

Magnetic intensity loss and core diagenesis in long-core samples from the East Cortez Basin and the San Nicolas Basin (California Borderland)

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We performed high resolution magnetic measurements on about 180 m of continuous U-channel samples from Sites 1012 (East Cortez Basin) and 1013 (San Nicolas Basin) that were recovered during Ocean Drilling Program Leg 167 to the California Margin. Measurements were made at 1–2 cm intervals from near-complete composite stratigraphic sequences at both of the studied sites with the goal of obtaining high spatial resolution of sediment magnetic properties, including detailed characterization of variations in magnetic mineralogy, concentration, and grain size. The decay of a metastable magnetic mineral or the dissolution of fine-grained magnetite by organic matter reduction had strongly affected both cores, reducing the magnetic intensity to 7%–10% of the initial magnetization. Measurements were carried out ca. 4–6 months after the cores were drilled. Despite the reduced magnetic signal we were able to define a stable characteristic remanence for most of the core. Cyclic variations that were observed over short and long stratigraphic intervals are strongly driven at Earth orbital periodicities and have been used to obtain a detailed age model based on comparison with the insolation record.

1. Introduction

With the development of automated long-core magnetometers that allows rapid and non-destructive measurements of magnetic properties at resolutions of about 1–5 cm, parameters like susceptibility, anhysteretic remanent magnetization (ARM), natural remanent magnetization (NRM), and sedimentary relative paleointensity proxies have become increasingly valuable in paleoceanographic, paleoclimatic, and stratigraphic studies. High-resolution magnetic measurements of sediment samples from the California Margin transect (Ocean Drilling Program Leg 167; Lyle *et al.*, 1997) have yielded records of relative paleointensity, environmental change, diagenetic proxies, and high-resolution magnetostratigraphies (Guyodo *et al.*, in press; Hayashida *et al.*, in press; Hayashida and Verosub, in press; Heider *et al.*, in press; Leonhard *et al.*, in press).

In this study, we report high-resolution rock magnetic results from Sites 1012 and 1013, situated in close proximity in a very similar sedimentary setting in the middle band of California Borderland basins (Emery, 1960). The basins are of tectonic origin and have accumulated thick and continuous sedimentary records that are controlled by discharge from several major rivers and the regional ocean circulation patterns. Sensitive to seasonal and global climatic varia-

tions is the southerly flowing California Current and the deep Davidson Countercurrent (Soutar and Crill, 1977; Sancetta *et al.*, 1992; Ortiz *et al.*, 1997). Site 1012 is located in 1783 m water depth in the East Cortez Basin about 100 km west of San Diego, California (Fig. 1) and Site 1013 is located 68 km to the northwest in the San Nicolas Basin in slightly shallower water (1564 m, Fig. 1). At locations removed from coarse clastic input the sedimentary column at both sites is rather similar and consists of organic-rich hemipelagic sediment. The deposits are dominated by cyclic alternations between calcareous plankton and terrigenous silt and clay components (Lyle *et al.*, 1997). Both sites yielded an excellent shipboard magnetostratigraphy with relatively strong magnetic intensities (15 mA/m at Site 1012 and 22 mA/m at Site 1013 on average) despite relatively high organic carbon contents averaging 1%–4% at Site 1012 and 2%–9% at Site 1013, and active methanogenesis in the sediment column (Lyle *et al.*, 1997).

Both sites were cored with the advanced hydraulic piston corer (APC) to about 100 meters below seafloor (mbsf) and deepened with the extended core barrel (XCB) to 270 mbsf (Site 1012) and 146 mbsf (Site 1013). The complete stratigraphic coverage at both sites was ensured by drilling three holes at each site and by matching high-resolution physical property records with a core-to-core correlation technique (Hagelberg *et al.*, 1992; Lyle *et al.*, 1997). Sedimentation rates are high, averaging 65 m/m.y. at both sites. The APC section reaches the uppermost Pliocene with excellent age control points provided by shipboard magnetostratigraphy and biostratigraphy (Lyle *et al.*, 1997). An isotope stratigra-

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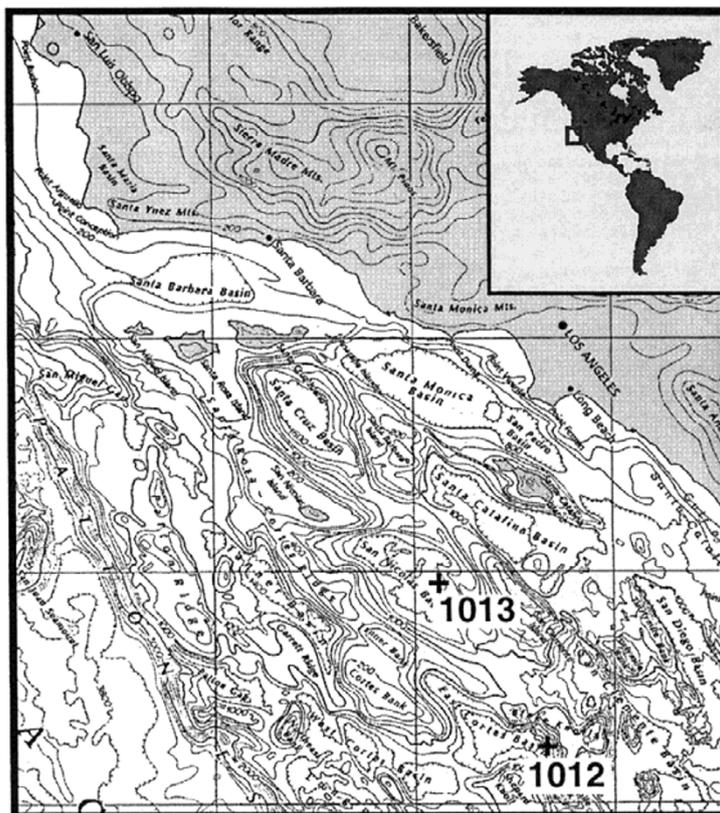


Fig. 1. Location map for Sites 1012 and 1013 in the East Cortez Basin and San Nicolas Basin. Site 1012 is located about 100 km southwest of San Diego and Site 1013 less than 100 km southwest of Los Angeles, California.

phy (Andreasen *et al.*, in press) was not available at the time this manuscript was prepared. The sediment at both sites has been affected by diagenetic processes, referred to as core diagenesis, after the initial measurements were taken (about 24 hours after core recovery).

2. Methods

Data acquired on shore have been obtained from U-channel samples (Tauxe *et al.*, 1983) collected in the archive halves through the composite sections of Sites 1012 and 1013 (see Lyle *et al.*, 1997). Samples were measured on a narrow-access 2G Enterprises cryogenic magnetometer (Weeks *et al.*, 1993; Nagy and Valet, 1993) at the University of California, Davis (Site 1012) and the Institut de Physique du Globe, Paris (Site 1013). U-channel samples were collected by pushing rigid U-shaped plastic liners (2×2 cm cross-section, up to 1.5 m in length) into the archive halves of core sections. Each sample was taken out of the core by guiding a fishing line under the U-channel. A plastic cap was then placed on the U-channel and the ends were sealed to minimize dehydration of the sediment. Magnetic measurements on U-channel samples were made at 1 cm (Site 1012) and 2 cm (Site 1013) intervals. However, the half-width of the response function of the magnetometer pick-up coils (4.5 cm; Weeks *et al.*, 1993) is such that adjacent measurements are not independent and the data are slightly smoothed. This might appear as a disadvantage, if compared to a continuous set of discrete samples that can be measured individually (and thus yielding

independent results). However, the U-channel method significantly decreases sediment deformation during sampling, and considerably improves the speed at which the measurements can be made.

Prior to U-channel measurements, archive halves of core sections were measured aboard the *JOIDES Resolution* using a 2G Enterprises pass-through cryogenic magnetometer at 10 cm intervals, after alternating field (a.f.) demagnetization at up to 20 mT. This wide-access magnetometer has a 15 cm smoothing window. The natural remanent magnetization (NRM) was measured for all U-channel samples after a.f. demagnetization at 20, 30, 40, 50, and 60 mT. An anhysteretic remanent magnetization (ARM) was imparted to the cores from Site 1013 using a 100 mT peak field and a 0.05 mT bias field and subsequently demagnetized at 20, 30, 40, and 60 mT a.f. field.

U-channel and shipboard magnetic data were compared with volumetric magnetic susceptibility (k) measurements that were made aboard the *JOIDES Resolution*. Magnetic susceptibility was measured at 3–5 cm intervals on whole-core sections, after the cores had equilibrated to room temperature for approximately 24 hrs, using a Bartington Instruments MS-2 susceptibility meter with an 8 cm diameter sensing loop that induces a field of 0.1 mT at a frequency of 470 Hz. SI volume units are used throughout. These data were resampled at the resolution of the U-channel measurements to enable direct comparison of results.

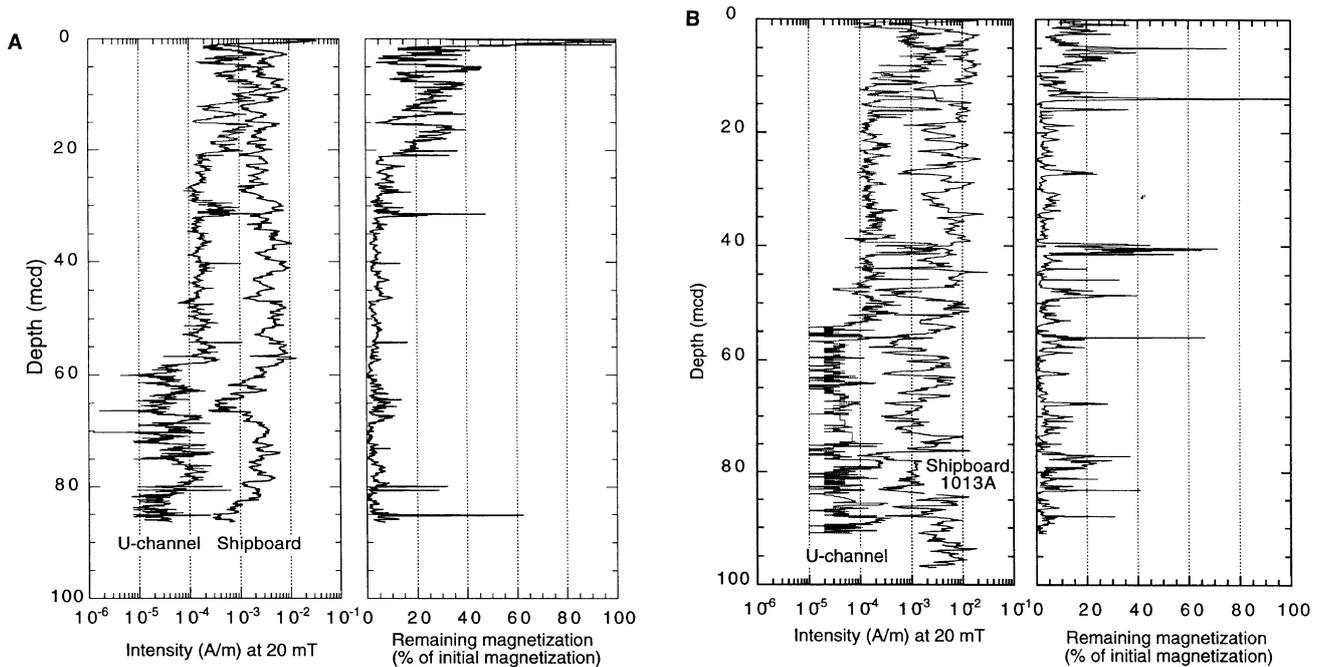


Fig. 2. Shipboard and U-channel magnetic measurements from A. Site 1012 and B. Site 1013 for the interval from 0 to about 90 mcd. Measurements have been resampled at the same depth intervals. Left side panels show magnetic intensity from shipboard measurements of split cores after a.f. demagnetization at 20 mT and of U-channels after a.f. demagnetization at 20 mT. Right side panels show loss in NRM intensity between shipboard and U-channel measurements at 20 mT expressed as percent of intensity remaining in the U-channels.

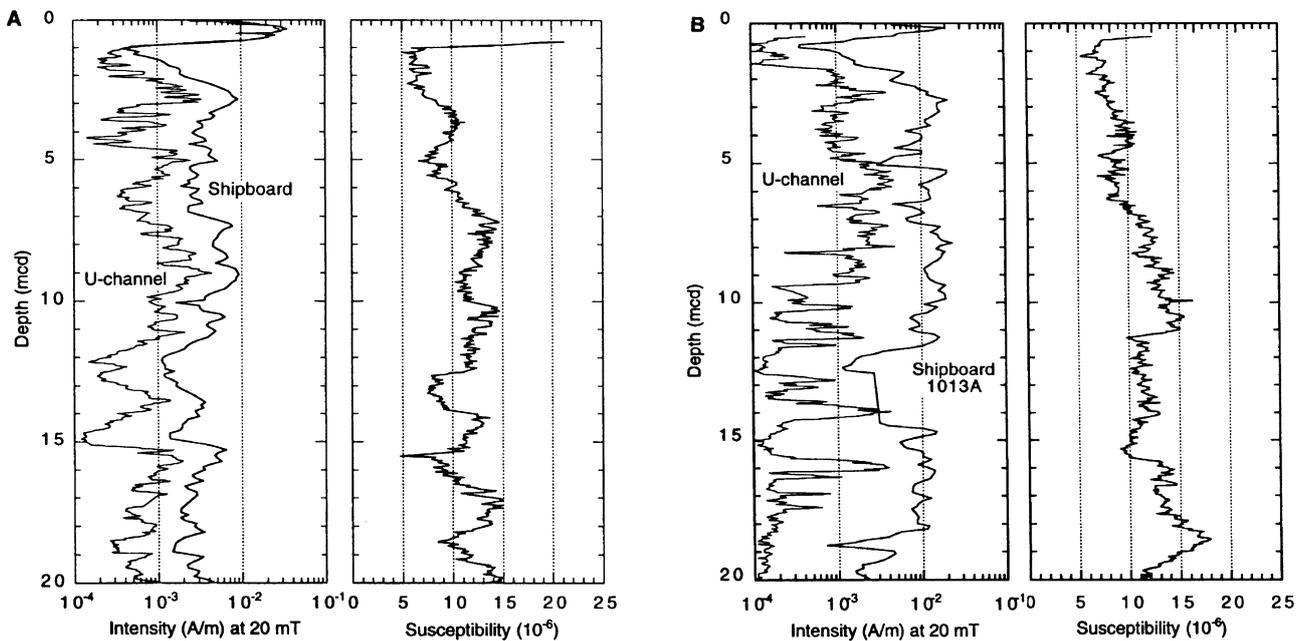


Fig. 3. Comparison between U-channel and shipboard magnetic intensity data and shipboard susceptibility measurements for the uppermost 20 m at A. Site 1012 and B. Site 1013.

3. Results and Discussion

3.1 Natural remanent magnetization

At both sites, the NRM measured after demagnetization at 20 mT (Fig. 2A) contains evidence of cyclic variations which are driven by environmental changes. This feature reflects predominantly variations in magnetic carrier concentration, and to some degree changes in the intensity of the Earth's magnetic field. Intensity of magnetization of the U-channels

(Fig. 2) displays a severe loss when compared to the initial shipboard measurements.

At Site 1012, the remaining intensity of the U-channels was about 10% on average after the 4–6 months of storage preceding the U-channel measurements. The loss was particularly significant below 20 meters composite depth (mcd; Hagelberg *et al.*, 1992; Fig. 2A). About 30% of the initial magnetization had remained between 1 to 20 mcd, and the

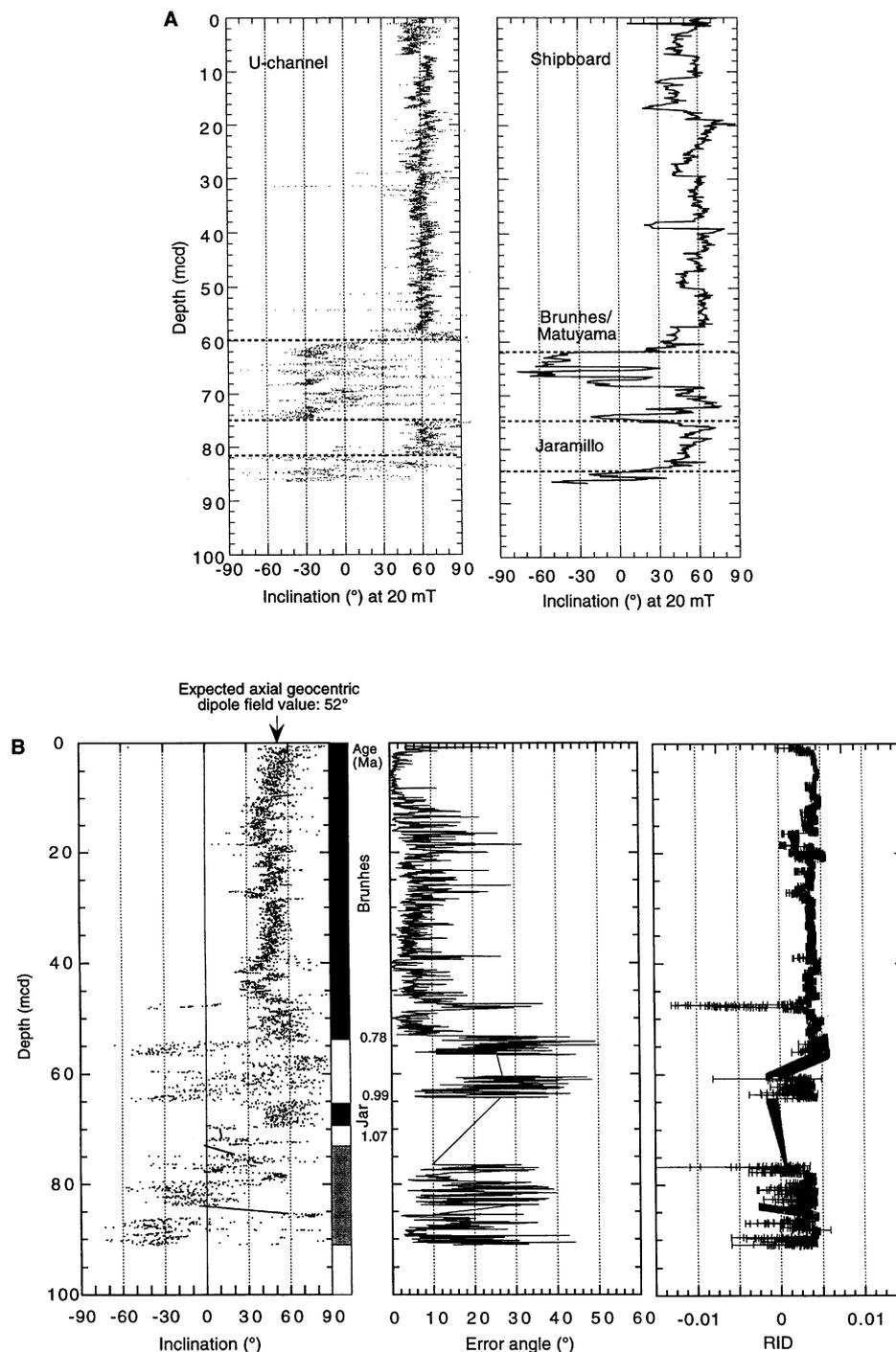


Fig. 4. A. Comparison between U-channel data of magnetic inclination with magnetic polarity interpretation and shipboard data at Site 1012. B. U-channel results of magnetic inclination with magnetic polarity interpretation, error angle, and rate of intensity decrease (RID) with standard deviation at Site 1013 (ages from Cande and Kent, 1995). Despite the severe magnetic intensity loss the magnetic behavior within the Brunhes Chron is acceptable with error angles under or around 10° and relatively small error bars of the RID which indicate linear behavior during demagnetization.

topmost part suffered no significant loss (Fig. 3A). Both of the shipboard and U-channel data show a downcore intensity drop between 0.8 and 1.0 mcd, corresponding to a decrease in magnetic susceptibility measured on board (Fig. 3A). This feature suggests a decrease in magnetic mineral concentration, which can be attributed to dissolution of fine-grained magnetite during reductive diagenesis.

At Site 1013, only 7% of the initial magnetization was left

on average (Fig. 2B). There are only a few intervals in which $>20\%$ of the initial magnetic intensity is preserved. The remanence loss is more pronounced in some intervals than in others, therefore altering most of the characteristic features of the shipboard intensity record. Figure 3B shows a direct comparison between the shipboard and the U-channel record for the uppermost 20 mcd in which only a few characteristics of the initial intensity curve are preserved.

3.2 Magnetostratigraphy

Downcore plots of magnetic inclinations from the U-channels of Site 1012 (Fig. 4A) show that the interval between 0 and 58 mcd has normal polarity, and between 60 and 80 mcd mostly reversed polarity. The weak magnetic intensity in the order of 10^{-5} A/m causes considerable scatter of the inclination in the intervals with reversed polarity. Examining both inclination and declination data of stepwise a.f. demagnetization, we interpret that the Brunhes/Matuyama boundary occurs between 58.1 and 60.0 mcd. The termination of the Jaramillo Subchron is located between 74.6 and 74.8 mcd, and its onset is between 79.9 and 81.9 mcd. Comparison of the U-channel and shipboard data (Fig. 4A) suggests that the magnetization measured onboard was more affected by a magnetic overprint in downward direction caused by the drilling process and possibly by a viscous overprint during the Brunhes Chron. We suggest therefore that the magnetostratigraphic datums are better defined by the U-channel measurements.

Despite this severe remanence loss, the samples behaved well during a.f. demagnetization in the uppermost 50 mcd (Brunhes Chron, Fig. 4B) of Site 1013. A magnetostratigraphy was constructed after determining the mean directions (declination and inclination) of the demagnetization vector. The identification of the primary component of magnetization is usually done graphically in vector component diagrams and intensity decay plots for each sample (Fig. 5). This approach is not possible with the large number of individual measurement points that a U-channel study yields. In order to assess the quality of the demagnetization behavior through the entire sedimentary sequence, we calculated the rate of intensity decrease (RID; Nagy and Valet, 1993) and its standard deviation. The RID is the mean slope of the intensity loss between successive demagnetization steps, after they have been normalized by the initial intensity. Therefore, the RID provides a quantitative evaluation of the demagnetization behavior, and can be plotted as a function of depth. The standard deviation of the RID is used to determine linear or non-linear behavior, where small standard deviations indicate linear demagnetization behavior (Fig. 4B). The char-

acteristic remanent component (ChRM) of the magnetization vector has been automatically calculated (see Nagy and Valet, 1993) by averaging the directions obtained at the 5 demagnetization steps. The error angle (Kirschvink, 1980) at each position is used to determine the dispersion of directions around the mean values. Error angles of $<10^\circ$ indicate a well identified single direction while larger values suggest a complex behavior during demagnetization (Fig. 4B). With the exception of anomalous intervals around 15–20 mcd and at 47–48 mcd, both error angle and RID indicate linear demagnetization behavior in the Brunhes Chron (c.f., Fig. 5). The average inclination is 47° , which is close to the expected axial geocentric dipole field value of 52° . We place the Brunhes/Matuyama boundary at 54.5 mcd. The deeper part of the section is characterized by large error angles in the order of 20° to 30° and unstable demagnetization, as indicated by the RID and the associated large error bars. Despite the fact that the magnetic intensity in the Matuyama Chron is at the detection limit of the magnetometer, a zone of normal polarity between 65 and 69 mcd can clearly be identified as the Jaramillo Subchron (C1r.1n).

3.3 Age model and rock magnetic parameters

At Site 1012, the Brunhes/Matuyama boundary occurs at 58.1–60.0 mcd associated with a susceptibility peak. In our age model, this peak is assigned to marine oxygen isotope Stage 19, which is consistent with the age of the Brunhes/Matuyama boundary at 0.78 Ma (Bassinot *et al.*, 1994). We refined the age model within the Brunhes Chron at both sites by tuning the shipboard susceptibility record to the orbital insolation curve (Fig. 6) as depicted by the oxygen isotope record of Bassinot *et al.* (1994). The correlation between the records is excellent, although we cannot rule out the possibility of other interpretations. Our correlation at both sites is characterized by low susceptibility values during glacial, and high susceptibility values during interglacials. The asymmetry of the warming and cooling cycles with rapid warming and slow cooling phases gives us confidence in this interpretation. The age versus depth diagrams of Fig. 7 show remarkably constant sedimentation rates of very similar magnitude (74 mcd/m.y. at Site 1012 and 71 mcd/m.y. at Site 1013) consistent with the shipboard estimates of Lyle *et al.* (1997).

To facilitate visual correlation between the different panels displayed in Fig. 6B, we have marked the main lows in magnetic susceptibility (here interpreted as glacial periods) with a gray bar. The anhysteretic remanent magnetization (ARM) is expressed as susceptibility of ARM, k_{ARM} (ARM/100 μ T) and responds predominantly to the fine-grained magnetite fraction. The pronounced intensity loss, which suggests dissolution of fine-grained magnetite, has a major effect on the k_{ARM} record. Under ideal conditions (no variation in magnetic mineralogy or magnetic grain size), both k_{ARM} and low field susceptibility reflect changes in the concentration of magnetic material. In our record, no apparent correlation between the k_{ARM} and the climatic signal has been found, suggesting partial dissolution of magnetic grains unrelated to cyclic deposition controlled by climate variation. As the dissolution process takes place at the surface of the grain, partial dissolution of magnetic particles generates a relative depletion in smaller sizes. The intervals of high k_{ARM} values

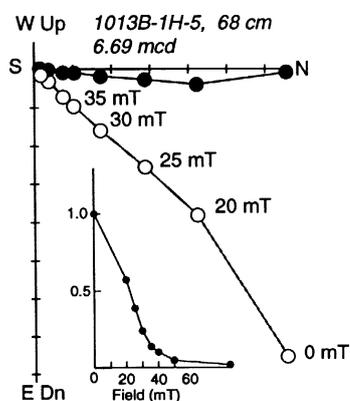


Fig. 5. Vector component diagram for a representative discrete sample from 6.69 mcd at Site 1013. Open (closed) symbols indicate projection onto the vertical (horizontal) plane.

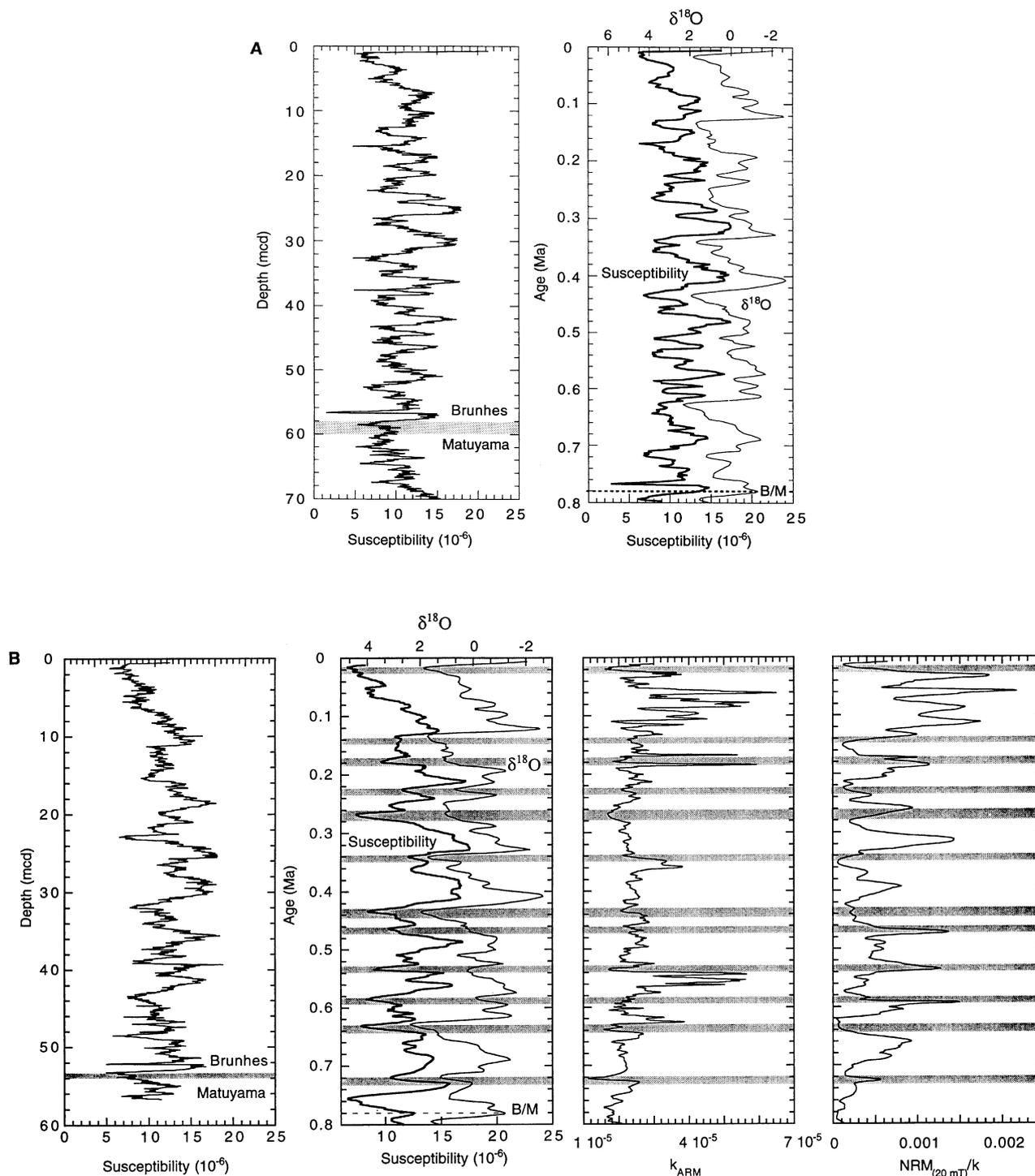


Fig. 6. Shipboard volume magnetic susceptibility of whole-cores (20 pt smooth) versus depth and versus age compared to the oxygen isotope record of Bassinot *et al.* (1994) A. at Site 1012, and B. at Site 1013. The age model was obtained by tuning the susceptibility to the $\delta^{18}\text{O}$ record. B. Shaded areas denote intervals of low susceptibility which are correlated to times of cool climate and low sealevel. Anhyseretic remanent magnetization (ARM) expressed as k_{ARM} from U-channel measurements at Site 1013. Shipboard magnetic intensity (Site 1013) after a.f. demagnetization with 20 mT normalized with magnetic susceptibility. No correlation with the normalizer is apparent, but the lack of quality control prohibits a quantitative interpretation as a relative paleointensity record.

at 0.05–0.12 Ma (5–10 mcd) and 0.54–0.56 Ma (39–41 mcd) would thus correspond to the preserved (or less affected) areas. These two intervals also correspond to the lowest values of the error angle (Fig. 4B), indicating very stable components of magnetization (c.f., Fig. 5) and further supporting

our interpretation of the high degree of signal preservation in these two intervals.

We normalized the shipboard magnetic intensity after a.f. demagnetization at 20 mT with the shipboard magnetic susceptibility to test the potential use of the shipboard data as

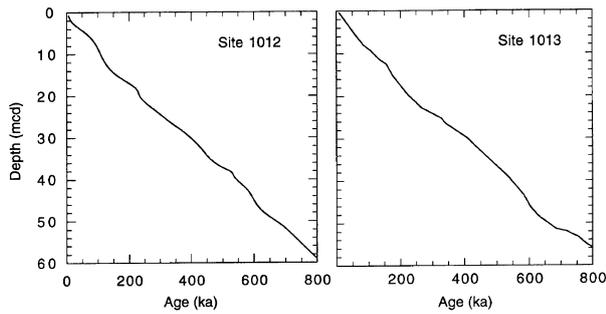


Fig. 7. Age versus depth (mcd) plot shows nearly constant sedimentation rates that are very similar at both sites.

a paleointensity proxy (review in Tauxe, 1993; Valet and Meynadier, 1993) at Site 1013 (Fig. 6B). Within the uncertainties inherent in our age-model, many of the lows in the NRM/ k ratio can be correlated with previously described geomagnetic events (Nowaczyk *et al.*, 1994; Langereis *et al.*, 1997), but the lack of quality control prohibits a quantitative interpretation of this normalized intensity record.

3.4 Early diagenesis and core diagenesis

The severe loss of magnetic intensity during the time between the recovery of the cores and the measurements of the U-channels is caused by a loss of magnetic material, either by (1) the dissolution of fine-grained magnetite or (2) the decay of metastable magnetic minerals (e.g., greigite). Both sites are characterized by high organic carbon concentrations (4–8 wt%), high sedimentation rates around 70 m/m.y., and ethane concentrations of around 900,000 ppm, indicative of organic matter degradation (Lyle *et al.*, 1997). Sedimentary environments such as this are known for early diagenetic reactions, organic carbon diagenesis by sulfate reduction, and possible authigenic mineralization reactions (Leslie *et al.*, 1990a,b; Roberts and Turner, 1993).

The drop in magnetic intensity and susceptibility observed in the first meter of the shipboard data of both sites (Fig. 3) suggests that the surficial sediments had suffered reductive diagenesis of fine-grained magnetite. The gradual increase of magnetic intensity and susceptibility below 1 mcd may suggest formation of an authigenic magnetic mineral, such as greigite. After the core recovery and shipboard work, these authigenic minerals could decay rapidly under the changed environmental conditions, especially elevated temperature and the presence of oxygen.

Magnetite (Fe_3O_4) is an iron oxide of mixed oxidation state (Fe^{2+} , Fe^{3+}) that plays a significant role in the diagenesis of marine sediments. Dissolution of magnetic minerals in marine environments can be caused by (1) changing redox conditions, (2) sulfate reduction, (3) biological reduction, and (4) organic carbon oxidation. Biogenic magnetite formation in rapidly-deposited sediments with high organic carbon contents has been observed just above the iron reduction zone (Karlin *et al.*, 1987; Petermann and Bleil, 1993; Tarduno, 1994). Deeper in the sediments, within the iron reduction zone, much of the fine-grained biogenic magnetite and the coarser detrital magnetite is dissolved. The decomposition of organic matter produces light-molecular-weight hydro-

carbons and a large amount of CO_2 (Hunt, 1979). The CO_2 release can cause CaCO_3 precipitation if sufficient Ca^{2+} is present in the pore water and result in the reduction of Mn^{4+} , Fe^{3+} , SO_4^{2-} by electron transfer from organic carbon, causing the gradual dissolution of magnetite as Fe^{3+} is reduced to soluble Fe^{2+} (e.g., Lu and Banerjee, 1994). In sulfate-reducing environments, dissolution of detrital magnetic minerals is wide-spread (Canfield and Berner, 1987), as has been extensively documented in marine sediments. Biological reduction of magnetite by the bacterium *Shewanella putrefaciens* has been described recently (Kostrá and Nealson, 1995) as a very rapid dissolution process at room temperature. Kostrá and Nealson (1995) estimate that the rates of remobilization of magnetite through bacterial reduction is in the same order of magnitude as those assumed for the reduction by sulfide.

4. Conclusions

Our rock magnetic study of 180 m of continuous U-channel samples from two California Borderland basins, the East Cortez Basin and the San Nicolas Basin, suggests that reductive diagenesis had affected the fine-grained magnetite fraction. After the coring process the magnetic intensity was reduced to 7%–10% of the initial magnetization. Possible mechanisms for this intensity loss are the decay of a metastable magnetic mineral, such as greigite, or the dissolution of fine-grained magnetite by organic matter reduction or bacterial activity. We used the stable characteristic remanence to establish a magnetostratigraphic record down to the Jaramillo normal polarity interval. Apparently the U-channel data were less affected by the coring overprint than the initial shipboard data. Despite the strong diagenetic and core-diagenetic alterations the California Borderland sediments are an excellent recorder of the Earth's magnetic field directions. The magnetic susceptibility recorded a paleoclimate signal that we used in connection with the established oxygen isotope record to obtain a detailed age model within the Brunhes Chron.

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