

Study of Marine Magnetic field

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Measurement of the Earth's magnetic field in the marine areas (marine magnetic field) is one of the most widely used marine geophysical techniques. Data about the variation of the marine magnetic field has various applications. The conventional uses are to determine depth of burial and trend of magnetized basement rocks, which in turn yields overburden thickness, basin demarcation and information about the underlying structures. Marine magnetic data are used as one of the tool to differentiate areas underlain by continental and oceanic crusts. Other usages are in the fields of marine archaeological investigations or search of sunken ferrous objects (such as ships). However, the most important use of marine magnetic data is to address questions pertaining to geodynamics.

The Earth's Magnetic field

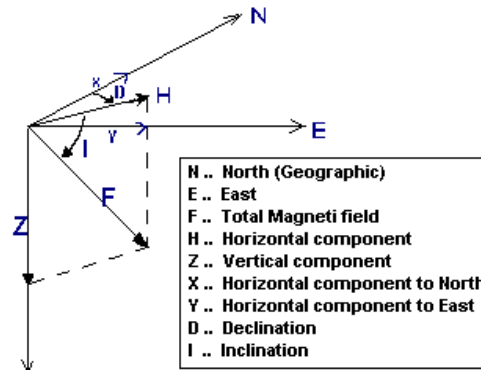
The Earth's magnetic field at any point on the surface of the Earth is a sum of the magnetic field components of the internal, external and anomalous origin. The Earth's magnetic field of internal origin (main magnetic field or geomagnetic field) is associated with the convection currents in the outer core, whereas the field of external origin is associated with the electric currents in the ionised layers of the outer atmosphere. The magnetic field of anomalous origin (local magnetic anomalies) is associated with the magnetized rocks in the upper crust. Knowledge of the behaviour of the geomagnetic field is necessary for reduction of the magnetic data to a suitable datum and for interpretation of the resulting anomalies.

The geomagnetic field is similar to that of a magnet, as if there is a powerful bar magnet at the center of the Earth aligned close to the axis of rotation of the Earth with lines of force passing between northern and southern hemispheres. However, this magnet is not aligned exactly along the axis of rotation but is presently tilted by 11.5° with respect to the axis of rotation, and so the magnetic north as given by a compass, generally differs from geographic or 'true north'. The places where the axis of the geomagnetic field meets the surface are called the north and south magnetic poles, and the magnetic latitude and equator follow from them. The strength of the geomagnetic field varies from roughly 30,000 nT at the magnetic equator to 60,000nT near the magnetic poles. The dip of the geomagnetic field in the northern hemisphere is downward (+ ve) towards the north and in the southern hemisphere is upwards (- ve).

This dip is vertical at the magnetic poles and horizontal at the magnetic equator.

Elements of the Earth's magnetic field

A total intensity vector F can describe the total magnetic field at any point on the surface of the Earth. The total field F can be resolved into a horizontal (H) and vertical (Z) components. The angle between the geographic and magnetic meridian is called declination (D). The angle that the total field vector makes with horizontal is called Inclination or Dip (I). All the above quantities constitute the geomagnetic elements.



The interrelationships of various geomagnetic elements are as follows:

$$\begin{aligned}
 H &= F \cos I & X &= H \cos D \\
 Z &= F \sin I & Y &= H \sin D \\
 F^2 &= H^2 + Z^2 & H^2 &= X^2 + Y^2 \\
 I &= \tan^{-1}(Z / H) & D &= \tan^{-1}(Y / X)
 \end{aligned}$$

The unit for measurement of magnetic field intensity is 'Oersted' (Oe) in cgs units. Since this is considered a large unit, a simplified unit 'gamma' (also known as nanoTesla), which is equal to 10^{-5} Oe is used.

Magnetic reversals and geomagnetic time scale

The paleomagnetic studies of rocks revealed that there are normal and reverse magnetizations, suggesting that the Earth's magnetic field had reversed its polarity many times in the geologic past at irregular intervals. The polarity is said to be "normal" when Earth's magnetic

field is oriented in the same direction as present and it is said to be “reverse” when it is oriented in opposite direction. On average, the field spends about half its time in each state. Reversals are observed from Precambrian times to the present although the frequency of reversals has changed considerably through time. During a reversal, the intensity usually decreases by about an order of magnitude for several thousand years, while the field maintains its direction. The field then undergoes complicated directional changes over a period of 1000 - 4000 years and finally intensity grows with the field having reversed polarity. The reversal sequence has been calibrated for the last 5 million years by dating basalts of known polarity. Portions of the time scale, which are of one dominant polarity are called ‘chrons’, and the most recent four chrons are named after scientists who contributed significantly to our understanding of the geomagnetic field (Brunhes, Matuyama, Gauss, Gilbert).

From a few carefully selected marine magnetic profiles, Heirtzler et al. (1968) constructed the first geomagnetic polarity time scale that covered the entire Cenozoic era (~ 65 my). This time scale not only was extremely valuable but also proved to be very durable. However, with the availability of new calibration points, there have been many revisions to this time scale since 1968. The geomagnetic polarity time scale proposed by Cande and Kent (1992) is the latest. This was constructed for the Late Mesozoic and entire Cenozoic era and was based on an analysis of marine magnetic profiles from the world’s ocean basins. Cande and Kent (1992, 1995) introduced a new term the “tiny wiggles” in the geomagnetic polarity time scale. These “tiny wiggles” are low-amplitude short wavelength second-order magnetic anomalies, which are systematically observed on magnetic anomaly profiles and are interpreted in terms of geomagnetic field behaviour.

In the marine geophysical studies, the temporal references of various tectonic events are provided, either with respect to polarity reversal time scale or with respect to the geological time scale. Therefore, synthesising the timing of geological events inferred in various studies sometimes becomes confusing. In such a situation, an integrated geological and geomagnetic time scale is very useful.

Ship-borne measurement of marine magnetic field

The measurements of the marine magnetic field is carried out by an equipment known as magnetometer. In land magnetic surveys, depending upon the objective, either total, vertical or horizontal component of the Earth’s magnetic field is measured. However, for measuring vertical or horizontal component of the Earth’s magnetic field, the magnetic sensor requires to be

orientated in specific direction. In the case of marine magnetic surveys, the measurements are made in a moving sensor towed behind a ship. Since in such a situation it is difficult to keep the sensor in specific orientation with sufficient accuracy, therefore in conventional marine magnetic surveys the Earth’s total magnetic field is measured and for that purpose the proton precession magnetometers, which need no specific orientation or levelling of the sensor are usually used.

a) Proton precession magnetometer

Protons are spinning mass carrying a positive electric charge. They act as small dipoles and normally align parallel to the ambient geomagnetic field (F). When an external magnetic field is applied (through a polarising coil), the protons tend to align in a direction parallel or antiparallel with direction of the external magnetic field. When the field is suddenly cut off, the protons will precess around, before it returns to original orientation. This precession of protons will induce a weak electric signal (current) in the polarising coil, which is a decaying sinusoid. The frequency of precession (Larmour frequency ‘f’), is related to the magnitude of the ambient total geomagnetic field (F) by the relationship,

$$f = (\gamma_P F) / 2\pi$$

Where;

γ_P -- is the gyro magnetic ratio of the proton, an accurately known constant, the value of which from the laboratory measurements of f in a known field is $26752.2 (\pm 0.3) \times 10^4 \text{ T}^{-1} \text{ s}^{-1}$, and

f -- is the precession frequency, which is the measurement of the alternating voltage of the same frequency induced to flow in the coil by the precessing protons.

The ambient total geomagnetic field (F) is therefore,

$$F = [(2 \times 3.14) / (26752.2 (\pm 0.3) \times 10^4 \text{ T}^{-1} \text{ s}^{-1})] \times f \text{ s}^{-1}$$

$$F = 23.4866 \times (10^{-9} \text{ T}) \times f$$

$$F = 23.4866 \times f \text{ nanoTesla}$$

The marine Proton Precession magnetometer consists of three main units – sensor, tow cable and onboard equipment. The sensor in the Proton Precession Magnetometer is a coil wound around a container filled with kerosene. The sensor called “fish” is towed behind the ship by a suitable low noise tow cable and is enclosed in a sealed cover. The length of the tow cable is governed by the nature of the vessel. For a steel hull ship, towing distance of about two times ship length is enough for reducing the magnetic effect of the ship. The onboard unit of the magnetometers, kept in a suitable location of the ship, consists of a triggering switch, an amplifier, a frequency counter and a recorder. During operation of the magnetometer, the information

received from the sensor (a weak electrical signal) is amplified using an amplifier. This signal is applied to frequency counter circuit, which gives the frequency of this electric signal (Larmour frequency). An electronic circuit in the onboard equipment calculates the total magnetic field and displays digitally on the display panel of the onboard unit and provide input to the digital and analogue data recorders.

b) Survey procedure

For mapping purposes, the observation should be uniformly distributed and separated by less than half the width of the smallest features of interest. Traverses usually should be planned on a grid pattern, with continuous coverage along the ship's track. A relatively close spacing should be maintained between lines set across the primary geological strike direction, and limited number of tie lines in the orthogonal direction to serve as check on cross over errors. In practice, some compromise is reached between an ideal specification and the resources available. In deeper waters, data are often collected along widely separated reconnaissance traverses. Usually various types of underway geophysical data (bathymetric, gravity, magnetic and seismic reflection) are acquired simultaneously along the track. Even if during a cruise the objective is to collect only the magnetic data still it is useful to collect bathymetric data alongwith it as it can be used as a constraint during interpretation.

c) Data acquisition and processing

Magnetic data during a typical geophysical cruise is recorded every few seconds as the ship moves along a pre-determined transect. These acquired data is digitally recorded in suitable computer media in specific formats. Essentially, the recorded data contains magnetic field values, date and time of observation and the position information of the point of observation. Along with the digital data, analogue records are also maintained to serve the purpose of back-up and for quality control during / after data acquisition. As a first step of processing the acquired data are edited to exclude periods of magnetic storms (if any) and obvious noise spikes. The edited data are then corrected for diurnal variation of the geomagnetic field, and finally the anomalies are computed by subtracting the effect of main (dipolar) magnetic field of the Earth, which is called the International Geomagnetic Reference field (IGRF). The IGRF is basically a weighted average of several candidate spherical harmonic models of the main field and its secular variation for a given epoch adopted by International Association of Geomagnetism and Aeronomy (IAGA). The first IGRF (IGRF-1965) was adopted by IAGA in 1968. Its validity was intended for the years 1955 to 1975. The second IGRF (IGRF-1975) was essentially an extrapolation of IGRF-1965 coefficients but with a new secular variation model.

Similar provisional IGRFs were defined for the followed epochs spanning 5 years each. At the end of each epoch, the predicted IGRF is revised based on the available data and Definitive Geomagnetic Reference Field (DGRF) is derived.

Preparation of magnetic anomaly profile and contour data

Depending upon the requirement, the processed magnetic anomalies are presented for interpretation either as profiles, contoured maps and as colour and relief images. Magnetic anomaly plot along ship's track is another very useful way of presenting marine magnetic data. The Generic Mapping Tools (GMT) software package (Wessel, P. and Smith, W. H. F., 1995), which can be downloaded over the internet is a very useful software package for presentation of marine magnetic data. This software package enables plotting of annotated anomalies map as well automatic contouring of anomalies. Many interpreter prefers to first plot an annotated magnetic anomaly map using GMT and then contour that data manually under the guidance of plots of profile / plot along track data and other geological controls.

Interpretation of marine magnetic data

Some of the main applications of marine magnetic data are described in the following paragraphs.

a) Interpretation of magnetic data for delineation of magnetized bodies/structures over the continental margins

Geological interpretation of magnetic data over the continental margin areas usually aims as a first objective to indicate the depth of burial of magnetized rocks. In the absence of magnetic sediments, magnetic data can provide information on the nature and form of the crystalline basement, which might influence the overlying sedimentary sequence. Magnetic data contain large amount of information, but due to inherent limitations of potential field it is rarely possible to provide a unique interpretation. Any different distribution of magnetic bodies can produce theoretically the same anomalies. In order to overcome this or say to minimise the ambiguity, the interpreter must adopt a synergistic attitude. Essentially, interpretation is a process of trying to reconcile various types of evidence into a complete geologically understandable picture. In practice, by integrating results of other methods, the interpreter derives a geologically acceptable model structure, whose computed magnetic anomaly is closely comparable with the observed pattern.

Much qualitative information may be derived from a magnetic anomaly contour map. Sediment covered areas with relatively deep basement are typically represented by smooth magnetic contours. Near surface

igneous / metamorphic complexes usually generate high wave number anomalies. Trend of anomaly suggest trend of the geological / structural features.

Quantitative interpretations of magnetic anomalies are usually based on forward or inverse modelling techniques. While modelling, constraints are imposed according to the best available information, either in the form of geological concepts or as more specific depth/lithologic controls. For interpretation of magnetic data over continental margin areas usually forward modelling is carried out along profiles. The models comprise a number of polygons defined on the basis of distinct magnetizations. The assumption is often made that the polygons have infinite strike extent (i. e. two dimensional). In forward modelling approach of magnetic anomalies, the synthetic magnetic anomalies are calculated over assumed initial model bodies and are matched with the observed magnetic anomalies. Based on the trial and error method, the parameters of the initial body are changed until a reasonable fit with the observed magnetic anomalies is obtained. Once the anomalies are matched, the theoretical model is adopted as one of the plausible interpretation of the causative magnetic body, which caused the observed magnetic anomaly. The results from forward modelling are inherently non-unique, therefore whenever possible, additional information (e.g. from seismic / bore hole data) are introduced to constrain models. The most common method of computing the field over a two dimensional body of arbitrary shape is the algorithms developed by Talwani and Heirtzler (1964).

b) Interpretation of magnetic data for inferring of nature of the crust

A fundamental subdivision of the Earth's surface is in terms of geological provinces composed of either continental or oceanic lithosphere (crust and uppermost mantle), each with their own characteristic lithological, geochemical, and physical properties. The continental margin is the zone separating the thin oceanic crust of the deep ocean basins from the thick continental crust. Continental margins underlie about 28% of the oceans, with transition from continental to oceanic crust commonly occurring beneath the outer part of continental margins. The continental margins are very important from both basic scientific and non-living resources point of view. The accurate demarcation of the Continent-Ocean boundary (COB) is again both a basic scientific requirement as well as at some places is a requirement under the UNCLOS related Legal Continental Shelf demarcation purpose. In the oceanic areas, the marine magnetic studies are one of the essential tools to distinguish the continental and oceanic crusts.

Magnetic anomalies over continental crust typically show a complex pattern reflecting the wide variety of geological terranes. Whereas, the oceanic

crust regions are characterised by presence of linear magnetic anomalies (~ 5 – 50 Km wide, often several hundreds of kilometres long and amplitude of several hundred gamma). Although linear magnetic anomalies, immediate seaward of the COB, are a common feature, but their origin is not same everywhere. Therefore, magnetic anomalies cannot be used as a diagnostic tool to demarcate COB. Magnetic anomaly map of an offshore region with good data coverage can help categorising regions according to the magnetic anomaly patterns, which in turn helps to predict how far the continental-style attributes extend offshore.

c) Interpretation of linear magnetic anomalies of the ocean basins and seafloor spreading

In oceanic areas the most important application of marine magnetic data is for the study of linear magnetic anomalies created by seafloor spreading processes. These linear magnetic anomalies were discovered during the oceanographic exploration in the 1950s. These linear magnetic anomalies at that time were described as zebra stripe-like magnetic patterns (i. e. alternate bands of positive and negative anomaly pattern) of the oceanic areas, where the stripes are symmetrical around the crests of the mid-ocean ridges. These patterns were unlike any seen for continental areas. These stripes are composed of numerous high amplitude magnetic anomalies (>100nT) with wavelengths of a few kilometres to several tens of kilometres. These remarkably linear magnetic anomaly striped patterns were found to extend over thousands of square kilometers. Discontinuities of these stripes at fracture zone were identified from physiography. Remarkable similarity of stripes was observed in different parts of the world oceans. In 1963, Vine and Matthews and independently Morley hypothesized that these magnetic striping are generated by the presence of juxtaposed strips of normally and reversely magnetized rocks comprising the ocean floor. They reasoned that, as the basaltic magma upwells to form new ocean floor at divergent plate boundaries, it gets magnetized in the direction of the Earth's magnetic field at that time. As seafloor spreading pulls the new oceanic crust apart, stripes of approximately the same size gets carried away from the ridge on each side. The basaltic oceanic crust formed at the mid-oceanic ridge thus serves as a 'tape recorder', recording the Earth's magnetic field as it reversed through the geological time. About the same time as these exciting discoveries were being made on the ocean floor, new techniques for determining the geologic ages of rocks ("dating") were also developed. The dating using Potassium – Argon (K–Ar) method provided convincing evidence for the seafloor spreading hypothesis. Vine and Matthews, and Morley, compared the known ages of magnetic reversals with the magnetic striping pattern found on the ocean floor. They found that there was a remarkable correlation between the

ages of the Earth's magnetic reversals and the stripping pattern. The Vine and Matthews (1963) method of measuring seafloor spreading implies a symmetrical anomaly pattern on both sides of a spreading ridge, and a world-wide distribution of magnetic anomalies given by the same pattern of reversals of magnetisation of the ocean bottom which differs from place to place only by the spreading rate. Plotting the same profile in the reverse direction and observing the correspondence of the individual features at the same distance from the central anomaly best demonstrate symmetry. The departures of the observed profile from the profile calculated from a model consisting of positively and negatively uniformly magnetised strips of infinite length and rectangular cross-section can arise from various causes like the intrusion of dikes of the opposite polarity, as well as departures from idealized geometry assumed for the models. The mapping of the magnetic lineations leads to the delineation of the magnetic lineations (isochrons), and fracture zones. The fracture zones are identified from the consistent orthogonal offset of the magnetic lineations. The seafloor spreading magnetic anomaly caused by a magnetized block formed during a particular chron is designated by relating to the corresponding chron. The boundaries of magnetized blocks thus are synonymous with chron boundaries. Therefore, the lineations drawn by joining the boundaries corresponding to the same chron on adjacent magnetic profile can be considered to represent an isochron.

The conventional method of interpretation of oceanic linear magnetic anomalies, in a broad sense are the following;

- a) Create a model of juxtaposed normally and reversely magnetised blocks by taking into consideration a geomagnetic polarity time scale and an approximate seafloor spreading rate.
- b) Compute the synthetic magnetic anomalies profile for that block model using two-dimensional forward modelling method.
- c) Compare the synthetic magnetic anomalies profile with the observed one and adjust the width of the blocks (in other way, the spreading rates) till a good match is obtained between the observed and synthetic magnetic anomalies profiles.
- d) Use the geomagnetic polarity time scale used to create the block model and identify the sequence of magnetic anomalies of the observed profile.
- e) Demarcate the boundaries of the magnetized blocks on the location map and denote them according to the convention of anomaly numbers.

This conventional method of interpretation of linear magnetic anomalies provided valuable insight about the evolution of world ocean basins since the late sixties. These studies considered three possible tectonic settings for the rigid plate boundaries, viz mid-ocean

ridges, transform faults and subduction zones. As the data coverage in world oceans increased, more and more deviations from this simplified model, such as propagating ridges and overlapping spreading centers were discovered. These observations enabled the study of new aspects of seafloor spreading process beyond the initial oversimplified model of orthogonal ridge segments and transform faults. Oblique offsets of magnetic lineations in the ocean basins are considered as the diagnostic feature of the propagating spreading ridges.

As mentioned earlier, the seafloor spreading process results symmetric magnetic anomalies in both the sides of the spreading centre. Once the conjugate magnetic isochrons and fracture zones are identified, they can be used to estimate the finite rotation parameters required for paleogeographic reconstructions. Paleogeographic reconstruction is the process of restoring lithospheric plates back to the relative positions they occupied in the geological past and this reconstruction method is used to study the stage-by-stage evolution of ocean basins and the adjoining continental margins.

Examples of marine magnetic studies from continental margins, deep-sea basins and mid-oceanic ridges offshore India

Following are some publications, which can be perused to appreciate the approach towards marine magnetic studies in varied geological environments relevant to Indian offshore areas.

- a) Studies on the continental shelf and slope settings:
 - o Bhattacharya, G. C. and Subrahmanyam, V. (1986)
 - o Murthy, K. S. R. et al. (1987)
 - o Ramana M. V. (1986)
 - o Rao, D. G. (1984)
 - o Subrahmanyam, V. et al. (1995)
- b) Studies on the deeper continental margin / extinct spreading segment settings:
 - o Bhattacharya, G. C. et al. (1994)
 - o Gopala Rao, D. et al. (1987).
 - o Krishna K. S. et al. (2006)
 - o Ramana, M. V. et al. (1994a, 1994b, 1997)
 - o Rao, D. G. et al. (1997)
- d) Studies on the deep ocean basins setting:
 - o Bhattacharya, G. C. et al. (1992)
 - o Chaubey et al. (1993, 1995, 1998, 2002)
 - o Dymant, J. (1998)
 - o Kamesh Raju, K. A. & T. Ramaprasad (1989)
 - o McKenzie, D. P. & J. G. Sclater (1971)
 - o Royer et al. (2002)
- e) Studies related paleo-geographic reconstruction:
 - o Besse, J and V. Courtillot (1988)
 - o Norton, I. O. & J. G. Sclater, (1979)

- Yatheesh, V. et al. (2006)
- f) Studies related to seamounts:
- Bhattacharya, G. C. & V. Subrahmanyam (1991)

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