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EXPANDING HORIZONS OF PALAEOMAGNETIC AND ROCK MAGNETIC APPLICATIONS

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Abstract

Techniques of palaeomagnetism and rock magnetism have potential applications to problems in sedimentary geology. Latest applications of these techniques to hydrocarbon exploration and environmental studies are reviewed. For hydrocarbon exploration, the palaeomagnetic data have been applied mainly to the following areas: Borehole core orientation, dating of hydrocarbon migration, magnetic anomalies associated with hydrocarbon seeps and plumes, and magnetostratigraphy for precise dating of the sedimentary strata. Rock magnetism, which provides theoretical basis for palaeomagnetic investigations, has been applied to environmental systems in the study of global environmental change and climatic processes. These studies form a separate discipline of study now known as "Environmental Magnetism". Materials that have been studied for environmental magnetism include lake and marine sediments, soils, atmospheric particulates, and biological entities. Various mineral magnetic parameters, such as susceptibility, IRM, SIRM and ARM are sensitive indicators of temporal variations in the concentration and grain size of terrigenous or lithogenous materials deposited on the seafloor or lake bottom. Studies of downcore susceptibility and palaeointensity variations have led to a better understanding of the environmental and palaeoclimatic conditions involved in the geologic processes in sedimentary records. Environmental magnetic techniques can also distinguish between the magnetic grains from different sources in the atmospheric particulates. Valuable insights into the processes of pedogenesis, authigenic/diagenetic formation of ferrimagnetic phases, and dissolution of magnetic minerals in marine and lake environments could be obtained through mineral magnetic techniques.

Introduction

Palaeomagnetism has traversed a long way from providing crucial evidence for the movement of large crustal blocks (inferred from the Apparent Polar Wander Path) to unraveling the more localized rotation of smaller tectonic blocks and motion histories of suspect terranes with respect to continental interiors. Today palaeomagnetism is providing major refinement of stratigraphic correlations and geochronologic calibrations of both marine and nonmarine fossil zonations. The scope of applications of palaeomagnetic data to problems in sedimentary geology is expanding at a fast pace. As summarized by Aissaoui et al. (1993), some of these applications include "testing the isochronous nature of sequence stratigraphic boundaries; relative timing of hydrocarbon migration and accumulation; high- resolution stratigraphic correlation, enabling enhanced interpretation of climate and faunal archives; the cause/effect relationship between sedimentation and tectonism, resolvable on the basin scale through palaeomagnetism; magnetostratigraphic dating of carbonate rocks that record major changes in the sea level; refined timing of major diagenetic/remagnetization events related to tectonism, regional hydrogeochemical regimes, and normal compaction/cementation reactions".

Rock magnetism provides the theoretical basis for understanding the nature of magnetic carriers and origin of magnetization in sediments and other rocks used for palaeomagnetic studies. Apart from their application to palaeomagnetism, the rock magnetic and mineral magnetic techniques are now being applied to the study of environmental systems to extract important information about global environmental change, climatic processes and the impact of humans on the environment. The pioneering work in such studies by Thompson et al. (1980) and Thompson and Oldfield (1986) has led to the

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● Paper presented at the 2nd International Seminar Geophysics Beyond 2000, held at Hyderabad during 15-20 November, 1996 development of a distinct field known as "Environmental Magnetism". The techniques of environmental magnetism have the potential of addressing problems in many diverse fields, such as climatology, ecology, geomorphology, hydrology, land-use studies, limnology, meteorology, oceanography, sedimentology, and soil science (Verosub and Roberts, 1995).

Presented in this paper is a brief overview of the present status in resect of applications of palaeomagnetic and rock magnetic methods to two major areas - hydrocarbon exploration and environmental studies. These studies are being conducted all over the world in an interdisciplinary context, particularly in conjunction with sedimentary geology. Because of the increasing emphasis on the interdisciplinary and multi-disciplinary aspects in the present day scientific research, and a growing shift from basic to applied research, it is likely that the scope of magnetic studies in the above fields will expand rapidly in the years ahead.

Hydrocarbon Exploration

The potential applications of palaeomagnetic data in the hydrocarbon exploration are: Borehole core orientation, dating of hydrocarbon migration, magnetic anomalies associated with hydrocarbon seeps and plumes, and magnetostratigraphy. Following is a brief description of the latest developments in each of these areas.

Borehole core orientation

As pointed out by Nelson et al.(1987), azimuthal orientation of rocks recovered from boreholes is very important in modelling the physical properties of rocks to infer depositional environments, deformational stress fields and diagenetic processes. The standard techniques used in the petroleum industry (outlined in Nelson et al. 1987), besides being very expensive, are subject to a number of problems which reduce the accuracy of an orientation. An alternative technique based on the basic principles of palaeomagnetism has recently been proposed by Rolph et al.(1995). In this method, the within-core orientation of the viscous remanent magnetization (VRM), a component of the sample magnetization acquired in the present geomagnetic field direction is determined. The underlying principle is that the earth's magnetic field has retained a stable orientation since the last polarity inversion (about 0.73 Ma); the average magnetic north pole during this time being coincident with geographic north. The basic assumption in this method is that heating a rock up to 300°C and cooling it down in zero magnetic field will remove a VRM whose true declination (D) will be due north for all locations and the inclination (I) will have a value dependent on the site latitude (λ). From the relation $\tan I = 2 \tan \lambda$ for a geocentric axial dipole (GAD) field, the VRM can be isolated by selecting a vector component in the lower temperature range (below 350°C) having an inclination close to the GAD value. The declination of this component is then corrected to geographical north. Thus the core is oriented. In this method, the only information required for the core is the site latitude, the 'up hole' direction and the angle and direction of any well deviation.

In addition to VRM, other stable component(s) of magnetization of ancient origin may be used for core reorientation provided the age of magnetization is reasonably well known. Unlike the VRM method in which the direction of north is specified directly, in this method north direction is given by reference to the direction predicted from published apparent polar wander curves for that plate or geographical region. Hailwood and Ding (1995) have illustrated the applications and effectiveness of this method in defining fracture orientations, and establishing sediment transport directions in a channel sand body. The most important advantage of the palaeomagnetic core orientation method is that the measurements are made on samples from the cores rather than by downhole instruments. This makes the technique not only cost-effective, but also ensures a greater precision.

Dating hydrocarbon migration and seepage through chemical remagnetization

Remagnetization of sediments is a widespread phenomenon and is a consequence of rock-fluid interactions. In a number of studies (e.g. Goldhaber and Reynolds, 1991; Machel and Burton, 1991), hydrocarbon seepage has been demonstrated to be a possible cause of remagnetization. The chemical changes caused by the hydrocarbons in the magnetic properties of rocks frequently result in the growth of authigenic magnetic minerals which could provide a palaeomagnetic record of the time of migration. This dating approach is based on the isolation of the magnetization carried by an authigenic magnetic phase that precipitates as a result of a migration event. A comparison of the pole position for the isolated magnetization to the Apparent Polar Wander Path (APWP) allows the determination of the timing of authigenesis and migration.

Magnetite and pyrrhotite are among the most important magnetic minerals precipitated, and haematite is the magnetic mineral that is dissolved or replaced in hydrocarbon diagenetic environments (Machel and Burton, 1991; Burton et al., 1993). Authigenesis of pyrrhotite or magnetite is possibly the result of biodegradation of hydrocarbons (Reynolds et al., 1990) which creates conditions conducive to the formation of these minerals. Using petrographic and magnetic techniques, authigenic magnetite has been identified in the shape of spherical aggregates in samples of solid bitumen (McCabe et al., 1987). Chemical remanence carried by diagenetic magnetite in speleothems with hydrocarbons has been reported by Elmore and Crawford (1990). Reactions involving hydrocarbons can cause either an increase or decrease in the intensity of magnetization of the rocks (Elmore et al.,1993). The presence and/or migration of hydrocarbons through sedimentary formations imparting significantly strong and stable remanences has been amply demonstrated in numerous studies (e.g. Reynolds et al., 1985; Elwood and Crick, 1988; Elmore and Leach, 1980; Kilgore and Elmore, 1989). Sulphide rich fluids, however, may replace iron oxides with weakly magnetic sulphides (pyrrhotite, greigite) resulting in a weaker remanent intensity. The dating of sulphide mineralization in several Gulf Coast salt dome caprocks has been reported by Gose and Kyle (1993). Pyrrhotite was the main remanence carrier that could be used for dating the sulphidization. Irrespective of a stronger or weaker remanent intensity associated with remagnetization, the secondary remanence corresponds to the magnetic field at the time of authigenesis/ diagenesis.

Identification of magnetic anomalies associated with hydrocarbon seeps and plumes

Secondary magnetization which may occur during hydrocarbon migration can cause detectable magnetic contrasts relative to the total magnetization. Machel (1995) has proposed that the contrasts can be measured from the air, at the surface or in drill cores and can be used for hydrocarbon exploration purposes in association with other exploration methods. Magnetic contrasts caused by the inorganic/chemical formation of magnetite are reported by Elmore et al. (1987) and McCabe et al. (1987). The oil impregnated samples exhibited increases in magnetic intensity up to an order of magnitude more than the samples that were not impregnated with hydrocarbons. Kilgore and Elmore (1989) have documented a magnetic contrast caused by the dissolution of haematite in a hydrocarbon environment. They showed that the NRM intensity of red beds (caused largely by haematite) unaffected by hydrocarbon seepage, is an order of magnitude greater than in oil-saturated red beds. This negative anomalous magnetization is due to the dissolution of haematite. Negative magnetic contrasts also result where the relatively non-magnetic sulphides replace detrital magnetite (Reynolds et al., 1993). A magnetic contrast caused by the formation of pyrrhotite in a hydrocarbon seepage environment of a carbonate caprock has been demonstrated by Sassen et al. (1989). Pyrrhotite was interpreted to have been formed as a by-product of bacterial sulphide reduction.

Magnetostratigraphy for absolute dating of sedimentary strata

A significant milestone in the development of palaeomagnetism was the discovery that marine magnetic anomalies represented reversals of the earth's magnetic field. Subsequent measurements of the ocean basins by Ocean Drilling Programmes have resulted in a reliable Geomagnetic Polarity Time Scale (GPTS) from the Middle Jurassic times to the present day (Harland et al., 1989). Magnetostratigraphies containing intervals of normal or reversed polarity can be used for absolute dating by comparison with the GPTS. This is particularly useful in strata devoid of fossils. It can also provide an effective tool for well-to-well correlation. On a local oil field scale, magnetostratigraphy can be used to strengthen a reservoir zonation for locating potential hydrocarbon pathways and providing information for sand volume calculations (Hauger et al., 1994). In a recent study (Hauger and van Veen, 1995), magnetic polarity zones have been demonstrated to provide time lines for a facies-independent reservoir zonation. By combining palaeomagnetically determined time lines with biostratigraphy and sequence stratigraphic interpretations, an integrated high resolution genetically oriented reservoir model can be determined.

In addition to the main applications discussed above, palaeomagnetic techniques can be applied to structural geology also. Stewart and Jackson (1995) have used the palaeomagnetic data to construct the geometry of trap structure so that the trap volume at the time of hydrocarbon generation can be estimated. In the realm of rock magnetic applications to hydrocarbon exploration, magnetic susceptibility has been demonstrated to be a useful lithomagnetic parameter for quantitative lithostratigraphic correlation in borehole core samples (Lovlie and Van Veen, 1995). Anisotrophy of magnetic susceptibility measurements can be used for petrofabric analysis of rocks (Tarling and Shi, 1995).

Environmental Studies

For studies of global environmental change and climatic processes, the rock and mineral magnetic techniques are applied to situations in which the transport, deposition and transformation of magnetic grains is influenced by environmental processes in the atmosphere, hydrosphere, and lithosphere. While the lake sediments provided the main impetus for the development of environmental magnetism (Oldfield,1991), other materials which have been studied include marine sediments, soils, atmospheric dust and biological entities.

Magnetic minerals generally occur only in trace amounts in sediments, but through rock magnetic and mineral magnetic techniques their definitive identification becomes possible. Important mineral magnetic parameters used in the "Environmental Magnetism" are: Susceptibility, Isothermal Remanent Magnetization (IRM), Saturated IRM (SIRM), Anhysteretic Remanent Magnetization (ARM), Coercivity and various ratios of these parameters. For the definitions of these and other magnetic parameters related to environmental studies, readers are referred to Dunlop (1995). The important point about these parameters is that they can be sensitive indicators of temporal variations in the concentration and grain size of terrigenous/lithogenous material deposited on the seafloor or lake bottom. Fluctuations in concentration and size of magnetic grains in deep sea and lake cores are climatically modulated in many environments (Oldfield and Robinson, 1985; Bloemendal and DeMenocal, 1989; Peck et al., 1994). For example, high concentrations of magnetic minerals characterize sediments deposited during glacial periods, with low carbonate productivity and increased amounts of ice-carried detritus, while interglacial periods are characterized by low magnetic mineral concentrations and high carbonate contents (Robinson, 1986).

Studies of fossiliferous deep-sea sediment cores from different marine environments have indicated that the magnetic parameters can be used to define fluctuations that are coincident with the Earth orbital periodicities (Bloemendal and DeMenocal, 1989). These studies can be done with a better speed and stratigraphic resolution than the conventional sedimentological or geochemical techniques (Doh et al., 1988; Bloemendal et al.,1992)

Downcore variations in magnetic susceptibility are routinely studied in most of the environmental magnetic investigations to correlate cores from a lake, or deep-sea. The downcore susceptibility variations in a lake may result from changes in the amount and nature of the magnetic grains brought into the lake from the surrounding catchment (Thompson and Turner, 1985). The changes in the magnetic mineralogy of the depositional record of the lake may arise from the fluctuations in the intensity of weathering due to climatic change, exposure of bedrock by landslides, or denudation of the landscape by fire. Chronological framework for the correlations could be provided by suitable radiometric techniques. In the case of deep-sea sediments, the main causes of variations in susceptibility are changes in the amount and nature of terrigenous material reaching the depositional site and changes in grain size associated with sorting by currents and/or aeolian processes (Bloemendal et al., 1992).

Magnetic susceptibility measurements have also been used to study the palaeoseismic record from the lake sediments in the western United States (Karlin and Abella, 1992). Downcore magnetic susceptibility patterns, supplemented with grain size analyses were used to identify and correlate episodic turbidite sequences in the sediments. These turbidites were interpreted to be triggered by large earthquakes. The radiometric dates of the lake cores indicate the sedimentary disturbances to be synchronous with independently documented palaeoseismic events.

The mineral magnetic parameters can be used to establish a reliable palaeointensity reference curve for the last several hundred thousand years (Meynadier et al., 1992) which may provide the basis for a new global stratigraphy that has a higher temporal resolution than that provided by the conventional magnetic polarity stratigraphy. One of the most important implications of a possible globally coherent relative palaeointensity stratigraphy is that it may provide a means for correlating between sedimentary environments. Variations in relative palaeointensity may provide the basis for comparing the palaeoclimatic record of a lacustrine sequence with marine palaeoclimate records (Roberts et al.,1994). Such connections could provide important insights about the relationship between marine/continental climate systems.

Environmental magnetic methods have been used to discriminate between terrigenous and aeolian components in the marine sediments of the Arabian sea and Somali Basin (Bloemendal et al., 1993). Magnetic parameters are also of considerable importance in distinguishing the magnetic components of atmospheric particulates derived from different source regions and fly ash from different industrial sources (Oldfield et al., 1985; Hunt, 1986).

Pedogenesis, authigenic/diagenetic formation of ferrimagnetic phases and dissolution of magnetic minerals in marine and lake environments are important subjects of environmental magnetic studies. These processes are ultimately related with the environmental and climatic changes. Mineral magnetic methods have been used to separate the local climate signal from the regional palaeomonsoon record (Banerjee et al., 1993) and to study the relationship between the formation of pedogenic magnetic minerals and palaeoclimate (Heller et al.,1993; Evans and Heller, 1994). Environmental magnetism has played a major role in the interpretation of the palaeoclimatic record of the loess/palaeosol deposits in China. The palaeosols, which represent warmer interglacial periods, have higher magnetic susceptibilities than the loesses which represent cooler glacial periods. In addition, there is a strong correlation between variations in magnetic susceptibility in the loess/palaeosol sequence and variations in oxygen isotope record in marine sediments, making the Chinese loess/palaeosol deposits one of the best records of terrestrial palaeoclimate (Kukla et al., 1988).

The environmental magnetic studies summarized above are just a few examples of numerous studies reported during the past fifteen years or so. Contributions to this relatively new field of research are coming in large numbers today from the international community of scientists which is unanimous in its view in the enormous potential of this technique towards environmental and climatic reconstructions.

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