, hydrosphere, cryosphere, and global climate.

Introduction

The Earth's magnetic field (the geomagnetic field) is generated by convection motions in the liquid outer core. The field is not steady but varies with time due to the dynamic of motions within the outer core leading to the ever-changing strength and position of its poles. In extreme cases and in irregular occurrences, hundreds of rapid reversals in the polarity of the field have taken place (Amit et al. 2010). The direction and strength of the geomagnetic field may get permanently imprinted into iron-rich rocks during their formation. The resultant remanent magnetization gives rise to local magnetic fields that generate "magnetic anomalies." Although continental magnetic anomalies may, in certain circumstances, provide some age constraints on the magnetized rocks, it is the marine magnetic anomalies that have crucial implications for the dating of the oceanic crust and serve as the basis for the Mesozoic and Cenozoic global plate reconstruction models (e.g., Seton et al. 2012).

The oceanic crust is formed along mid-ocean ridges, where melt rises and cools to form the crust (Vine and Matthews 1963). The cooling crust becomes magnetized in the direction of the geomagnetic field and retains magnetization proportional to its strength. After initial formation, the newly formed crust moves away and ages progressively from the ridge in a process known as seafloor spreading. In that way, a symmetric and unique magnetization pattern is formed across the spreading ridges. Although the oceanic crust is formed in a complex accretion process that varies in space and time, a remarkably consistent pattern of lineated anomalies are found globally (Maus et al. 2009). This pattern of anomalies predominantly reflects past reversals of the dipolar geomagnetic field and has been calibrated with radioisotopic age control at certain tie points, or astronomical cyclicity in stratigraphic sections, to form the basis for the geomagnetic polarity timescale (GPTS, Cande and Kent 1995; Channell et al 1995). Comparison of the predicted pattern of anomalies (based on the GPTS and a simple two-dimensional magnetic structure) with the observed marine magnetic anomalies (for example see Fig. 1) allows researchers to globally map lines of equal and known age (i.e., isochrones) (Fig. 2).

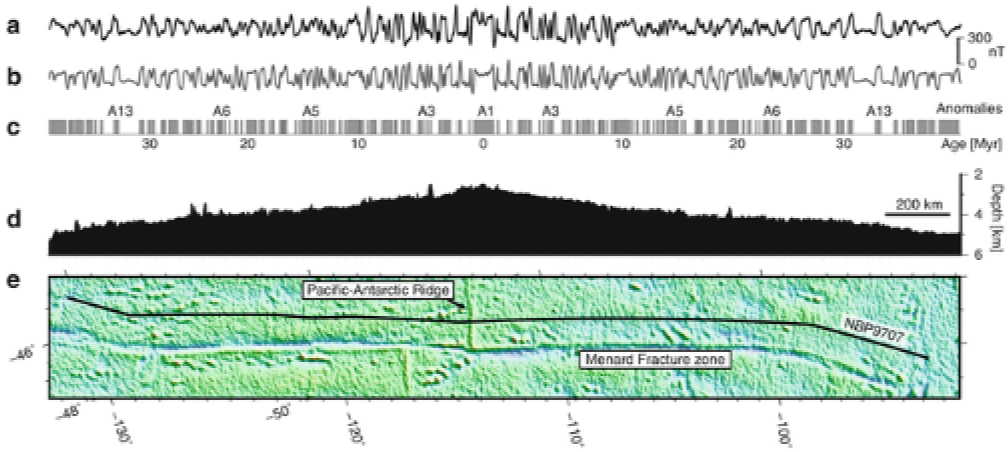

Fig. 1
A representative magnetic anomaly profile (NBP9707 cruise) across the Pacific-Antarctic Ridge. (a) Observed magnetic anomalies along the NBP9707 track. The synthetic magnetic anomaly profile (b) is calculated based on the geomagnetic polarity timescale of Cande and Kent (1995) where the positive chrons used are shown in the bar graph (c). The numbers beneath the graph are ages (in millions of years) and the key polarity chrons are identified above the graph. The forward synthetic model uses this polarity pattern in a 0.5-km-thick source layer that has a mean magnetization of 10 Am^{-1}. Spreading rates that were used to construct the model follow Croon et al. (2008). Seafloor depth (d) was used as the top of the magnetic source layer. The location of the NBP9707 track is shown in panel (e), projected on top of a satellite-derived free-air gravity anomaly map (Sandwell and Smith 2009)

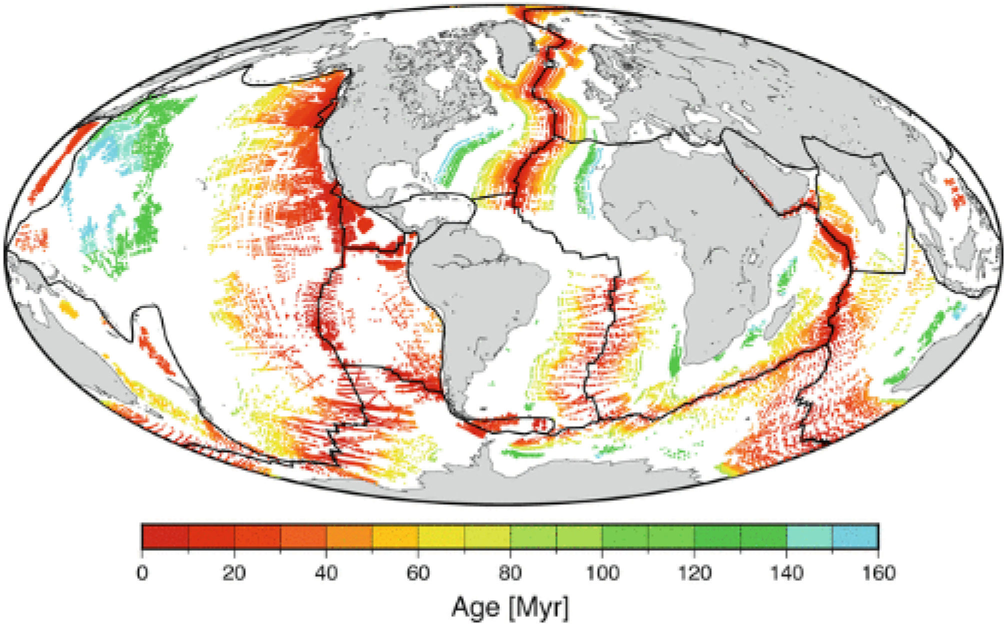

Fig. 2
Identified locations of marine magnetic anomalies with known age (compiled by Seton et al. 2014). Note the absence of identifications in the equatorial regions and in the Cretaceous quiet zones

Magnetic Anomaly Data and Their Physical Properties

The collection of marine magnetic data is traditionally made with magnetometers that measure the magnitude of the magnetic field. To avoid contamination of the signal by the survey platform (e.g., submarine vehicles, ships, helicopters, and airplanes), the magnetometers are usually towed some distance away from the towing platform. The measured values are the summation of the strength of the present-day geomagnetic field and the magnetic fields induced by the igneous crust in the direction of the geomagnetic field. The contribution of the geomagnetic field is computed and subtracted from the total value using the appropriate International Geomagnetic Reference Field model (e.g., Finlay et al.

2010). Minor additions are induced by external magnetic fields but these are usually rather negligible and contain shorter wavelengths as compared to the typical geological signature. These additions can be accounted for using gradiometer data or data collected in a reference magnetic base station. Modern magnetometers have an absolute accuracy of ~1 nanotesla (nT), which is two to three orders of magnitude smaller than the target magnetic anomalies.

The shape of a magnetic anomaly depends on the orientation of the spreading axis, the direction of the ambient geomagnetic field, the magnetization direction of the source rocks, and the shape of the magnetic boundaries. Therefore, in most places, the anomalies are skewed and spatially shifted from the actual location of the magnetization contrasts that generate them. To assign an accurate location for each of the magnetic contrasts with known age, it is essential to take into consideration the various parameters affecting the shape of the anomalies through a comparison against a two-dimensional forward magnetic modeling computed with the appropriate parameters (Blakely 1995 and Fig. 1). The resultant magnetic anomaly picks (Fig. 2) delineate isochrons of the igneous oceanic crust. These isochrons, found on both sides of the spreading ridges, together with fracture zone locations, provide the basis for the computation of relative motions between adjacent plates and serve as the basis for the construction of global plate reconstruction models.

Outstanding Issues

Marine magnetic anomalies have outstanding issues that stem from the physical principles that govern their formation and from limitations that relate to the recorded geomagnetic field. In the equatorial region, where spreading ridges are oriented in a north-south direction parallel to the direction of the geomagnetic field, no obvious (i.e., large amplitude) magnetic anomalies exist. Hence, locating magnetic anomalies there is virtually impossible, leading to the absence of accurate age models for the equatorial Atlantic and Pacific (Fig. 2). Oriented three-axial magnetometers that measure the components of the anomalous field allow the detection of the magnetization boundaries with better confidence (Gee and Cande 2002). Although efforts have recently been made to constrain the age of the oceanic crust in certain equatorial regions (Barckhausen et al. 2013, 2008), the age of the oceanic crust there remains poorly defined and is the focus of geophysical investigations.

Thus far, dating of the oceanic crust has been based on reversals-related anomalies. Therefore, the spatial resolution of which magnetic anomalies can date the crust depends on past reversal frequency of the geomagnetic field. Periods that had frequent reversals, such as during the Cenozoic period, allow for the construction of well-constrained crustal age models (Fig. 2). However, during the Cretaceous period, the reversal frequency of the geomagnetic field was low (less than once every million years), with the extreme case of the Cretaceous Normal Superchron that lasted between 121 to 83.5 million years ago (Cande and Kent 1995; He et al. 2008). Therefore, the age of the crust that was formed during the superchron period (termed "quiet zone," Fig. 2) remains poorly resolved. Luckily, past fluctuations in the intensity of the dipolar geomagnetic field are also recorded by the magnetized rocks, resulting in globally correlatable wiggles found between the primary, reversals-related magnetic anomalies (Bouligand et al. 2006; Cande and Kent 1992; Gee et al. 2000; Granot et al. 2012). Ongoing efforts are being made to refine the existing crustal age models using these magnetic wiggles as a means to establish internal isochrones between the primary anomalies.

Remanent magnetization directions of the magnetic source layer influence the shape of magnetic anomalies. Therefore, if a plate drifted during its geological history in a known fashion, one could potentially utilize the predicted remanent magnetization directions to constrain the age of the crust. "Paleomagnetic poles," the magnetic poles of a certain plate, are calculated from independent paleomagnetic sites with known ages (see entry "Palaeomagnetism, Continental Drift"). These poles place constraints on past motions of the plates, thereby allowing the prediction of the directions of magnetization for every location on a given plate. Forward modeling of the expected magnetic anomalies for different periods of time based on the paleomagnetic poles of the appropriate plate until a reasonable match is found provides a crude, yet important, age constraint on the source rocks. This methodology may, under certain conditions, help to constrain the age of continental magnetic anomalies.

Cross-References

Ar-Ar and K-Ar Dating
Continental Drift (Palaeomagnetism)
Magnetometer
Milankovitch Cycles

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DOI: 10.1007/SpringerReference_359098
URL: http://www.springerreference.com/index/chapterdbid/359098
Part of: Earth Sciences Series. Encyclopedia of Scientific Dating Methods

Editors: Dr. W. Jack Rink and Ph.D. Jeroen Thompson
PDF created on: May, 31, 2014 04:20