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ROCK-MAGNETIC PROPERTIES AND ANISOTROPY OF MAGNETIC SUSCEPTIBILITY - SUPPLEMENTARY PROXIES IN TSUNAMI DEPOSITS IDENTIFICATION: THE 22 JUNE 1932 EVENT, PACIFIC COAST OF MEXICO

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RESUMEN

Los depósitos de tsunamis han sido ampliamente estudiados en latitudes de climas templados, pero las dificultades asociadas al trabajo en ambientes tropicales y la intensidad de bioturbación en estos hábitats limitan las oportunidades para analizar estos depósitos. Hasta ahora, no hay una una técnica analítica que por sí sola identifique a los depósitos de tsunami enterrados. Aquí aplicamos una combinación de indicadores de propiedades magnéticas, Susceptibilidad Magnética (MS) y Anisotropía de la Susceptibilidad Magnética (AMS), para corroborar los resultados de análisis histórico-etnográficos, geomorfológicos, estratigráficos, sedimentológicos (tamaño de grano, contenido de materia orgánica), microfósiles (diatomeas, foraminíferas, y ostrácodos), geoquímica, geocronología (210Pb, 14C) y modelado para reconocer depósitos indicadores de inundación por tsunami. Las evidencias de MS y AMS corroboran que las dos unidades de arena anómalas con contactos basales abruptos son el producto de dos tsunamis, uno de ellos asociado al sismo de Mw 6.9 del 22 de Junio de 1932 y el otro por un evento prehistórico.

Palabras clave: Depósitos de tsunami, Susceptibilidad Magnética (MS), Anisotropía de la Susceptibilidad Magnética (AMS), ambiente tropical, Costa del Pacífico Mexicano

ABSTRACT

Tsunami deposits have been widely studied in temperate latitudes, but the intrinsic difficulties associated with working in tropical coastal environments, and the intensity of bioturbation in these habitats limits the opportunities for analyzing these deposits. To date, no single analytical technique will with certainty identify buried tsunami deposits. We applied a combination of magnetic properties, Magnetic Susceptibility (MS) and Anisotropy of Magnetic Susceptibility (AMS) proxies, to corroborate historical/etnographic, geomorphological, stratigraphic, sedimentological (grain size, organic matter content), microfossil (diatom, foraminifera and ostracods), geochemical, geochronological (210Pb and 14C dating) analyses and modeling in order to recognize deposits indicative of tsunami inundation. MS and AMS evidence aid in demonstrating that anomalous sand units with sharp basal contacts are the products of two tsunamis, one of them related to the Mw 6.9 June 22, 1932 event and another by a prehistorical event.

Keywords: Tsunami deposits, Magnetic Susceptibility (MS) and Anisotropy of Magnetic Susceptibility (AMS), tropical environment, Pacific coast of Mexico

1. Introduction

Our ability to identify the impact of prehistoric tsunamis in the geological record has been greatly improved through analysis of the deposits of the tsunami in the Indian Ocean in 2004 (*e.g*. Moore *et al.* 2005; Hawkes *et al.* 2007), Java 2006 (Moore *et al.* 2011), and in the aftermath of more recent events (*e.g*. Goto *et al.* 2011, 2012). Despite these advances, it is still difficult to distinguish between tsunami deposits and those laid down by other high-energy inundation events, such as storm surges. Only a few studies have used a large number of proxies to not only identify tsunami deposits on tropical coasts (Ramírez-Herrera *et al.* 2007, 2009, 2012) but to distinguish between tsunami and storm deposits in this environment (Morton *et al.* 2007; Ramírez-Herrera *et al.* 2012). The principal source of tsunamis along the Pacific coast of Mexico is the plate boundary between the Rivera-Cocos plates and the North American plate. The locked zone at this plate interface ruptured in two stages in June 1932. A Mw = 8.2 earthquake on the 3rd June was followed by a large (Mw = 6.9) aftershock on the 22nd. Both ruptures triggered tsunamis that caused local flooding. The 22nd event, although been of lower magnitude, produced a larger tsunami with reported waves 11 m high in Cuyutlán, Colima (Sánchez, Farreras, 1993; Corona, Ramírez-Herrera, 2012a,b).

This study represents the first attempt to locate and describe the remnant deposits of the 22nd June 1932 tsunami testing a novel technique: Magnetic Susceptibility (MS) and Anisotropy of Magnetic Susceptibility (AMS) sediment properties. We present stratigraphic and MS-AMS-proxy evidence from sampling sites in the Palo Verde estuary, in an attempt to determine whether these anomalous sand beds were laid down by the 22nd June tsunami of 1932.

2. Materials and methods

We applied a combination of multiple proxies to recognize deposits that show characteristics of tsunami inundation (e.g. Morton *et al.* 2007). Here we test the efficience of a relatively unexplored tool: MS and AMS to reveal the feasibility of testing it for tsunami deposit identification.

Low-frequency magnetic susceptibility measurements were carried out using AGICO Kappabridge MFK1-B equipment. To obtain the susceptibility (k) measurements at high and low-frequency (k *hf* at 4700 Hz, k *lf* at 470 Hz) we used the Bartington MS2B apparatus. Mass-specific susceptibility (κ) was calculated using these k values. Equally, frequency-dependent susceptibility k_{FD} [%] = (k*lf* -k*hf*) *100/k*lf* was used to determine the possible presence of superparamagnetic (SP) grains in the magnetic fraction (Evans, Heller, 2003).

AMS in low field was measured in room temperature using a Kappabridge KLY – 2 device. The measured values *K1*, *K2*, *K3* correspond to maximum, intermediate, and minimum susceptibility respectively. Based on these magnitudes of principal directions of AMS, shape parameter $T = 2\ln(K_2 / K_3) / \ln(K_1 / K_3) - 1$ (Jelínek, 1981), degree of anisotropy $P = K1 / K3$ (Nagata, 1961), and mean magnetic susceptibility $Km = (K1 + K2 + K3) / 3$ were calculated. Measured data was processed using Anisoft 4.1 software.

3. Results

Magnetic properties (MS and AMS)

We applied an alternative approach to identify tsunami-induced deposits using environmental magnetism. This method first was tested for the Lisbon 1755 event (Font *et al.* 2010) and later tested in tropical settings (Ramírez-Herrera *et al.*, 2012; Goguitchaichvili *et al.*, 2013). Samples for magnetic susceptibility (MS) analysis were taken *in situ* in the three trenches and this explains a slight mismatch of a few, 2-3 cm, with the other proxy profiles. In the Palo Verde stratigraphic sequence, the upper sand unit (PV1) coincides with a considerably higher MS values, at 13 to 30 cm depth, and a slightly higher peak at 32 cm depth. Down the MS profile no variation is observed and the top, 0-13 cm is also homogenous (fig. 2).

AMS results for all the set of samples from Palo Verde Locality (PV) show that minimum susceptibility direction (*K3*) is almost parallel with pole of horizontal bedding, and mean maximum susceptibility direction (*K1*) mean direction is oriented at 105° azimuth. *K1* direction is more scattered, in comparison with *K3* (fig. 1a). The diagram with degree of anisotropy (*P* – Nagata, 1961) *vs*. mean magnetic susceptibility (*Km*) allows distinguishing 2 clusters. Difference between data in light blue and red color is 1 order of magnitude in *Km* value (fig. 1b). Diagram with *P* parameter *vs*. shape parameter (*T*; Jelinek, 1981) shows that majority of samples have oblate character of magnetic fabric (*T* value is in between values of 0 and 1) and is remarkable that 1 sample (yellow) is situated out of main cluster of data due to its higher *P* parameter (fig. 1c).

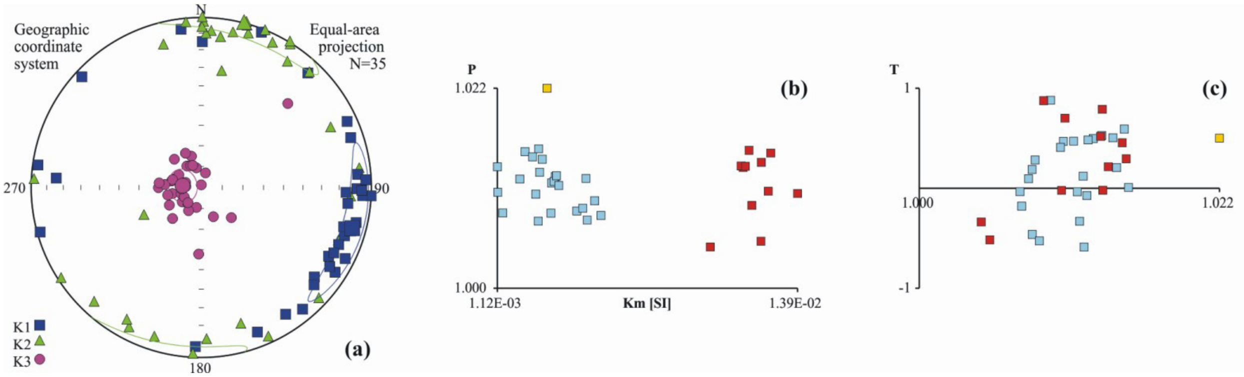

Figure 1. a) Principal directions of AMS for all the set of samples from Palo Verde plotted to lower hemisphere equal-area projection. *K1*, *K2* and *K3* represent maximum, intermediate and minimum susceptibility directions; b) degree of anisotropy (*P*) *vs*. mean magnetic susceptibility (*Km*); c) Jelinek's shape parameter (*T*) *vs*. degree of anisotropy (*P*). See text for details.

The Palo Verde stratigraphic profile reflects a combination of 4 different magnetic fabrics in each different unit. These fabrics were separated and correlated with the stratigraphic profile (fig. 2). Samples from the 1st unit (soil) represent an almost non- preferred orientation of *K1*. AMS fabric in 2nd unit (sand) has preferred orientation 116° in azimuth, just one sample from that horizon shows different orientation 43° in azimuth (*K1* and *K2* swtitching positions); this sample was collected close to the unit basal contact of the unit. The 3 rd unit (soil) is characterized by scattered *K1* direction with weaker preferred orientation. AMS fabric in the 4th unit (sand) has stronger preferred orientation 96° in azimuth.

Remarkably, at the Palo Verde site we identified 4 different magnetic fabrics which are related to different stratigraphic units. Fabrics from the 1st and 3rd units, which are soils, can be interpreted as sedimentary fabrics from a calm sedimentary environment with no significant current flow, and where *K1* direction is scattered (Tarling, Hrouda, 1993). In comparison, the fabrics from 2nd and 4th units, *i.e*. PV1 and PV2 respectively, can be interpreted as sedimentary fabrics with significant current flow in *K1* direction (Tarling, Hrouda, 1993), with ESE – WNW direction (116° azimuth) and E – W direction (96° azimuth) (fig. 2). The sample from the lower part of PV1 (fig. 2, yellow mark) can be interpreted as sample from a dynamic environment with very strong current flow, because high velocity flow tend to reorient the *K1* direction to a perpendicular orientation in relation to current flow (*e.g*. Ellwood, Ledbetter, 1977; Taira, Scholle, 1979; Tarling, Hrouda, 1993). In this case, it could be the result of a tsunami current flow.

4. Conclusions

MS- and AMS-proxy data were measured from sediments in the Colima coastal area, from which depositional evidence for the 22nd June 1932 tsunami and a historical (?) or paleotsunami in the Palo Verde estuary were inferred. The use of MS and AMS proxies probes to be a potential tool in tsunami deposits identification.

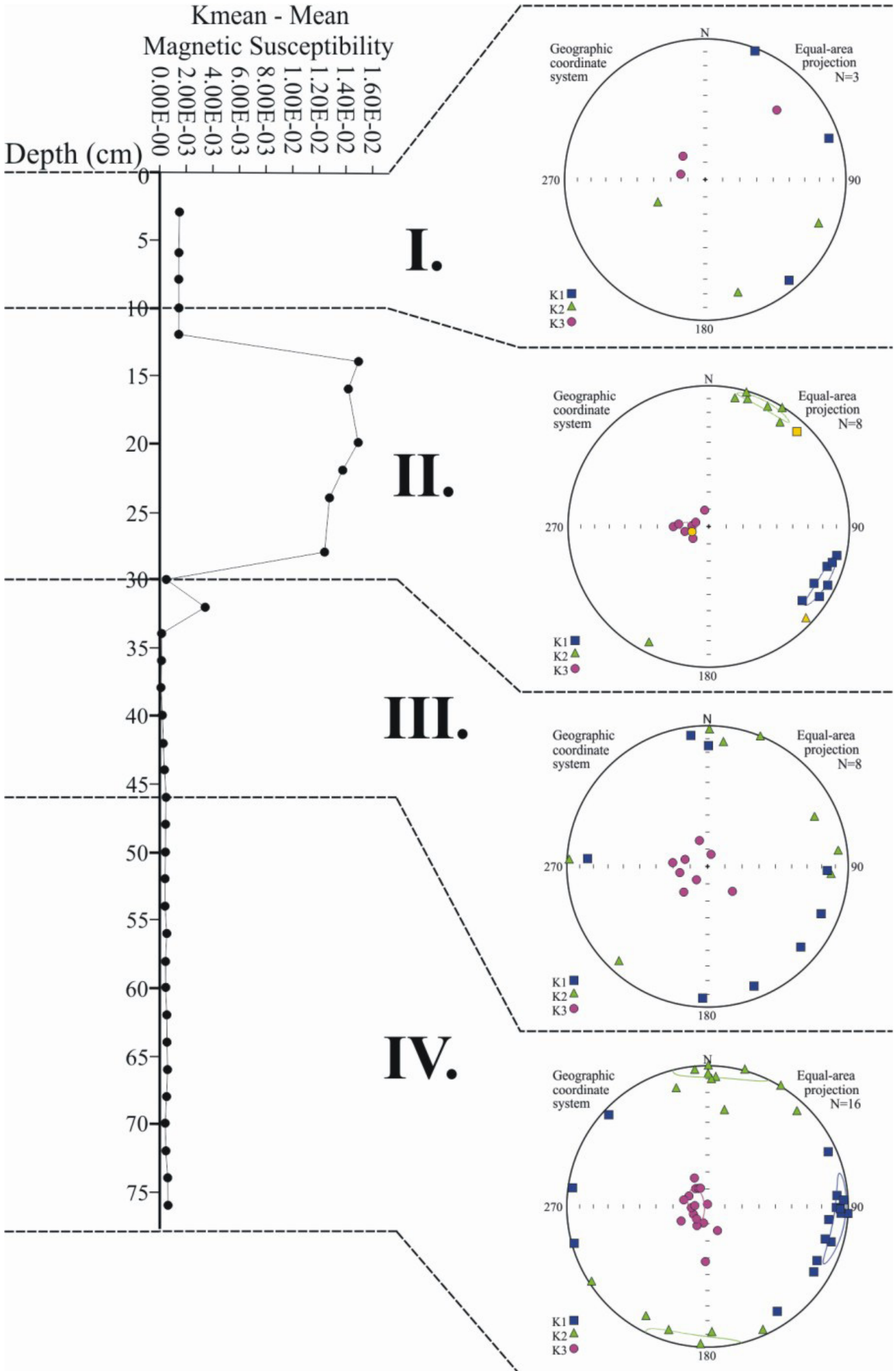

Figure 2. Magnetic susceptibility *vs*. depth in relation to 4 different magnetic fabrics. Yellow colored sample represents significant change in magnetic fabric. Red dots represent remarkable changes in Magnetic Susceptibility in 4th horizon. *K1*, *K2* and *K3* represent maximum, intermediate and minimum susceptibility directions. See the text for details.

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