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Environmental Magnetism and it's application towards Palaeomonsoon Reconstruction

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ABSTRACT

Environmental mineral magnetic techniques are designed to measure the response of natural materials to a range of artificially applied magnetic fields. Magnetic measurements are easily and rapidly made in the laboratory or *in situ*, and they are highly accurate apart from being non-destructive. The magnetic properties of samples can be used to carry out sediment provenance studies, understand magnetic grain-size, attempt palaeoclimatic reconstruction, and monitor anthropogenically-generated particulate atmospheric pollution. Mineral magnetic measurements have been performed by the Environmental Magnetism Group (IIG) on samples collected from India covering different depositional environments and provenance, namely the Himalayan lake deposits of Garbayang and Goting (~10 ka to 30 ka), modern playas within the Thar desert (~10 ka), Nalsarovar (~6 ka), Lonar (~50 ka) and Mastani (~5 ka), and near shore deltaic and estuarine environments of Godavari, Iskapalli and Mandovi. Apart from these studies, the technique has also been applied to Himalayan loess deposits and late Quaternary palaeosols of Saurashtra. Case studies from these diverse environmental situations reveal the utility and application of mineral magnetic techniques in palaeomonsoonal reconstruction. Specifically, these studies bring to the fore the sensitivity of the S-ratio (backfield IRM/SIRM) to climatic changes, as opposed to magnetic susceptibility (χ). Our studies caution against using χ indiscriminately in palaeomonsoon reconstruction. Efforts are underway to build-up a master curve of secular variation for the Indian subcontinent and will serve as a relative chronological tool for the Holocene.

INTRODUCTION

Environmental magnetism (also called mineral magnetism) derives its origin from the pioneering works given in the benchmark text by Thompson & Oldfield (1986). Mineral magnetism investigates the inherent magnetic mineralogy and granulometry of natural samples while palaeomagnetism studies the intensity and direction of the Earth's magnetic field as recorded by the natural remanent magnetization of rock and sediment samples. Thus, the magnetic parameters used in mineral magnetism are independent of the Earth's magnetic field at any point and are largely a function of the volume of magnetic minerals (O'Reilly 1976). These non-naturally remanent characteristics (also called non-directional magnetic measurements) are the basis of this branch of geophysical study. The biggest and unparalleled advantage of mineral magnetic studies is the speed of measurement. The speed of measurement for understanding important magnetic properties like magnetic susceptibility (χ) and SIRM (refer to Appendix I for definitions) is such that it takes only a few seconds to measure them, and the sample requirement is little, between 0.02 and 20 g. Induced/remanent magnetization of these specimens are measured by placing them in different kinds (AC, DC) and magnitudes (1 mT to 9T) of magnetizing fields that are artificially generated in the laboratory. In some cases, extremely low concentrations (ppm) of magnetic minerals can also be easily detected. As a consequence, it opens up new vistas of understanding into different environmental processes that lead to ecological as well as climatic changes on a wide range of timescales at a rate faster than any other technique. So far detailed studies in India have not been performed. With the establishment of the environmental magnetic laboratory at the Indian Institute of Geomagnetism, it is now possible to measure all the magnetic parameters discussed in Appendix I.

The reconstruction of the Indian monsoonal record has been a daunting task. Some progress has been made on the basis of studies on Arabian Sea cores and lake deposits of Peninsular India and the Himalayas mainly by studying the pollen composition of sedimentary deposits or the geochemical composition of organic matter or calcium carbonate. In context of the latter technique, the stable isotopes of carbon and oxygen have been extensively used. All these studies require specific criteria to be met with which may not be fulfilled under some conditions. For example, some deposits may have poor pollen preservation and also not contain authigenic carbonate. This is particularly the case of proglacial varve deposits and some coastal deposits. Recourse can then be taken to bulk sediment geochemistry, which is both time-consuming and expensive. One then needs to measure some physical property of sediment that may be sensitive to environmental processes, relatively rapid in measurement and requires low sample quantity. As outlined above, these criteria are met with, while examining the mineral magnetic property of sediments. It is this proxy measure whose application towards solving environmental problems has been successfully and amply demonstrated (Thompson & Oldfield 1986; Verosub & Roberts 1995; Dekkers 1997 & references therein); that is the theme of this special issue.

The primary advantage in using a single proxy measure (i.e. mineral magnetic parameter) is that it allows one to compare different records across thousands of kilometers. Since little is known in India about the immense potential of environmental magnetism studies for palaeomonsoon reconstruction, this paper serves to provide a brief overview of the subject. Examples, some of which are discussed in detail later in the volume, are succinctly touched upon.

IRON, IRON OXIDES AND MAGNETIC MINERALS

Iron is one of the most important and abundant elements on the Earth. The most important property of iron is its ability to occur in multiple ionic states, which contributes towards the global biogeochemical cycling of iron. This property also results in a tight integration of the iron cycle with the global oxygen and carbon cycles. A typical iron cycle (Stumm & Sulzberger 1992) comprises reduction of Fe (III) oxides by organic ligands and oxidation of Fe (II) by oxygen. Iron plays an important role in the oxidation of organic matter by oxygen. In the soil environment, microorganisms and plants produce a large number of acids of which oxalic acid is the most abundant. The presence of these acids governs pH based dissolution rates and solubility of iron oxides.

Pure oxides of iron such as magnetite, titanomagnetite, haematite and maghaematite and iron sulphides (greigite) usually impart the magnetic properties to rocks. Iron oxides crystallize with two different structures - spinel and corundum. Magnetite, titanomagnetite, ulvospinel, maghaemite and titanomaghaemite have spinel structure. Magnetite is also biochemically precipitated and is found in body tissues of organisms like bacteria, algae, insects, birds and mammals. Some of the magnetotactic bacteria synthesize magnetite particles from soluble iron. These bacteria are anaerobic or micro-aerophillic which occur in concentrations of 100 or 1000 per milliliter in a wide range of environments (Kirschvink et al. 1985). Also, the combustion of fossil fuel leads to the transformation of primary iron compounds to magnetic oxides. Magnetic spherules are an important component of fly ash gained by burning solid fuel. Industrial effluents discharge loads of magnetic particulates into the environment.

Haematite and titanohaematites, on the other hand exhibit a corundum structure. Pyrrhotite, an iron sulphide mineral, has a monoclinic structure while iron hydroxides of goethite crystallize in the orthorhombic system. Goethite typically forms as a weathering product and is antiferromagnetic mineral. Other magnetic minerals include iron and ferromanganese minerals.

Genesis of magnetic minerals

During the deuteric cooling of magma, two processes are at work tending to make the rock more magnetic. The first process involves spontaneous separation of magnetite-ulvospinel solid solution into end-members, while the other involves the oxidation of ulvospinel towards ilmenite. Also, the speed of cooling has an important effect on the crystallization of magnetic minerals. Where cooling is very rapid and escape of volatiles is allowed, the iron and titanium oxides stay in solid solution for a long time in metastable equilibrium. As a result, iron-titanium oxides within basaltic lavas tend to have low magnetic susceptibility. Mafic intrusions, though they contain the same amount of opaque oxide minerals as basaltic lavas, but have cooled more slowly, generally contain more magnetite and have a higher magnetic susceptibility. Extrusive rocks of acidic and intermediate composition are the most highly oxidized and therefore contain oxides having the highest Fe:Ti ratios. Basic extrusive rocks are in a distinctly more reduced state and form oxides having low Fe:Ti ratios. Rocks that are unusually low in silica tend to contain more magnetite than siliceous rocks having the same amount of iron.

The effects of re-heating and re-cooling during regional metamorphism promote the exsolution of magnetite, if external supply of oxygen is available. Regional metamorphism involves mechanical deformation and heating tending to cause the opaque oxide minerals to re-crystallize into coarser textures. Coarser crystalline magnetite has a higher magnetic susceptibility, but a lower magnetic remanence than the finely crystalline magnetite. This is because, in finely crystalline magnetite there is an ease of magnetic domain boundary movement.

Diagenesis may lead to conversion of paramagnetic iron to ferri- or ferro-magnetic material and vice versa. Exposure of rock surfaces to atmospheric processes and biogenic elements, resulting in weathering and soil formation, may lead to the concentration, dilution and transformation of iron compounds into secondary iron oxides. These secondary magnetic oxides formed at or near the soil surface differ in crystal form and size from the primary magnetic oxides.

MAGNETIC BEHAVIOUR OF MATERIALS

Magnetism arises from the uncompensated spin moment of the outermost electrons orbiting around a nucleus, giving rise to properties like dia-, para- and ferro-magnetism. Diamagnetic minerals such as quartz, feldspar, calcite, water etc. are weakly magnetic and the property results when an applied magnetic field interacts with the orbital motion of electrons which gives rise to very weak negative magnetization and is independent of temperature. However, the magnetization is lost as soon as the magnetic field is removed. On the other hand, paramagnetic behaviour arises when magnetic dipoles align themselves parallel with the direction of applied magnetic field to cause weak positive magnetization, which is dependent on temperature. Natural minerals like olivine, biotite, garnet, pyroxene and carbonates of iron and manganese are paramagnetic. Ferromagnetism is a property characterized by spontaneous magnetization, which exists even in the absence of magnetic field. This phenomenon results when all elementary magnetic moments of neighboring electrons are aligned parallel with one another resulting in net magnetic moment much greater than paramagnetic and diamagnetic materials. This property is temperature dependent because above a critical temperature, the Curie temperature, the ferromagnetic ordering breaks down by thermal energy and it behaves like a paramagnet.

Ferrimagnetism and antiferromagnetism are the basic variants of Ferromagnetism (Fig. 1). Ferrimagnets have antiparallel magnetic moments of different magnitudes such that the sum of the moments pointing in one direction exceeds that in the opposite direction. Antiferromagnets too have antiparallel magnetic moments, but of similar magnitude such that they exhibit zero bulk spontaneous magnetization in contrast to alignment pattern of canted antiferromagnets.

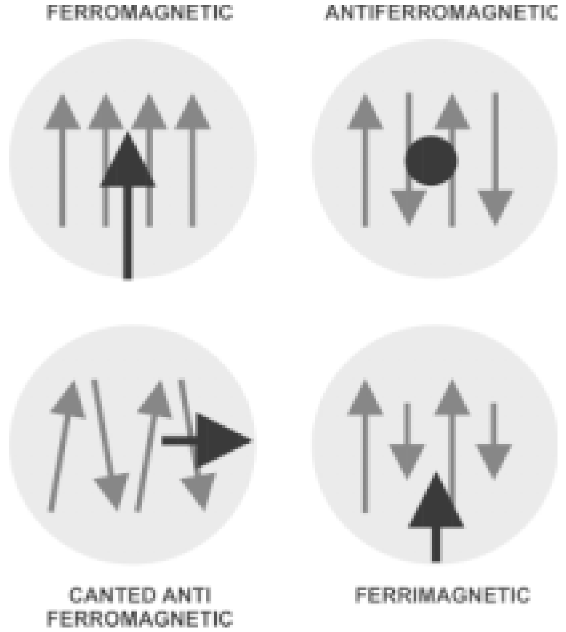

Figure 1. Four principal types of magnetic behaviour in natural materials. Dark gray lines depict atomic magnetic moments while black symbols (arrow and filled circle) show net magnetization vectors

Hysteresis loop

A hysteresis loop displays the field dependence of magnetization (Fig. 2a). When an unmagnetized piece of iron is magnetized, its magnetization slowly increases on application of the field and the magnetization returns to zero on removal of the field. On applying a stronger field, beyond a critical field called the coercive force, the magnetization is no longer reversible. It retains some remanent magnetization. On application of extreme applied field in one direction and then in the opposite direction and back gives rise to a loop called hysteresis loop, which is indicative of magnetic mineralogy as well as grain-size. Hysteresis properties are closely related to the arrangement of magnetic domains. The concept of domain was invoked by Weiss (1907) to explain a mechanism by which material with spontaneous magnetization can exist in a demagnetized state by splitting into many domains or regions, each spontaneously magnetized in any direction, thus rendering domain magnetization to be zero. Bloch

(1930) has suggested that magnetic domains were separated by zones of finite thickness. Domain structure is fundamentally linked with the relaxation times and magnetic properties of a mineral. The smallest grains (0.001-0.01 mm) with short relaxation times (T<150 S) are paramagnetic (super paramagnetic, SP). Slightly larger grains (~ 0.03 - ~ 0.50 mm), are termed stable single domain (SSD). At normal temperatures, the superparamagnetic/stable single domain boundary occurs at 0.03 mm diameter (Dunlop 1973). SSD grains have extremely long relaxation times. Larger grains (~10 mm), which contain few domains only, are called pseudo-single-domain (PSD), since their properties resemble those of SSD. The largest grains (> ~ 10 mm) with many domains are multidomain (MD). The magnetic properties of SSD and MD grains are quite different. The magnetic remanence of SSD grain assemblage is higher and more stable than that of MD grain. SSD grains have a slightly lower initial susceptibility (χ_{in}) than MD grains. SP grains possess higher initial susceptibility (χ_{in}) than that of SD or MD grains (Dekkers 1997). MD, PSD and SP grains produce much thinner loops (Fig. 2c) than SSD grains (Fig. 2b). Paramagnetic and diamagnetic minerals do not exhibit hysteresis loops whereas haematite produces flat and fat loops (Fig. 2d: dashed) and its occurrence with magnetite gives rise to the loop of Fig. 2d (solid).

MAGNETIC GRAIN SIZE AND SEDIMENT PARTICLE SIZE

Although magnetic grain size (e.g. MD to SSD to SP) can never be independent of sediment particle size (sand to silt to clay), it is important to appreciate the difference between the two. Coarse sediments may contain fine magnetic grains, in which case, magnetic parameters will reflect the size of the latter and not the sediment size distribution. For example, Earth's surficial processes such as erosion, weathering,

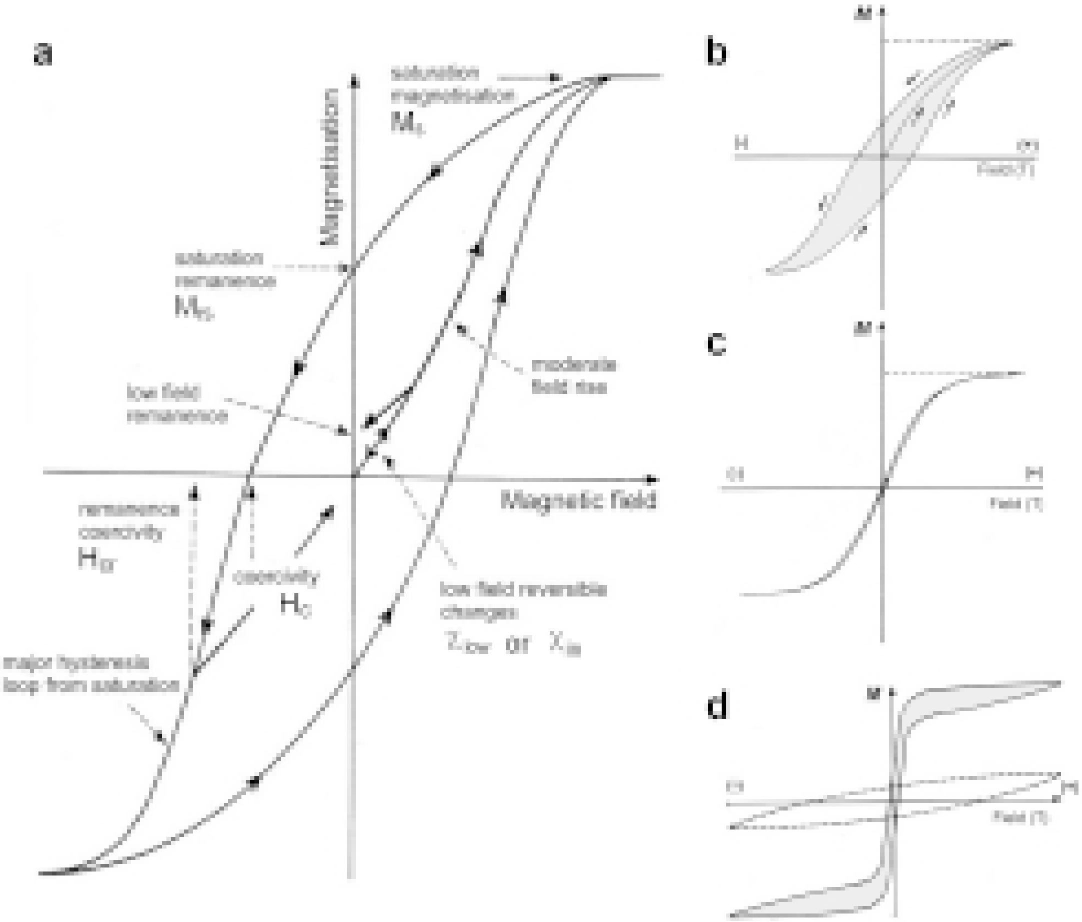

Figure 2. a) A general hysteresis curve showing the parameters measured during mineral magnetic experiments. Hysteresis curves for SSD magnetite (b), MD (c) and (d) shows hematite (dotted line) and two components (hematite and magnetite) hystereses curves. For details on the magnetic parameters refer Appendix I.

chemical alteration, pedogenesis, fire or bacterial activity may alter the magnetic grains from multi-domain (MD) to stable (SSD), pseudo-stable single domain (PSD) and super paramagnetic (SP) grains. However, during the transport of material, if no physical or chemical changes are involved, then the mechanism of sorting will nevertheless be operative. This mechanism may further lead to magnetic parameters of sediments to fundamentally differ from those observed at the source and to understand which one has to comprehend the distinction between particle size and magnetic grain size. Magnetic properties vary with the magnetic grain size (Maher & Taylor 1988). However, in a natural setting there isn't clear-cut demarcation between the magnetic grain size and particle size. Their properties either coalesce or hinder each other, or one masks the other completely subjecting itself to wrong or misleading interpretations (Walden & Slater 1993). Hence, it is necessary to have particle-size specific magnetic measurements where broad particle size distribution is encountered (e.g. Oldfield et al. 1985; Walden et al. 1992). These issues are particularly important for palaeomonsoon studies as outlined below.

In order to succeed in the reconstruction of a proxy monsoon record, it is utmost necessary that certain pre-requisites are satisfied (Fig. 3). In environmental magnetism as we measure the bulk sediment property, any transition in sediment grain size would also be reflected in magnetic parameters. Such lithological changes, which are accompanied, by magnetic parameter changes may be on account of autogenic processes. An example of such a process is the lateral migration of a meandering channel within its floodplain (Fig. 3). Autogenic changes are an intrinsic feature of any depositional system. Hence mineral magnetic changes at lithological boundaries may not be climatologically significant. This leads us to our first pre-requisite of lithological homogeneity, which also implies that there are no changes in the depositional sub-environment. Within homogeneous lithologies (clay in Fig. 3), variations in magnetic parameters may be attributed to either an allogenic climatic influence (i.e. the true proxy record) or could also be under special circumstances, due to provenance changes. If one assumes that a site may potentially receive sediment from 2 catchments (A and B in Fig. 3) that have dissimilar provenances, such changes in provenance may be confirmed using the approach of Walden et al. (1993). In this approach, similar type of sediments from each catchment is separated granulometrically and is analyzed mineral magnetically. The distribution of the mineral magnetic properties across grain classes is a diagnostic feature of each

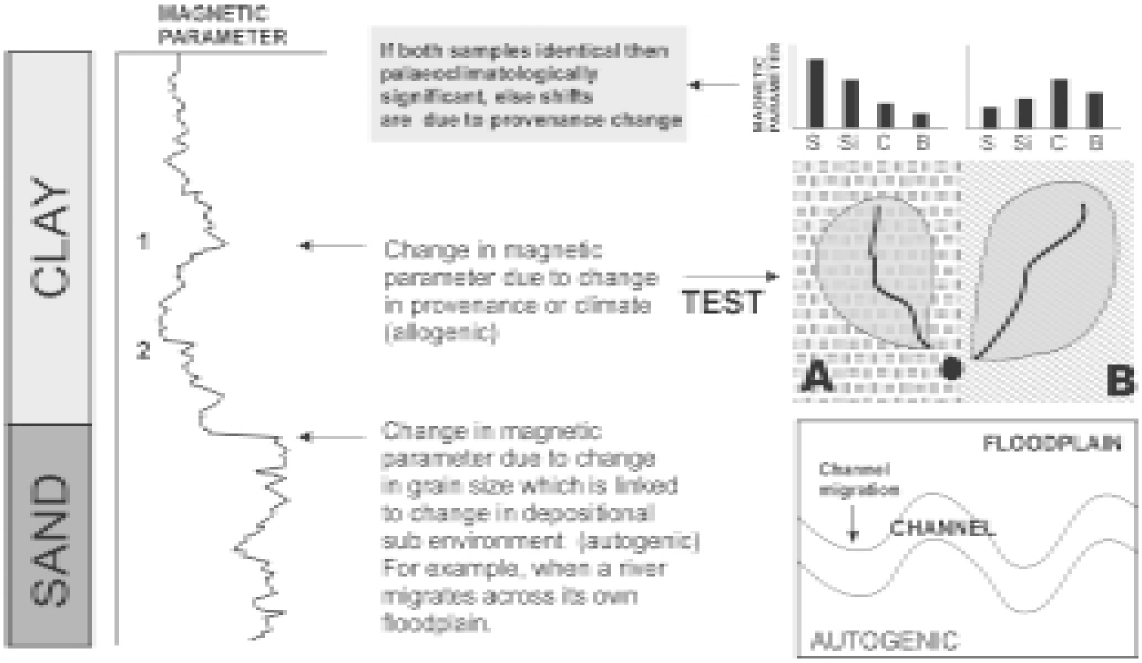

Figure 3. Principles of mineral magnetic measurements for reconstructing a palaeomonsoon record from sediment archives. For details see text.

provenance. For example, Provenance A may thus have the major component of the susceptibility signal in the sand fraction. As the lithology sampled is clay, bulk susceptibility would be low. Provenance B, which has the major component of the susceptibility signal, concentrated in clay fraction would show higher susceptibility in this fraction, thus allowing discrimination of provenances. Such studies should be carried out when doubts arise about the significance of excursions in mineral magnetic parameters within a lithologically homogenous profile.

ENVIRONMENTAL MAGNETISM AND PALAEOMONSOONS

Palaeomonsoon changes have till date been studied using isotopic and foraminiferal proxies from the Arabian Sea. These studies have increased our knowledge of changes in past monsoon wind strengths. Recently, studies by Sarkar et al. (2000) and Yadava & Ramesh (1999) have shown the nature of monsoon rainfall changes over the Holocene period. Monsoon wind intensity and rainfall may not necessarily be proportional as has been shown recently by Basavaiah et al. (comm.). A millennium of reduced rainfall and strong winds led to the formation of aeolian dunes in Gujarat, north of Nal Sarovar. Past monsoon rainfall changes need to be documented in more detail. This section provides an overview of recent results from sites in India spanning the Himalayas, Thar Desert, Gujarat and the east coast (Fig. 4). The sediments are from disparate environments such as lacustrine, fluvial, coastal, and aeolian on which various magnetic techniques have successfully been employed to reconstruct the palaeomonsoon history of different regions in India.

Lakes and lacustrine deposits

Lake sediment study has now firmly entrenched itself as an important branch of environmental study in India. The magnetic minerals, especially magnetite and haematite, found in a lake are mostly of allogenic origin, though diagenetic or authigenic origin cannot be entirely ruled out. The magnetic mineralogy reflects the course of climatic changes by recording evidence of the associated changes in sedimentation, weathering and pedogenic regimes. Mineral magnetic measurements, whether concentration dependent or not, can reflect palaeoclimatic conditions as a result of the effect that changing climate has on the environmental processes which control the concentrations and types of magnetic minerals deposited in lake sediments.

Mineral magnetic studies on Garbyang proglacial lake deposits in the Trans-Himalayan region provided a continuous record of climate change since Last Glacial Maximum (LGM) to the beginning of Holocene (Basavaiah et al., this volume). Luminescence dates suggest the timing of LGM at 20 ± 3 ka to 18 ± 3 ka.

It must be noted that magnetic susceptibility and elemental concentration in levels corresponding to 13 ± 2 ka to 11 ± 1 ka provide a first evidence of Younger Dryas cooling from Indian Subcontinent. Variation in χ indicates changing concentration of magnetic minerals while the S-ratio provides a measure of the relative proportions of higher coercivity magnetic minerals (haematite) to lower coercivity magnetic minerals (magnetite). Relatively high values of magnetic susceptibility and S-ratio indicate a close relationship between the erosional processes and increasing detrital titanomagnetite concentration (Williamson et al. 1998). However, a direct climatic connection needs consideration on the influence of changes in lake chemistry that is modulated by fluctuating fresh water influx and has strong influence on the type and concentration of magnetic mineralogy (Williamson et al. 1998; Wang et al. 2001). Magnetic parameters, especially χ and S-ratio are affected by dilution caused by precipitation of diamagnetic carbonate and aquatic growth of organic matter. Additionally, under anoxic condition, ferrimagnetic magnetite and titanomagnetites are susceptible to chemical dissolution (Robinson 1986; Lean & McCave 1998; Williamson et al. 1998) leading to mineralogical modification of detrital mineralogy. Low susceptibility and S-ratio correspond to two distinct lithological units.

Studies from Nal Sarovar (Gujarat) and Iskapalli (eastern India) have provided evidence for the presence of a prolonged drought period between 4000 to 3000 cal yr BP (Basavaiah et al. comm.). This period of reduced rainfall is reflected extremely well in the S-ratio (Fig. 5), which provides a measure of the relative proportions of reduced and oxidized state of iron oxides in the sediments. These oxidation states are primarily governed by weathering and water saturation of soils, which in turn is sensitive to mean annual rainfalls. These studies confirm the reduction in monsoon rainfall observed in pollen records of a Himalayan lake (Phadtare 2000) and from Karwar (Caratini et al. 1994) and also provide compelling evidence of a causal relationship between civilization collapse and climate change. Other typical high latitude events such as the Little Ice Age have also been identified in the S-ratio records from mangrove deposits (Fig. 5) from eastern India (unpublished data).

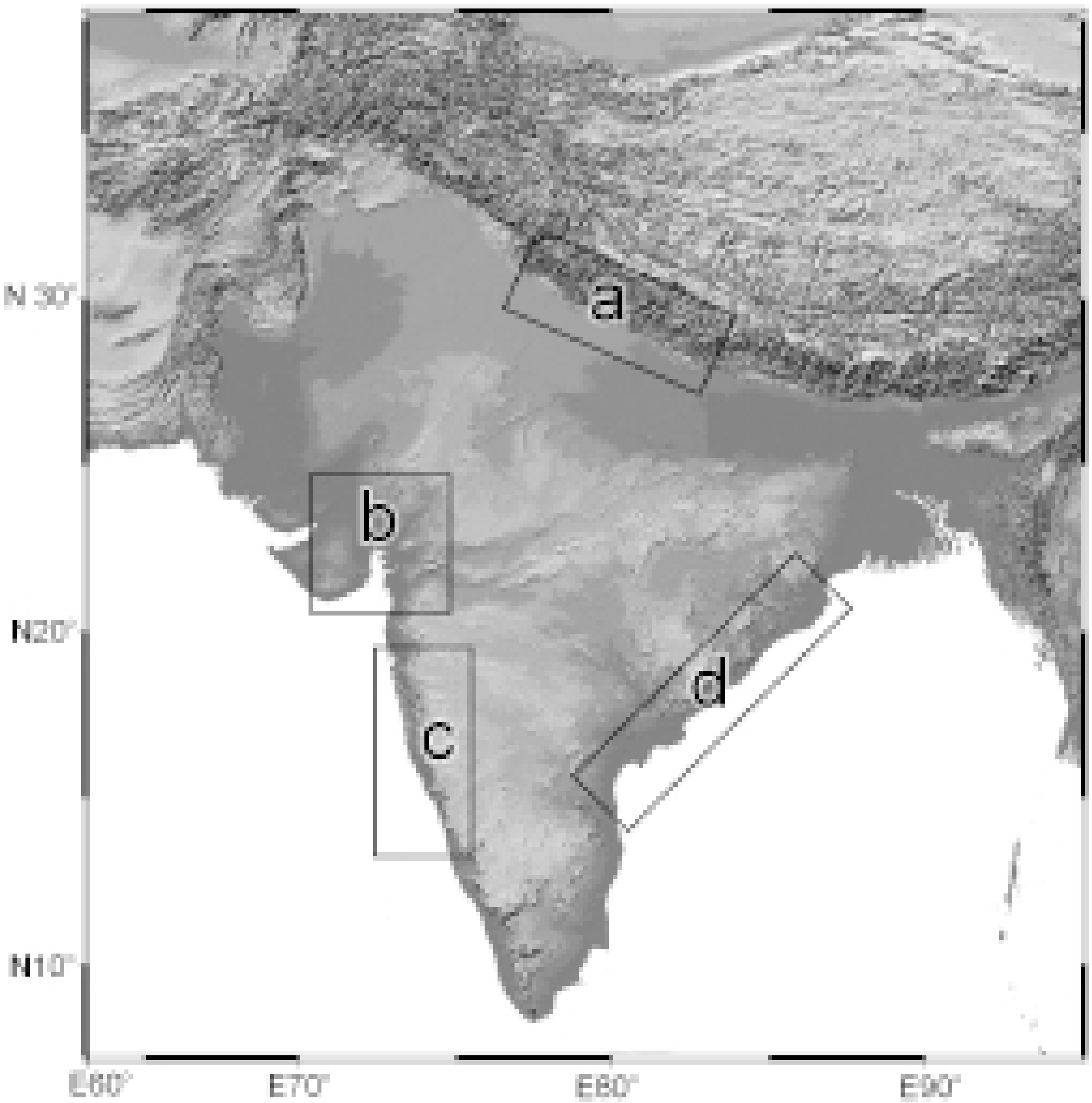

Figure 4. Regions in which studies are being carried out by the Environmental Magnetism Group, IIG. a) Proglacial lake deposits from Central Higher Himalayas, b) Thar desert lakes and playas, Gulf of Kachchh coastal deposits and continental deposits in Mainland Gujarat, c) Mumbai lakes and Konkan belt covering estuaries in Goa and mangroves along the west coast, d) East coast deltas viz. Mahanadi, Krishna, Godavari, Cauvery and Pennar. In these regions stress is being given on mangrove deposits as they are ideal sites for using the mineral magnetic approach.

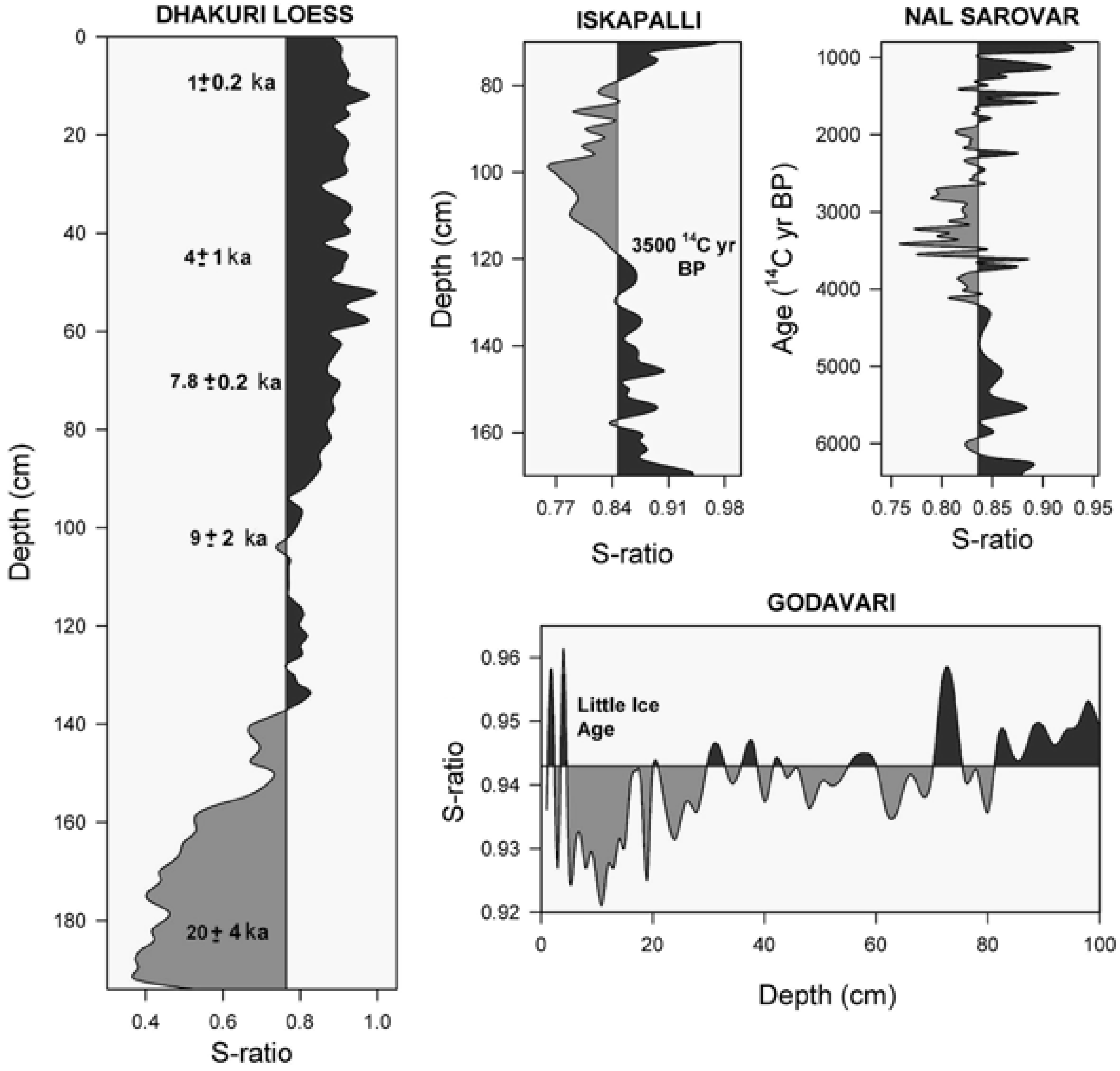

Figure 5. The S-ratio, a reverse field remanence parameter as an accurate proxy of palaeomonsoon rainfall. Dhakuri loess (unpublished data) site is in the Central Higher Himalaya. Iskapalli and Godavari sites are within the Godavari delta region while Nal Sarovar site is situated in mainland Gujarat and is a palaeolagoon. In all these diverse environments low S-ratios identify periods of reduced rainfall (shown in orange) on various time scales. This mineral magnetic parameter has enabled in identifying several key events hitherto unreported for the summer Indian monsoon. These include the reduction of monsoon rainfall in tune with higher latitude climate events such as the Younger Dryas and the Little Ice Age.

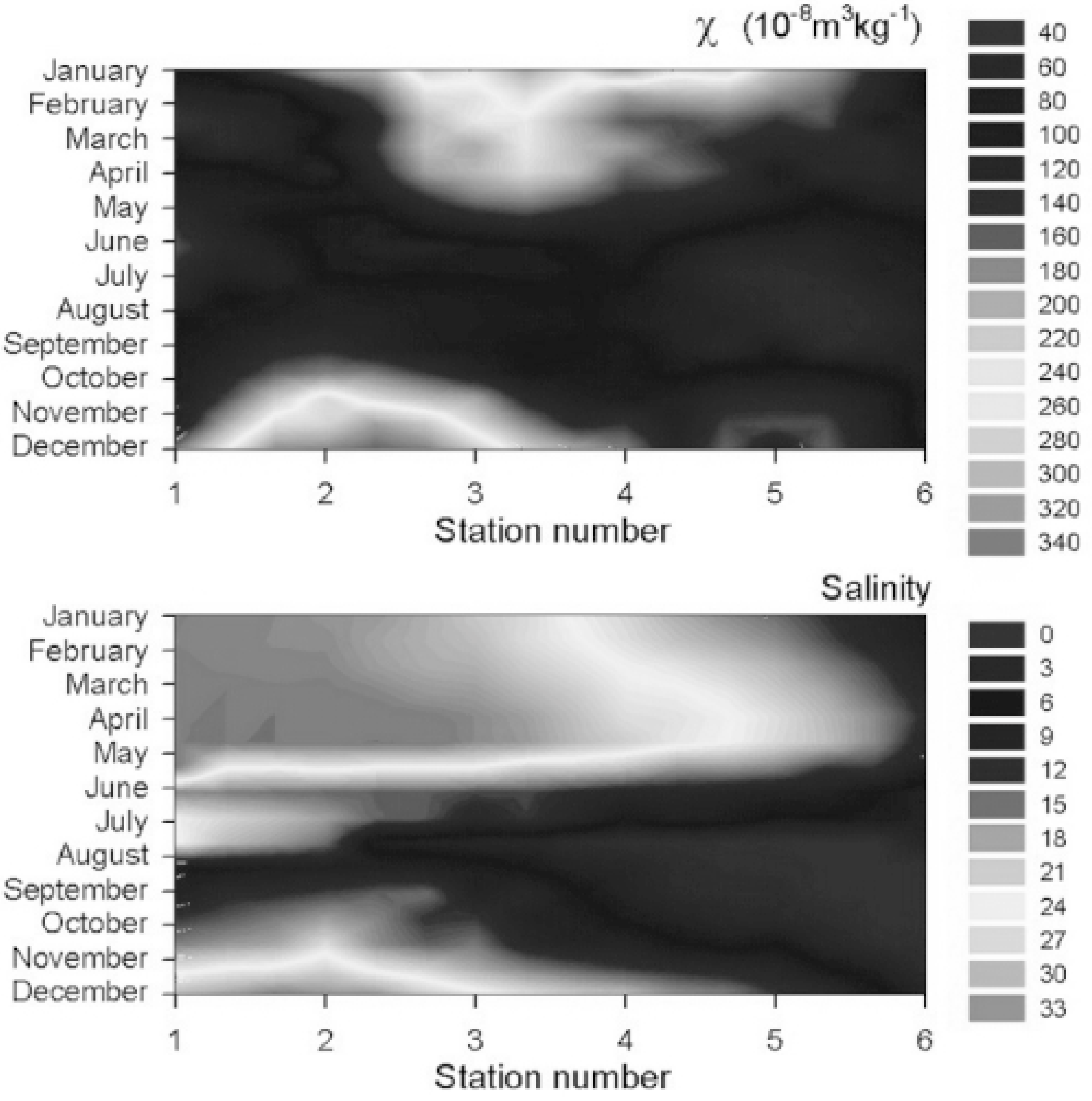

Figure 6. Variations in magnetic susceptibility, χ in the Mandovi estuary in relation to salinity changes in the year 1985-1986. These studies are being carried out to understand temporal and spatial variability of mineral magnetic parameters over shorter time scales. The plot shows the strong dependence of χ on salinity changes (tidal changes). During the monsoon months high discharges flush out the high susceptibility sediments in the suspended load, which re-enter during the winter months inside the estuary.

The ability of the S-ratio to sensitively document climate change as demonstrated from various sites is very encouraging.

Deltaic and coastal sediments

The natural physiographic setting of the eastern coast of India and its geomorphology has endowed it with numerous deltaic and mangrove setting. Mangroves play an important role to preserve the imprint of sea-level fluctuations related to climate, eustasy or tectonic movements. A comprehensive study has been carried out on the five deltas of the east coast, viz., Pennar, Cauvery, Krishna, Godavari and Mahanadi. These studies have been carried out on mangrove sediments, which are characteristically enriched in clay and silt. As Kumaran et al. (this issue) and Seetharamaiah et al. (this issue) point out, peculiar rooting systems aid in the preservation of the mineral magnetic signal of environmental change in such sediments. The fine-grained nature of mangrove sediments too is largely a result of sediment trapping through the interaction of tides and mangrove root systems.

Loess, palaeosols and modern environments

Soil magnetic properties of Terra Rossae from southeastern Saurashtra are similar for three palaeosol events related to climates around 250, 120, 50 ka BP. These palaeosols show similar levels of χ_{fd} implying that mean annual rainfalls during these three periods were not largely different (Khadkikar & Basavaiah, in press). Himalayan loess-palaeosol deposits also reflect the efficiency of the S-ratio in accurately outlining key climatic events over the past 20,000 years. Preliminary results reveal lower S-ratio values during the last glacial maximum, which increase steadily in line with northern Hemisphere deglaciation (Fig. 5).

For palaeomonsoon studies using environmental magnetism, it is extremely important to understand spatial variability of mineral magnetic properties of sediments in modern depositional environments. A first step towards implementing this philosophy has been the study of the Mandovi estuary. Monthly bedload sample measurements illustrate how magnetic susceptibility varies in response to river discharge and tidal influence through a typical year (Fig. 6). Such studies on the magnetic properties of suspended sediment load from coastal regions and modern lakes and aerosol samples are important for aiding palaeomonsoon reconstruction using sediment archives.

The S-ratio as a proxy of palaeomonsoon

To sum up, it can be said that by far the most important result obtained after studying deposits collected from different regions of Peninsular India and the Himalayas is the extreme sensitivity of the mineral magnetic parameter S-ratio (backfield $IRM_{-0.3T}$/SIRM) to palaeomonsoon changes. This parameter, as described in the Appendix I, essentially documents changes in the relative abundances of two oxidation states of Fe in the upper layers of the soil environment leading to the formation of either the reduced or oxidized mineral phase. Empirical evidences from palaeo-records have demonstrated that the upper soil environment (A horizon) responds to changing redox environment, which in turn is governed by mean annual rainfalls. This is possible as variable degrees of water saturation of the soil alter the redox states leading to the formation of magnetite (possible through a microbial pathway) during periods of enhanced rainfall, whereas the formation of haematite/goethite is made possible through oxidative processes during periods of reduced rainfall. This may obviously be complicated if there is a detrital source of haematite/goethite. However, in Peninsular India we are aided by the presence of Deccan Traps, a rich source of magnetite and titanomagnetite, which contributes to the success of the S-ratio as a proxy for palaeomonsoons. Hence, in line with this observation, in principle, the S-ratio may be used to reconstruct climate changes in regions of continental flood basalt provinces. χ (magnetic susceptibility) does not respond sensitively to climate change in the Indian context and we advocate extreme caution in using this environmental magnetic parameter, in solitary, for palaeomonsoon reconstruction.

Secular variations

In the absence of conventional radiometric dating and fossil evidence, magnetostratigraphy is considered to be a very powerful tool to correlate rock formations. The magnetic clock, driven incessantly by electric currents in the Earth's liquid outer core, oscillates back and forth switching between its two stable modes of a 'normal' state- in which the Earth's magnetic field points north, and a correspondingly 'reverse' state- in which the field points south. The geomagnetic chronometer lacks a regulator, so it runs unevenly switching intervals along the way, varying from a few thousand years to several tens of millions of years. However, sedimentary deposits can be dated directly from their Natural Remanent Magnetization (NRM) by matching their palaeomagnetic secular variation signature with historically documented geomagnetic field fluctuations (especially for the past 400 years). When master curves of palaeomagnetic declination and inclination are calibrated by instrumental/archaeomagnetic parallels, radiocarbon dates and/or by varve chronology, they may provide a rapid means of dating sedimentary deposits which have preserved a sufficiently strong and stable primary palaeomagnetic remanence in their sediments. Such studies are currently being carried out on Garbyang, Goting and Milam lakes (Himalaya), Mastani and Lonar lakes (Maharashtra) and mudflats of Gulf of Kachchh (Fig. 4). The objective is to erect a master curve of inclination and declination that may serve as a relative chronological tool for unconsolidated deposits especially for the Holocene part. However, the accuracy of the secular variation derived from magnetostratigraphic method depends largely on the accuracy of dating of the "type palaeomagnetic record". At best the dating of type records is accurate to within one or two hundred years. However, this uncertainty does not prevent secular variation derived from magnetostratigraphy as complementing other dating methods.

CONCLUSIONS

Mineral magnetic approach can be a favoured tool for resolving climatic conditions that prevailed during the Quaternary. These techniques have been employed on different samples collected from diverse environmental settings of India in a bid to reconstruct the palaeomonsoonal record of tropical India. This technique has two unparalleled advantages. The first is the ease and speed of measurements that cannot be attained by any other conventional techniques now employed. The other is the correlational capability in comparing inter-site similarity separated by several kilometers by virtue of similar proxy parameters that are measured.

The reconstruction of palaeomonsoonal record of the Indian Subcontinent has thrown up the remanence parameter, S-ratio, as being more reliable and reflective of the changing environment (climate). The general tendency in India is to use magnetic susceptibility (χ) in palaeoclimatic reconstruction. But, our results caution against the indiscriminate use of this parameter in the Indian context. The identification of Younger Dryas (11 ka), Little Ice Age (1780 AD), and reduced monsoon during 4000-3000 cal yr BP, imparts a great deal of confidence in establishing the efficacy of S-ratio, in Indian context, as an accurate proxy of climate change. However, to better understand the relationship between the magnetic properties of soils, sediments and climate change, detailed studies on modern environments are needed. Work is currently being carried out on modern environmental regimes such as Mandovi and beach sediments of Maharashtra. Also, efforts need to be intensified to provide a master curve of inclination and declination to serve as a relative chronological tool for the unconsolidated samples of the Indian subcontinent, supplementing the absolute dating techniques.

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Figure 5. The S-ratio, a reverse field remanence parameter as an accurate proxy of palaeomonsoon rainfall. Dhakuri loess (unpublished data) site is in the Central Higher Himalaya. Iskapalli and Godavari sites are within the Godavari delta region while Nal Sarovar site is situated in mainland Gujarat and is a palaeolagoon. In all these diverse environments low S-ratios identify periods of reduced rainfall (shown in orange) on various time scales. This mineral magnetic parameter has enabled in identifying several key events hitherto unreported for the summer Indian monsoon. These include the reduction of monsoon rainfall in tune with higher latitude climate events such as the Younger Dryas and the Little Ice Age.

APPENDIX 1: ENVIRONMENTAL MAGNETIC PARAMETERS

<table>
<tr><td colspan="2">HYSTERESIS PARAMETERS (Fig.2a-d)
Instrumentation: Molspin Vibrating Sample Magnetometer (VSM) and Princeton Measurements Alternating Gradient Force Magnetometer (AGFM)</td></tr>
<tr><td>Saturation Magnetization
M_s [mAm^2kg^{-1}]</td><td>Maximum induced magnetization at 1T and is calculated by extrapolating the high field magnetization curve to the y-axis (Fig.2b,c)</td></tr>
<tr><td>Saturation Remanent Magnetization
M_{rs} [mAm^2 kg^{-1}]</td><td>Magnetization retained even after complete removal of magnetic field following magnetization at 1T and in theory the same as SIRM on the Molspin spinner</td></tr>
<tr><td>Coercive Force, H_c [mT]</td><td>The backfield that makes magnetization zero</td></tr>
<tr><td>Coercivity of Remanence, H_{cr} [mT]</td><td>Measured as larger backfield strength required than H_c to return M_{rs} to zero</td></tr>
<tr><td>Reverse low field (χ_{low}) or initial magnetic susceptibility χ_{in} [$10^{-6}m^3kg^{-1}$]</td><td>The slope of magnetization curve at the origin of a hysteresis loop within a small magnetic field and is reversible, i.e. no remanence is induced</td></tr>
<tr><td>High field susceptibility
χ_{hf} [$10^{-6}m^3kg^{-1}$]</td><td>Measured as the high-field slope of a hysteresis curve between 800 mT and 1 T. χ_{hf} refers to paramagnetic susceptibility χ_{para} and is used to calculate the ferrimagnetic component χ_{ferri} in the total magnetic susceptibility χ_{total}</td></tr>
<tr><td colspan="2">MAGNETIC SUSCEPTIBILITY
Instrumentation: MS2 Bartington Susceptibility Meter and Dual Frequency Sensor (noise level $3x10^{-9}$ m^3kg^{-1}) and Agico KLY-2 Kappabridge (noise level $2x10^{-10}$ m^3kg^{-1})</td></tr>
<tr><td>Volume Susceptibility
κ [dimensionless]</td><td>Defined as $\kappa = M/H$, M being volume magnetization induced to intensity of magnetizing field H</td></tr>
<tr><td>Specific susceptibility, χ [m^3 kg^{-1}]</td><td>Measured as the ratio of volume susceptibility to density $\chi=k/\rho$</td></tr>
<tr><td>Frequency dependent of susceptibility χ_{fd} [percentage or m^3 kg^{-1}]</td><td>Variation in χ between low (0.47kHz) and high frequencies (4.7kHz).
χ_{fd} indicates viscous grains at the superparamagnetic/stable single-domain boundary</td></tr>
<tr><td colspan="2">MAGNETIC REMANENCE
Instrumentation: Molspin Spinner Magnetometer (noise level $0.1x10^{-5}Am^2kg^{-1}$); Agico JR-6 Spinner Magnetometer; 2G-Enterprises SQUID Magnetometer (for 10 g samples, noise level $3x10^{-9}Am^2kg^{-1}$); Magnetic Measurements MMPM9 Pulse magnetizer and Molspin Pulse Magnetizer</td></tr>
<tr><td>Natural Remanent Magnetization
NRM [mAm^2kg^{-1}]</td><td>Acquired in the Earth's magnetic field either by cooling of a mineral through its Curie (blocking) point, crystal growth through the blocking volume or deposition and 'fixing' of detrital particles</td></tr>
<tr><td>Viscous (Time-Related) remanent magnetization,VRM [mAm^2kg^{-1}]</td><td>Acquired on exposure to a new magnetic field and is a time-dependent magnetization unrelated to Earth's magnetic field</td></tr>
<tr><td>Anhysteretic remanent magnetization ARM [$10^{-5}Am^2kg^{-1}$]</td><td>An ideal magnetic remanence for being free from hysteresis and is imparted in a peak 100mT AF that smoothly decreased to zero in a small DC field's presence. ARM allows estimation of concentration and presence of finer ferrimagnetic minerals. For example, SSD particles have high ARM intensities per unit mass compared to MD particles</td></tr>
<tr><td>Susceptibility of ARM,χ_{ARM}[m^3kg^{-1}]</td><td>Normalized ARM for the strength of the steady field</td></tr>
<tr><td>Isothermal remanent magnetization IRMs [10^{-5} Am^2kg^{-1}]</td><td>Acquired in different DC forward and back fields (10mT to 2T or even up to 9T) at a given temperature, commonly at room temperature</td></tr>
</table>

Saturation isothermal remanent magnetization SIRM [$10^{-5}Am^2kg^{-1}$]	Measured as the highest volume of magnetic remanence that can be produced in a sample by application of a very high field (usually >1T). SIRM relates to both mineral type and concentration
'Soft' IRM, IRM_s, [Units are same as for SIRM]	Remanent magnetization after a magnetization either in a relatively low forward field of 20mT, 30mT, 40mT or 50mT or reverse fields 'back IRMs'
'Hard' IRM, IRM_h, [Units are same as for SIRM]	Difference between SIRM and IRM measured after magnetization in a field of 300mT or difference between SIRM and IRMs in a reverse field of 300mT, i.e. HIRM= $SIRM\text{-}IRM_{-300mT}$
USEFUL PERCENTAGES AND QUOTIENTS (RATIOS): INTERPRETATION OF RESULTS	
χ_{fd}[%]	~10% or 5-10% would indicate a large fine viscous (magnetite) component of SP range
SIRM/χ	Useful to distinguish between different types of magnetic behaviour. For example, if both χ and SIRM are low, but SIRM/χ is relatively high, there may be a large amount of haematite. If χ is positive but there is little or no remanence, then the magnetic minerals in the sample will probably be mostly paramagnetic minerals
SIRM/χ; ARM/χ & ARM/SIRM	High SIRM/χ, ARM/χ and ARM/SIRM values denote significant SSD (magnetite) grains
ARM/SIRM	Low ARM/SIRM values indicate a large MD (magnetite) component
Backfield IRM/SIRM or S-ratio; High field remanence HIRM	S-ratio defined here as $IRM_{-0.3T}$/SIRM recognizes samples with haematite to magnetite proportions because ferrimagnets are expected to saturate in fields below 0.1 T. Larger high field remanences, HIRM are due to proportionally high imperfect antiferromagnetic components such as haematite and goethite
M_{rs}/M_s ratio	Indicator of magnetization state of a sample; ratio values of 0.5 represent SSD grains; less than 0.1 for MD and still lesser values for SP grains.
H_{cr}/H_c ratio	Provides magnetization state of a sample; uniaxial SSD grains have ratio of 1.09, MD grains around 4.0 and SP grains in excess of 10.0

Figure 6. Variations in magnetic susceptibility, χ in the Mandovi estuary in relation to salinity changes in the year 1985-1986. These studies are being carried out to understand temporal and spatial variability of mineral magnetic parameters over shorter time scales. The plot shows the strong dependence of χ on salinity changes (tidal changes). During the monsoon months high discharges flush out the high susceptibility sediments in the suspended load, which re-enter during the winter months inside the estuary.