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# Magnetostratigraphy of the Makran Margin Sediments

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ABSTRACT: *Five piston cores were recovered from N-S slope transect across the Makran Continental Margin during the joint research programme between Pakistan and The Netherlands in 1992. These cores are from upper slope region (Water Depth 1325 m; 5.5 m length). Three are from mid-slope basins (Water Depth 1768 to 2482 m; 5.5 to 14 m length) and two from abyssal plain (Water Depth 3274 m; 10.5 m length). Oxygen Isotope stratigraphy and magnetostratigraphy studies of the two cores (MKM - 469 from mid-slope and MKM-472 from abyssal plain) reveal the climatic change leading to more dominant monsoonal condition in the early Holocene and hence an increased supply of terrigenous material including magnetic grains.*

*Observed short duration palaeomagnetic excursions (6000-8000 yrs B.P and 26000 yrs B.P) noted in both cores reflect true geomagnetic field behaviour on the Makran Margin.*

## INTRODUCTION

In general terms, unconsolidated sediments will, in part, consist of discrete magnetic grains or magnetic fragments in close association with other non-magnetic detrital grains. When such sediment is deposited the magnetic moments of the mineral grains or fragments tend to align parallel to the ambient geomagnetic field direction at the deposition site, assuming that no other aligning forces are acting. The alignment of the magnetic moments of the grains produces remanant magnetization in the sediment i.e. magnetization reflecting the direction of the ambient geomagnetic field at the time of deposition. Following compaction and consolidation, the remanent magnetization direction may be retained by the sedimentary rock.

Further sedimentation will result in the formation of a sedimentary sequence. This sequence represents a "time slice" back through time to the onset of sedimentation. Measurement of the remanent magnetization at various levels in this sequence may, therefore, accurately record any variation in the direction of the geomagnetic field with time. In most magnetostratigraphy studies it is assumed that the primary characteristic direction of magnetization was acquired at the time of formation of the sedimentary sequence. Later remagnetization acquired can reset the "inferred" magneto-stratigraphy in some instances (O'Brien, 1989).

The results of measurements of sedimentary sequences have shown that the direction of the geomagnetic field has reversed at irregular intervals through time. A sedimentary succession can, therefore, consist of a series of normally and reversely magnetized stratigraphic units. The thickness of a magnetized unit depends not only on the length of time of magnetization in that particular direction, but also on factors such as sedimentation rates and whether sedimentation was continuous occurring or was punctuated by intervals of non-deposition, or by periods of erosion. Directions of remanent magnetization which are shallower than expected at a particular site may be observed. These directions may be observed if the sedimentary sequence records the behaviour of the field during a period of magnetic reversal or has been modified by depositional and post-depositional factors related to inclination errors.

A uniform magnetized stratigraphic unit is termed a magnetozone. The polarity of a magnetozone is termed normal if the characteristic remanence is directed in the same sense as the present day field, and reverse if the magnetization direction is in the opposite sense to the Earth's magnetic field.

Magnetozone boundaries are assumed to represent synchronous changes in the direction of the geomagnetic field, on a global basis. As such these boundaries represent world wide time planes within rock sequences. These magnetozone time planes are important, as they are usually independent of the depositional environment and hence of any facies controls which are known to affect bio-stratigraphical correlation schemes.

## EARTH'S MAGNETIC FIELD

The Earth's magnetic field, when averaged through time (over periods of $10^{4}$ to $10^{-5}$ yr), is found to be a dominantly dipolar nature coincident with the axis of rotation (Opdyke and Henry, 1969). The present day magnetic field can be closely approximated to a single dipole (W.Gulbert, 1600) located at the centre of the Earth and inclined at about 11.5° to the rotational axis. The point of intersection of the axis of the dipole and the Earth's surface define the north and south "Geomagnetic Poles" which lie at 79°N, 70°W and 79°S, 110°E respectively (Fig. 1) (O'Brien, 1989). Direct observations from magnetic observatories on the Earth's surface show that the intensity of the field varies from 60 mT near the poles to about 30 mT near equator. Smaller non-dipole field components can be specified when the dipole field is subtracted from the total field observed over the surface of the Earth (McElhinny, 1973).

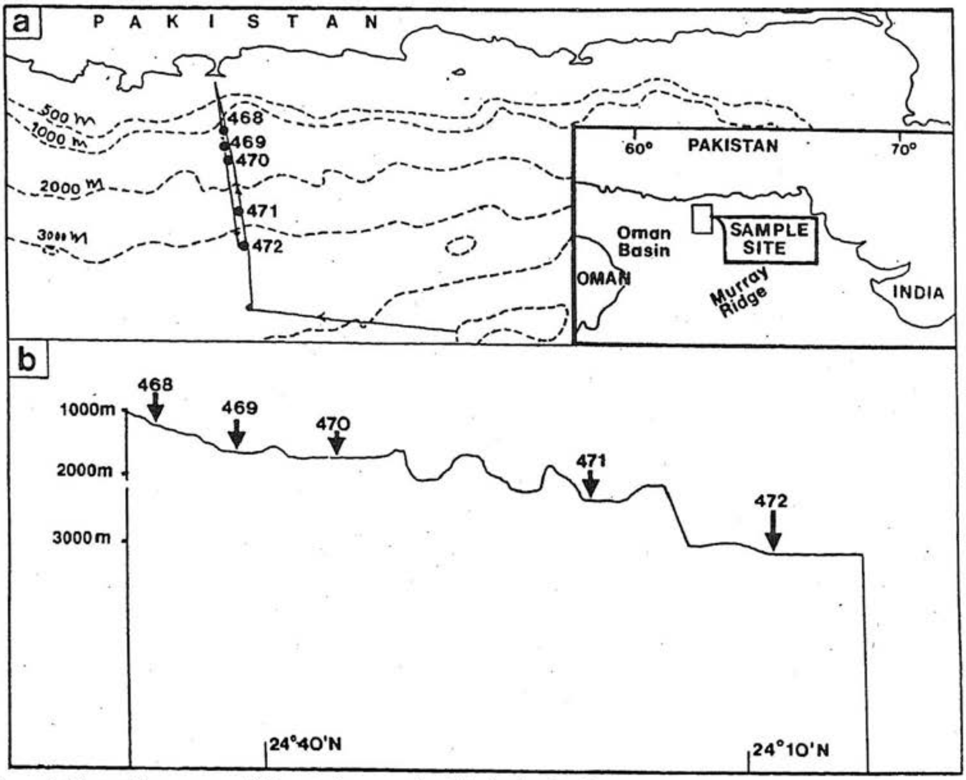

Fig. 1. (a) Location map of the study area (solid circles indicate core sites and solid lines are survey track of 3.5 kHz profles). (b) Bathymetric profile through core site.

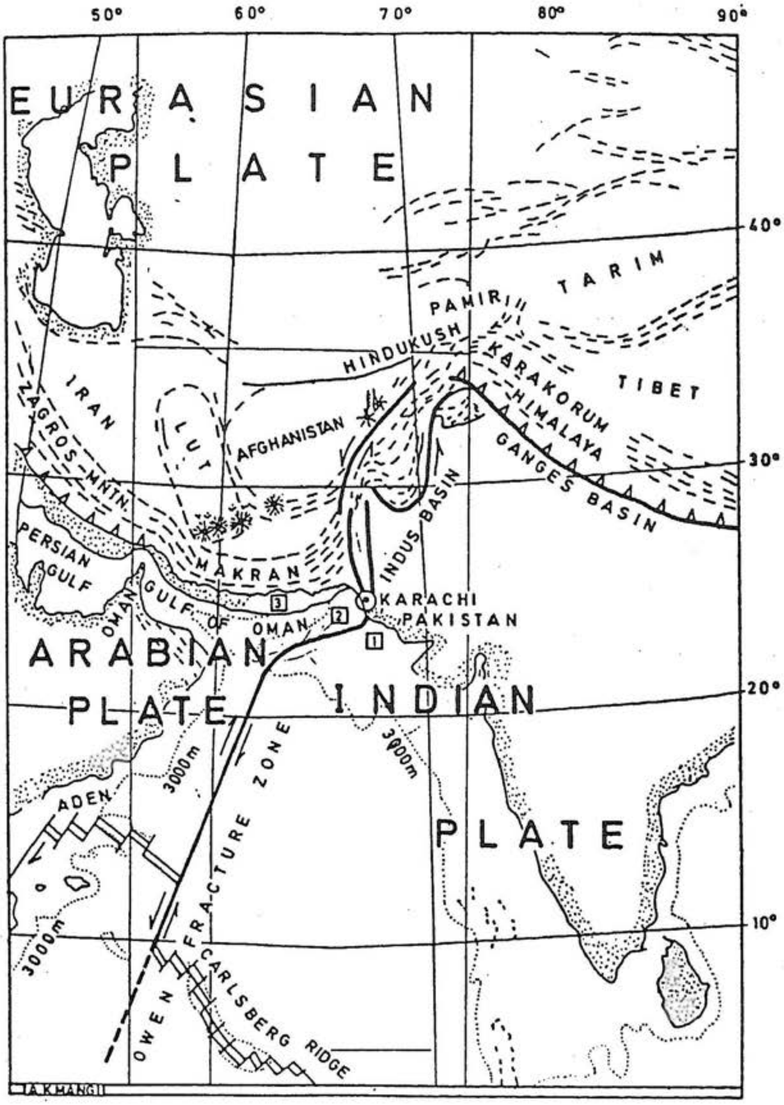

Fig. 2. Plate tectonic setting of the Arabian Sea Floor. 1 Passive continental margin. 2 Murray transform domain. 3. Makran Subduction margin (After Farah & Lawrence, 1988).

## ELEMENTS OF THE GEOMAGNETIC FIELD

The magnetic field is a vector field. The result is that for its full determination, both the direction and strength of the field need to be measured as shown in Fig. 2.

The declination (D), is the angular deviation of the magnetic meridian from true geographical North measured in a clock wise direction. The inclination (I), is the dip of the total field vector measured from the horizontal plane. A downward dip is regarded as positive and upward dip is regarded as negative. The total intensity (F), is the magnitude of the vector field. The total intensity, the inclination and the declination can be used to define the magnetic field at any point on the Earth's surface. The magnitudes of these elements of the geomagnetic field are related as follows:

$$H = F \cos I; Z = F \sin I; \tan I = Z/h \quad .....1$$

$$X = H \cos D; Y = H \sin D; \tan D = Y/X \quad .....2$$

$$F^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2 \quad .....3$$

where X,Y, and Z are the cartesian components of the elements of the geomagnetic field.

As stated earlier, the Earth's geomagnetic field can be represented by a time-averaged axial dipole field model, in which the dipole axis is directed along the rotational axis. According to this model the geographic latitude (l) has the same value as the geomagnetic latitude. Since the mean declination is always zero, the horizontal component of the field points towards the north pole along lines of longitude. The relationship between the latitude l and the inclination (I) of the geomagnetic field is given by the relationship:

$$\tan I = 2 \tan\lambda \quad .....4$$

The main purpose of this research work is to stablished a magnetostratigraphy of the late Quaternary sediments of the Makran Continental Margin. This attempt is a first kind of this work in this region which correlate with the stablished Oxygen Isotope Statigraphy of the Makran Margin.

## GEOLOGY OF THE AREA

The offshore region of Pakistan from Rann of Kutch in the east to Makran Margin (Pakistan) in the west, has three distinct geological divisions: (1) the Passive Continental Margin including the Indus River Delta and submarine Indus Fan, (2) the Murray Ridge, which is a topographic high along a leaky transform fault, and (3) the Active Makran subduction zone.

The Passive Continental Margin began its geological history with the fragmentation of Gondwanaland about 135 Ma. ago. The Murray Ridge, identified as a northeasterly trending positive feature south-west of Karachi, separates the passive continental margin from the active subduction zone of the Makran. Its north-eastern end may mark the triple junction between the Arabian, Eurasian and Indian Plates (Fig. 3). The Makran subduction zone is a convergent ocean-continent boundary where the Arabian Plate is believed to dip at a shallow angle beneath the rapidly accreted thick pile of sediments of the Makran Margin. It is the shallow dip combined with rapid accretion that has hindered the development of a typical trench bathymetry.

Current plate motions in the Gulf of Oman area are illustrated in Fig. 4. For the Makran subduction zone, Euler vectors are derived from global plate circuits (DeMets et al., 1990) and suggest slight convergence at a rate of 40 mm/yr, consistent with earthquake slip vectors (Jackson & McKenzie, 1984). The Makran is bounded to the west by the Strait of Hormuz, where there is a transition to continent-continent collision in the Zagros fold belt, and to the east by a triple junction with the Indian Plate near Karachi (Fig. 5). There is very little relative motion across the Owen Fracture Zone and Murray Ridge. Based on earthquake focal mechanisms, seismic moments, and spreading rates from the mid-ocean ridges to the south, Gordon & DeMets (1989) suggest a right-lateral slip rate of 0.2 - 7.0 mm/yr along the Owen Fracture Zone, and oblique extension at a similar rate on the Murray Ridge.

The Arabian Sea evolved after the rifting of the Indian Margin from Madagascar during the late Cretaceous, and subsequent northward drift of the Indian Plate due to seafloor spreading since Paleocene (64 Ma) (Whitmarsh 1974; Norton & Sclater 1979; Naini & Talwani 1983). Seismic data west of the Murray Ridge, however, suggest that a portion of Indus Fan may indeed be located off the active Makran Margin (Kolla & Coumes, 1987).

The geology of the Makran Coastal Margin is described in some detail by Harms et al.,

1984) and Leggett & Platt (1984). Gravity and seismic traverses in the Makran subduction zone have been described by White (1979), who provided information on thickness and structure of the offshore sediments of the Makran accretionary wedge.

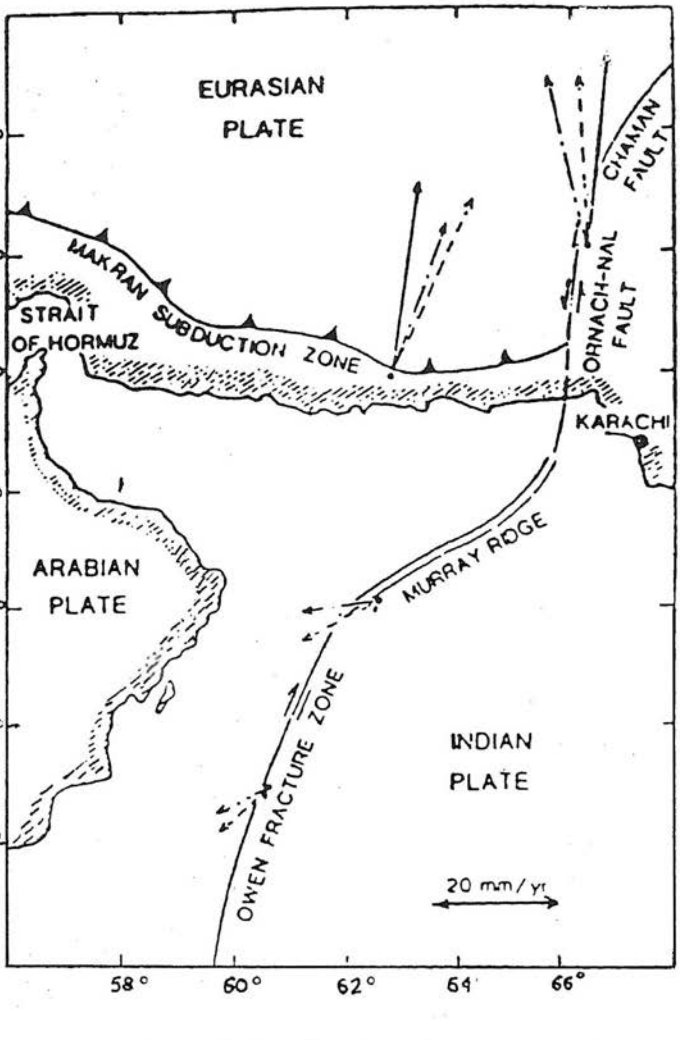

Fig. 3. Current plate motion in the Gulf of Oman. Solid arrows are from NUVEL-1 model of Gordon and DeMets (1989) and DeMets et al. (1990); broken arrows from Minster and Jordan (1978); dashed arrows from Chase (1978). Scale bar excludes arrow heads.

This subduction margin has unusual properties. It has (i) an unusually wide trench-arc gap, (ii) shallow seismic activity, (iii) a buried trench, and (iv) a complex stress regime (Farah & Lawrence, 1988). These are believed to be typical features related to peculiarities in the subduction process in this area. Extensive forearc flysch sedimentation of Eocene through Miocene epochs produced very rapid progradation of the accretionary prism which probably obscured the development of a typical topographic trench.

## GEOLOGICAL SETTING/PLATE GEOLOGY

The plate tectonic configuration and reconstruction of the Northern Indian Ocean is now relatively well known (Mountain and Prell, 1990) (Fig. 4).

A proto-Owen Basin formed in Jurassic time when India-Madagascar-Antarctica separated from Africa-Arabia. However, following late Cretaceous separation of India from Madagascar, the new spreading ridge was offset along the SE Oman Margin, not at the Owen Ridge as is assumed by many. During this stage of tectonic development, the proto-Owen Basin was carried northeastward towards subduction and eventual collision and subduction with Asia. The result was a strike-slip Owen Margin adjacent to a late Cretaceous Owen Basin. Ophiolites now found along the SE coast of Oman are fragments of this late Cretaceous Owen Basin crust, and were probably emplaced as a result of transpressional motion along this plate boundary (Mountain & Prell 1990).

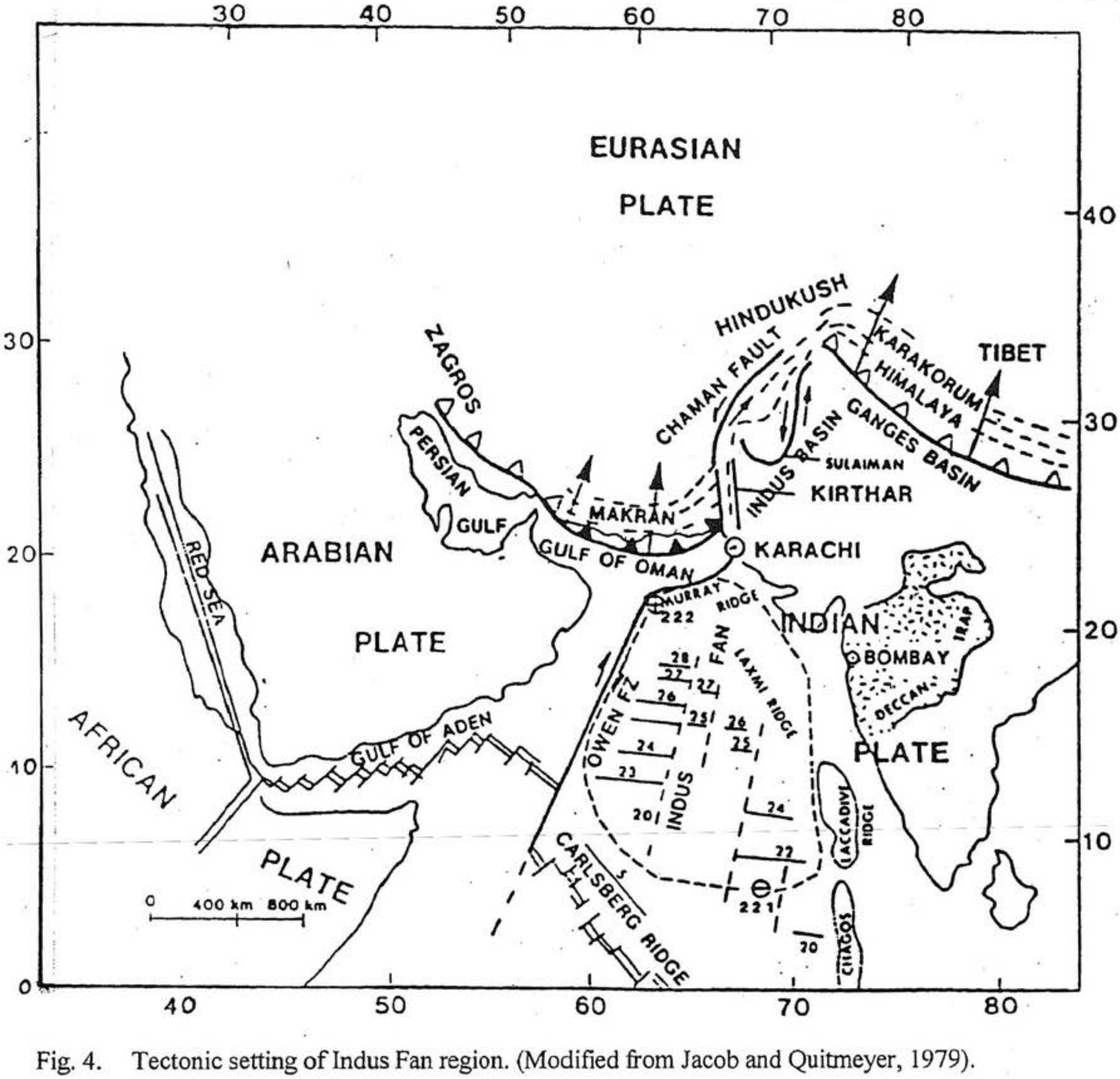

Fig. 4. Tectonic setting of Indus Fan region. (Modified from Jacob and Quitmeyer, 1979).

To explain the apparent age anomaly of the Owen Basin, Mountain and Prell (1990) suggested instead that the axis was offset along the east Oman Margin, perhaps landward of the Jurassic continent-ocean boundary, until the late Cretaceous, when the basin formed by spreading along the proto-Carlsberg Ridge. In this model, the crust formed during the Jurassic rifting has either been transported northwards and consumed in the Makran subduction zone, where sediment accretion began in the late Cretaceous (Arthurton et al., 1982), or has become part of the complex of blocks comprising south-central Asia. A problem with this latter model is that it predicts a fragment of Eocene-Miocene age lithosphere in the eastern Gulf of Oman, bounded on the west by a fracture zone parallel to the Murray Ridge while the bathymetric expression of such an age discontinuity may be hidden by the subsequent sedimentation. It is difficult to reconcile the model with heat flow measurements, which show no systematic E-W variations (Hutchison et al., 1981).

## METHODS

The Natural Remanent Magnetization (NRM) of 59 specimens from core MKM-469 and 40 specimens from MKM-472 were measured on a 2G cryogenic magnetometer. All specimens were subjected to stepwise A.F. Demagnetization using the in-line demagnetization facility of the 2G system field upto a maximum field value of 40mT. Bulk susceptibility measurements were made with a Bartington meter.

## RESULTS

The upper 650cm of core MKM-469 shows that the NRM intensity values are generally higher than in the lower part of the core. After step-wise demagnetization, intensity values are reduced, but still reflect the same downcore trend (Fig. 6).

Core MKM-472, shows NRM intensity values of variable magnitude to a depth of 630cm. Below this depth an interval approximately 200cm thick shows higher NRM intensities. After progressive demagnetization to the peak field value of 40mT for this core there is a reduction of intensity values and it is noticeable that the maxima of the higher intensity peak is displaced upcore (600cm). Above this depth, intensity variation shows an intensity minimum (Fig. 7). Core MKM-469 indicates a mean down-core inclination value after 30mT demagnetization at 44.2°. This adheres to the expected axial dipole inclination of the geomagnetic field at these sites of 45° (using equation 1.4 ($\mathrm{Tan}\ I = 2\ \mathrm{Tan}\ l$ )). Assuming that sediments deposited at these sites acquired their characteristic remanent magnetization at or close to the time of deposition, it may be inferred, as expected, that the site latitude has not changed significantly through the Holocene/Pleistocene time period represented.

For core MKM-469, generally the inclination values range between 10° and 45°; below 1000cm depth a number of specimens show steepened inclinations. This is believed to indicate that probably two short geomagnetic excursions are present, one at 376cm evident after 20mT demagnetization step (inclination,-1.07°) and the second at 1392cm (after 20mT demagnetization,-24.1°).Demagnetization values show the same trend as NRM inclination (Fig. 8).

After demagnetization of samples from core MKM-472, with the exception of the 20mT demagnetization step, results still reflect the same trends as NRM inclination results (Fig. 9).

Core MKM-469 samples are associated with relatively higher bulk susceptibility values than in core MKM-472 (Fig. 10).

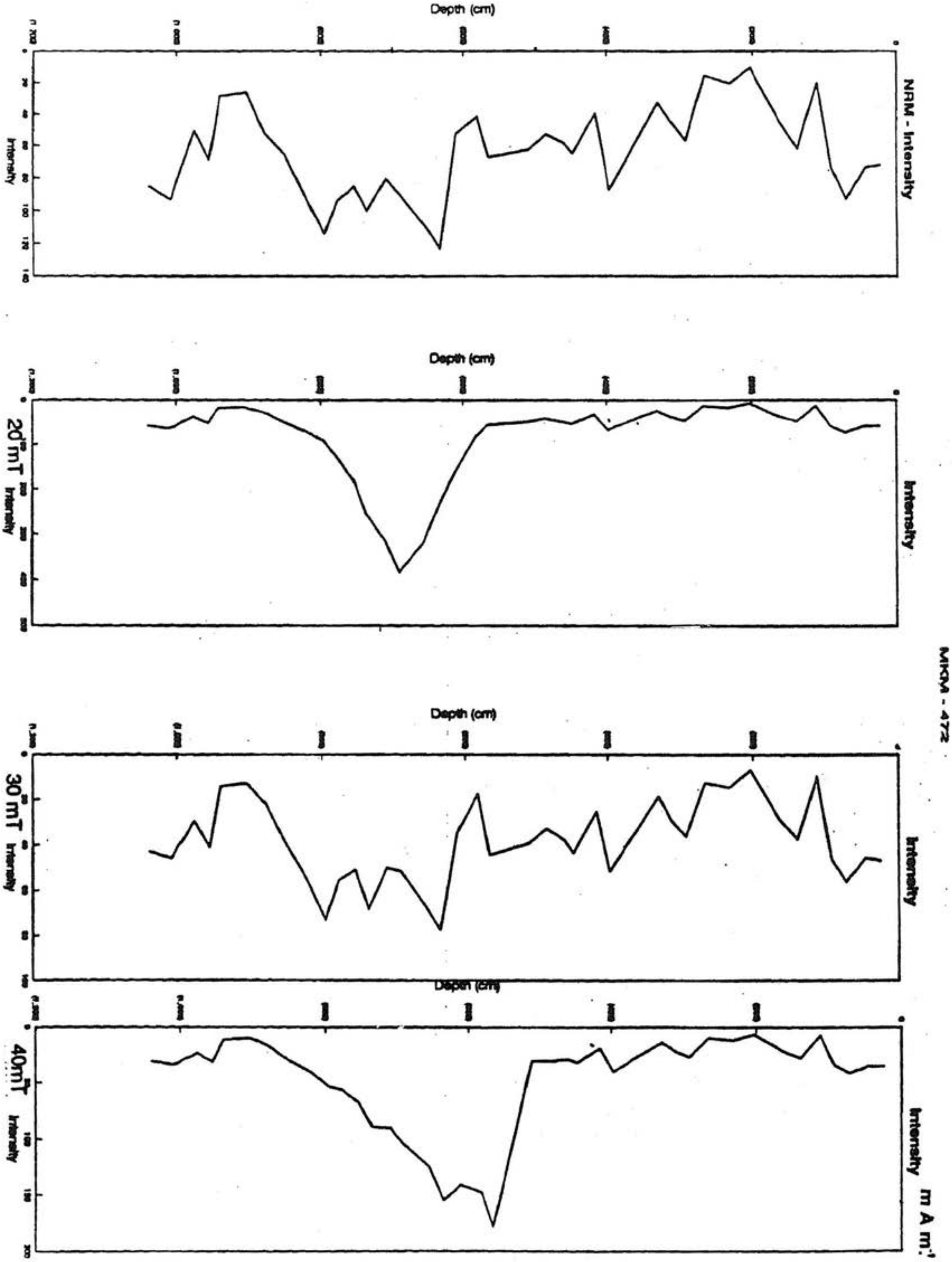

Fig. 5. NRM and Demag. intensity plots of site MKM-472.

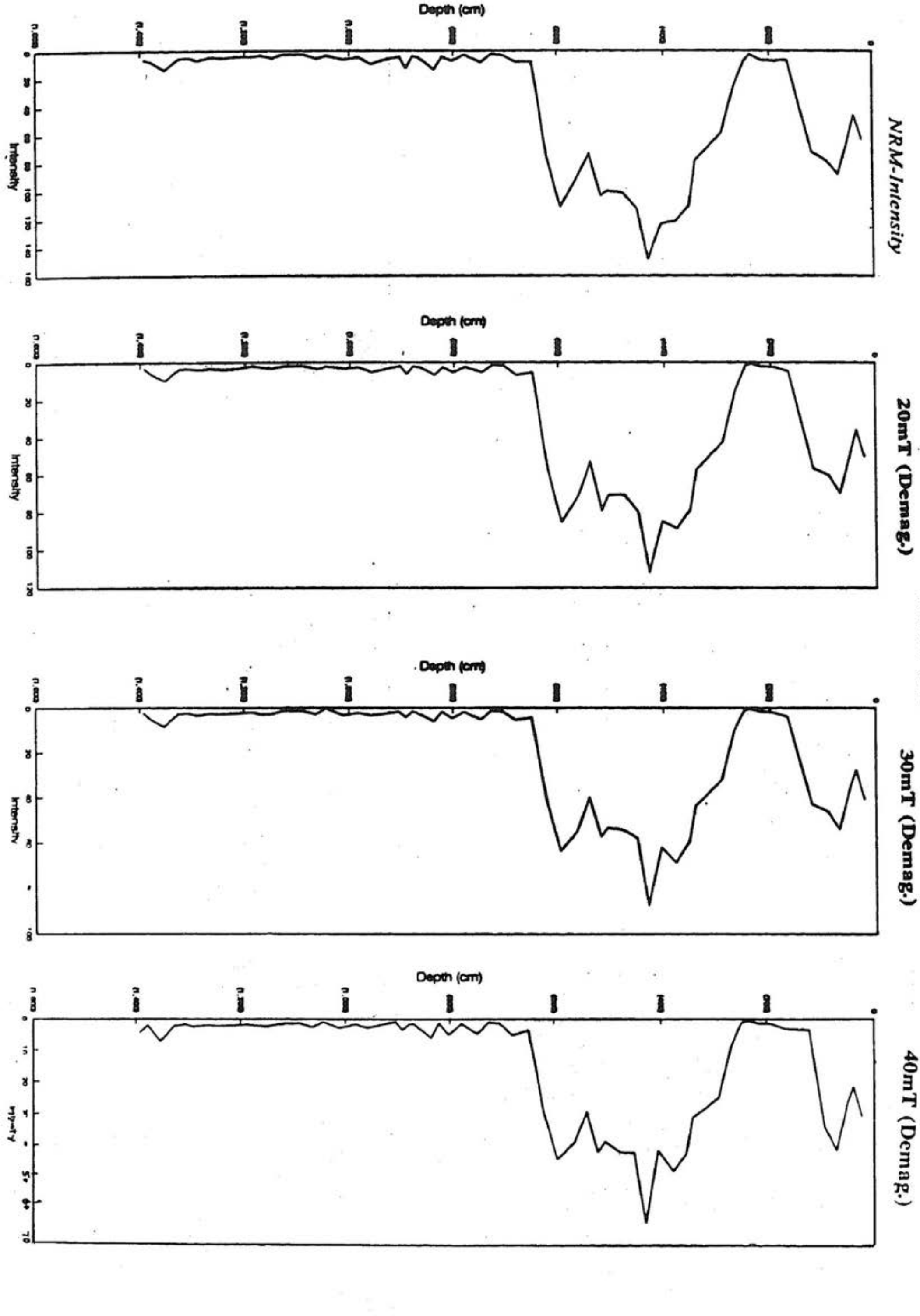

Fig. 6. NRM and Demag. intensity plots of site MKM-469.

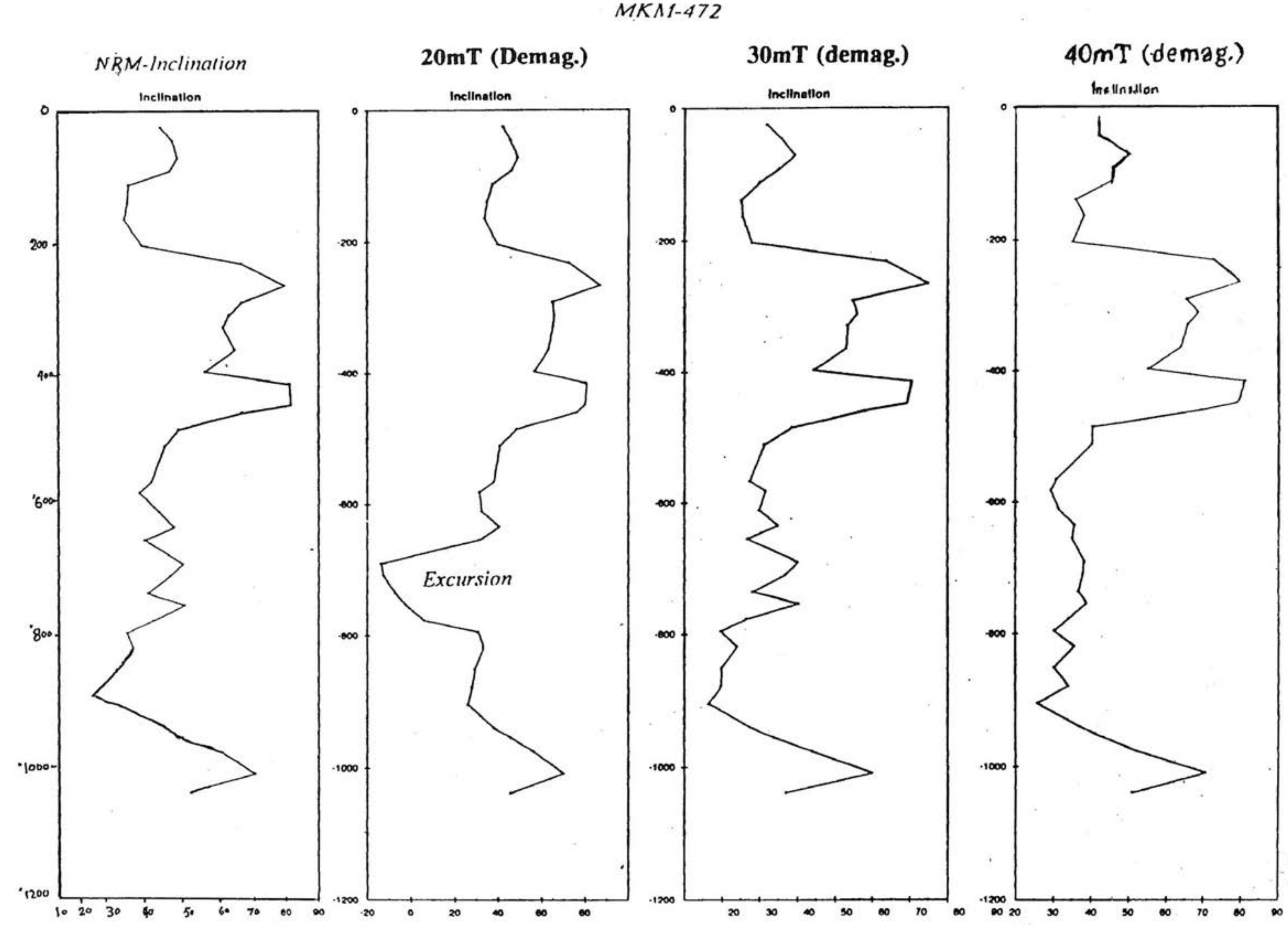

Fig. 7. NRM and Demag. inclination plots of site MKM-472.

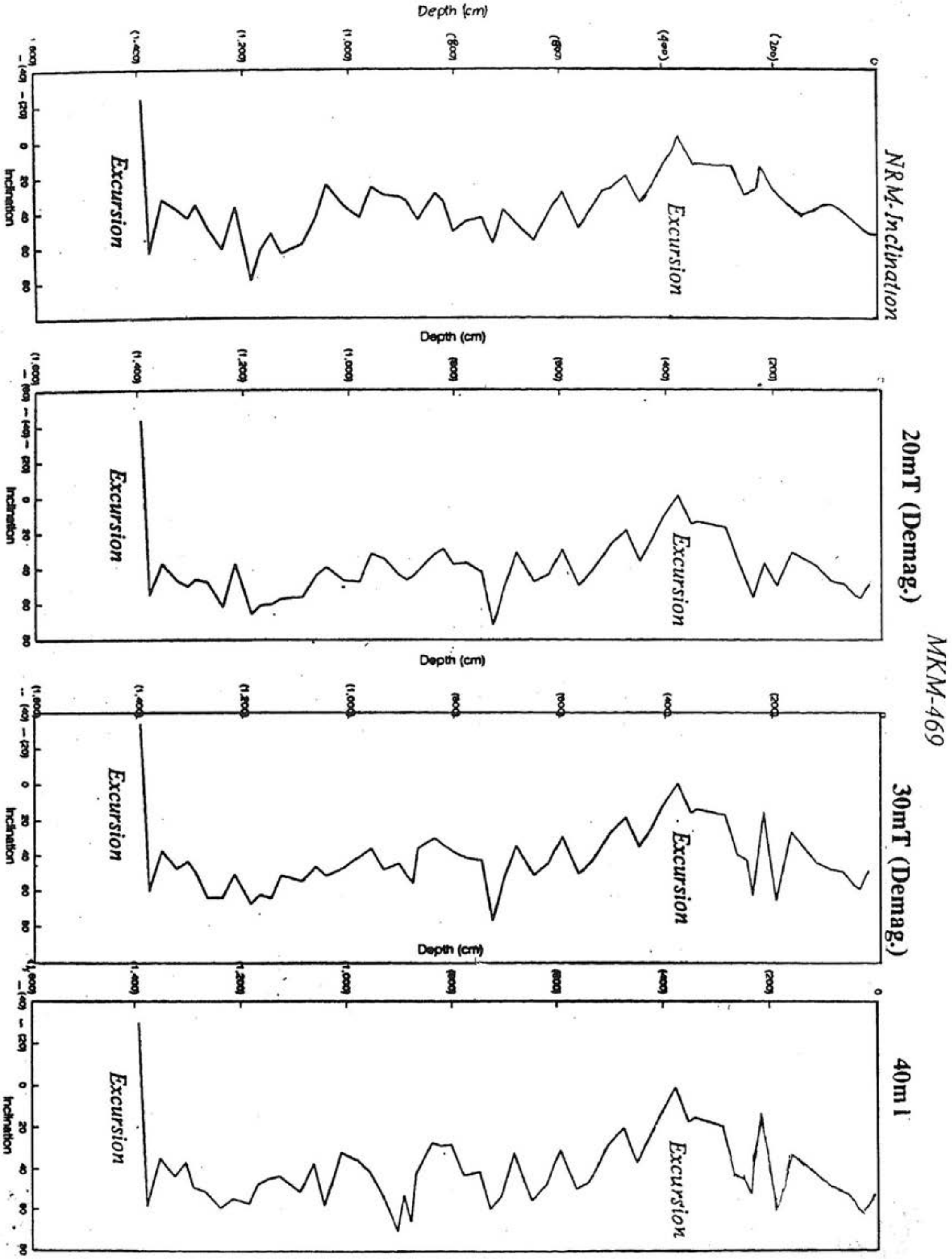

Fig. 8. NRM and Demag. inclination plots of site MKM-469.

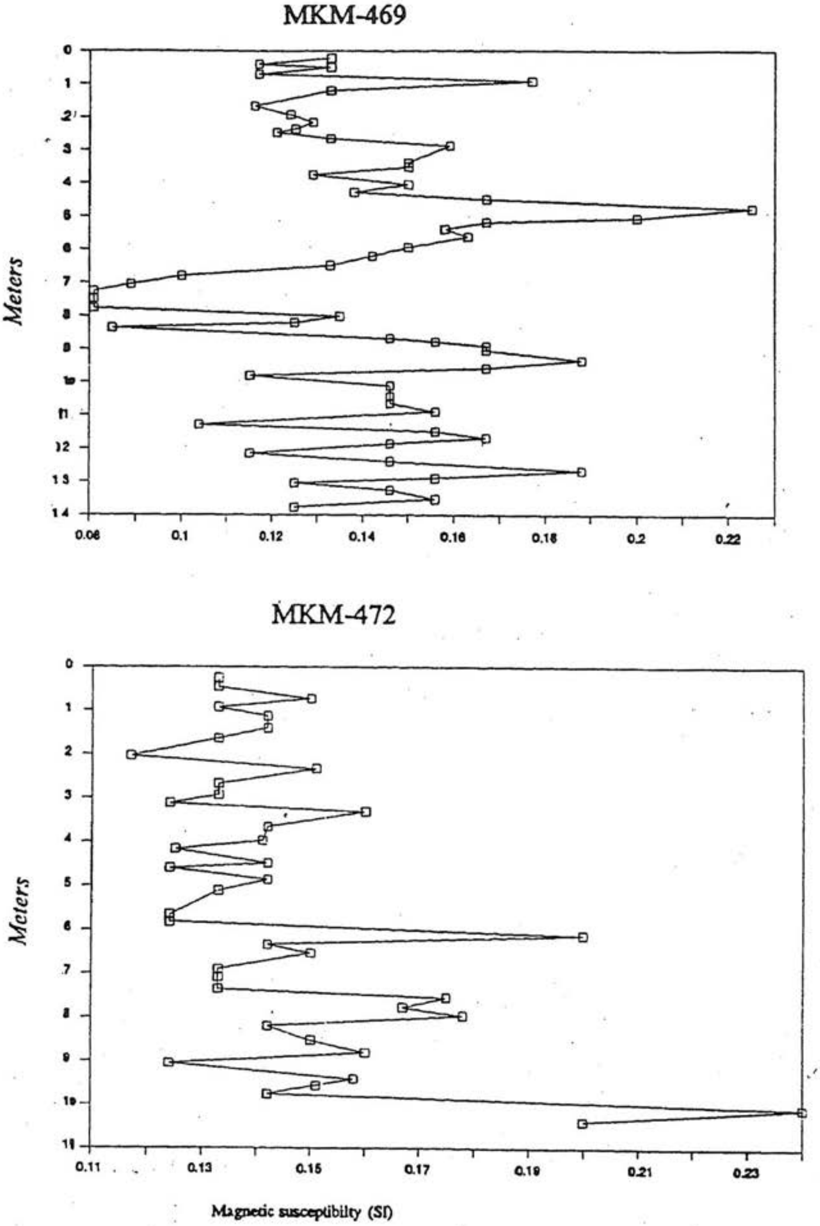

Fig. 9: Magnetic susceptibility plots of site MKM-469 and 472.

Bulk magnetic susceptibility values of core MKM-469 vary between 0.08 and 0.23 SI units. Generally the values are consistently between 0.11 and 0.19, but a few peaks of low and high susceptibility are also noticeable. For example, there is a minimum value of 0.08 between 7 and 8m depth and high values (0.18) at 1m, at 4.5m (0.225) and 9m, 12.5m (0.19). Core MKM-472 gives magnetic susceptibility values in the range from 0.11 to 0.24SI units. Two peaks of 0.20 and 0.24 are apparent at 6m and at 10m depth respectively.

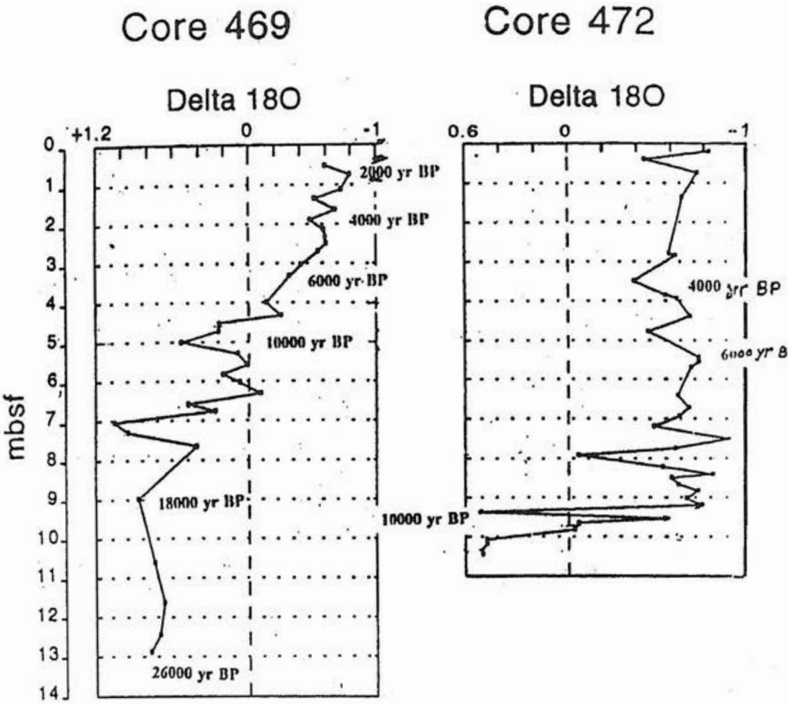

Fig. 10. Oxygen isotope results of site MKM-469 and 472.

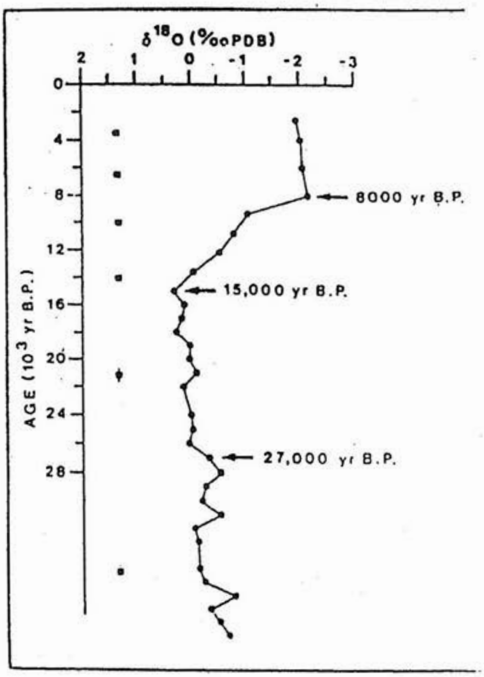

Fig. 11. Standard oxygen isotope stratigraphy of the Arabian Sea (after Sirocko et al., 1991).

## INTERPRETATION

On the basis of correlation with oxygen isotope stratigraphy, both cores show increased magnetic susceptibility values in around the Holocene/ Pleistocene boundary (Fig. 11). This increase may reflect climatic change leading to more dominant monsoonal conditions in the early Holocene (Sirocko et al., 1993), and hence an increased supply of terrigenous material including magnetic grains.

Short-duration paleomagnetic excursions as reported in marine and lake sediments can be the result of the geomagnetic field moving toward a reversal, then returning to a more stable normal magnetic configuration before reaching a fully reversed state (Doell and Cox, 1972). If the dipole is inclined from the spin axis, a global excursion occurs, whereas nondipole behaviour during a period of diminishing dipole intensity yields an excursion that is detectable only regionally (Freed and Healy, 1974). Because such regional excursions are likely to be of shorter duration, their recognition in sediments requires a relatively high rate of deposition. The Makran Margin coring sites are associated with such high sedimentation rates (e.g., 95 cm/kyr MKM-472 and 30-50 cm/kyr for MKM-469) and therefore it can be argued that the observed short duration excursion noted above reflects true geomagnetic field behaviour.

A particular feature of core MKM-469 is the shallow inclinations observed at a depth of approximately 370cm (Fig. 8). This may be interpreted as a low latitude geomagnetic excursion. Using the oxygen isotope stratigraphy established (Tabrez, 1995), this excursion is dated to occur between 6000-8000 yrs B.P. (Fig. 12). It is apparently younger than previously reported excursion events such as the Gulf of Mexico event between 12,500 -17,000 yrs B.P. (Clark and Kennett, 1973 ; Freed and Healy, 1974). Other events are also reported by Noltimer and Colinvaux (1976) for Imuruk Lake, Alaska between 17,000 - 18,000 yr B.P. and Baffin Bay around 18,000 yr B.P. (Thouveny, 1988).

Correlation with core MKM-472 shows a similar excursion at a depth of approximately 700cm depth after 20mT demagnetization. The recognition of the presence of this event in both the cores suggests that it is an accurate record of field behaviour on the Makran Margin and not an artefact of the sedimentation process. An older possible reversal apparently occurs at the base of core MKM-469 (1392cm depth). It is suggested that this could be assigned to a time prior to the last glacial maximum and may therefore correlate with the Mono Lake event between 24,000 yrs and 29,000 yrs (Liddicoat and Coe, 1979) if sedimentation was continuous.

## CONCLUSION

Magnetostratigraphic characteristics of core samples from Makram margin support the oxygen isotope stratigraphy constructed for the two longest cores and correlated with other work in the area. This has allowed relatively accurate dating of the cores back to about 26,000 year B.P. Magnetostratigraphy study supported these findings. Correlation to the other cores was possible on the basis of lithostratigraphic characteristics.

Presence of short duration paleomagnetic excursions in two cores from Makran discussed in this paper suggests that it is an accurate record of field behaviours. An older possible reversal apparently occurs at the base of core MKM-469 (1329 cm depth) which could be assigned to a time prior to the last glacial maximum. An increased supply of terrigenous material including magnetic grains found in both the cores occurred around the Holocene/Pleistocene boundary, which may reflect climatic change leading to more dominant monsoonal conditions in the early Holocene time.

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