NE BRAZILILIAN CLIMATIC RESPONSE TO HEINRICH STADIALS: A ROCK MAGNETIC SIGNATURE OF SOIL EROSION

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ABSTRACT

Rock magnetic parameters and 134 IRM acquisition curves were obtained from a 7 meters long core recovered at the continental margin off NE Brazil (GeoB3912-1). We applied a statistical unmixing procedure to decompose the bulk magnetic signal into end-members (EM) representing different terrigenous sources. Using a 3 EM model we discriminated between soil magnetic minerals (goethite/hematite) and non-oxidized bedrock minerals (detrital magnetite). Two EMs show an increase during Heinrich stadials (HS) that is consistent with the enhanced precipitation assigned to a southern position of the Intertropical Convergence Zone (ITCZ). These EMs represent two terrigenous fractions at our study site, which reflect changing contributions from local rivers (Jaguaribe and Piranhas-Açu) that are mainly influenced by precipitation on land. We identified two periods of sedimentation, with dominance of high coercivity minerals in the beginning of the HSs and a higher contribution of low coercive phase towards the end. The same pattern is evident in the magnetic paramters. We propose that after the onset of the humid HSs there was enhanced soil erosion that resulted in higher input of hematite/goethite to the continental shelf. After the development of a dense vegetation cover, the soils were stabilized and the contribution of magnetic minerals derived from bedrocks became more important. A third source represents the modern sedimentation and probably reflects a background signal derived from changes in the strength of North Brazilian Current and North Brazilian Under Current, which brings material from São Francisco River (about 10° S) to lower latitudes.

Key words: IRM end-member analysis (EM): NE Brazil, environmental magnetism, paleoclimate, terrigenous input, Heinrich events (HE)

Introduction

The Equatorial Atlantic region is very responsive to atmosphere and ocean dynamics such as changes in the Intertropical Convergence Zone (ITCZ) position and meridional overturning circulation. Southward migration of ITCZ is related to both decreasing sea surface temperature (SST) in the North Atlantic and increase of the temperature gradient between north and south Atlantic (Nobre and Shukla, 1996). As a consequence, changes in the SST in North Atlantic has a profound impact in the NE Brazil rainfall (Cruz *et al*., 2009). A multiproxy analysis of the marine sediment core GeoB3912-1 revealed higher terrestrial input during Heinrich stadials (HSs; Arz *et al*., 1998). Later on Jennerjahn *et al*. (2004) found an internal sedimentation pattern during the HSs and underlined the regional climate and hydrology as possible causes for these rapid millennial-scale changes. Dupont *et al*. (2009) show a two-step response of the vegetation in the catchment area of Piranhas-Açu River during HS1. The authors suggest dominance of dry caatinga remaining from the last glacial maximum in the beginning of HS1, and a denser vegetal coverage in the second phase. End-member (EM) modeling techniques unmixing the magnetic fraction with distinct coercivities, are a powerful tool in reconstructing variations of transport and sources of terrigenous material influenced by changing climate conditions (Just *et al*., 2012). It was previously proved that higher input of terrigenous sediment to the continental shelf adjacent to NE Brazil is a response to enhanced precipitation during HSs. However, it is still a matter of discussion if this rainfall is induced solely as a response of HEs or if other processes (*i.e.* change in strength of currents) could be a cause for the internal features of the

HSs. Essentials of the complex circulation of the Equatorial Atlantic comprise the northwestward flow North Brazilian Current (NBC) and northward North Brazilian Under Current (NBUC). Seeking a better understanding about the processes that control the internal fluctuations on terrigenous material during the HSs we performed rock magnetic analysis and IRM curve acquisition up to 2.5 T on 134 cubic samples from a 7 meters long gravity core (GeoB3912-1) recovered off NE Brazil (03° 40' S, 37° 43') at a water depth of 722 m. Our findings suggest that beside the enhanced rainfall during HSs, changes in the oceanic circulation over Equatorial Atlantic may have a key role in carrying material from more southerly latitudes (about 10° S) up to the margin adjacent to Fortaleza (fig.1).

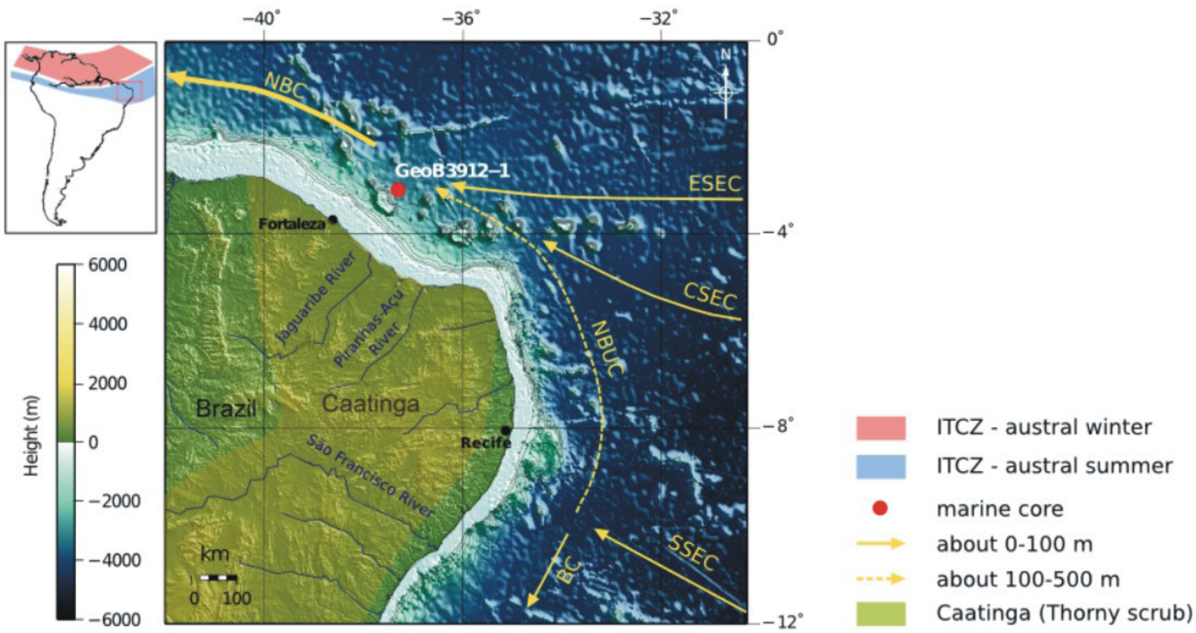

Figure 1. Map of the study area with the location of the investigated core GeoB3912-1. The arrows are a schematic representation of the geostrophic currents: North Brazilian Current (NBC), Equatorial (ESEC), Central (CSEC), Southern (SSEC) branches of the South Equatorial Current, North Brazilian Under Current (NBUC) and Brazilian Current (BC) (Stramma and England, 1999).

Study Area

The semi-arid climate in NE Brazil (Nordeste) is strongly affected by the seasonal migration of the ITCZ. Over the tropical Atlantic sector the ITCZ reaches the equator during February, March and April producing the rainy season of NE Brazil (Cruz *et al*., 2009; Garreaud *et al*., 2009). The terrigenous fraction at our study site is derived mainly by the local rivers Jaguaribe and Piranhas-Açu, which have catchment areas of 75,700 and 17,500 km^2, respectively (fig. 1). Additionally, advected material from São Francisco River could contribute to the sedimentation. This river reaches the Atlantic Ocean at a more southern latitude (about 10° S) and has a catchment area of 630,000 km^2 (Oliveira *et al*., 2012). The drainage basins of these rivers run through a region dominated mainly by caatinga vegetation (fig. 1; Gatto, 1999)

Narrow and open to sea the NE Brazilian continental shelf is a typical example of passive margin governed by western boundary currents. The North Brazilian Current (NBC), a strong, up to 300 km wide northwestward flow, crosses the equator and represents the major warm water pathway from the southern to the northern hemisphere (Knoppers *et al*., 1999; Stramma and England, 1999; fig. 1). Between 100 and 500 m depth the southern branch of the SEC (SSEC) impinges the Brazilian coast at about 16° S and flows northwards, forming the North Brazilian Under Current (NBUC; Stramma and England, 1999), which raises to the surface at about 5°S and together with the NBC and the equatorial branch of the SEC strengthens the northwestward flow (Stramma and England, 1999).

Material and Methods

The 7 m long gravity-core GeoB3912-1 was recovered at 772 m water depth from the continental shelf off NE Brazil on board RV METEOR (fig. 1). In its uppermost part (top 200 cm) the core consists of yellowish brown foraminiferal nannofossil ooze. Below, alternating sections of olive grey and very dark grey sediment occurs, indicating fluctuations in terrigenous and marine (nannofossil) components. Over the whole core length, and especially the lower part, the sediment is bioturbated (*Fischer*, *et al.*, 1996).

The age model for the core GeoB3912-1 was obtained from 12 radiocarbon AMS ages and correlation with GeoB3104-1 recovered from the same site. For ages older than 40,000 yr oxygen isotopes records were correlated to the SPECMAP curve (for detail see Arz *et al*., 1998).

The magnetic susceptibility was measured at each centimetre using a Bartington M.S.2 F-sensor. We sampled the core in 5 cm intervals using 6.2 cm^3 plastic cubes and obtained Anhysteretic and Isothermal Remanent Magnetizations (ARM and IRM, respectively) and IRM acquisition curves (up to 700 mT) using the automated 2G 755R DC superconducting rock magnetometer. For fields higher than 700 mT we used an external pulse magnetizer (up to 2700 mT). Additionally, ARM/IRM, Hard-IRM (HIRM) and S-Ratio ($0.5 * [1 + (IRM_{300mT} / IRM_{1500mT})]$) were calculated. We applied EM unmixing to 134 IRM acquisition curves aiming to separate the different magnetic contributions according to distinct coercivities (Heslop and Dillon, 2007). The magnetic measurements performed in this work were compared with element concentrations based on X-Ray fluorescence measurements of the bulk-sediment, which was performed by (Arz *et al*., 1998).

Results

The rock magnetic parameters of core GeoB3912-1 show remarkable changes in the ferromagnetic content that were linked with Younger Dryas (YD) and HEs (fig. 2). We defined the timing of the corresponding HSs using the drops in S-Ratio (fig. 3e).

The magnetic susceptibility (MS; fig. 2a) and HIRM (fig. 2f) increase sharply in the beginning of the HSs coinciding with an increase in Fe/Ca (fig. 3d; Arz *et al*., 1998), suggesting an enhancement in terrestrial input. There is an interesting internal feature in almost all HSs: Parameters ARM_{100mT} and ARM/IRM (fig. 2b, c) have a minimum in the beginning of the HSs and than a gradual increase. This can be attributed to a coarsening, followed by a contribution of finer magnetic phases. The IRM_{300mT} exhibits the same behavior and suggests the dominance of magnetite with respect to more coercive phases towards the end of the HSs (fig. 2d). This progressive change in the contribution (*i.e.* magnetic mineral/coercivity) is confirmed also by decrease/ increase in S-Ratio/HIRM during the first phase of HSs suggests the presence of hematite or goethite regarding magnetite.

Discussion

We selected three EMs to unmix the magnetic assembly from core GeoB3912-1. Two EMs (EM1 and EM2) represent the terrigenous fraction carried by Jaguaribe and Piranhas-Açu rivers. Differences between these 2 EMs reflect changes in vegetal coverage/denudation of the soil. A third EM was taken into account considering that a strengthen of NBC/NBUC would influence the transport of sediment from São Francisco River up to the latitude of our core. The IRM acquisition curves for the three EMs suggest a mixture between high- and low- coercivity minerals with different proportions (fig. 3a). EM1 has the most important contribution of high coercivity minerals. The curve is not so steep up to 50 mT and shows subsequently a linear behavior up to about 100 mT, when the low coercive fraction was saturated. The remaining not saturated high coercivity component (about 40% of the magnetization) was attributed to goethite/hematite. The EM2 has the steepest slope in low fields and the remanence is acquired over a narrow field interval,

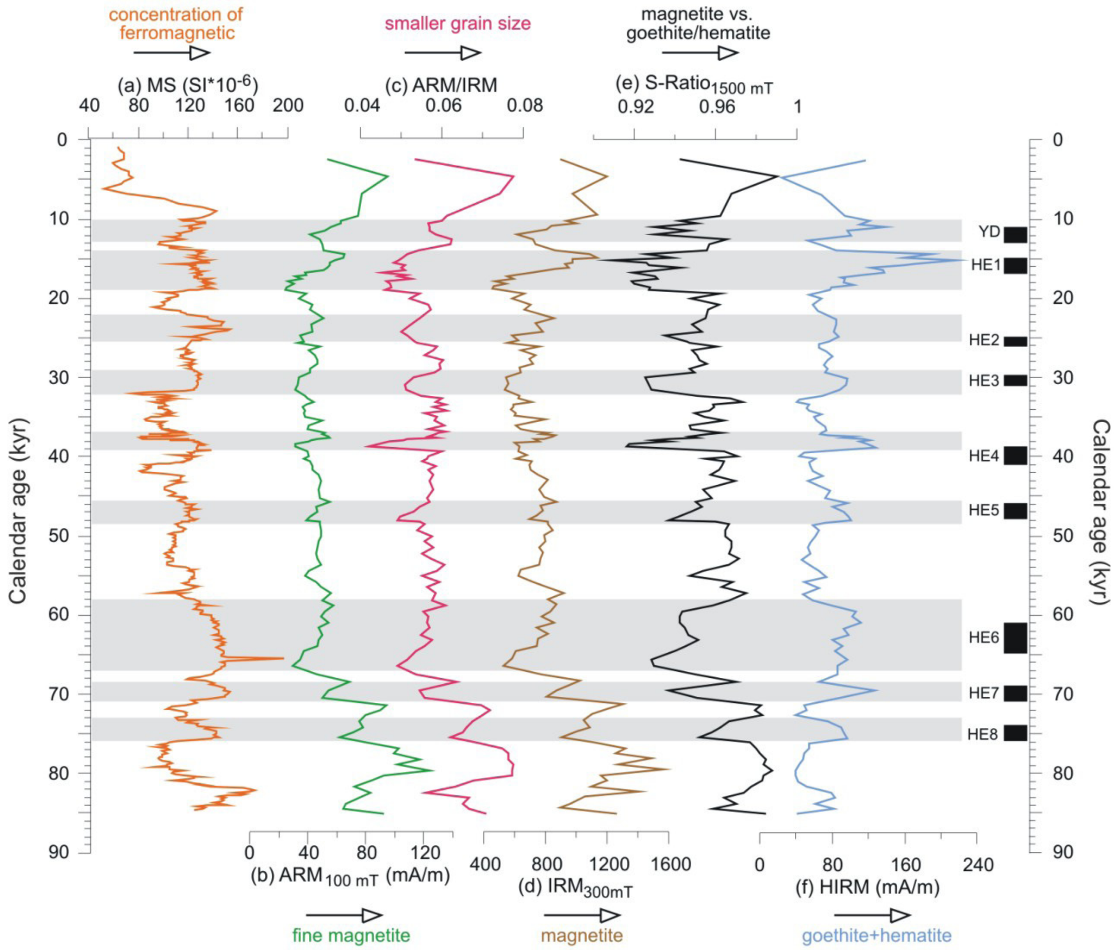

Figure 2. Rock magnetic parameters for core GeoB3912-1. Pulses in magnetic content are highlighted by gray areas, which are synchronous to Heinrich stadials (HS). The timing of such events from literature is displayed by the black rectangles: Younger Dryas (YD, Fairbanks, 1989) and Heinrich Events (HE6 to HE8, McManus *et al*., 1994; HE1 to HE5, Vidal *et al*., 1997).

so that curve is completely saturated at about 100 mT. This low coercivity component represents mainly detrital magnetite. The acquisition of the EM3 starts in low fields (about 20 mT), with the soft phases saturating at about 76 and 130 mT, and a high coercivity phase that was not saturated. The EM3 consists of a mixture between detrital magnetite and goethite/hematite.

Many paleoclimatic and -oceanographic records have shown that weakening of the Atlantic Meridional Overturning Circulation (AMOC) and cold-water discharge in the North Atlantic are linked with southern shift of the ITCZ, inducing wet conditions in NE Brazil (Cruz *et al*., 2009; Paillard, 1994). It is widely accepted that during HSs there is an enhancement in the rainfall over NE Brazil. Some studies shows internal changes in the input of terrestrial material during HS1 and attributed that to the response time of vegetation (Dupont *et al*., 2009; Jennerjahn *et al*., 2004). Similarly as observed for the downcore parameters, the EM unmixing also reveals this internal structure during the HSs. The high coercive EM1 (goethite/hematite) peaks, whereas the EM2 (detrital magnetite) has successive peak when EM1 already decreases (fig. 3b). (Dupont *et al*., 2009) suggested rapid increase in humidity and sparsely vegetated landscapes on the catchment area of the Piranhas-Açu River in the beginning of the HS1, leading to an increased erosion of the soils. In the second phase wetter climate dominated but the vegetation became denser, resulting in

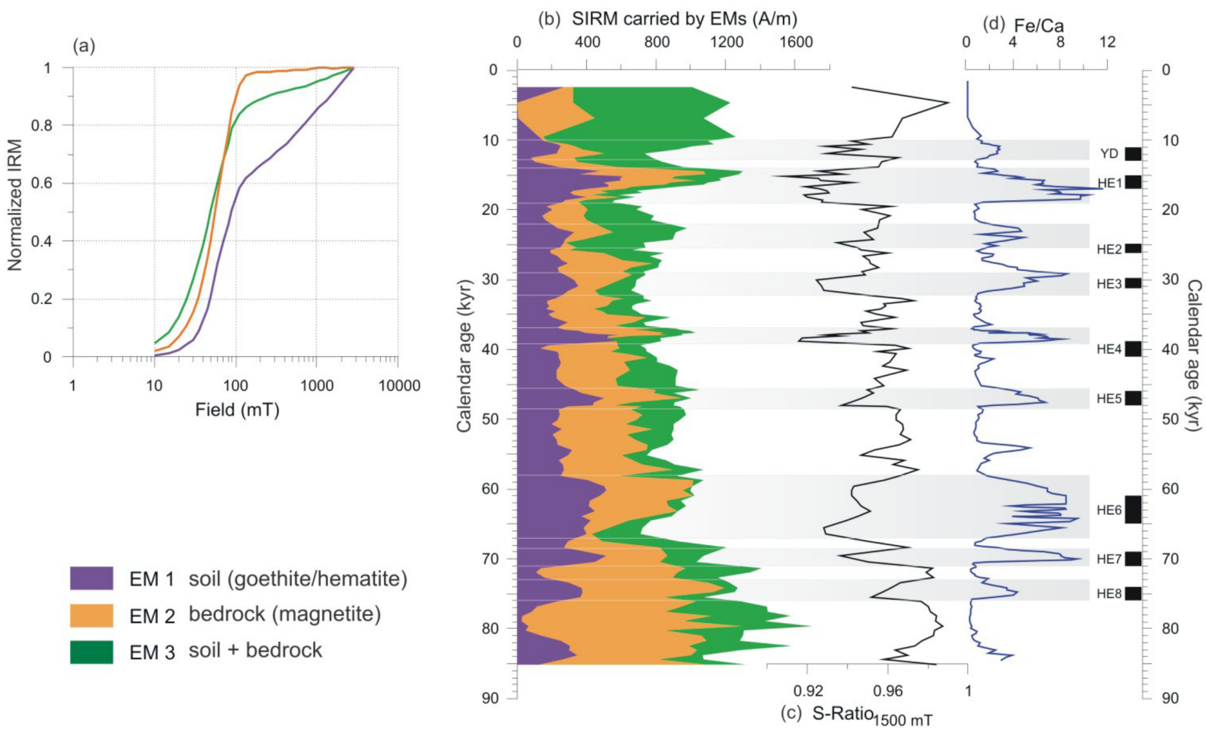

Figure 3. (a) IRM acquisition curves of the end-members, (b) cumulative plot for the down-core contribution of the EMs, (c) Fe/Ti ratio (blue curve) (Arz *et al*., 1998) and (d) S-Ratio (black curve). For the gray areas and black rectangles please see caption of Figure 2.

a stabilization of the soil. According to these findings we suggest that the double-phased pattern observed in our magnetic record during the HSs 2, 3, 4, 5, 7 and 8 reflects the dominance of soil magnetic minerals (hematite/goethite) in the beginning of each event and the prevalence of magnetic phases originated from the bedrocks (magnetite) towards the end. This interpretation is supported by the trends in the S-Ratio and HIRM. The YD and HSs 1 and 6 recorded in this study also show a delay in the peak of EM2 regarding the EM1, but there is a striking difference in the trend regarding the other HSs. EM1, unlike in the abrupt increase during the other HS increases gradually. Moreover the HIRM also exhibits a gradual increase towards the end of HSs 1 and 6 (*i.e*. gradual increment in minerals with high coercivity).

Previous multiproxy analysis performed by (Jennerjahn *et al*., 2004) in the core GeoB3912-1 showed a time lag between the onset of rapid millennial-scale changes and the response of the continental bio- and geospheres. These authors proposed that these delayed response results from the nature of regional climate and hydrological changes affecting the seasonal rainfall pattern. Some works have shown also that changes in the moisture in NE Brazil can be also result of Antarctic cold-front occurrence (Sifeddine *et al*., 2003) or remote forcing of the South America Monsoon which orbitally drives precipitation changes (Cruz *et al*., 2009). (Hall *et al*., 2006) proposed further that changes in the AMOC are not only due cold water surges. This different mode variability of the EMs 1 and 2 during the HEs 1 and 6 demonstrate that cold-water discharge in North Atlantic is not the sole component involved with local rainfall over NE Brazil.

The variation of EM3 is independent from the patterns of EM 1 and 2, which were driven by climatic events (YD and HSs). Regarding that the EM3 is a background signal and does not change according to rainfall variability we suggest that changes in the oceanographic circulation also played a key role for sediment transport over the continental shelf of NE Brazil. The western equatorial Atlantic is dominated by a complex circulation pattern comprised by exchanges of surface and intermediated waters between austral and boreal hemispheres (Knoppers *et al*., 1999; Stramma and England, 1999; fig. 1). Accordingly, the northward flow NBUC can bring terrigenous material from farther south, *e.g*., from the Sao Francisco River. We propose that EM3 represents material from a more distal source.

Further analysis are claimed to better understand the internal changes observed in NE Brazil during the HSs. Continuing this study, magnetic measurements of another core in the same region (GeoB3911-3) is going on. Towards a better understanding of the weathering processes that took place during enhanced rainfall in NE Brazil we are performing XRF scanning on both cores. In addition, trace elements (Al, K, Si, Fe, Ti) measurements from both cores will be helpful in elucidating about the differences between soil contributions from the drainage basin of São Francisco River and the local rivers (Jaguaribe and Piranhas-Açu).

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