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The concepts of Magnetostratigraphy and its application in understanding the Earth processes

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Abstract: The study of Earth's magnetic field in the past times is known as Paleomagnetism. The most characteristic feature of the Earth's magnetic field is that it reverses its polarity at irregular intervals, producing a 'bar code' of alternating normal (north directed) and reverse (south directed) polarity chrons with predictable durations. The study of magnetic polarities acquired during the deposition of sediments and volcanic flows is known as Magnetostratigraphy. This technique is frequently used to date sequences that generally lack fossils or interbedded igneous rock. In Earth sciences, Magnetostratigraphic correlation to the geomagnetic polarity time scale (GPTS) constitutes a standard dating tool. The results of magnetostratigraphy of two sections (12.90 to 2.5 Ma) in Kangra district, Himachal Pradesh, India are demonstrated. Comprehensively, magnetostratigraphy works at best when integrated with other dating tools, as illustrated by the case study discussed in this paper.

Keywords: Magnetostratigraphy, paleomagnetism, earth processes.

Introduction

Magnetism is one of the oldest real sciences, and it has the distinction of being the only geographical property of the Earth that can be satisfactorily measured and evaluated across time. Early Man may have been aware of magnetised rocks with the properties of attraction and repulsion. The ability of such magnetic rocks, also known as lodestones, to induce magnetization by rubbing and striking iron needles was probably discovered very early in the Iron Age, and such attracting and repelling forces were regarded as magical. In his Epistola de Magnete of 1269, Petrus Peregrinus (Pierre de Maricourst), a French military engineer reported a remarkable series of experiments with spherical pieces of Lodestone, whereas the first ever experimental study on magnetism which is regarded as the first Scientific treatise ever written, entitled "De Magnete" was published by William Gilbert in 1600. Chinese were the first to know the magnetic declination, magnetic inclination (or dip), and discovered by George Hartmann in 1544 and separately by Robert Norman in 1576 (Norman, 1581). Delesse (1849) and Melloni (1853) were the first to measure the remanent magnetization of volcanic rocks and concluded that these rocks magnetize as they cool. Folgheraiter (1894, 1895, 1899a, b) concluded that younger volcanic materials magnetized in opposite directions. Mercanton (1926, 1931, 1932) proposed that the observations of his studies could be used to verify theories of polar wandering and continental drift. Earlier rock magnetic studies were conducted by Koenigsberger (1938), Griffiths (1953, 1954, 1955), Griffiths and King (1954), King (1955), Rees (1961), King and Rees (1962, 1966). Hamilton (1963) have studied the magnetization of sedimentary rocks. The magnetostratigraphy was first studied by Hospers (1951, 1953a, b, 1954a, b), and Einarsson and Sigurgeirsson (1955). Blacket (1952) was the chief architect and developer of the Astatic Magnetometer, which paved the way for more active Palaeomagnetism research around the world. Magnetostratigraphy refers to the application of well-known principles of stratigraphy to the pattern of polarity reversals registered in a rock succession by natural magnetic acquisition processes. This requires that the rock accurately recorded the ancient magnetic field at the time of its formation, a prerequisite that must be verified in the laboratory using palaeomagnetic and rock magnetic techniques. Palaeomagnetism constitutes the study of the magnetic field of the earth in the geological past as recorded in rocks. The hypothesis of sea floor spreading provided the mechanism for continental drift. The magnetism of the rock as a whole is usually carried by a small percent of the total minerals present in the form of iron oxides, which exhibit magnetic properties and are aligned in the direction of the earth's magnetic field whenever they are formed, providing us a record of it in its history. Fossil magnetism or natural remanent magnetization (NRM) of certain minerals in their natural state. The subject of Paleomagnetism and its application to geological, geophysical, and geochronological problems has been lucidly explained by Cox and Doell (1960), Irving (1964), McElhinny (1973), Tarling (1983), and Butler (1992). Improved techniques and extensive palaeomagnetic investigations in many parts of the world have significantly increased the amount of palaeomagnetic information and provided a very detailed Geomagnetic Polarity Time Scale (Opdyke and Channell 1996), of which the Neogene part is fully astronomically calibrated (Lourens et al., 2004) through the extensive use of cyclostratigraphy (Strasser et al., 2006). Now magnetostratigraphy has evolved as an indispensable stratigraphic tool for Earth Sciences after the first reversal of the Earth's magnetic field was discovered by Brunhes (1906) a century ago, more than half a century after the start of the modern era of magnetostratigraphy (Hospers, 1951), and almost half a century after the first development of the modern Geomagnetic Polarity Time Scale (Cox, 1963). A geocentric dipole source with an axis aligned to geographic north-south rotation axis is the model used for relating a palaeomagnetic direction to a pole position relevant to unraveling ancient continental movements (Fig. 1). The principles and concepts of magnetostratigraphy are defined in this paper as a dating tool that uses the record of polarity (normal or reverse) of the ancient geomagnetic field imprinted in igneous or sedimentary rock sequences by natural magnetic acquisition processes to better understand Earth processes.

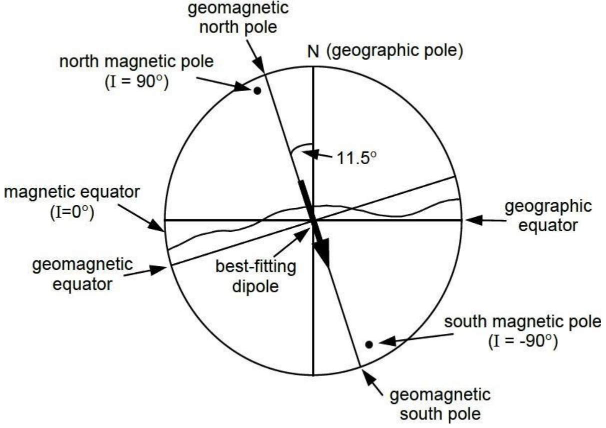

Fig. 1. Illustrates the best-fitting inclined Geocentric Dipole.

Magnetization in Rocks

The mechanism by which remanence is acquired depends upon the mode of formation and subsequent history of rocks, as well as the characteristics of the magnetic minerals. Iron is the chief constituent, which helps acquire the magnetization in a rock. The Earth’s magnetic field is generated a dynamo process that is maintained by convective fluid motion in the liquid outer core. At the surface of the Earth, the field can be conveniently described as a dipole field, which is similar to having a bar magnet at the Earth’s core. Such a dipole accounts for approximately 90% of the observed field. Higher order, or the non-dipole field, accounts for the remaining 10%. The original magnetism preserved in a rock, that was acquired at the time of formation is termed as primary magnetization. Subsequent to formation, this primary magnetization may decay either partly or wholly and other components may be added through a number of processes. This subsequent magnetization is called secondary magnetization. Initially, it was believed that the field reversed periodically, but as more results on lava flows became available, it became clear that geomagnetic reversals occur randomly. On geological time spans, a polarity reversal typically takes several thousands of years, which is rapid enough to be called globally synchronised. The occurrence of reversed magnetization in rocks was one of the earliest important discoveries of palaeomagnetic research. A reversal can occur in one of two ways: (1) the rock could sometimes acquire magnetization in opposite directions to the ambient field, or (2) the geomagnetic field periodically reverses its polarity.

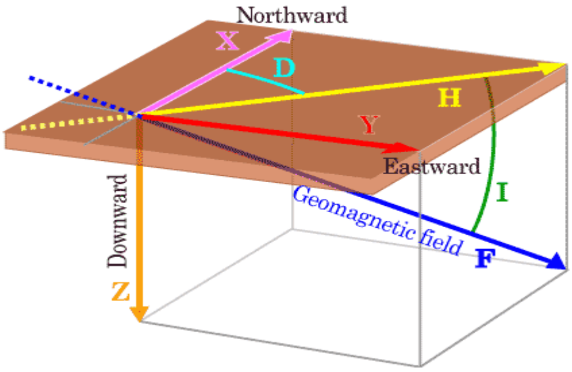

Fig. 2. The Geomagnetic field at any point on the Earth’s surface is a vector (F) and a horizontal component (H) that makes an angle (D) with the geographical meridian. The declination (D) is an angle from north measured eastward ranging from 0° to 360°. The inclination (I) is the angle made by the magnetic vector with the horizontal. By convention, the north-seeking vector is positive if it points downward and negative if it points upward.

Brunhes (1906) was the first to notice reversals in the earth's magnetic field. Self-reversal of rock can occur through a variety of mechanisms. Palaeomagnetism is also used to unravel the history of the geomagnetic field polarity reversals. Mercanton (1926) and Matuyama (1929) were the first to attempt to delineate when the field was reversed. Reversals have not occurred at regular intervals, despite a long-term trend for frequent reversal intervals to become less frequent over time, leading to long periods with no reversals (superchrons). Such intervals may last for tens of millions of years and when reversals recommence their frequency tends to increase again; this is a geomagnetic definition of a long-term behavioral transition within the Earth's interior. The vector sum of different magnetic components is called total natural remanent magnetization (NRM) (Fig. 2). In order to carry out Magnetostratigraphic studies one must collect block samples after orientation using a Brunton compass and a precision spirit level (Fig. 3).

Fig. 3. An in-situ outcrop sample is oriented using a Brunton compass for the north marking arrow and a spirit level for horizontal marking.

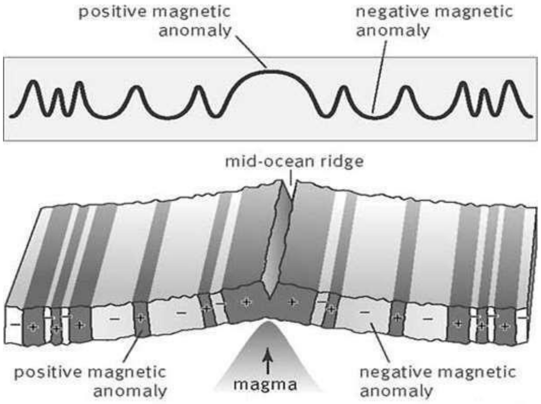

Fig. 4. Demonstrates the formation of marine magnetic anomalies during seafloor spreading. The oceanic crust is formed at the ridge crest and is covered by an increasing thickness of oceanic sediments as it spreads from the ridge. The initial normal (reversed) polarity of the thermoremanent magnetisation (TRM) acquired after cooling at the ridge is represented by the black (white) blocks of the oceanic crust.

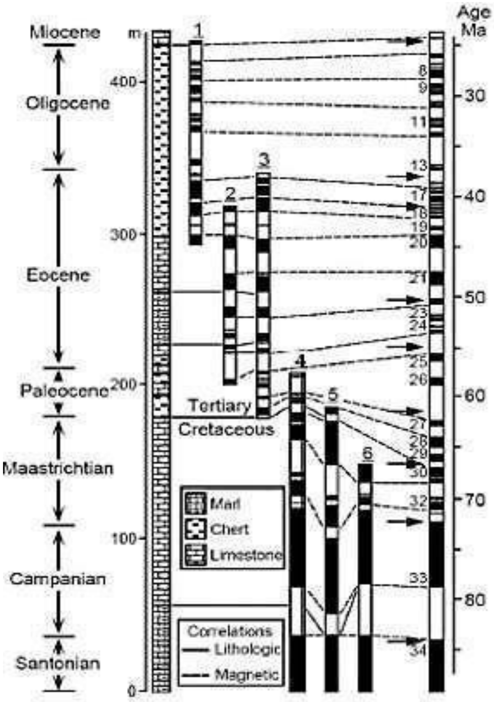

Fig. 5. Development of the geomagnetic polarity time scale (GPTS) (after Butler, 1992).

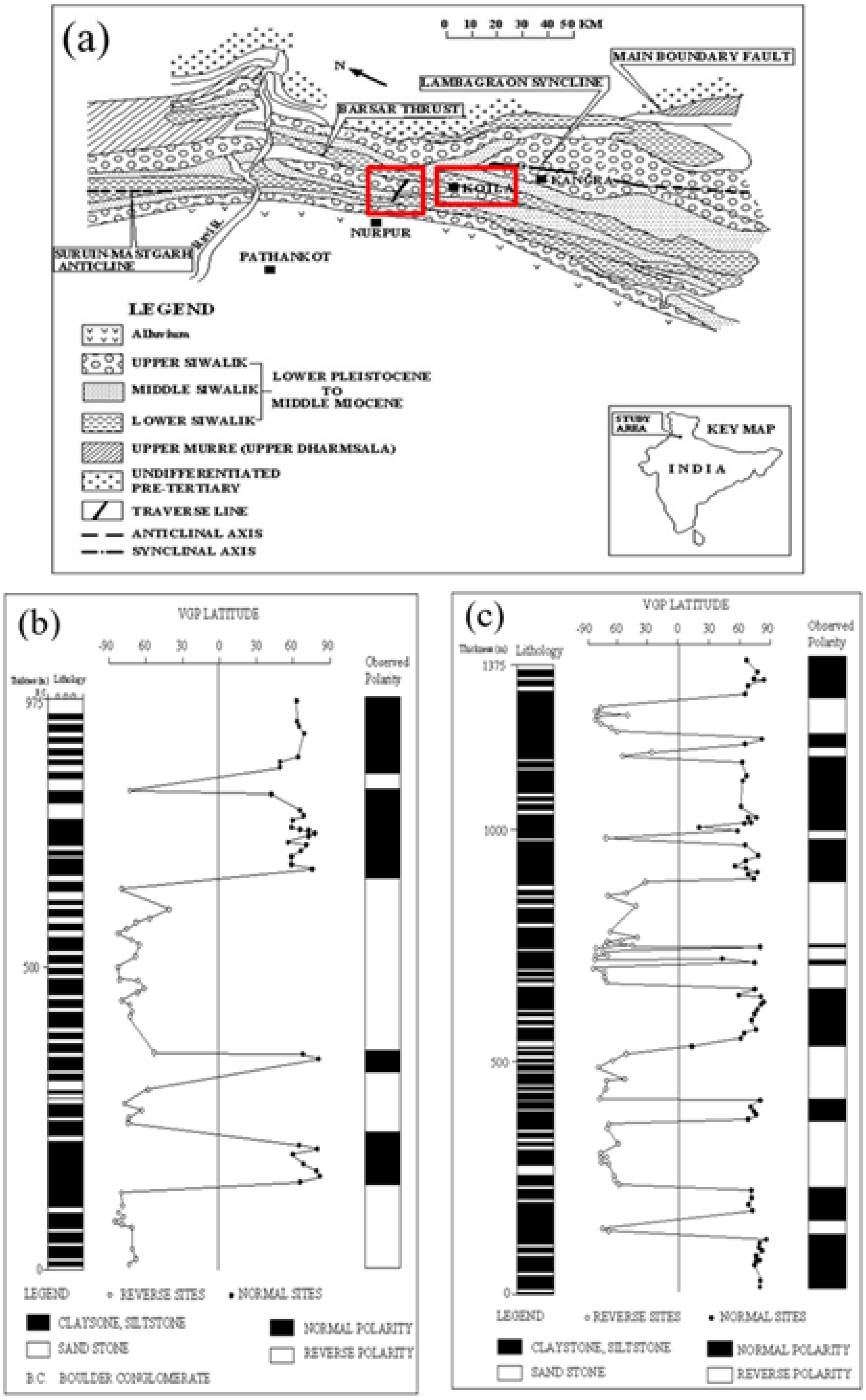

Fig. 6. Geological Map of the Himalayan Foot-Hills in Kangra district, Himachal Pradesh, India with study areas highlighted in red boxes(a). Magnetostratigraphy plot of Middle Siwaliks (b) and Upper Siwaliks (c) of Nurpur section, Kangra District, Himachal Pradesh, India. VGP latitude against Stratigraphic thickness with observed polarity.

Development of Geomagnetic Polarity Time Scale

The geomagnetic polarity time scale (GPTS) is a chronology of periods of normal and reversed polarity that documents the history of magnetic reversals. The continuous process of rising and cooling of magma at the ridge results in magnetised crust of alternating normal and reverse polarity, causing a slight increase or decrease in the measured field: marine magnetic anomalies (Fig. 4). Figure 5 shows the development of Geomagnetic Polarity Stratigraphy for the last 85 million years (Butler,1992). The magnetic anomaly template was thoroughly revised by Cande and Kent (1992), up to the Cretaceous Normal Superchron over the last 84 Ma. The initial assumption of periodic behavior (Cox, 1962) was soon abandoned as new data became available. The first modern GPTS based on marine magnetic anomaly patterns was established by Heirtzler et al. (1968). Labreque et al. (1977), Berggren et al. (1985), and Cande and Kent (1992) made subsequent versions that showed improved age control and resolution. A major breakthrough came with the astronomical polarity time scale (APTS) in which every individual reversal is accurately dated (Hilgen et al., 1997). The principles of magnetostratigraphy can be understood only by understanding the development of geomagnetic polarity time scales. Magnetostratigraphy helped and contributed to the development of the geomagnetic polarity time scale.

Case Studies

The author presents a case study to demonstrate how magnetostratigraphy can be used to date and correlate rocks. The study deals with the Neogene part of the GPTS, based on the direct dating of polarity reversals using magnetostratigraphy as a proxy in Nurpur and Kotla sections of Kangra District, Himachal Pradesh, India (Venkateshwarlu, 2008, 2011, 2015).

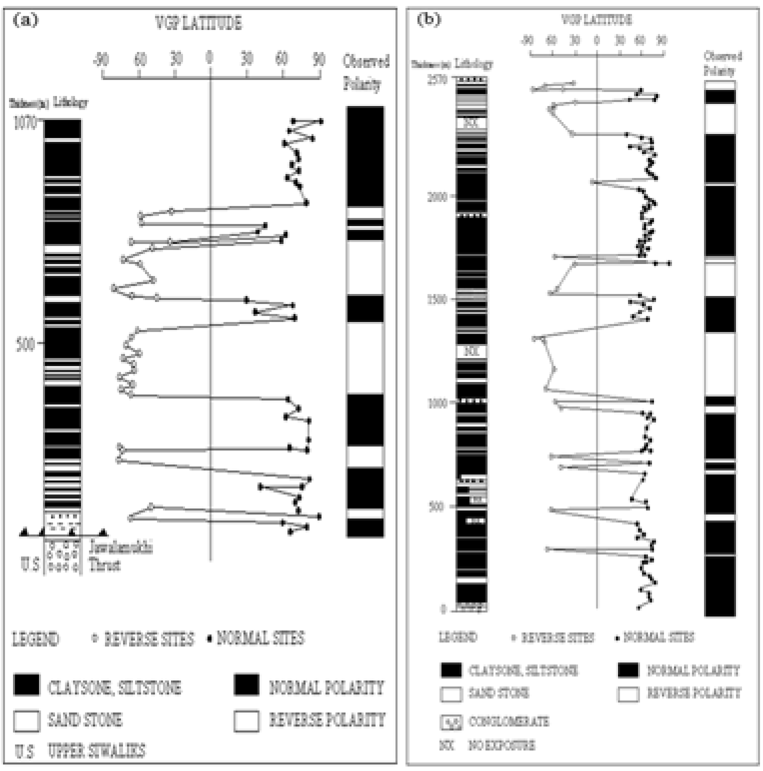

Fig. 7. Shows Magnetostratigraphy plot of the Lower Siwaliks (a) and Middle Siwaliks (b) of Kotla section, Kangra District, Himachal Pradesh, India. VGP latitude against Stratigraphic thickness with observed polarity.

Neogene case study: The Middle Miocene to Lower Pleistocene Siwalik Sections, Himachal Pradesh

About 213 sites were sampled from middle and upper Siwalik subgroups in the Nurpur section with a stratigraphic thickness of 2350 m, while 286 sites were sampled from lower to middle Siwalik subgroups in the Kotla section with a stratigraphic thickness of 3640 m, in Kangra district, Himachal Pradesh, India (Fig. 6a). Magnetostratigraphic studies show that the magnetic polarity scale (MPS) of the sections can be correlated with the standard geomagnetic polarity time scale of La Brecque et al. (1977). The Nurpur section (Fig. 6b, c) has 26 polarity magnetozones, while the Kotla section has 36 polarity magnetozones (Fig. 7a, b). Based on fossil evidence, the Nurpur section is correlated with the Geomagnetic Polarity Time Scale (GPTS) (Fig. 8a). In the Kotla section a long normal polarity magnetozone is present in the middle Siwaliks which can be correlated to the chron 9 of any standard GPTS (Fig. 8). This is a characteristic magnetozone observed in almost all the middle Siwalik sections studied. In the Kotla section, this magnetozone serves as a control to correlate with the GPTS. The age assignments for this GPTS are based on Mankenin and Dalrymple GPTS (1979). From this correlation, the ages of these subgroups were estimated to be 8.14 to 2.50 Ma for the Nurpur section and 12.90 to 5.00 Ma for the Kotla section. Overall, the Siwaliks range in age from 12.90 to 2.50 Ma in the Kangra district. The correlation was also helpful in estimating the rate of sedimentation, which is 0.50 m/1000 years and 0.33 m/1000 years for the middle and upper Siwaliks of Nurpur, respectively. For lower Siwaliks and middle Siwaliks of Kotla, it is 0.34 m/ 1000 years and 0.54 m/1000 years respectively.

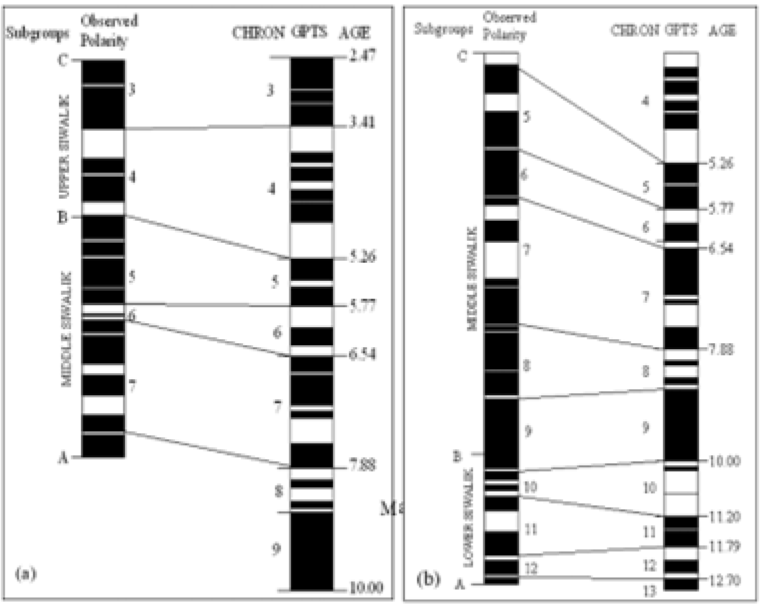

Fig. 8. Correlation of Nurpur (a) and Kotla (b) Magnetostratigraphy with the GPTS of La Brecque et al. (1977). The age assignments are taken from Mankinen and Dalrymple (1979) polarity time scale.

Conclusions

Magnetostratigraphy is one of the best tools to date and correlate the sedimentary succession in the absence of fossils. This method is also useful in dating igneous and volcanic rocks. Unfortunately, the GPTS is constructed good up to ~160 Ma for any cross-correlation. Future efforts should focus on extending the GPTS beyond 160 Ma based on available rocks of different times. Further, the advanced research in magnetostratigraphy in the sedimentary sequence must depend on integration with biostratigraphy and cyclostratigraphy, supported by paleoclimatic and palaeoenvironmental proxy records.

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