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ARTICLE

Evidence of an Marine Isotope Stage 3 transgression at the Baixada Santista, south-eastern Brazilian coast

Evidência de uma transgressão na Baixada Santista durante o Estágio Isotópico 3

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ABSTRACT: In this paper, we present new evidence regarding a Marine Isotope Stage 3 (MIS3) transgression on the south-eastern Brazilian coast (Baixada Santista coastal plain). Data collected from a Standard Penetration Test (SPT) drilling reveal the occurrence of myxohaline sediments between cal BP 45,000 and 41,000. A deeper sequence, which shows a clear transition from terrestrial to a myxohaline environment, was associated with MIS5e. Organic and inorganic proxies have been used to recognize the variations on the terrestrial/myxohaline/marine deposits, as well as to infer about climate and energy of the depositional environment. Environmental change, which could correspond to a sea-level peak or the occurrence of drier conditions, was recognized between 43,000 and 42,000 cal BP. The results reinforce the need for future works on MIS3 variability on the South American Atlantic coast.

KEYWORDS: Marine Isotope Stage 3; Late Pleistocene; sea-level.

RESUMO: *Neste artigo, apresentamos novas evidências sobre a transgressão ocorrida Estágio Isotópico 3 (MIS3) na costa do sudeste do Brasil (Baixada Santista). Dados coletados por meio de um ensaio de penetração em solo (SPT) revelam a ocorrência de sedimentos mixohalinos entre 45.000 e 41.000 anos a.P. Uma sequência mais profunda, que mostra clara transição de ambiente continental para um mixohalino, foi associada ao Estágio Isotópico 5e (MIS5e). Marcadores orgânicos e inorgânicos foram usados para reconhecer as variações dos ambientes terrestre/mixohalino/marinho, bem como inferir sobre o clima e a energia do ambiente deposicional. Uma mudança ambiental, que poderia corresponder a um pico do nível do mar ou à ocorrência de condições mais secas, foi reconhecida entre 43.000 e 42.000 anos a.P. Os resultados reforçam a necessidade de futuros trabalhos sobre a variabilidade do MIS3 na costa atlântica sul-americana.*

PALAVRAS-CHAVE: *MIS3; Pleistoceno superior; nível do mar.*

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INTRODUCTION

The Marine Isotope Stage 3 (MIS3) corresponds to the time interval between 60 and 25 ka (Siddall *et al.* 2008) and is marked by a series of abrupt oscillations, corresponding to in the form of warming periods (Chappell 2002, Van Meerbeeck *et al.* 2009). Estimates based on $\delta^{18}O$ chronologies and U/Th dating of coral reefs indicate that during this time interval sea level oscillated between 80 and 30 m below present sea level (mbsl) (Chappell & Shackleton 1986, Lambeck and Bard 2000, Chappell 2002, Pahnke *et al.* 2003, Rabineau *et al.* 2006). Short-term oscillations in time intervals between 6,000–7,000 years followed by 10–15 m sea-level rise events, corresponding to Heinrich events, occurred in this time interval (Chappell 2002).

On the other side, there are several papers that report the occurrence of MIS3 highstands at levels considerably shallower than those ones reported by the traditional sea level curves (Cann *et al.* 1993, Murray-Wallace *et al.* 1993, Rodriguez *et al.* 2000, Murray-Wallace 2002, Hanebuth *et al.* 2006, Simms *et al.* 2009, Doğan *et al.* 2012).

In South America, other examples of MIS3 highstands have been described both in the Atlantic and Pacific coasts (Isla 1990, Isla & Schnack 2016), but part of these data have been disproved by Schellmann and Radtke (1997), who compared radiocarbon data with Electron Spin Resonance (ESR) information. In the Brazilian coast, Silva *et al.* (2014) recognized a lagoonal environment, dated from 47,000 to 36,000 BP, in the Maricá coastal plain (state of Rio de Janeiro).

Additionally, a complete set of coherent (no age reversal) radiocarbon ages in both organic matter and foraminifera, ranging from 39,000 to about 24,000 BP, marks the transition of myxohaline to freshwater conditions in a shallow-water (6 mbsl) deposit in the São Sebastião Channel (state of São Paulo) (Mahiques *et al.* 2011). Other unpublished (thesis) data, from the Paraná state, also report MIS3 high levels in the shelf and adjacent coastal plain (Souza 2005, Veiga 2005).

The main criticism of the papers dealing with MIS3 highstands is associated with the limitations of the radiocarbon as a geochronological tool. Indeed, a significant part of the MIS3 interval cannot be dated with confidence beyond cal BP 45,000, and contamination of older materials with young carbon can result in apparent MIS3 ages (Murray-Wallace *et al.* 1993, Yim 1999, Hanebuth *et al.* 2006). On the other hand, the introduction of the Accelerator Mass Spectrometry (AMS) technique to radiocarbon dating (Dorn *et al.* 1989) brought another perspective to the original chronology limitation of cal BP 30,000 years. Thus, it is possible that several Pleistocene samples dated in the original studies of the Brazilian coast might need to be reviewed due to the possible occurrence of an MIS3 highstand.

In this paper we analyze a new set of sedimentological and geochemical data, coming from a drilling performed in the Baixada Santista coastal plain (southeast Brazil), with evidence of two transgressive events, one of them with evidence of an MIS3 transgression. Data will be compared with other evidence of an MIS3 sea-level rise, reported in the SW Atlantic as well as in other coastal areas.

STUDY AREA

The study site (Fig. 1) is located in the so-called Baixada Santista coastal plain, an area covered by Late Pleistocene / Holocene coastal and marine muddy to sandy deposits, originally associated with two main transgressive events: Cananeia (MIS 5e) and Santos (Mid-Holocene) (Suguio & Martin 1978b).

Towards the continent the coastal plain is limited by the Serra do Mar mountain range, exhibiting a width, variable from a few to almost 20 km. The Quaternary sediments are locally interrupted by Pre-Cambrian massifs, forming groups of hills that are aligned according to SW-NE (Almeida & Carneiro 1998).

According to Suguio and Martin (1978a), the Cananeia Transgression is associated with a sea level rise that reached about 8 m above present sea level (mapsl), while the Santos Transgression reached 4.5 mapsl. Aspects of the evolution of the deposits were studied by Suguio and Martin (1978a) and Coelho *et al.* (2010). Angulo *et al.* (2006) reviewed the Mid- to Late Holocene sea-level changes and defined an envelope in which the maximum sea-level of 5.6 cal yr BP ranged from 2 to about 4 mapsl.

On the other hand, there is almost no information about the position of the sea-level of the eastern to southern Brazilian between the climatic optimum of the MIS5e and the early Holocene. Corrêa (1996) proposed a sea-level curve between the Last Glacial Maximum and the early Holocene, based on the position of abrasion terraces on the southern Brazilian continental shelf and comparing them with global sea-level curves. Vicalvi *et al.* (1978) recognized a paleo-lagoon at the Abrolhos Depression (Eastern Brazilian shelf), dating them at 10,600 yr BP (uncalibrated). Finally, Mahiques *et al.* (2011), presented four datings on different material from a beach-rock located at 13 mbsl São Sebastião (southeastern Brazil), which gave calibrated ages around 8,200 yr BP.

Suguio and Martin (1978a) provided an interpretative profile of sedimentary deposits in the area (Fig. 2), recognizing continental sediments, marine and sand dunes of Late Pleistocene age, transitional sediments and Holocene lagoonal deposits, in addition to modern alluvium deposits located at the base of the Serra do Mar range.

The lower terrains lead to the establishment of a complex of estuarine channels, bordered by mangrove vegetation. On the other side, the sandy deposits and a significant part of the hills are presently occupied by urban, industrial and port infrastructure, which makes the Baixada Santista one of the most developed areas of Brazil.

METHODS

In this paper, we analyzed a 58.45 m long Standard Penetration Test (SPT) drilling, located at the coordinates 23°57.2512'S and 46°24.6018'W, at the altitude of 8 mbsl (Fig. 1). From the SPT drilling, a cylinder of 15 cm was recovered at each 1 meter. Samples were then air-dried and kept in polyethylene vials until laboratory analysis.

Radiocarbon dating was performed on the organic fraction of sediment samples by the Accelerator Mass Spectrometry (AMS) at Beta Analytic Laboratories (Miami, United States). Calibrated ages have been calculated according to the SH13 Southern Hemisphere Calibration (Hogg *et al.* 2016).

Grain size was performed in a Malvern Mastersizer 2000 laser diffraction system. Approximately 4 g of dry sediment were leached with H_2O_2 until the complete removal of the organic matter. Finally, 20 mL of a solution of 25% sodium hexametaphosphate was added as a dispersant. Results were obtained in intervals of 1/4φ, and statistical parameters were calculated with the aid of the Gradistat macro (Blott & Pye 2001).

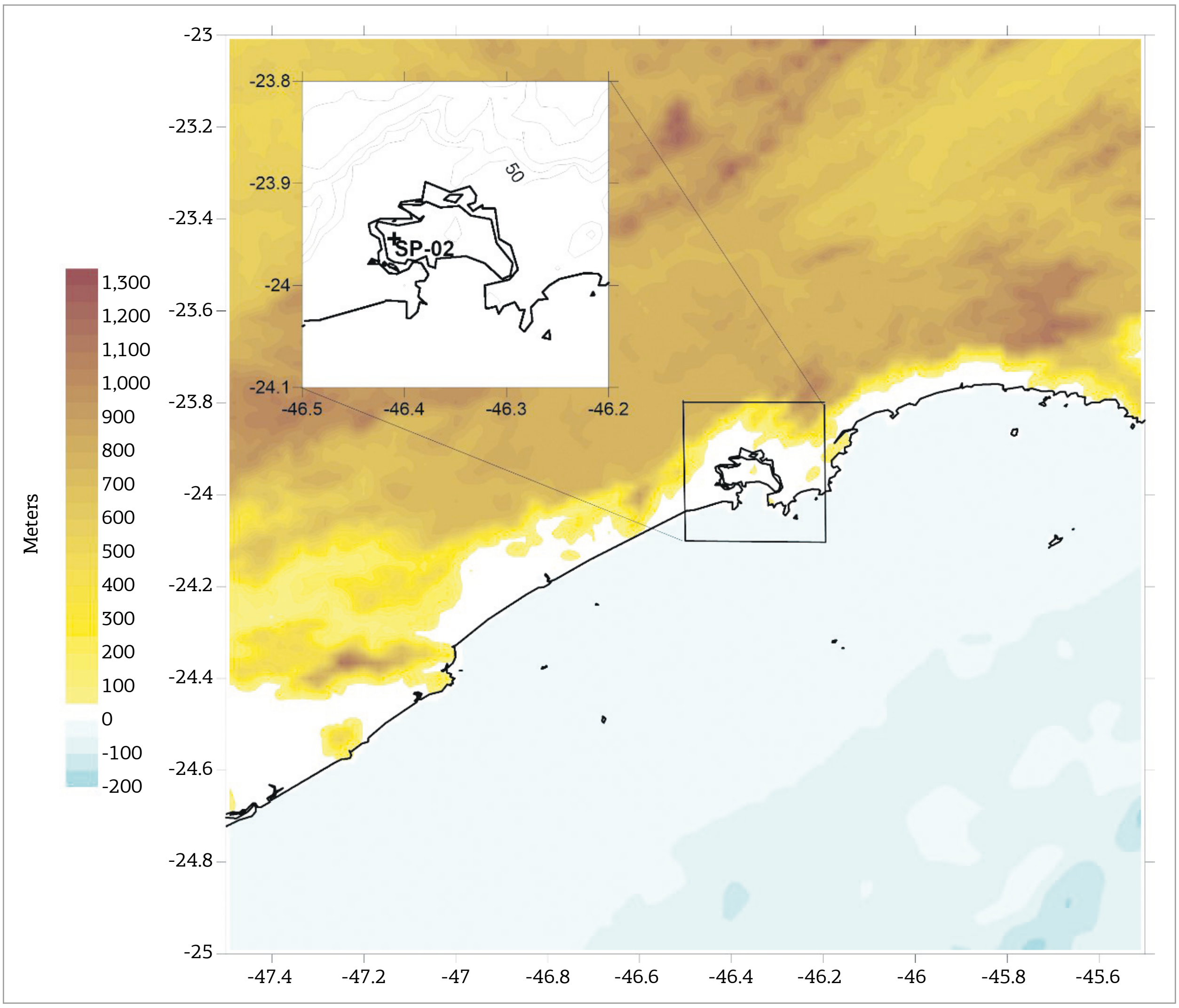

Figure 1. Hypsometric map of the central coast of the State of São Paulo and adjacent continental shelf (data source ETOPO1, NOAA 2016). In detail, the location of the drilling site.

CaCO3 content was determined by the weight difference of the sediments before and after acidification with 10% HCl.

Organic Carbon (C_{org}) and total Nitrogen (N_{tot}), as well as the isotope ratios $\delta^{13}C_{PDB}$ and $\delta^{15}N_{AIR}$, were determined by using a Finnigan Delta V Plus mass spectrometer coupled with a Costech Elemental Analyser. The IAEA 600, USGS40, Leco™ Soil and a secondary marine sediment standard from Ubatuba (SE Brazil) were used as reference materials.

Metals (Al, Ba, Ca, Fe, K, Mg, Sc, Sr, Ti, and V) were analyzed with a Varian 710 ICP-OES, following the procedures of total digestion established in the US Environmental Protection Agency 3052 Method. The methodology for metal determination is fully described in Mahiques *et al.* (2017). Metal/metal ratios in their logarithmic forms have been used to help the interpretation of the marine/terrestrial character, source rock and climate (Govin *et al.* 2012, Razik *et al.* 2015, Mahiques *et al.* 2017).

Values of $d^{13}C_{PDB}$, N/C and ln(Ti/Ca) (Govin *et al.* 2012), have been used to evaluate the marine *versus* terrestrial contribution. The values of ln(Fe/K) (Govin *et al.* 2012) have been used as a proxy of weathering of source rocks. The values of ln(Ti/Al) have been used as proxies of changes in energy of the environment (Govin *et al.* 2012, Chen *et al.* 2013).

For both inorganic and bulk organic contents, we present only the results that reached values higher than the Limit of Quantification (LQ), defined as five times the Limit of Detection (LD) for each parameter.

For grain size data, a Correspondence Factor Analysis, with the aid of the software Past version 3.15 (Hammer *et al.* 2001) was performed. For the metal content, an R-mode cluster analysis, using the Correlation matrix and Unweighted Pair Group Method with Arithmetic (UPGMA) clustering technique was used.

All of the altitude/depth results are reported in meters relative to the present sea level, and samples are named according to their position (*i.e.*, sample -12 refers to a sample collected at 12 mbsl).

RESULTS AND DISCUSSION

All of the results are presented as Supplementary Material of this paper.

A field macroscopic description is presented in Figure 3A.

Concerning chronology, a sample, located at 40 mbsl, provided an age beyond the limit of the radiocarbon dating (MIS5e?). The $\delta^{13}C_{PDB}$ of this sample (-29.6‰) indicates a terrestrial organic matter. Another sample, located at 19 mbsl, was dated at Cal BP 44,890 (2s: 45,580–44,200) (MIS3) and provided a $\delta^{13}C_{PDB}$ value of -24.4‰, indicative of a mixture of marine and terrestrial organic matter. Finally, a third sample, collected at 7 mbsl, provided a cal age of 40,950 (2s: 41,530–40,300) (MIS3) and a $\delta^{13}C_{PDB}$ value of -24.5‰, also indicative of mixed organic matter.

SPT values (Fig. 3B) vary significantly along the drilling. Higher values correspond to its base, which has been described as weathered rock. The lowest values of SPT correspond to the interval between 12 and 18 mbsl.

Values of mean diameter (Fig. 3C) are roughly correlated with values of SPT (R = -0.26, p = 0.04), with variations between 1.93 φ (medium sand) to 5.39 φ (medium silt). Sorting varies from very poor sorted, at the base, to well sorted, associated with fine and very fine sands (see Supplementary Material, Tab. 1).

The lack of an expected high correlation between Mean Diameter with SPT should be associated to the increasing compaction of the sediments, towards deeper strata.

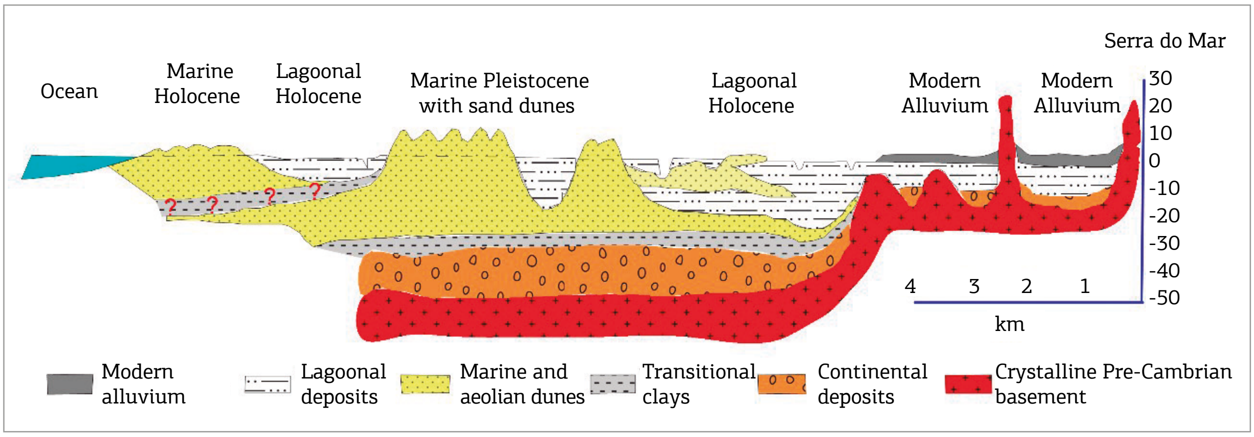

Figure 2. Schematic geological transect of the Baixada Santista coastal plain, with the main geological units. Adapted from Suguio and Martin (1978b).

The $CaCO_3$ contents are always low, varying from less than 0.5% to about 9.4%. This parameter correlates significantly with both SPT (R = -0.49, p = 0.00) and Mean Diameter (R = 0.76, p = 0.00).

The Correspondence Factor Analysis (Fig. 4) allowed recognizing four main types of grain size distributions. The first one is represented by a poorly sorted coarse to medium silt, platykurtic and positively skewed distribution, represented by sample -40. It corresponds to the muddy sequences dated as MIS3 and beyond the limit of radiocarbon dating (MIS5e?).

The second group, represented by sample -3, has a bimodal distribution. The main mode is centered at 3 φ, with a leptokurtic symmetric distribution. The secondary mode is centered at 5.75 φ and shows a much lesser expression. It expresses the sandy sediments associated to the MIS3 muds.

The third group is expressed by sample 1. It corresponds to a leptokurtic symmetric distribution, centered at 2 φ, and represents the topmost sediments of the drilling.

Finally, the fourth group, expressed by sample -34, consists of a strongly asymmetric distribution, meso- to platykurtic, with the main mode at 1.75 φ, and progressively small amounts of silts and clay. This group is mainly related with the sandy sediments associated with the MIS5e muds.

Concerning the proxies of sediment provenance and energy (Figs. 5A to 5F), there is a clear evidence of a terrestrial environment in samples -39 and -40, both in organic (Figs. 5A and 5B) and inorganic (Fig. 5C) parameters.

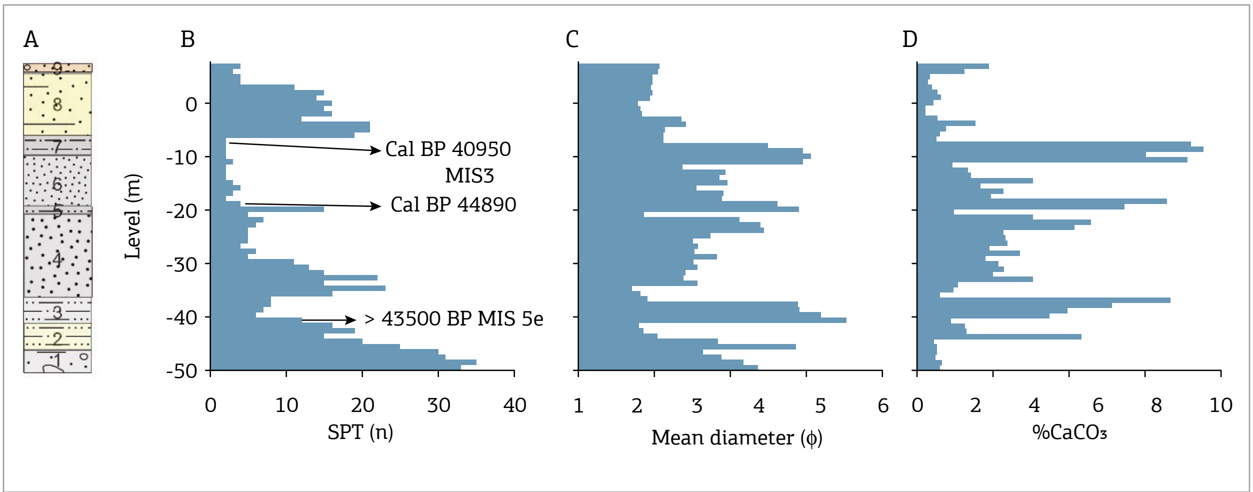

Figure 3. (A) General macroscopic description: (1) Variegated light grey to yellow micaceous sandy-clayey silt, with rock fragments; (2) Variegated micaceous yellow to grey sandy-clayey silt; (3) Variegated grey sandy-clayey silt; (4) Grey fine to coarse sand, with silt; (5) Dark grey sandy-clayey silt; (6) Dark grey silty fine sand; (7) Dark grey sandy-clayey silt; (8) Yellowish grey fine to medium sand, with silt; (9) Landfill; (B) Standard Penetration Test (SPT) values; (C) Grain size diameter; (D) Content in $CaCO_3$ of the drilling.

Table 1. Radiocarbon datings of the samples collected in the drilling

Beta	Submitter no	Corrected level (m)	(Material): pretreatment	$\delta^{13}C$ ‰PDB	Conventional age	Median probability and (2 sigma calibration)	Percent Modern Carbon (pMC)	Fraction Modern	Δ14C
455953	SP02_15	-7	(organic sediment): acid washes	-24.5	36,350 ± 280 BP	cal BP 40,950 (cal BP 41,530-40,300)	1.1 ± 0.0 pMC	0.0108 ± 0.0004	-989.2 +/- 0.4 ‰
444760	SP02_27	-19	(organic sediment): acid washes	-24.4	41,480 ± 370 BP	Cal BP 44,890 (cal BP 45,580-4,4200)	0.6 ± 0.1 pMC	0.0057 ± 0.0003	-994.3 +/- 0.3 ‰
444761	SP02_48	-40	(organic sediment): acid washes	-29.6	> 43,500 BP		< 0.4 pMC	< 0.0044	< -995.6 ‰

This condition changed in the sample -38, and myxohaline sediments are recognized in all of the analyzed samples. A single sample (-14) shows an indication of an inner shelf environment, presenting the more positive values of both $\delta^{13}C$ and N/C.

The variations of ln(Fe/K) indicate oscillations in the input of illite or kaolinite to the depositional environment and can be used as proxies for changes in local and regional weathering (Ziegler *et al.* 2013, Nace *et al.* 2014, Simon *et al.* 2015). A higher level in K is found in samples -12 and -13 (Fig. 5D).

Ti/Al ratios are used as indicators of energy variations due to changes in hydraulic equivalence of these elements (Schmitz 1987, Chen *et al.* 2013). As a rule, except few samples, located in the basal layers, most of the sediments deposited reveal conditions of low energy (Fig. 5E).

The cluster analysis of the distribution of metals (Fig. 6) reveals the existence of two main groups, which can be associated to the dominant mineralogy. The first group involves K, Ba, Sc, Al, Mg, and Sr, and can be associated with the dominance of clay minerals. The second group encompasses Fe, Ti, Cr, V, Mn, Cu, Ni and Zn, and corresponds to the elements associated with oxides. Calcium remains isolated since it presents an exclusive biogenic origin. Based on this differentiation, a Metal Ratio (MR) was applied (Fig. 5F)(Eq. 1):

$$MR = \frac{\Sigma(K+Ma+Sc+Al+Mg+Sr)}{\Sigma(Fe+Ti+Cr+V+Mn+Cu+Ni+Zn)} \quad (1)$$

The distribution of the MR along the sedimentary sequence shows a distinct pattern when comparing to the two muddy sequences (Fig. 5F). The basal sequence is richer in metals associated oxides, such as Fe and Ti. On the other hand, elements characteristics of clay minerals (silicates), such as Al, K, and Sc, are more conspicuous in the intermediate muddy sequence. Worth to note that the "oxide-like" sediments correspond to the terrestrial facies, while the "silicate-like" sediments are associated with the myxohaline environment. It points to the possibility of distinct source rocks or climatic conditions between MIS5e and MIS3.

In their interpretation of the stratigraphy of the Santos coastal plain, Suguio and Martin (1978a) recognize the

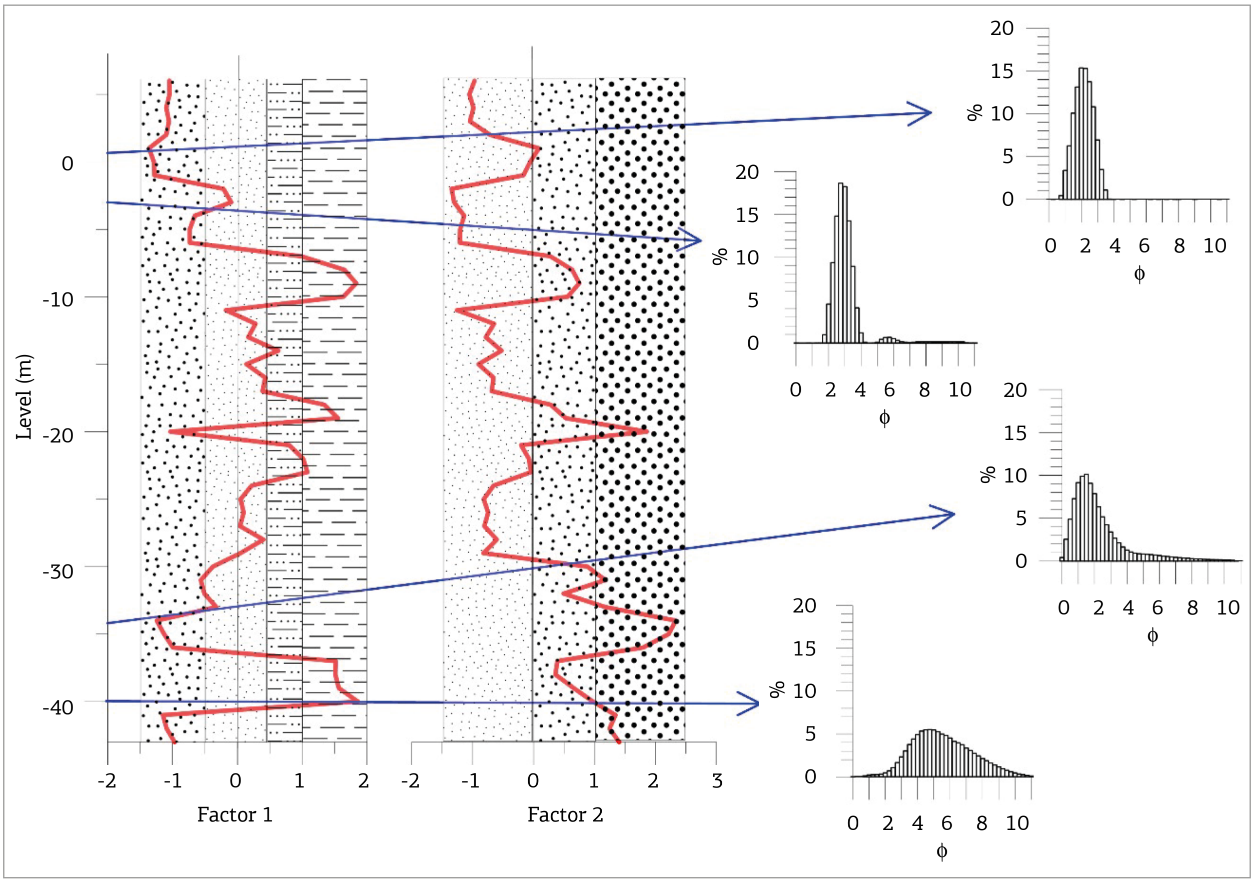

Figure 4. Vertical variations of factors 1 (53.0% of explained variance) and 2 (34.2% of explained variance) of the grain size data. Extreme grain size distributions are also shown as histograms.

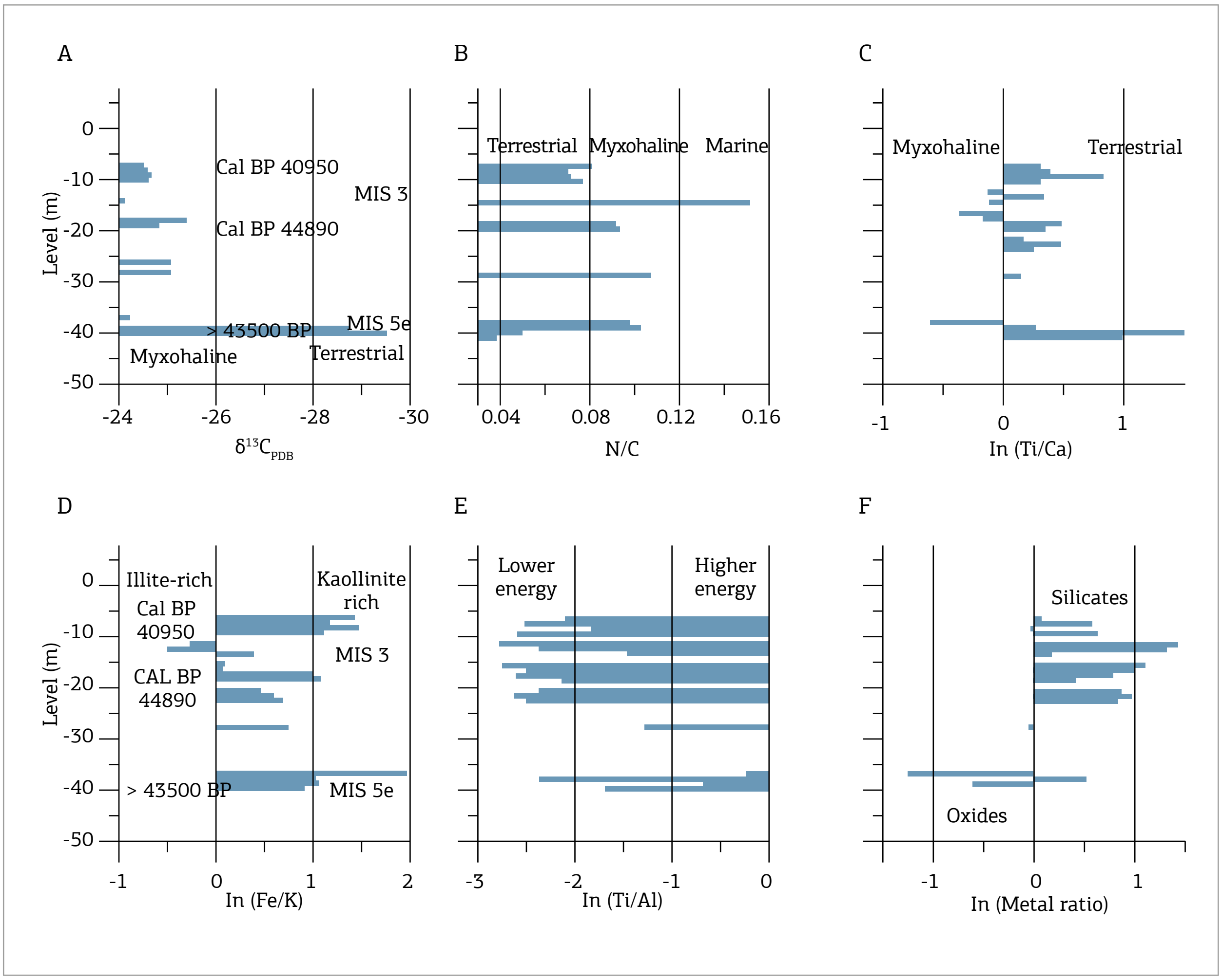

Figure 5. Variations in (A) d^{13}C; (B) N/C ratio; (C) ln(Ti/Ca) along the drilling; (D) ln(Fe/K); (E) ln(Ti/Al); (F) ln(Metal ratio) along the drilling.

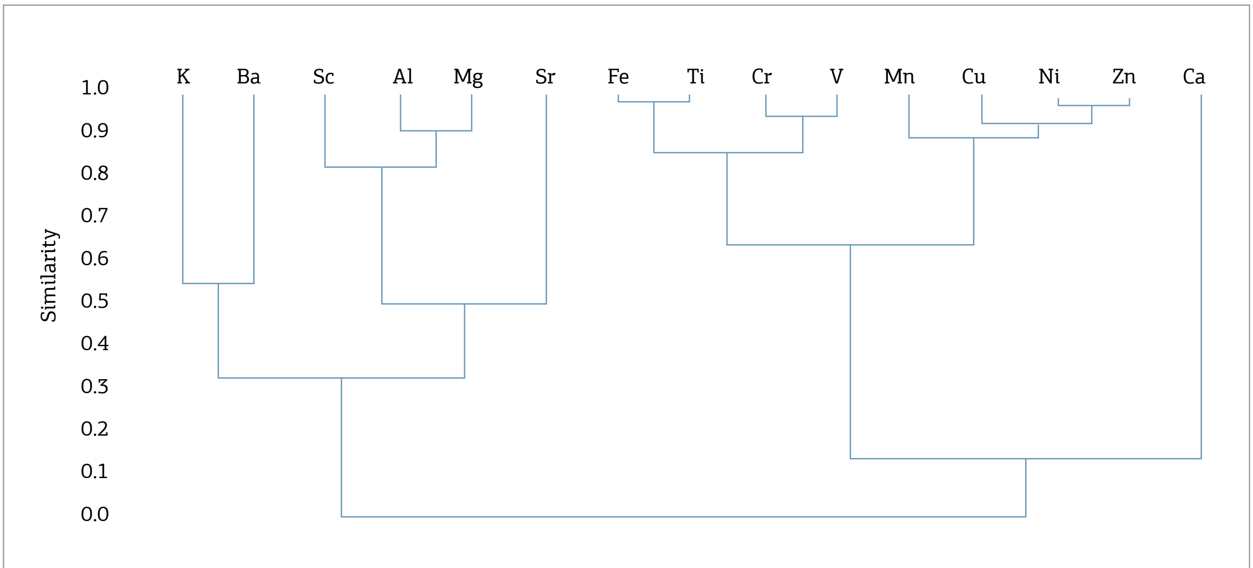

Figure 6. R-mode cluster analysis (Correlation Coefficient, UPGMA clustering) of the metals analysed in this work.

existence of transitional clays on top of the Late Pleistocene sediments and below the Holocene deposits (layer marked with question marks in Fig. 2), located at depths varying from 5 to 20 mbsl. These deposits apparently occupy the distal areas of the plain, in a position that could be associated with the location of the SPT drilling. Therefore, even without recognizing the possibility of an MIS3 transgression, the authors pointed to the occurrence of myxohaline sediments positioned between the MIS5e and Holocene deposits.

In the drilling analyzed here, sediments from the MIS5e lie down directly over weathered rocks of the crystalline basement. The basal sequence corresponds to terrestrial sediments that give place to myxohaline muds, whose age is beyond the limit of the radiocarbon method. Therefore, a fine to very fine sand sequence is deposited, corresponding to the regressive sediments deposited under low sea level. A second muddy layer yielded ages between cal BP 45,000 and 40,000 (MIS3), and all sedimentological and geochemical characteristics point to a myxohaline environment. Between cal BP 43,000 and 42,000 a change in environmental conditions, as indicated by the ln(Fe/K) as well as the higher values of $\delta^{13}C$ and N/C ratios, points to a rise in the sea level or to a climatic change, which led to a decrease terrigenous sediment input from the adjacent continental area.

The occurrence of transgressive deposits, associated with the MIS3, at positions above the predicted by the oxygen isotope curves (Chappell & Shackleton 1986), is reported in several coastal areas. Rodriguez *et al.* (2000) identified a 15 mbsl deposit, associated with MIS3, on the Texas continental shelf. Also in the United States, Doar III and Kendall (2017) reported MIS3 ages for the 3 mabsl of the Silver Bluff formation, in South Carolina.

In Turkey, a shoreline located at 39–40 mbsl has been dated at 53,000 yr BP, but, in this case, a strong tectonic component cannot be discarded, since the area is located between the African-Arabian and Eurasian plates (Doğan *et al.* 2012).

In Southeast Asia, coastal deposits, dated between 40,000 and 49,000 yr BP, located around 20 mbsl, also indicate the occurrence of a possible transgressive event during MIS3 (Zhao *et al.* 2008). A differential tectonic regime was proposed to explain the occurrence of shallow MIS3 deposits in the Changjiang Delta (China). Nevertheless, the MIS3 deposits would remain at depths of about 10 mbsl if the effect of tectonic is removed (Zhao *et al.* 2008).

Also in Southeast Asia, Hanebuth *et al.* (2006) recognized the possibility of occurrence of an MIS3 highstand in the region of the River Delta, Vietnam.

In Southeast Brazil, the papers by Mahiques *et al.* (2011) and Silva *et al.* (2014) are the first published references that point to the occurrence of MIS3 transgression, represented by myxohaline/lagoonal deposits, located close to the present sea-level.

Close to the area of study, Mahiques *et al.* (2011) describes a full transition from myxohaline to terrestrial environments, based on radiocarbon datings of foraminifera and organic matter, from ca 39,000 to 24,000 yr BP in a core collected in the São Sebastião Channel, state of São Paulo.

Silva *et al.* (2014) describe the formation of a sandy barrier, dated on 45,000 yr BP, deposited over lagoonal sediments, presenting ages from 48,000 and 45,000 yr BP, at Maricá region, Rio de Janeiro.

When gathering the information obtained by Mahiques *et al.* (2011), Silva *et al.* (2014) and this work, a picture emerges (Fig. 7). It does not correspond to a sea-level curve for the period between cal BP 50,000 and 40,000, but to the position, relative to present sea level, of myxohaline environments, suggesting a trend of sea-level rise in the period. It is important to note that other geological events, such as Late Quaternary crustal movements (Riccomini *et al.* 1989, Riccomini & Assumpção 1999, Walker *et al.* 2016), should be considered in the case of an evaluation of the sea-level curves for the region.

Our findings are in agreement with the conclusions of short-term climatic oscillations which occurred in the first half of the MIS3 (Siddall *et al.* 2008, Frigola *et al.* 2012). The transgression here reported can be associated with a sea-level rise phase recorded between events Heinrich HE4 and HE5 (Arz *et al.* 2007, González & Dupont 2009).

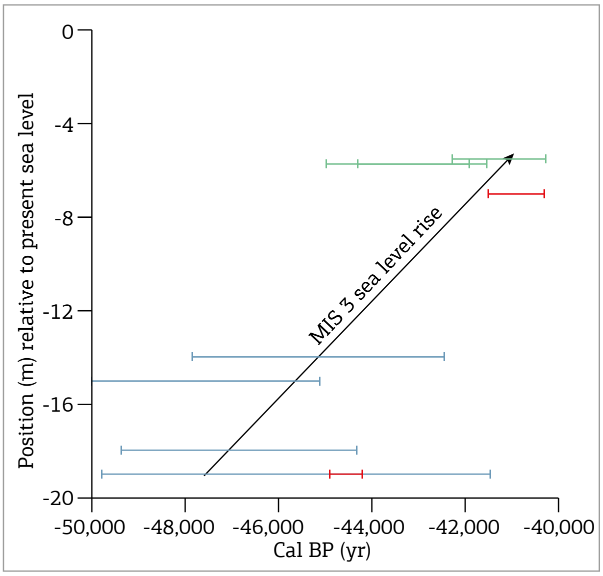

Figure 7. Scatter plot of datings of myxohaline sediments along depths. Data source are Mahiques *et al.* (2011) (green); Silva *et al.* (2014) (blue); and this work (red).

CONCLUSIONS

Radiocarbon ages, as well as organic and inorganic proxies, have been used to discriminate the MIS3 transgression of the Baixada Santista (SE Brazil) coastal plain, from an older (MIS5e) transgressive event.

The data indicate that, between cal BP 45,600 and 40,300, a myxohaline environment developed at levels between 7 and 19 m below the present sea level. Also, geochemical proxies suggest a marine transgression (or a climatic change) between cal BP 43,000 and 42,000.

Different metal ratios between the two muddy sequences point to distinct characteristics of the terrestrial *versus* myxohaline environments, associated with source rocks or climatic conditions.

Previous works, performed on the northern coast of the state of São Paulo as well as on the Rio de Janeiro coastal region (southeast Brazil), corroborate our results and point to the need for a revision of the Late Quaternary sea-level curves in the SW Atlantic coast, as well as of the southeastern Brazilian coastal plains.

Our findings agree with one of the short-term climatic oscillations that occurred in the first half of MIS3.

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