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Magnetic mineral study of Holocene marine sediments from the Alfonso Basin, Gulf of California - implications for depositional environment and sediment sources

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Resumen

Se presentan los resultados del estudio de propiedades magnéticas en sedimentos marinos colectados en la Cuenca Alfonso en la Bahía de la Paz, los cuales se analizan en términos de las fuentes de aporte y el ambiente de depósito en el sur del Golfo de California durante el Holoceno. El control estratigráfico se basa en fechamientos de radiocarbono, que indican una edad para los sedimentos de fondo del núcleo de alrededor de 7597-7831 años cal. B.P. La señal magnética está dominada por minerales de grano fino de titanomagnetitas, los cuales provienen de las secuencias de tobas silícicas expuestas en la Bahía de la Paz. La mineralogía magnética es relativamente homogénea como lo indican las mediciones de propiedades de susceptibilidad magnética, magnetización remanente y coercitividad. Los ciclos de histéresis magnética indican la ocurrencia de componente paramagnéticas y los ciclos correspondientes después de la corrección paramagnética muestran ciclos que saturan en campos bajos y altos valores de magnetización de saturación. Las gráficas de discriminación de estado de dominio magnético empleando cocientes de los parámetros de histéresis muestran que las muestras se agrupan en el campo de dominio pseudos-sencillo, sugiriendo mezclas de dominios sencillo y múltiple. Los registros de susceptibilidad magnética revelan valores altos de factores de dependencia de frecuencia, en particular en el segmento del Holoceno Medio, lo que sugiere contribuciones de minerales superparamagnéticos de grano fino y posible transporte eólico. La presencia de laminaciones finas, características de la secuencia de Alfonso indica condiciones anóxicas en el fondo de la cuenca. El ambiente de depósito durante el Holoceno parece ser dominado por sedimentos detríticos pluviales y sedimentos de grano muy fino y transporte eólico, con menor contribución de sedimentos biogénicos.

Palabras clave: Magnetismo de rocas, sedimentos marinos laminados, Holoceno, Cuenca Alfonso, Bahía de La Paz, Golfo de California.

Abstract

Results of a rock magnetic study of marine sediments from the Alfonso Basin, Bay of La Paz are used to investigate sediment sources and depositional environment in the southern Gulf of California during the Holocene. Radiocarbon dating provides stratigraphic control, with age for the core bottom sediments of 7597-7831 cal. yr B.P. Magnetic signal is dominated by fine-grained titanomagnetites, derived from the silicic volcanic units surrounding the Bay of La Paz. Magnetic mineralogy is relatively homogenous as seen in bulk magnetic properties of low-field susceptibility, remanent intensity and coercivity. Magnetic hysteresis loops show strong variable paramagnetic components; after paramagnetic correction loops show saturation at low fields and high saturation magnetization values. Plots of hysteresis parameter ratios for domain state show that samples group in the pseudo-single domain field, with mixtures of single and multi-domain particles. Magnetic susceptibility log shows relatively high frequency dependence factors, particularly for the Middle Holocene, suggesting contribution of fine-grained superparamagnetic minerals related to eolian deposition. The well-preserved laminated sequence indicates predominant anoxic conditions in the basin floor. Depositional environment had a dominant supply of pluvial detrital sediments and eolian fine-grained dust composed of siliciclastic volcanically-derived material with less abundant biogenic input.

Key words: Rock magnetism, laminated marine sediments, Holocene, Alfonso Basin, Bay of La Paz, Gulf of California.

Introduction

The Gulf of California (Fig. 1) in northern Mexico is a young oceanic basin that has developed by sea floor spreading and transforms faulting along the tectonic boundary between the North American and Pacific plates. The Gulf is a NNW-SSE elongated 1,100 km-long and 50-240 km wide narrow basin, which extends from 24° N to 32° N across the Tropic of Cancer. Arid and semiarid lands of mainland Mexico and the Baja California peninsula surround the Gulf, providing characteristic ´geology-climate-morphology´ sources for the sediments. On the north, the Gulf receives the bulk of its sediments from the Colorado River basin and the desertic and semi-desertic areas of the Mojave-Sonora Desert. The Gulf is open to the Pacific Ocean at its southern end and to the influence of the tropical Pacific equatorial water masses. Sediments in the Gulf constitute rich archives of paleoclimatic and paleoceanographic information. Studies have been reported for various parts of the Gulf (e.g., Pérez-Cruz and Molina-Cruz, 1988; Molina-Cruz *et al*., 2002; Pérez-Cruz, 2006; Silverberg *et al*., 2007); although many have concentrated in the sediments of Guaymas Basin, which are characterized by varved sequences (e.g., Donegan and Schrader, 1982; Baumgartner *et al*., 1991; Sancetta, 1995; Pike and Kemp, 1997; Thunnell, 1998; Barron *et al*., 2004; Dean *et al*., 2004).

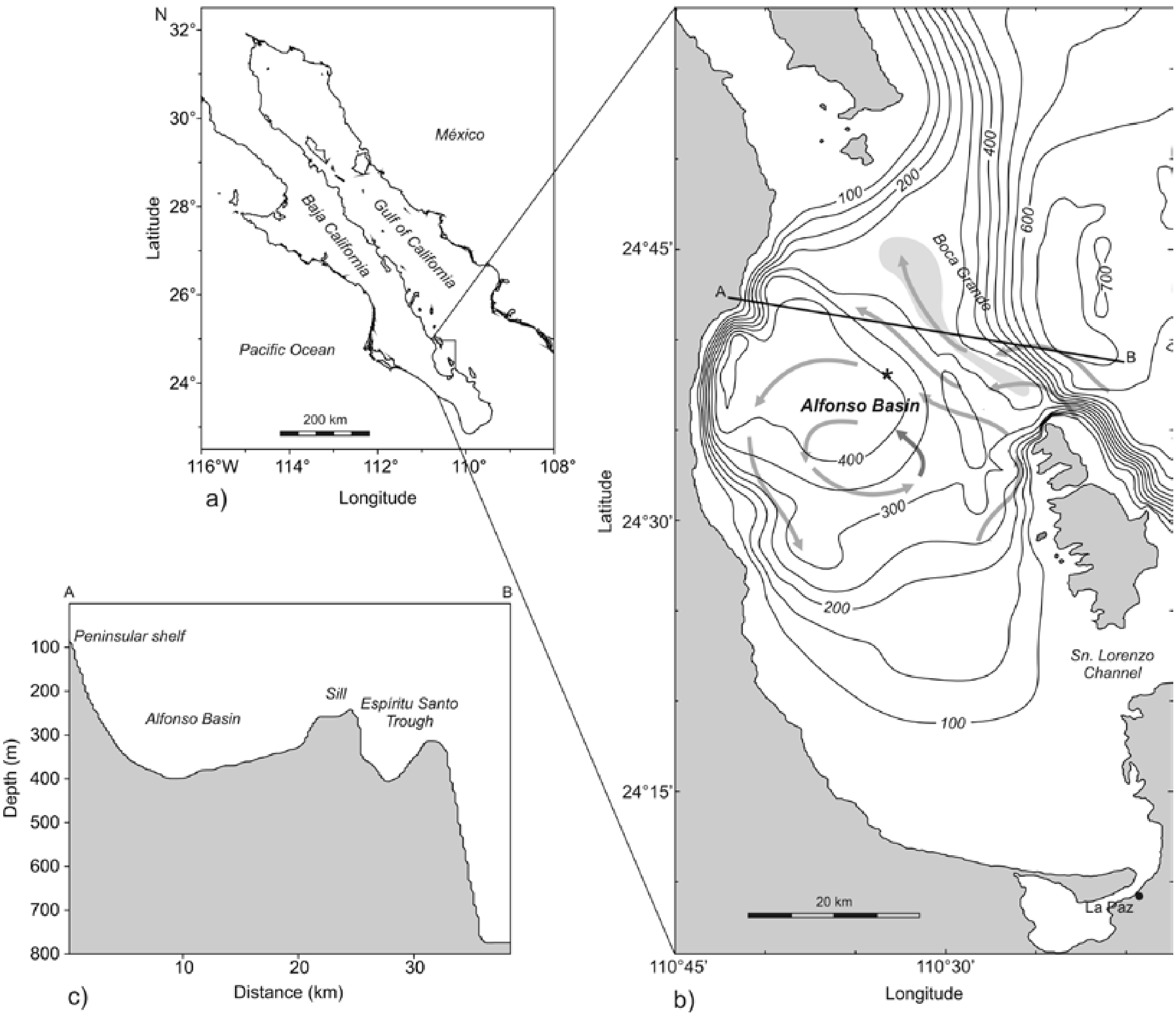

Fig. 1. (a) Location of study area in the southern Gulf of California with La Paz Bay and Alfonso Basin is indicated by the square. (b) Study area is in Alfonso Basin, northern sector of La Paz Bay. Location of coring site in the central sector of Alfonso Basin (indicated by the asterisk). (c) Profile A-B illustrates the bathymetry of the Basin and position of the submerged sill and Espiritu Santo Trough in the eastern limit.

Despite the potential as high-resolution paleoclimatic and geomagnetic records, the sediment sequences in the Gulf of California have not been studied for paleomagnetism and rock magnetism. Initial investigations on the sediment sequence from the Alfonso Basin in the Bay of La Paz have provided a paleoclimatic and paleoceanographic reconstruction for the Holocene (Pérez-Cruz, 2000, 2006). The reconstruction is based on microfauna (radiolarian), radiocarbon and magnetic susceptibility data for a laminated sediment core from the deeper part of the Basin (Fig. 1). In this paper, new magnetic mineral data for samples from the same core are used to analyze the laminated sedimentary sequence, depositional environment and source of terrigenous material.

Alfonso Basin, Southern Gulf of California

Alfonso Basin is a margin closed depression (maximum depth 420 m) located inside the Bay of La Paz, at the southwestern sector of the Gulf of California (Fig. 1). Its location at southern Gulf of California in the transition area between the Gulf and the open Pacific Ocean makes the Bay a sensitive recorder of regional variations in the Gulf and the larger scale climatic and oceanographic circulation of the subtropical Pacific Ocean (Monreal-Gómez *et al*., 2001).

The Bay of La Paz exchanges mixed–layer waters with the Gulf of California predominantly through Boca Grande, at the northeastern part of the Bay. Equatorial Surface Water (ESW) flows from the Gulf into the Bay and once there due to evaporation processes, this water increases its salinity above 35.00 transforming to Gulf of California Water Mass (GCW) (Monreal-Gómez, *et al*., 2001). The isolation of the bottom of the Bay by a bathymetric sill (275 m depth) (Fig. 1c) induces low oxygen content conditions, particularly in the Bay bottom-waters (O_2< 0.1 ml/l).

The regional climate of the southern Baja California peninsula and Gulf of California regions is semi-desertic with evaporation (300 mm/year) exceeding precipitation (average 180 mm/yr), and river discharges from the peninsula are scarce. Climatic conditions are dominated by seasonal processes related to monsoon activity resulting in marked changes along the peninsula, mainland Mexico and Gulf of California (Douglas *et al*., 1993). During winter and spring, north-west winds along the Gulf and peninsula are dominant, with surface circulation in the Gulf directed to the south where they meet with the northerly Pacific equatorial current. During summer and fall, wind pattern reverses, with southeasterly dominant winds and incursions of the Pacific equatorial current into the Gulf. During winter, when northern hemisphere insolation is at its lowest, the Inter-Tropical Convergence Zone (ITCZ) is located at or below the equator in the Pacific Ocean (Fig. 2) (Chiang *et al*., 2002; Poore *et al*., 2004). Under these conditions strong northwesterly winds dominate the Gulf of California, as a result, intense upwelling occurs during this period (Bray and Robles, 1991), leading to large increases in primary productivity of surface waters and associated maxima in sinking fluxes of biogenic materials (Thunell, 1998). During summer when northern hemisphere insolation is at its maximum, ITCZ moves northward (Fig. 2). The resulting atmospheric regime is one in which weak winds dominate the central and southern regions of the Gulf of California.

The Alfonso Basin receives sediments from small local intermittent drainages carved into the steep east cliff faces of the tilted volcanic blocks that form the volcanic ranges in the southern Baja California Peninsula (Fig. 3). These units form part of thick siliceous tuff sequences of the Comondu Formation. In summary, terrigenous input is therefore relatively low and mostly regulated by pluvial runoff. Biogenic input appears to be also minimal, related to low biological productivity.

Alfonso sediment core, methods and rock magnetic results

Our samples come from the Kasten core BAP96-CP (24°38.12’ N, 110°33.24’ W) recovered from the central sector of Alfonso Basin in the Bay of La Paz (at 390 m depth). Survey and drilling/coring information, core description and details of microfossil analyses have been reported in Pérez-Cruz (2006). The core was X-ray examined and described and shown to be characterized by a finely laminated sequence (Fig. 4). Radiocarbon dating was carried out on benthic foraminifer’s shells (*Bolivina subadvena*), with three intervals providing accelerator mass spectrometry AMS dates: 210-211 cm, 7500±50, 101-102 cm, 3830±35 and 19-20 cm 1730±45 ^{14}C yr B.P (Pérez-Cruz, 2006). To construct an age model, dates were converted to calibrated years B.P. using program CALIB 5.0 (Stuiver *et al*., 2005). Quoted dates are expressed in radiocarbon calibrated years (cal. yr B.P.). Average sedimentation rates range from 0.34 mm/yr near the top of the core to 0.26 mm/yr below 100 cm, with whole core average sedimentation rate about 0.30±0.04 mm/yr.

A 212 cm long section of sediments was sampled, using standard paleomagnetic acrylic 2.2 cm cubic sample holders, from top to bottom for the analysis of rock magnetic properties, with 143 overlapping samples. The sequence is finely laminated, which indicates predominant anoxic conditions in the basin floor. Micro-burrows can be observed in the lamina, indicating activity of foraminifera and other small organisms which however

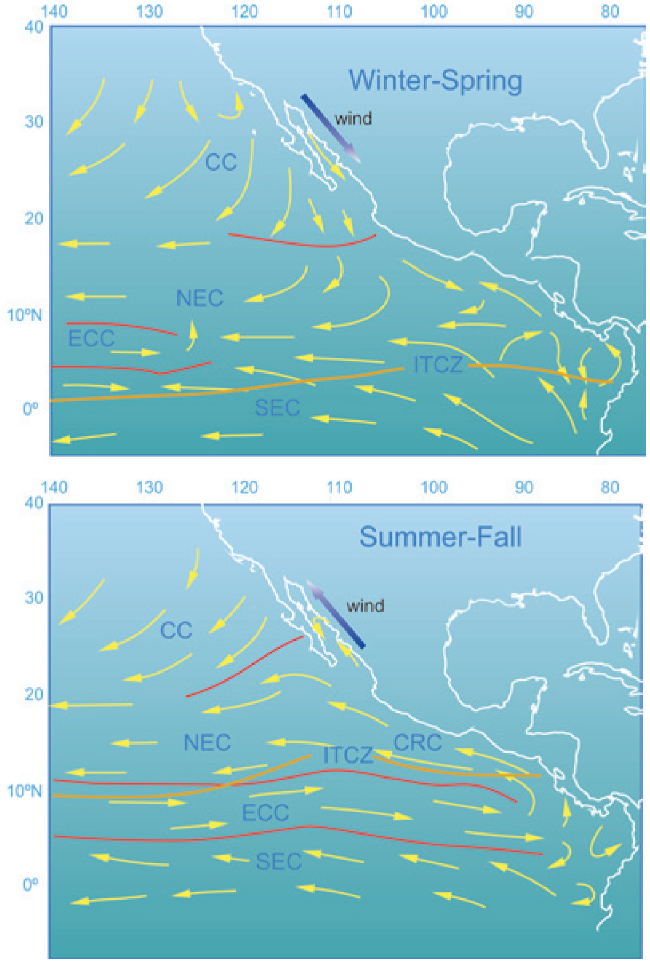

Fig. 2. Schematic representation of major climatic conditions in the Gulf of California during Winter-Spring with dominant northwesterly winds and surface Gulf currents, and Summer-Fall with dominant southeasterly winds and surface Gulf currents.

Fig. 3. Partial view of the volcanic tuff sequences around the Alfonso Basin. Note the thick volcanic sequences and the steep scarps that form the peninsular limits of the Basin. The BAP96-CP core studied was drilled in the central sector of Alfonso Basin at 390 m water depth.

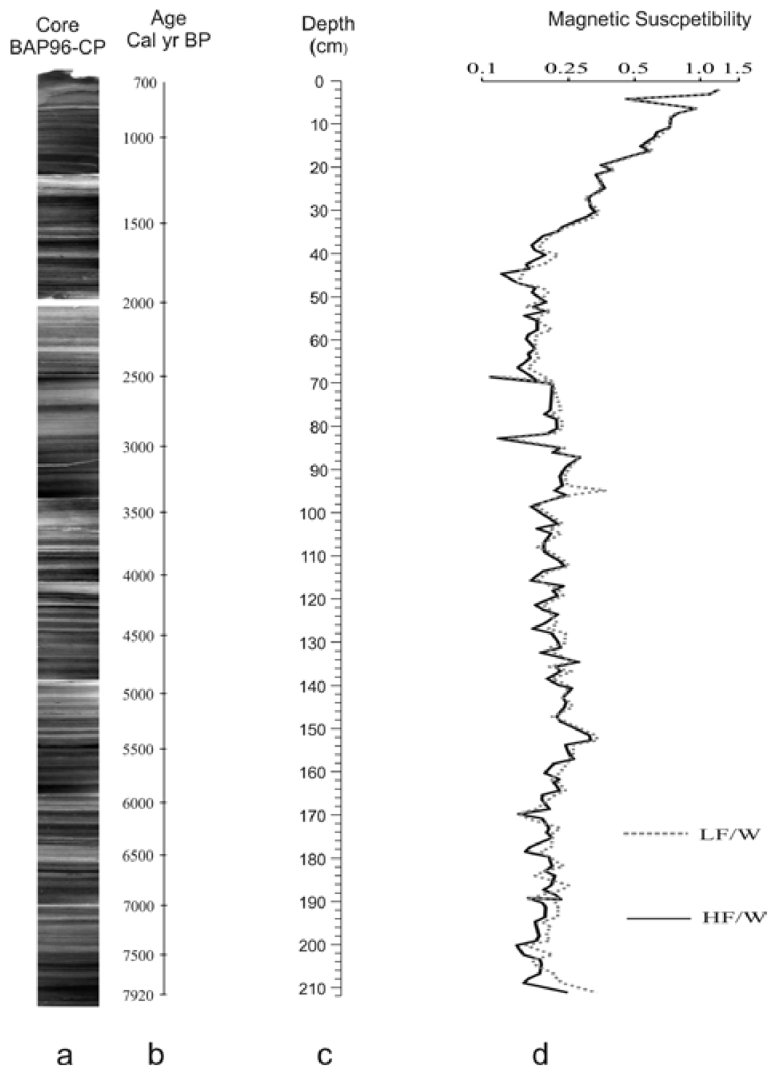

Fig. 4. Alfonso Basin core BAP96-CP. Age model determined from AMS calibrated radiocarbon dates. Sequence is composed of terrigenous (70-90 %) and organic-rich (5-10 %) hemipelagic sediments. It is characterized by dark and light lamina, which can be observed in the X-ray core image. Sequence contains several thin flood layers and turbidites. (a) X-ray core image, (b) age in calibrated radiocarbon years, (c) depth along core, and (d) magnetic mass susceptibility for low and high frequencies.

does not modify the fabrics. This supports no significant disturbance or mixing within the sediment column after deposition and during coring operations. The sequence is composed of terrigenous (70-90 %) and organic-rich (5-10 %) hemipelagic sediments, characterized by clay and lime dark and light laminae pairs. Sequence contains several thin flood layers and turbidites. Light laminas are formed by abundant coccoliths or diatoms.

The low-field magnetic susceptibility was measured in 143 samples in the laboratory at low and high frequency with a MS2 Bartington susceptibility instrument equipped with the MS2B dual frequency sensor at low 0.465 kHz (LF) and high 4.65 kHz (HF) frequencies. Weights of sediment samples were determined with an electronic balance. The frequency dependence of low-field susceptibility is estimated in terms of the frequency factor (f_d), determined as 100(LF-HF)/LF (Dearing *et al.*, 1996). The intensity of the natural remanent magnetization (NRM) was measured with a fluxgate spinner JR-5 magnetometer. Viscous acquisition was measured at different time scales, during remanence measurements and longer term exposition to the Earth's magnetic field (Urrutia-Fucugauchi, 1981). Viscous remanent magnetization (VRM) components acquired after two month periods were negligible. Isothermal remanent magnetization (IRM) acquisition curves were measured by using a Molspin pulse magnetizer. The partial IRMs were measured after field application using the JR-5 magnetometer until saturation was reached. The variation of low-field susceptibility at high temperatures was studied by heating and cooling samples with a modified Highmoor susceptibility bridge. The signal was in most cases below the detection limit and few relatively noisy curves could be obtained from magnetic mineral concentrates obtained from dry-disaggregated sediments using a magnet. Preliminary Curie temperatures range 420º-530º C, compatible with Fe-rich titanomagnetites.

Magnetic mineralogy, grain size and domain state are further investigated by remanence and coercivity analysis. Magnetic hysteresis and IRM acquisition experiments were carried out using the AGFM MicroMag instrument. Experiments were conducted in fields up to 1.4 Tesla.

Hysteresis loops are dominated by paramagnetic components, whose relative contribution varies through the sequence. After slope correction, well defined hysteresis loops showing low coercivity spectra are determined (Fig. 5). Back-field demagnetization of saturation IRM was also measured in all samples (Fig. 5). Hysteresis parameters are calculated after correction for the paramagnetic contribution (S*). Domain states are estimated from the ratio plot of hysteresis parameters (Day *et al*., 1977; Dunlop, 2002).

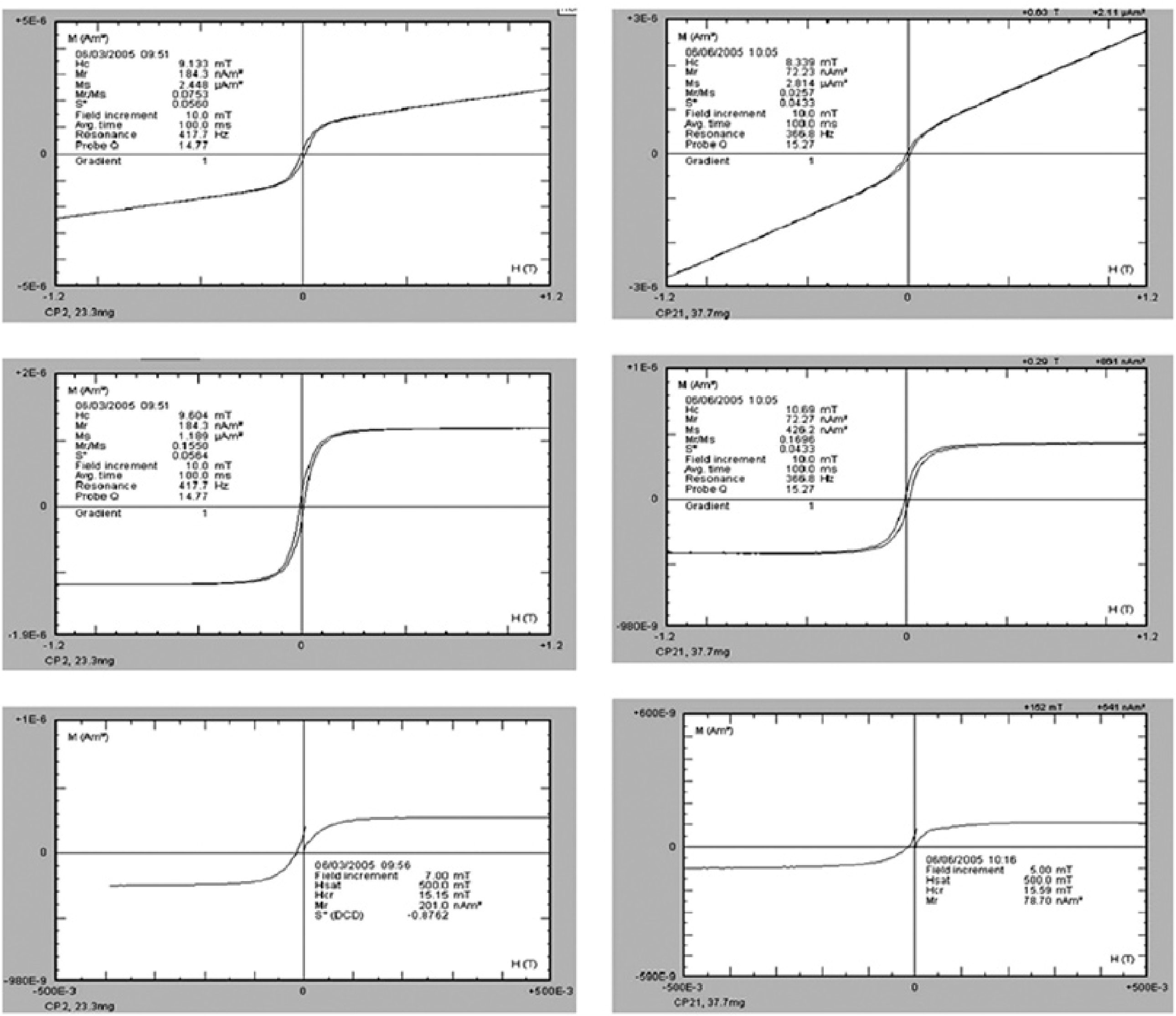

Fig. 5. Characteristic examples of magnetic hysteresis loops before and after paramagnetic slope correction. and curves of isothermal remanent magnetization (IRM) acquisition and back-field demagnetization of saturation IRM.

Results of the magnetic mineral analyses are summarized in Fig. 6. Data are plotted as a function of relative stratigraphic position through the core; ages are referred to calibrated age model. The low field magnetic susceptibility at low and high frequency ranges between 0.1 and 1.4 10^{-8} m^3/kg. Magnetic susceptibility measurements are normalized by sample weight and reported in the SI unit system per unit mass (10^{-8} m^3/kg). High and low frequency susceptibility are higher at the top of the sequence and displays a relatively smooth pattern of variation with depth, around a mean value of 0.2 10^{-8} m^3/kg (Fig. 6b). Characteristic small amplitude frequency variation patterns reflecting changes in concentration of magnetic minerals through the laminated sequence are present in the susceptibility logs. The frequency dependence factors fluctuate from –25% to 25 %, being mainly positive and with a tendency to increase towards the bottom of the core (Fig. 6c). The intensity of remanent magnetization displays a pattern similar to the magnetic susceptibility, with higher values in the top sediments and a relatively smooth pattern with depth (Fig. 6d). NRM intensity values vary between about 1 and 2 mA/m, with values up to 8 mA/m in the top surface sediments.

Magnetic hysteresis loops measured at different depths are similar, suggesting homogeneous magnetic mineralogy and restricted grain size range (Fig. 5). The hysteresis loops are dominated by paramagnetic components whose contributions vary through the section. Hysteresis loops after slope correction show saturation at low fields with relatively high saturation magnetization values, characteristic of titanomagnetites and magnetite. Hysteresis loops display no potbellied and wasp-waisted behaviors near the origin, which reflects restricted ranges of the magnetic mineral coercivities. Plots of hysteresis parameter ratios show that samples fall in the pseudo-single domain (PSD) field (Fig. 7). The dominant magnetic minerals are low coercivity fine-grained titanomagnetites and magnetite with PSD behavior, likely representing mixtures of fine-grained single domain (SD) and larger multidomain (MD) particles. Contribution of superparamagnetic (SP) very fine-grained material is also present at some intervals.

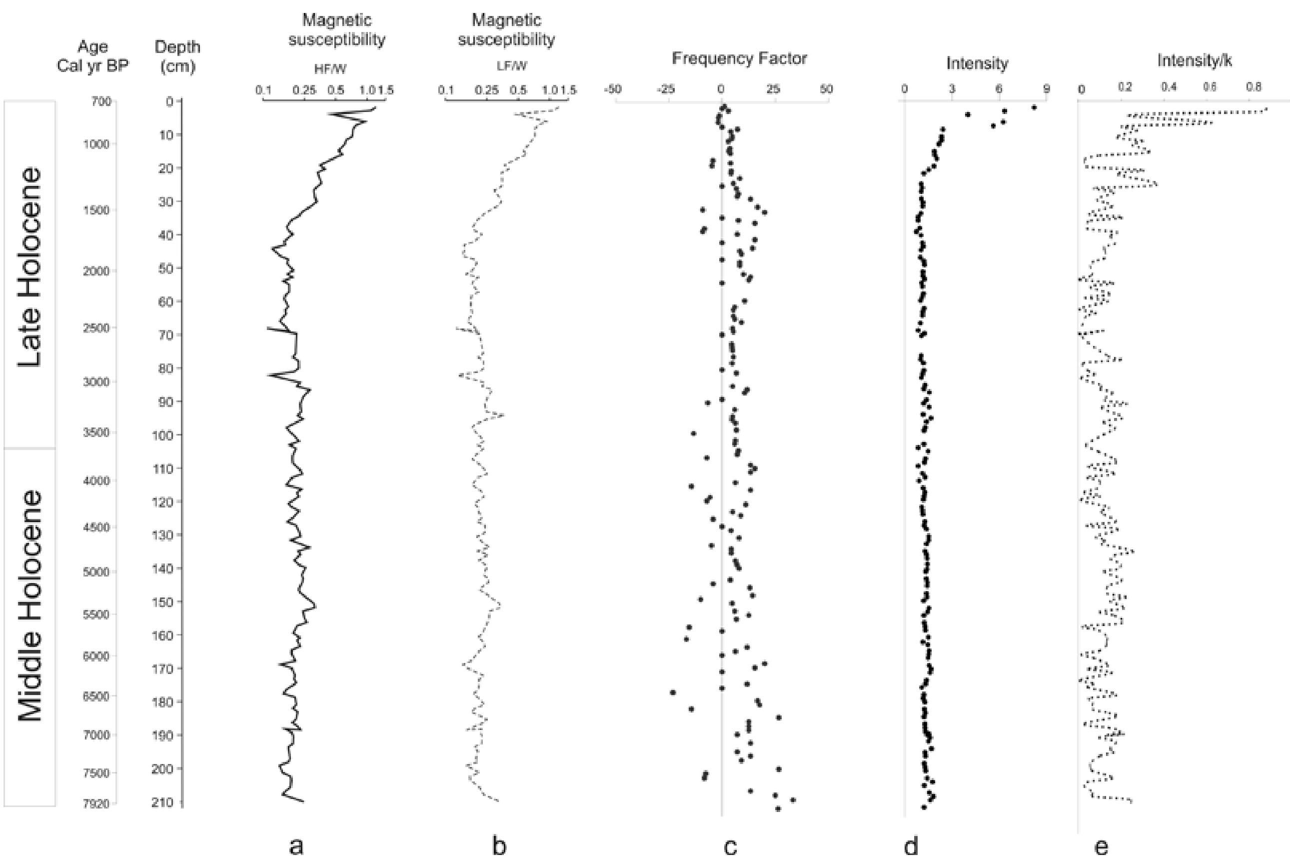

Fig. 6. Rock mineral data for BAP96-CP core plotted as a function of stratigraphic position and age. (a) Magnetic mass susceptibility at low frequency, (b) magnetic mass susceptibility at high frequency, (c) frequency dependence factor, (d) intensity of remanent magnetization in mA/m, (e) Koenigsberger ratio calculated as ratio of natural remanent magnetization intensity and magnetic mass susceptibility.

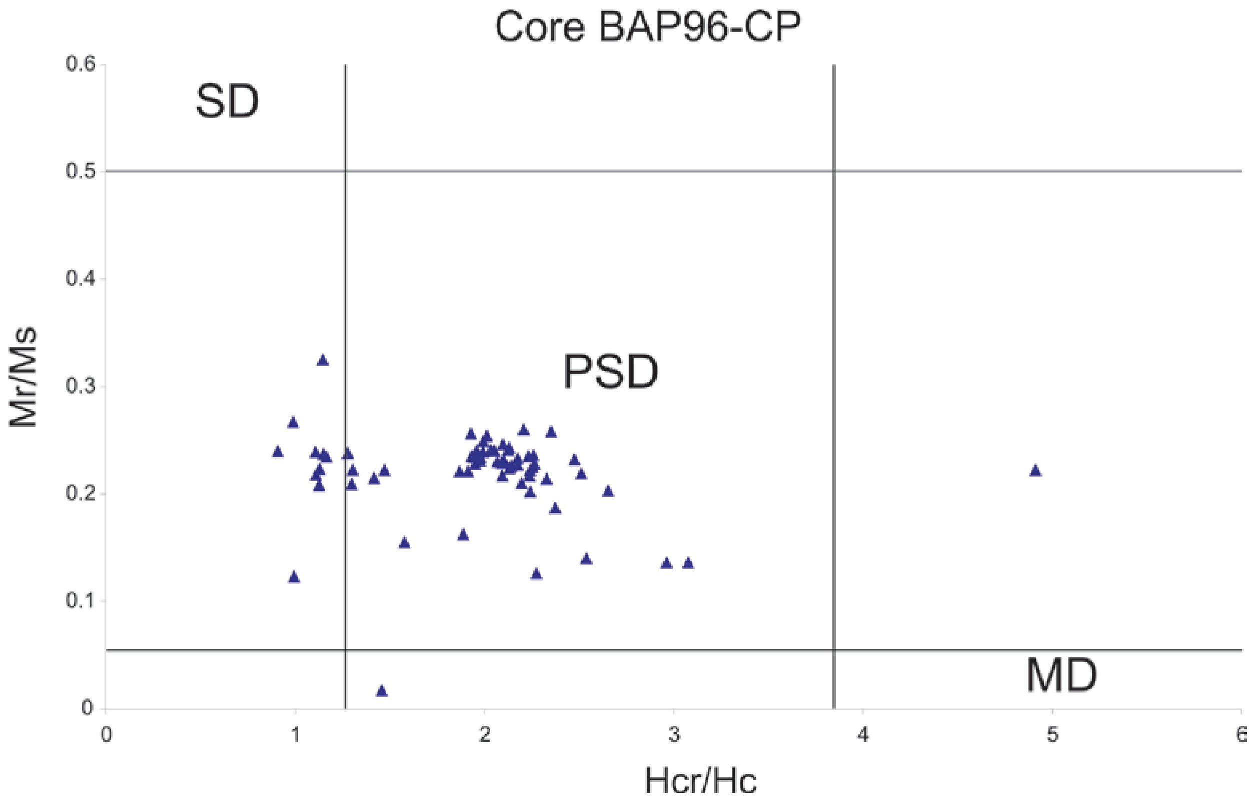

Fig. 7. Domain state plot of hysteresis parameter coercivity and magnetization ratios for microsamples from core BAP96-CP. Note that samples fall preferentially within the pseudo-single domain, indicating mixtures of single-domain and multi-domain particles.

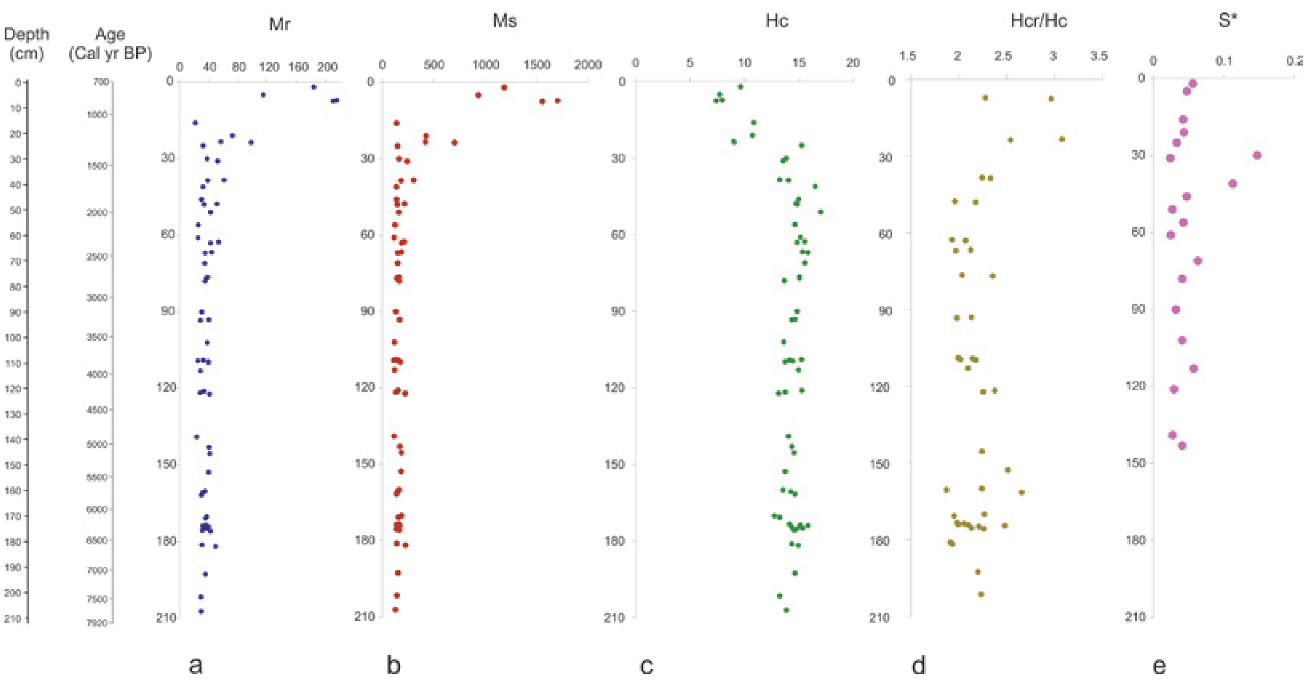

Fig. 8. Hysteresis parameter plots for BAP96-CP core plotted as a function of stratigraphic position and age. (a) Remanent magnetization (nA/m), (b) saturation magnetization (nA/m), (c) coercivity (mT), (d) coercivity ratio of remanence coercivity and coercivity, and (e) paramagnetic factor.

The stratigraphic variation of hysteresis parameters is summarized in Fig. 8. The intensities of remanent and saturation magnetization are higher in the top surface sediments and display smooth variation pattern with depth (Figs. 8 a and b). The coercivity is slightly lower between 6 and 11 mT in the top surface sediments and increases for the rest of the section, varying around mean values of 13-15 mT (Fig. 8c). The paramagnetic slope correction parameter shows higher values between 30 cm and 40 cm depth and an apparent cyclic pattern of variation (Fig. 8e). Magnetic susceptibility gets higher towards the core top in the surface sediments up to about 1000 cal. yr B.P.; it shows peaks at ~5500, 3400 and 1500 cal yr B.P. The magnetic susceptibility signal exhibits an apparent cyclicity of roughly 1200-1500 years.

Discussion

With the opening of the Gulf of California by sea floor spreading and transform faulting, a series of deep basins related to the spreading centers have developed into the central Gulf axis. Marine magnetic anomalies at the mouth of the Gulf give maximum ages of about 3.6 Ma. Early development of the Gulf is associated with tectonic extension and breakup as part of regional extension along the western North America continental margin (e.g., Atwater, 1989; Urrutia-Fucugauchi, 1995). Tectonic extension in the southern Basin and Range province extends eastward into the continental interior. The basins in the central and marginal sectors of the Gulf have accumulated thick sedimentary sequences, which represent rich archives of paleoclimatic, paleoceanographic and tectonic processes. These sedimentary archives have been only partly studied, mainly for the Late Pleistocene and Holocene. There is a need to study additional basin sequences in the Gulf, using wider spectrum of proxies.

Magnetic mineral analyses have been successfully used to investigate on depositional environment, sediment fluxes and sediment sources, and on their paleoclimatic and paleoenvironmental associations (e.g., Thompson and Oldfield, 1986; Robinson, 1986; Bloemendal *et al.*, 1988, 1992; Karlin, 1990; Stoner *et al.*, 1995; Maher and Thompson, 1999). These studies require detailed measurements of rock magnetic parameters. Complex magnetic assemblages, with mixed mineralogy of varying grain size, often characterize marine sediments. Magnetic minerals in marine environments can come from different sources, including terrigenous material, diagenetic minerals, biogenic minerals, and cosmic magnetic minerals (Bloemendal *et al.*, 1992; Maher and Thompson, 1999; Smirnov and Tarduno, 2000). Terrigenous material may be transported by fluvial, pluvial and eolic processes, depending on distance to shore, and climatic and geographic conditions. Sediments may also be transported and re-deposited by bottom currents and turbiditic flows. Nature of terrigenous material depends on the source lithologies and weathering and transport processes. Post-depositional processes and sediment diagenesis also result in formation of magnetic minerals, including sulfides, greigite and pyrrothite. Bacterial magnetites have been found to be important components in oceanic pelagic sediments. Similarly, cosmic magnetic spherules have been identified in pelagic sediments. For magnetic mineral analyses of marine sediments, we need identification (information on) of mineral type, concentration and grain size.

Magnetic susceptibility log and sediment fluxes

Magnetic susceptibility measurements on marine sediments have been used for rapid nondestructive methods for high resolution core logging and lateral correlations. Additionally, they are valuable as an aid in macroscopic lithological unit descriptions, identification of tephra layers, and characterization of core physical properties.

For core BAP96-CP, magnetic susceptibility data show low values around 0.2 10^{-8} m^3/kg, except at the surface sediments where values increase up to 1-1.5 10^{-8} m^3 /kg (Figs. 4 and 6). Correlation of magnetic susceptibility logs with the x-ray images and lithological column suggests that magnetic susceptibility responds to variation in terrigenous input. Further, the analyses of the radiolarian assemblages in terms of factor loadings related to (factor 1) Gulf of California water mass, (factor 2) equatorial water mass and (factor 3) cold events showed a relationship with the magnetic susceptibility variations. This is explored in more detail below, considering the new magnetic mineral data.

No microtephra layers could be identified, which was one of the initial expectations in the core analyses from reports of Holocene and historic volcanic activity to the north in the peninsula (Tres Virgenes volcano) and on mainland Mexico (e.g., Ceboruco, Tequila, Nevado and Colima volcanoes).

Low-field mass specific magnetic susceptibility, saturation magnetization and saturation remanent magnetization as concentration-dependent parameters are used to estimate magnetic mineral relative variations.

The magnetic susceptibility logs are characterized by higher frequency dependence factors (Fig. 6c), which suggest contribution of very fine-grained SP particles particularly for the Middle Holocene (>3,800 cal. yr BP). Relative contribution of SP particles is also supported by

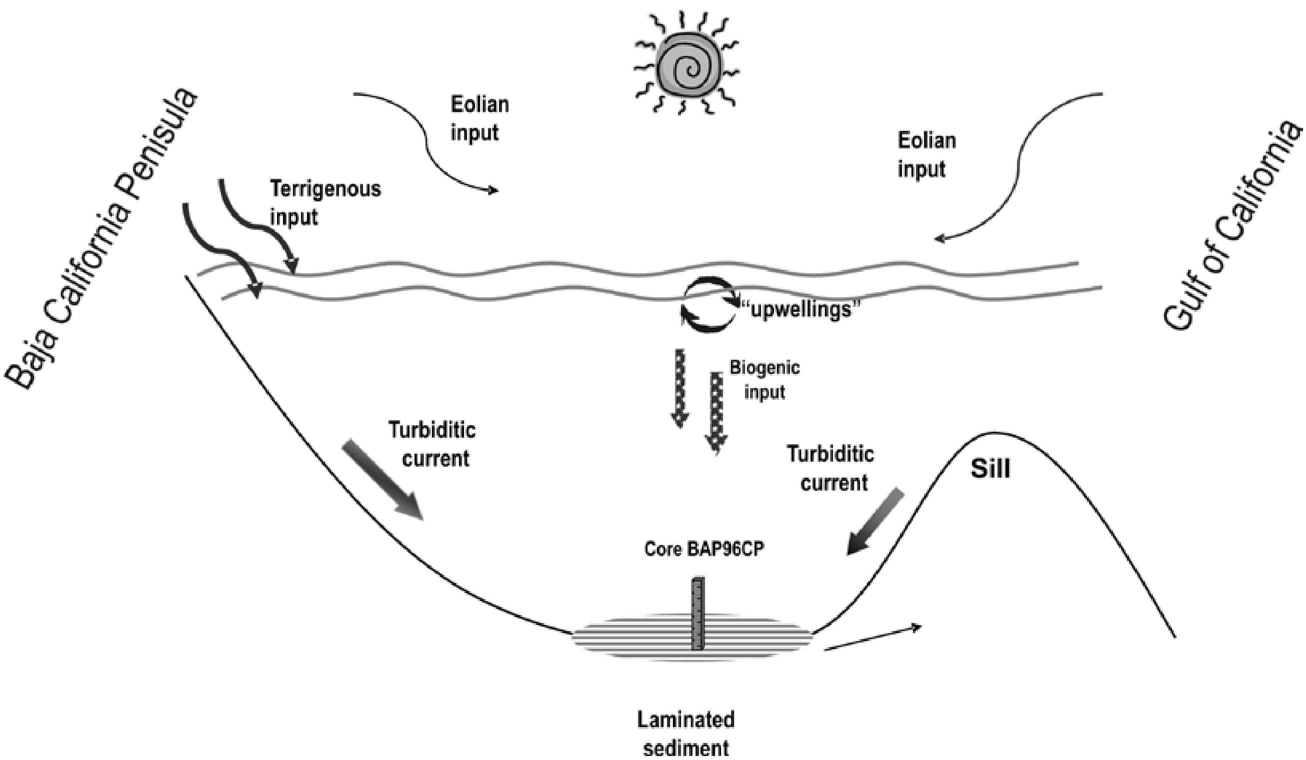

Fig. 9. Schematic depositional model for the Alfonso Basin, Bay of La Paz showing dominant sedimentary input into the basin, with the terrigenous sediments, biogenic material and turbiditic currents. See text for discussion

the distribution trends of hysteresis parameter ratios in the domain state plot. The pattern of frequency dependent susceptibility displays a marked change at about the Middle to Late Holocene transition, with high more variable values in the Middle Holocene than during the Late Holocene (Fig. 6). These changes are compatible with having warmer and drier periods in the Middle Holocene and increased precipitation and intensification of El Niño Southern Oscillation (ENSO) in the Late Holocene (e.g., Clement *et al*., 2000; Cole *et al*., 2002; Pérez-Cruz, 2006; Miao *et al*., 2007).

Magnetic minerals and sediment sources

The magnetic hysteresis loops are characterized by paramagnetic components (Fig. 5). After subtracting the paramagnetic contributions, hystersis loops show presence of low coercivity ferrimagnetic minerals (Fig. 5). Plot of the paramagnetic correction parameter S* as a function of stratigraphic position indicates varying relative amounts of paramagnetic minerals (Fig. 8e). The curve displays an apparent cyclic pattern, indicating variations of terrigenous input.

For the Alfonso Basin sediments, hysteresis loops after correction for paramagnetic contribution, coercivity analysis and IRM acquisition curves indicate the dominance of low coercivity minerals, likely titanomagnetites and magnetite. This is in concordance with the dominant volcanic terrain of pyroclastic flows and tuffs that surround the Bay of La Paz. The lack of rivers in the Bay area and the arid climate result in mechanical and chemical weathering of the volcanic rocks and sediment transport into the Bay by pluvial and eolian processes. Nevertheless, hematite, titanohematites, maghemite, and iron sulfides could be present in the basin sediments. Combinations of magnetic parameters have been shown useful for assessing magnetic mineralogy (Peters and Thompson, 1998; Maher and Thompson, 1999; Peters and Dekkers, 2003), and we tried several plots of magnetic parameters. Plots of the ratios of saturation remanent magnetization to susceptibility as a function of remanent coercitivity indicate minor amounts of high coercivity minerals such as hematite, goethite and iron sulfides. The organic matter contents in the BAP96-CP core appear low reflecting the low biological primary productivity in the Alfonso Basin, but this process may have resulted in formation of iron sulfides. Titanohematites may represent oxidation products of detrital magnetic minerals. Oxidation may have taken place during weathering and pluvial transport into the basin and during sediment early diagenesis, dewatering and compaction.

Model for sediment deposition

Major variables for sediment deposition are schematically illustrated in the model of Fig. 9. The depositional conditions in Alfonso Basin are mainly controlled by its geographic location at southern Gulf, with the interplay and connections between the equatorial Pacific Ocean and the Gulf. Regional climate is influenced by the monsoon activity and strong seasonality. ENSO events exert strong influence in the region, affecting sea surface temperatures, ocean circulation, precipitation, storm activity and wind patterns. Also, northward migration of the ITCZ causes that transport of moist air by southerly winds brings increased precipitation in the Gulf. Interhemispheric teleconnections appear important at different time scales, as well as the influence of high latitude processes (e.g., Clement *et al*., 2000; Bond *et al*., 2001; Cole *et al*., 2002; Viau *et al*., 2002; Asmerom *et al*., 2007; Miao *et al*., 2007). Alfonso Basin lies within the northern sector of La Paz Bay surrounded by volcanic scarps of silicic tuffs on its western and northern limits and separated by a sill towards the open waters of the Gulf (Fig. 1). The terrigenous input, although time dependable and variable, appears greater than the biogenic input in the Basin and Bay. In general, primary productivity of La Paz Bay has been generally lower as compared to other basins in the central Gulf (Pérez-Cruz, 2006; Douglas *et al*., 2007). Low-field mass specific magnetic susceptibility, saturation magnetization and saturation remanent magnetization provide a proxy for magnetic mineral input as concentration-dependent parameters. Magnetic mineral analyses suggest occurrence of Ti-poor titanomagnetites and magnetite, which have been derived from the silicic tuffs and transported into the basin. Very fine-grained superparamagnetic particles are indicated in the frequency dependence susceptibility and hysteresis measurements, which document eolian input, mainly during middle Holocene.

Terrigenous material is transported by pluvial input with lesser amounts of eolian fine grained material. The absence of rivers along the eastern margin of the peninsula makes a major difference in the sediment deposition in the marginal basins. This difference can be assessed by comparing to conditions of sediment transport and deposition on the western margin of the peninsula, where detrital sediments are of fluvial origin. Magnetic mineral analyses of a Late Pleistocene and Holocene sediment sequence on the Pacific Ocean side documents dominance of pluvial and eolian terrigenous material (Blanchet *et al*., 2008). Along the eastern Gulf margin, fluvial input is much larger, due to the presence of large rivers and drainage basins on mainland Mexico. Sediment composition is more heterogeneous and variable, related to the igneous, metamorphic and sediment sources. These conditions are also present along the entire peninsula and Gulf of California, providing the major constraints on the sediment deposition processes in the marginal and central Gulf basins. In the La Paz Bay area, source rocks appear more homogeneous, mainly volcanic silicic tuffs. Towards the tip of the peninsula, intrusive rocks of the Los Cabos batholith dominate, with some metamorphic and sedimentary rocks contributing as sediment sources. Terrigenous input increases during periods of intense precipitation, which in the area are related to El Niño events. El Niño events may have increased in frequency and intensity during the late Holocene and may have been suppressed during the Middle Holocene (Clement *et al*., 2000; Cole *et al*., 2002).

In the BAP96-CP core terrigenous pluvial material dominates, giving a dark coloration to the sequence and biogenic input appears smaller even in the light laminae, which is reflected in the geochemistry and the ratio relationships of terrigenous/biogenic material (e.g., CaO_2 versus contents of SiO_2, Al_2O_2, FeO and MgO). Sediments are finely laminated, with presence of dark/light lamina, which indicate dominant anoxic conditions for the basin floor. This supports no significant disturbance or mixing of sediment column in Alfonso Basin, and the only major discontinuities in sediment deposition are related to the emplacement of the turbiditic currents as discussed in previous section. Light laminations are interpreted in terms of increased biogenic input during periods of increased upwelling and enhanced productivity.

In interior North America, periods of severe drought and enhanced eolian activity during the Holocene have been related to ENSO and Pacific Decadal Oscillation (PDO) intensity and frequency. Miao *et al*. (2007) document periods of drought and enhanced eolian activity at 0.7-1.0 ka, 4.5-2.3 ka (with peaks at 2.5 and 3.8 ka) and 6.5-9.6 ka in the central Great Plains. They suggest the record could be linked to sea surface temperature anomalies in the Pacific and Atlantic oceans and ENSO activity, without finding a conclusive connection.

Conclusions

The Alfonso sediment sequence is dominated by terrigenous material, mainly siliceous-aluminous detrital sediments derived from the Comondu volcanic tuff sequences forming the mountain ranges surrounding the Bay. The sediments are finely laminated, with presence of dark/light lamina. The terrigenous material is dominant through the section, giving the sequence dark colors. Biogenic input is relatively lower, even in the light color laminae, as shown in the geochemistry and the ratio relationships of terrigenous/biogenic material. Laminations reflect increasing relative abundance of biogenic material that is mixed with the terrigenous sediments giving lighter colors.

Magnetic mineral data suggests relatively stable depositional conditions in the Basin, with dominance of Ti-poor titanomagnetites and magnetite derived from the volcanic rocks and transported by pluvial processes into the basin. The magnetic susceptibility logs are characterized by high frequency dependence factors, suggesting contribution of very fine-grained superparamagnetic minerals related to eolian deposition. The well-preserved laminations indicate predominant anoxic conditions in the basin floor. Depositional environment in Alfonso Basin appears to have been relatively stable with steady dominant supply of terrigenous material composed of siliciclastic volcanically-derived material (reflected in the dark laminae) from the volcanic tuff sequences surrounding the basin, with less abundant biogenic input (reflected in the light laminae). Terrigenous detrital input is modulated by precipitation and runoff, with enhanced erosion processes in the siliceous volcanic ranges and coastal narrow alluvial fans

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