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Modern sedimentation in the Cabo Frio upwelling system, Southeastern Brazilian shelf

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ABSTRACT

The analyses of $U^{k'}_{37}$ paleotemperatures and sedimentological parameters in box cores from the Cabo Frio upwelling zone, southeastern Brazil, were used to understand the modern sedimentation as well as to evaluate the role played by the upwelling process in the sedimentary patterns.

Three box-cores located closer to the upwelling area show a general trend of cooling waters taking place in the last 700 years. Since the present upwelling is dependent on local and remote wind regime, a phase of dominating NE winds favors a more effective upward transport of the cold thermocline level South Atlantic Central Water towards the coast. The intensification in the upwelling regime for the last ca. 700 years can be associated with the strengthening of the NE winds off the area and a possible increase of the Brazil Current mesoscale activity.

Nevertheless, the lack of significant correlation of the paleotemperatures and most of sedimentological parameters indicate that upwelling is not the only sedimentation mechanism in the area. Also, the comparison of sedimentological parameters reveals that eventual temporal changes are superimposed by the geographical variability. Sedimentation rates vary from 0.26 mm.yr^{-1} to 0.66 mm.yr^{-1}.

Key words: sedimentation, alkenones, bulk organic matter, upwelling, Brazil, South Atlantic.

INTRODUCTION

Upwelling zones and other high sedimentation rate regions are considered key areas for the comprehension of Quaternary climatic changes. Because of this, the eastern South Atlantic tropical and subtropical margins have been studied much more than its western counterparts (Cohen and Tyson 1995, Ternois et al. 2000, DeMenocal et al. 2000, Sicre et al. 2001). The western tropical South Atlantic margin is characterized by the oligotrophic waters of the Brazil Current (BC) and the North Brazil Current (NBC), as well as by a relative scarcity of fluvial terrigenous input, leading to a general scenario of very low sedimentation rates.

The Cabo Frio upwelling zone seems to be one of the exceptions to this pattern. Descriptive studies of this coastal upwelling process have been reported in the literature since the South Atlantic Meteor Expedition, during the 1920s (Böhnecke 1936, Emilsson 1959, 1961, Silva and Rodrigues 1966, Ikeda et al. 1974, Miranda and Castro 1979). More recent studies have approached the dynamics of the

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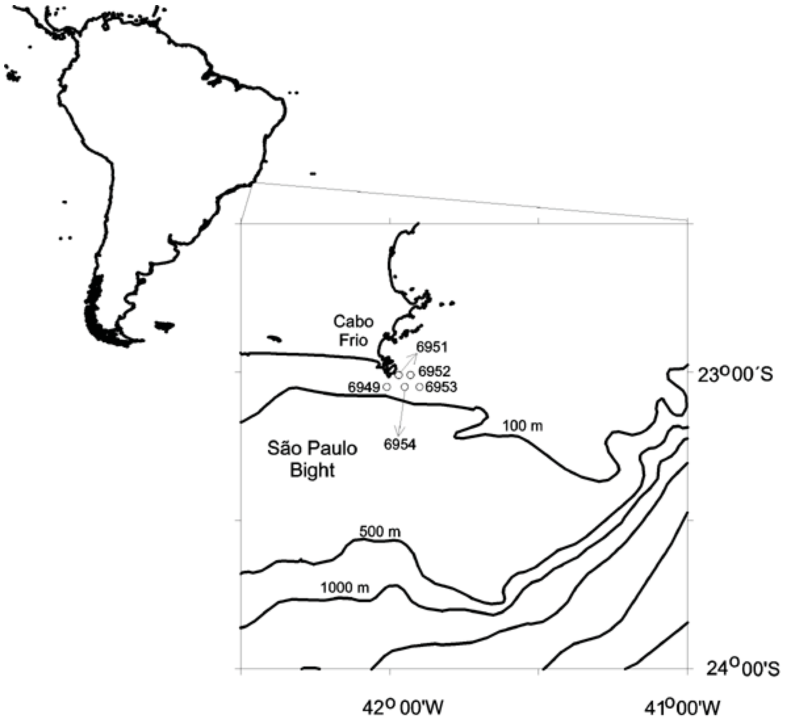

Fig. 1 – Location of the study area.

upwelling process and did not deal only with the Ekman wind-driven phenomenon but also with the supporting role played by the BC meandering (Lorenzzetti and Gaeta 1996, Castro and Miranda 1998, Campos et al. 2000). The consequences of the coastal upwelling in the local primary productivity have also been investigated (Valentin 1984a,b).

The aim of this paper is to understand the modern sedimentation in the Cabo Frio upwelling area as well as to evaluate the role played by the upwelling process in the sedimentary patterns. Also, the analysis of the shallow sedimentary column has been used to evaluate the occurrence of changes in the upwelling process during the last centuries.

STUDY AREA

The Cabo Frio region represents a conspicuous break in coastline orientation in the South American shoreline and marks the limit between two distinct oceanographic, physiographic and sedimentary provinces of the southwestern Atlantic Margin (Figure 1).

North of Cabo Frio, the continental margin is narrow with a dominating north-south orientation and predominant carbonate sedimentation, with few rivers to account for the local terrigenous supply. The warm and salty Tropical Water (TW) transported by the BC at surface levels is what maintains the carbonate production and preservation. South of Cabo Frio, the margin is wide and characterized by an arc-shaped feature known as the São Paulo Bight (Zembruscki 1979) and sedimentation is mainly terrigenous. Wind-driven circulation acting on the inner portions of the shelf and the BC meandering on the outer shelf are the most important hydrodynamic factors that determine the sedimentation in the area (Mahiques et al. 2002).

THE PRESENT CABO FRIO COASTAL UPWELLING DOWNWELLING PROCESS

The modern coastal upwelling-downwelling process is presented in the literature as a quasi-seasonal phenomenon. The coastline orientation change around 23°S aligns the Cabo Frio margin to the direction

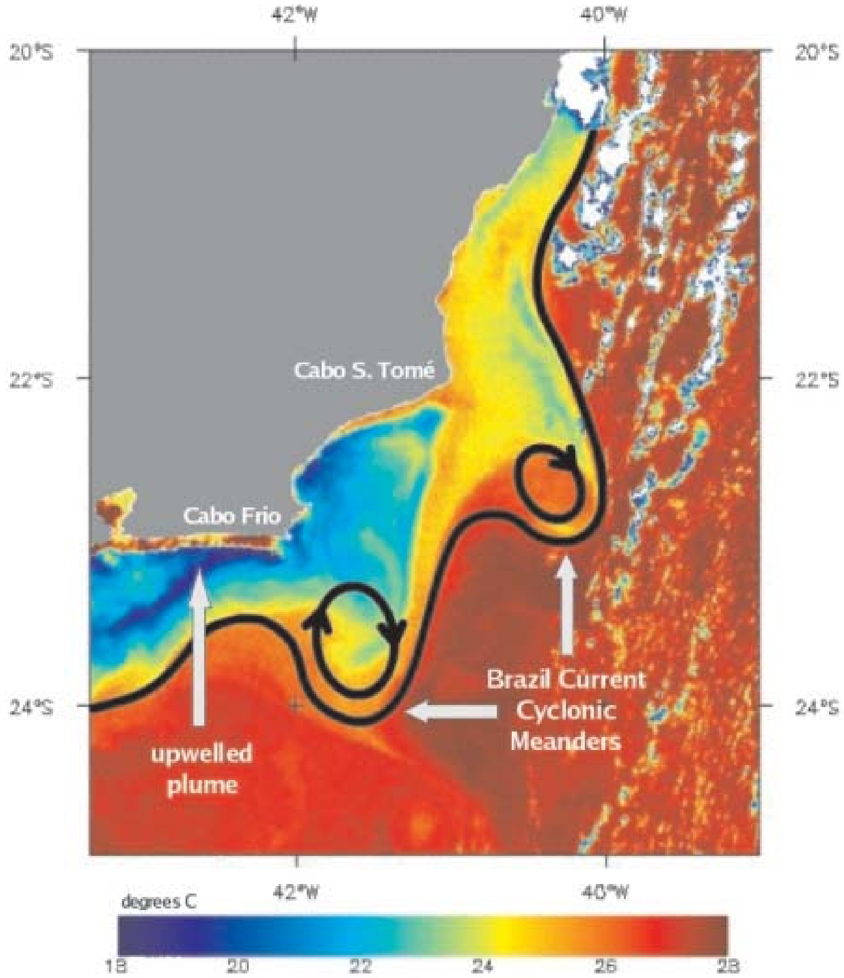

Fig. 2 – AVHRR image showing the coastal upwelling system off Cabo Frio and the Brazil Current meandering. Image provided by J.A. Lorenzzetti (INPE, Brazil).

of the dominant NE trade winds during the austral summer season. According to Ekman dynamics, the combination of these factors yields Coastal Water (CW) to be displaced oceanward as well as TW to be prevented from penetrating the shelf. Consequently, the cold waters of the South Atlantic Central Water (SACW), which occupy the thermocline region of the water column in the open ocean area, enter the inner shelf close to the ocean bottom, and eventually upwell to surface near the coast. The more constant in direction the wind is in time, the more effective and intense is the phenomenon. As sea level lowers near the coast and thermocline rises as response to CW offshore motion, the generated pressure gradient drives a geostrophically balanced alongshore-coastal current that carries the upwelled waters toward southern portions of the São Paulo Bight. Its signature is easily depicted in AVHRR images (Figure 2).

The downwelling phase is associated to the passage of cold fronts through the area, most common during the austral winter season. The wind then reverses from NE to SW. The surface Ekman transport is toward the coast and composed of TW and the oceanic thermocline retracts toward the open ocean.

A recent experiment by Silveira et al. (2002) that consisted of a daily sampling of a hydrographic transect normal to the Cabo Frio Island, allowed a more precise description of both coastal upwelling and downwelling phases. During the austral summer of 2001, the authors identified upwelling of 13°C–14°C isotherms at a vertical speed ranging from 2.8 to 3.2 × 10^{-4} m s^{-1}. During the austral winter of 2001, the quasi-synoptic temperature and salinity distribution time series captured two events of displacement of TW domes toward the coast. They were characterized by a subsurface maximum temperature core exceeding 20°C, and a corresponding salinity core higher than 37. These domes represented the signature of the downwelling and were linked to a cold front motion into the area.

As both phases are linked to the inshore-offshore motion of oceanic water masses transported by the BC (i.e., TW and SACW), Campos et al. (2000) raised the hypothesis of the current cyclonic meandering enhancing the coastal upwelling. The cold core of these meanders would raise the thermocline near the slope and facilitate the penetration of SACW. As exemplified in Figure 2, there seems to be a strong link between well-developed cyclonic meanders in the area and a more robust upwelling process under favorable wind conditions.

MATERIALS AND METHODS

Sampling

Five box cores were collected during two cruises of the R.V. Prof. W. Besnard (Figure 1, Table I). The cores were sub-sampled continuously at intervals of 2 cm and the sub-samples were immediately frozen and later freeze-dried.

Radiocarbon Dating and Age Model

Due to the lack of sufficient well-preserved carbonate material it was decided to use the organic fraction of the sediment for AMS ^{14}C dating. Calibrated ages were obtained with the Calib Software (Stuiver et al. 1998), using the SW Atlantic average reservoir correction for marine samples (Δ = 82.00, U = 46.00).

The age model and the average sedimentation rates were established with the aid of the DepAge software, developed by Louis Maher Jr., from the USGS. Calibrated ages (in yr. B.P.), and sedimentation rates (in mm. yr^{-1}) are presented in Table I.

Alkenone Analysis

About 15 g of freeze-dried sediment samples were extracted in an ultrasonic bath using successively 15 ml of ethanol, 10 ml of ethanol: methylene chloride (1:1) and 10 ml of n-hexane. The extracts were treated with 3 ml 6% potassium hydroxide in ethanol for the elimination of wax ester interferences. Compounds were recovered in n-hexane and the extract was submitted to an adsorption chromatographic column with 2 g of a 95% activated silica gel and eluted with 12 ml of a mixture of n-hexane: methylene chloride (8:2). This fraction was concentrated to 250 μl and injected in a gas chromatograph (GC).

The analyses were performed with an Agilent GC model 6890 equipped with an on-column injector, a flame ionization detector and an Ultra-2 capillary fused silica column coated with 5% diphenyl/dimethylsiloxane, 0.32 of internal diameter, film thickness of 0.17 μm. Hydrogen was used as carrier gas. The oven temperature was programmed from 40°C, holding for 2 minutes, 40-60°C at 20°C/min, then to 250°C at 5°C/min, and finally to 320°C at 6°C/min holding for 20 minutes.

The identification of the alkenones was based on the retention time obtained from a standard mixture. The quantification was made using n-hexatriacontane as internal standard. The QA/QC was made analyzing sediment samples provided by the Autonomous University of Barcelona (Spain) for an intercomparison exercise for alkenone analysis. Our results were compared to the published data from Rosell-Melé et al. (2001) and were within the range proposed.

Alkenone-based water temperature ($U^{k'}_{37}$) was calculated according the equation proposed by Müller et al. (1998) for the global ocean from 60°N to 60°S and confirmed by Benthien and Müller (2000) for the surface sediments of the SW Atlantic.

TABLE I

Location, radiocarbon ages and average and sedimentation rates of the box-cores.

Sample	Latitude	Longitude	Sampling depth (cm)	Beta No.	Conventional 14C Age (yr B.P.)	Error	Calibrated 14C Age (yr B.P.)	Avg. Sed. Rate (mm/yr)
6949	23°03.0'S	042°00.6'W	04-06	165998	630	40	230	
6949			12-14	165999	880	40	450	0.51
6949			24-26	166000	1130	40	630	
6951	23°00.6'S	041°58.2'W	04-06	166004	550	40	60	
6951			06-08	166978	570	40	100	0.26
6951			12-14	179047	1050	40	540	
6951			20-22	179048	1220	40	670	
6952	23°00.6'S	041°55.8'W	04-06	166007	590	40	130	
6952			08-10	179049	810	40	380	0.38
6952			22-24	179050	1180	50	650	
6953	23°03.0'S	041°54.0'W	04-06	166979	690	40	270	
6953			12-14	166980	760	40	300	0.57
6953			26-27	166010	1130	40	630	
6954	23°03.0'S	041°57.0'W	04-06	166981	670	40	260	
6954			12-14	166982	790	40	320	0.66
6954			28-30	166011	1100	40	610	

Grain-size and Calcium Carbonate Content Analyses

Grain size was determined with a Malvern 2000 Laser Analyzer. Calcium carbonate was determined by weight difference prior to and after the acidification of each sample with 1N HCl.

Bulk Organic Matter Analyses

Organic carbon, total nitrogen, and total sulfur were determined with a LECO CNS200 Analyzer after the total elimination of the calcium carbonate of the samples with 1N HCl.

$\delta^{13}C$ (reported in ‰ PDB) and $\delta^{15}N$ (reported in ‰ Air) analyses were performed with a VG-SIRA 10 Mass Spectrometer at the Coastal Science Laboratories (Austin, TX, USA).

Statistical Procedures

Due to the small number of samples for each box-core we applied a non-parametric Kendall-τ for identification of correlation among the parameters. For the comparison among the cores we have used the non-parametric Friedman Analysis of Variance. Significant values were considered for $\alpha \Leftarrow 0.100$.

RESULTS AND DISCUSSION

The variations of sedimentological and geochemical parameters along box cores are shown in Figures 3 to 7. Results from coretops in the upwelling zone show values of organic carbon ranging from 0.76 to 1.73%, total nitrogen varies from 0.06 to 0.19%, $\delta^{13}C$ ranges from –20.90 to –21.30‰, and $\delta^{15}N$ from 6.60 to 6.90‰.

Sedimentation rates varied from 0.26 mm.yr^{-1} obtained for core 6951 to 0.66 mm.yr^{-1} obtained for core 6954. Cores 6949, 6952, and 6953 exhibit sedimentation rates of 0.38, 0.51, and 0.57 mm.yr^{-1}, respectively (Table I).

In box-cores 6949, 6951, and 6954, located closer to the upwelling zone a statistically significant trend of upward decreasing values of sea-surface

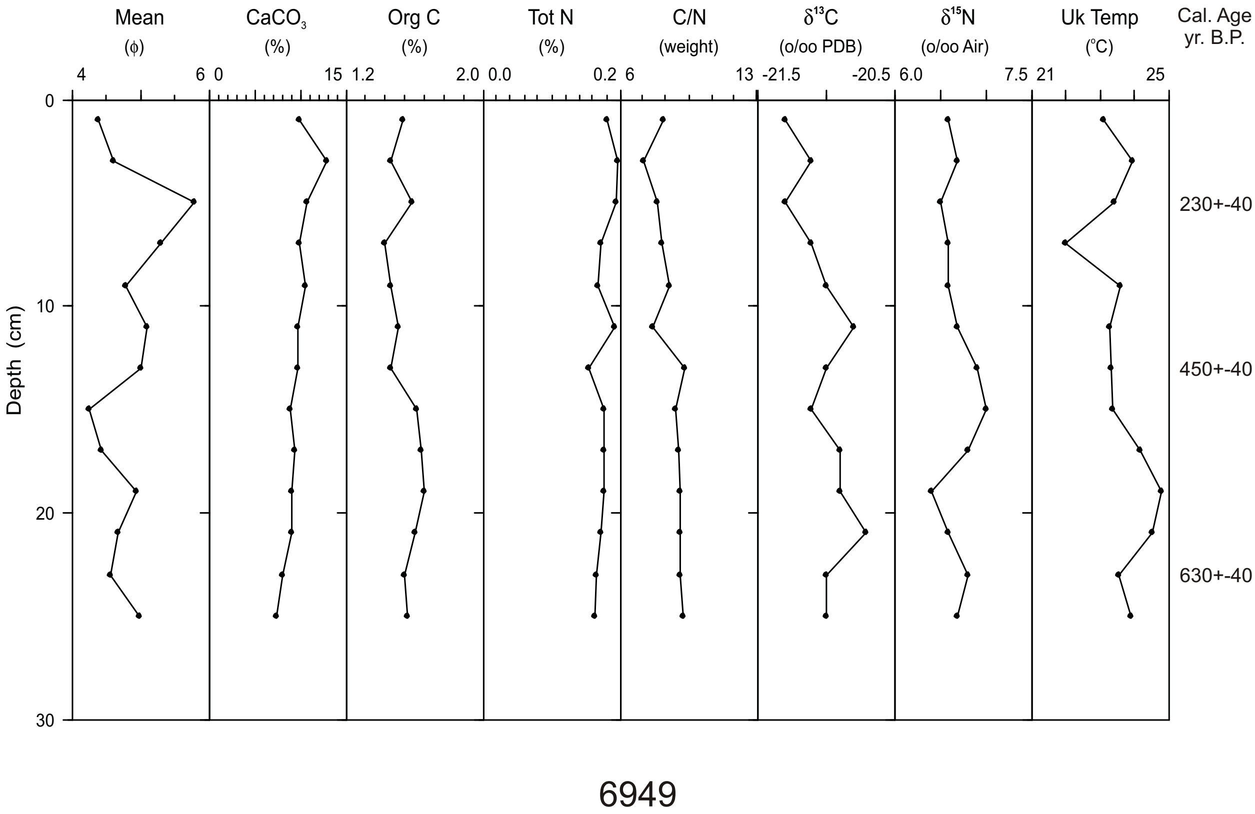

Fig. 3 – Mean grain-size, compositional, isotopic, and paleotemperature variations along core 6949.

temperatures, is observed (Table II). A decreasing trend of total sulfur was observed in all of the cores and an increasing trend of calcium carbonate was observed in cores 6949, 6953, and 6954. Significant trends of the other sedimentological parameters, when observed in one or two cores, were not considered.

The significant negative correlations between C/N ratio and organic carbon and total nitrogen, as observed in the cores, must be critically evaluated since high C/N values can result from low organic matter content of the sediment (Nitrogen values close to the detection limit). This is particularly valid in the cases where δ^{13}C values do not show significant correlations with the organic carbon content, which weakens the hypothesis of a source control on the deposition of the organic matter.

The Friedman test (Table III) revealed that with exception of the grain-size mean, all of the parameters show significant differences for at least one core, indicating that the distribution of most of the parameters is geographically dependent.

The results also show that from approximately 700 years B.P. to the present the Cabo Frio upwelling zone had a decrease in water temperature which, by its side was not followed by a response in the sedimentological parameters. The absence of significant correlation between paleotemperatures and most of the sedimentological parameters as well the geographic variability, as expressed by the sedimentation rates and sedimentological parameters of the coretops indicate that other processes such as geographical variations in the terrigenous input or the interplay between hydrodynamics and coastal and shelf morphology may also act as controllers in the sedimentary patterns of the area.

The intensification of upwelling conditions for the last 700 years can be related to a probable strengthening of the South Atlantic High Pressure, and therefore, the NE trade winds off Cabo Frio. This strengthening may dynamically have caused

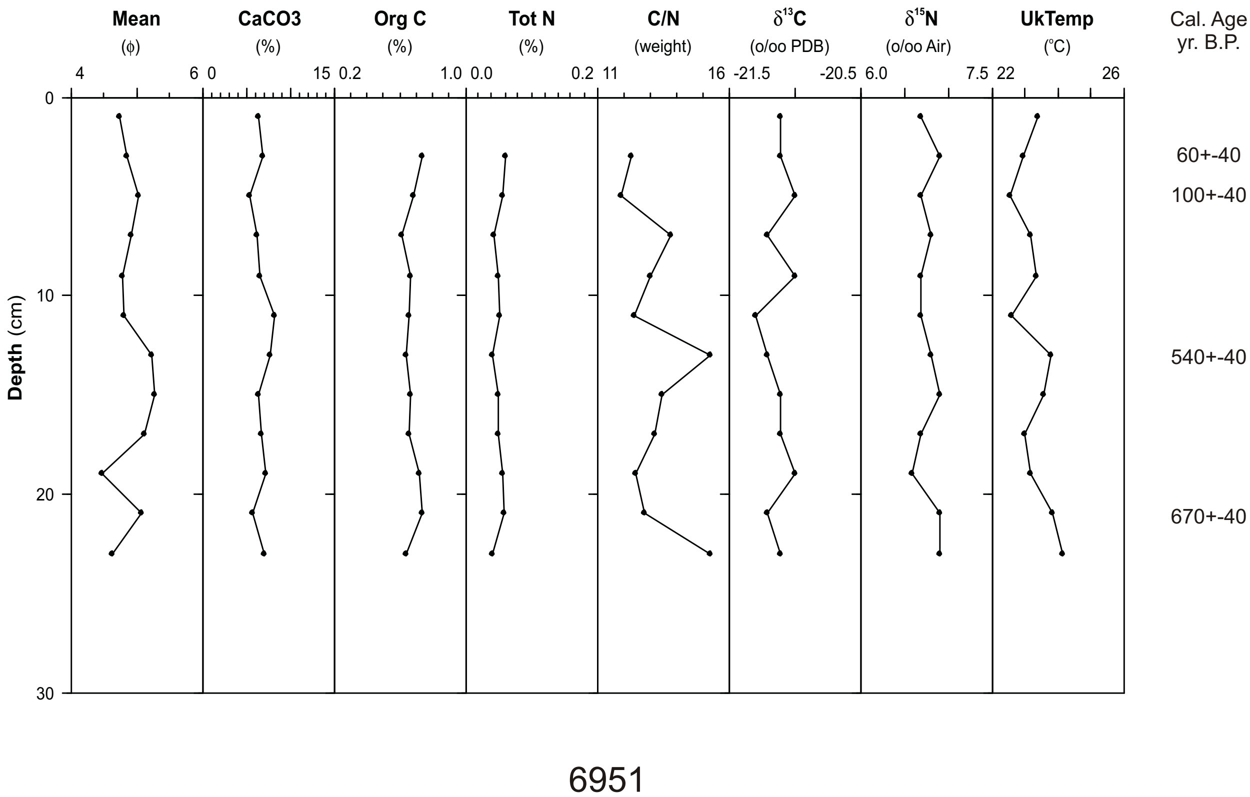

Fig. 4 – Mean grain-size, compositional, isotopic, and paleotemperature variations along core 6951.

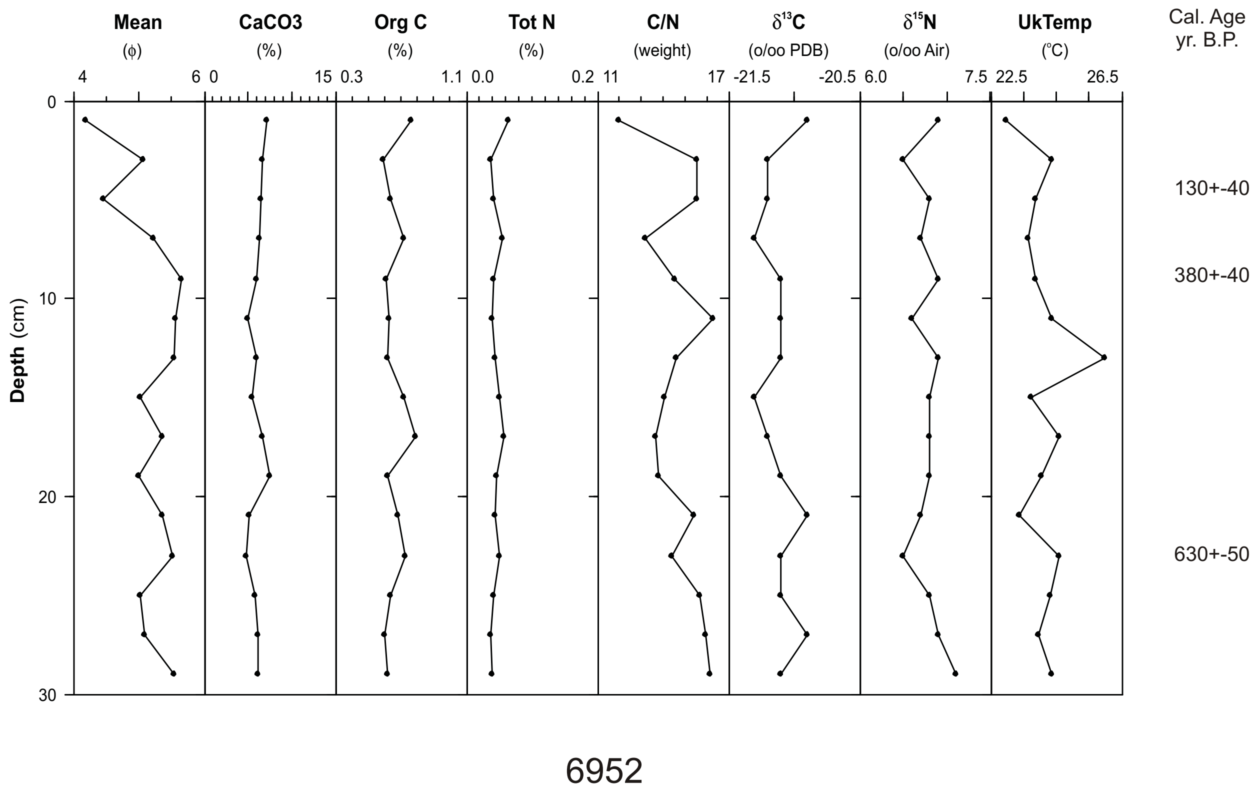

Fig. 5 – Mean grain-size, compositional, isotopic, and paleotemperature variations along core 6952.

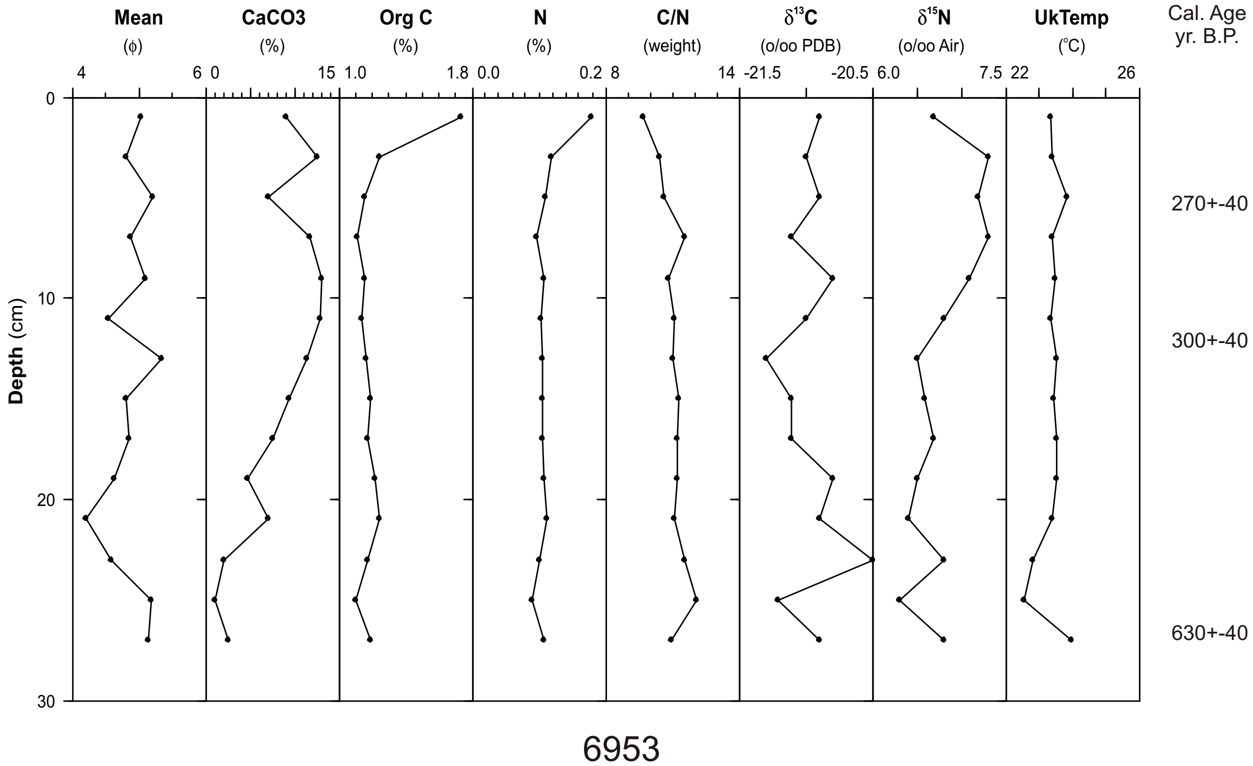

Fig. 6 – Mean grain-size, compositional, isotopic, and paleotemperature variations along core 6953.

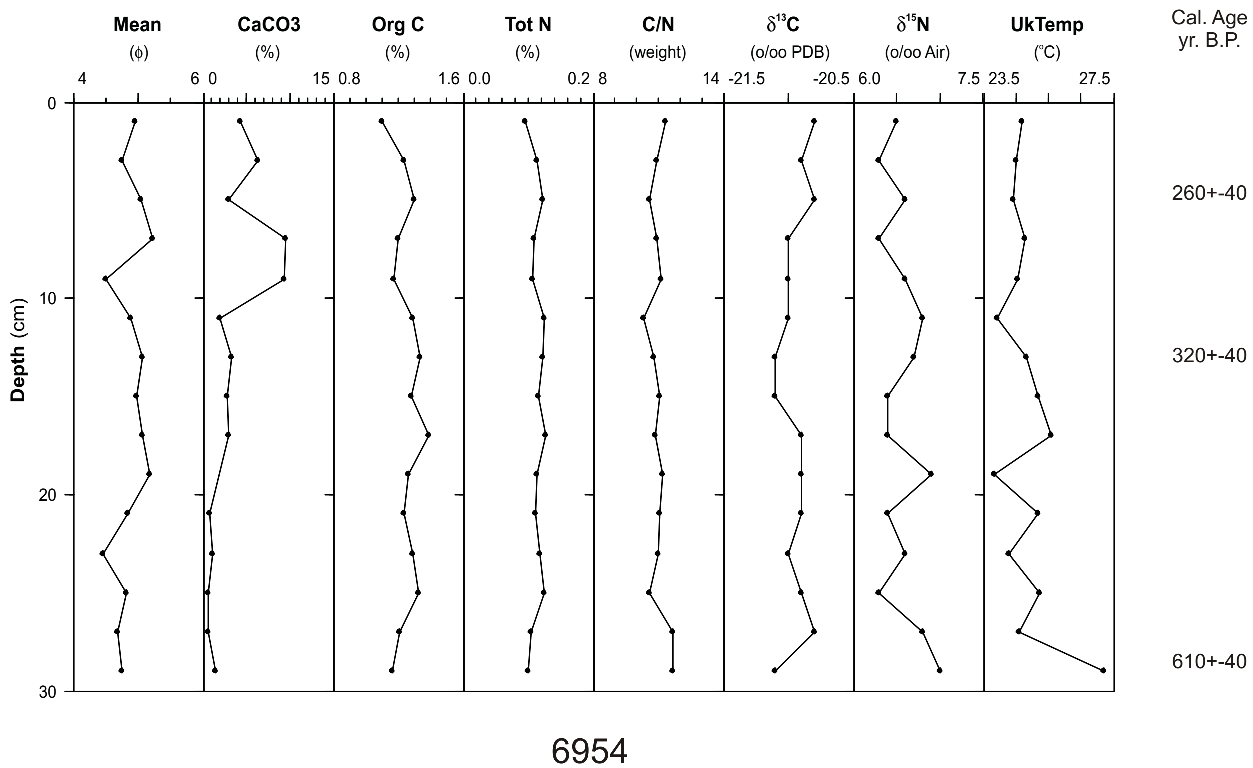

Fig. 7 – Mean grain-size, compositional, isotopic, and paleotemperature variations along core 6954.

TABLE II

Kendall-τ correlations among the sedimentological parameters. Only significant correlations ($\alpha \Leftarrow 0.100$) are presented.

	6949								
	Mean	Sorting	Carbonate	Carbon	Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	Uk Temp
Depth	–	0.38	–0.78	0.35	–0.44	0.61	0.51	–	0.38
Mean	*	–0.36	–	–	–	–	–	–0.36	–
Sorting	*	*	–0.40	0.38	–	0.45	–	–	0.44
Carbonate	*	*	*	–0.37	0.40	–0.57	–	–	–
Carbon	*	*	*	*	–	–	–	–	0.43
Nitrogen	*	*	*	*	*	–0.64	–	–	–
Sulphur	*	*	*	*	*	0.58	0.55	–	0.40
C/N	*	*	*	*	*	*	–	–	–
$\delta^{13}C$	*	*	*	*	*	*	*	–	0.40
$\delta^{15}N$	*	*	*	*	*	*	*	*	–
	6951								
	Mean	Sorting	Carbonate	Carbon	Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	Uk Temp
Depth	–	–	–	–	–	0.41	–	–	0.39
Mean	*	–	–	–	–	–	–	–	–
Sorting	*	*	–	–	–	–	–	–	–
Carbonate	*	*	*	–	–	–	–	–	–
Carbon	*	*	*	*	0.83	–0.65	–	–	–
Nitrogen	*	*	*	*	*	–0.83	–	–	–
Sulphur	*	*	*	*	*	–	–	–	0.42
C/N	*	*	*	*	*	*	–	–	0.47
$\delta^{13}C$	*	*	*	*	*	*	*	–	–
$\delta^{15}N$	*	*	*	*	*	*	*	*	0.44
	6952								
	Mean	Sorting	Carbonate	Carbon	Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	Uk Temp
Depth	–	–	–	–	–	–	–	–	–
Mean	*	–	–0.44	–	–	–	–	–	–
Sorting	*	*	–	–	–	–	–	–	–
Carbonate	*	*	*	–	–	–	–	–	–
Carbon	*	*	*	*	0.69	–0.42	–	–	–
Nitrogen	*	*	*	*	*	–0.75	–	–	–
Sulphur	*	*	*	*	*	–	0.32	–	–
C/N	*	*	*	*	*	*	–	–	–
$\delta^{13}C$	*	*	*	*	*	*	*	–	–
$\delta^{15}N$	*	*	*	*	*	*	*	*	–

TABLE II (continuation)

	6953								
	Mean	Sorting	Carbonate	Carbon	Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	Uk Temp
Depth	–	–	–0.56	–	–	0.51	–	–0.47	–
Mean	*	–0.54	–	–	–	–	–	–	–
Sorting	*	*	–	–	–	–	–	–	–
Carbonate	*	*	*	–	–	–	–	–	–
Carbon	*	*	*	*	0.66	–0.35	–	–	–
Nitrogen	*	*	*	*	*	–0.72	–	–	–
Sulphur	*	*	*	*	*	–	–	–0.49	–
C/N	*	*	*	*	*	*	–	–	–
$\delta^{13}C$	*	*	*	*	*	*	*	–	–
$\delta^{15}N$	*	*	*	*	*	*	*	*	–
	6954								
	Mean	Sorting	Carbonate	Carbon	Nitrogen	C/N	$\delta^{13}C$	$\delta^{15}N$	Uk Temp
Depth	–	–	–0.61	–	–	–	–	–	0.37
Mean	*	–	0.32	–	–	–	–	–	–
Sorting	*	*	–	–	–	–	0.35	–	–
Carbonate	*	*	*	–	–	–	–	–	–
Carbon	*	*	*	*	0.86	–0.53	–	–	–
Nitrogen	*	*	*	*	*	–0.68	–	–	–
Sulphur	*	*	*	*	*	–	–	–	–
C/N	*	*	*	*	*	*	–	–	–
$\delta^{13}C$	*	*	*	*	*	*	*	–	–
$\delta^{15}N$	*	*	*	*	*	*	*	*	–

TABLE III

Friedman Analysis of Variance among the cores.

Significant values ($\alpha \Leftarrow 0.100$) are underlined.

Parameter	Friedman ANOVA	p
Mean	7.65	0.10536
Calcium Carbonate	32.95	0.00000
Organic Carbon	40.65	0.00000
Total Nitrogen	40.65	0.00000
C/N ratio	40.90	0.00000
$\delta^{13}C$	20.21	0.00046
$\delta^{15}N$	8.35	0.07971
Temperature	20.58	0.00038

an intensification of the Brazil Current transport and its accompanying mesoscale activity. Both stronger and persistent NE winds and BC meandering may have acted in combination to enhance the upwelling process.

Considering the morpho-tectonic framework, the Holocene sea-level changes curves available for the southeastern Brazilian coast, and the extension of the Holocene emerged deposits (Martin et al. 1997), it may be assumed that the potential conditions of coastline configuration for the occurrence of upwelling in the Cabo Frio area have been present at least since the maximum of the Holocene, represented by the Santos Transgression (Suguio and Martin 1978) which occurred 5,100 years B.P.

Important climatic changes have already been observed in the Late Holocene in South America. Veit (1996) observed the occurrence of a higher climatic variability in the subtropical region of Chile (27-33°S) over the last 3,000 years, associating it with disturbances in the circulation of the westerly wind. Changes in the relative humidity conditions in S and SE Brazil have been related by Behling (1995, 1997) and Behling et al. (2001) to a more humid phase beginning after 1000 years B.P. Also Ybert et al. (2003) recognized alternating phases of humidity in the Southeastern Brazilian coast for the last 5,000 years but no evidence of climatic changes for the last millennium has been recognized.

Conditions for long-term changes in the dynamic regime responsible for depositional changes seem to have occurred throughout the Holocene on the eastern coast of Brazil, as shown by several authors who have dealt with the development of beach ridges in the Paraíba do Sul (approximately 60 nautical miles northward from the Cabo Frio) and Doce coastal plains (Dominguez et al. 1983, Martin et al. 1984 a,b, 1985).

Furthermore, climatic changes related to the intensification of SE cold front winds in the South Atlantic have been used by Arz et al. (1998) and Behling et al. (2000) to explain paleoceanographic and paleovegetational changes in NE Brazil during the Last Glacial Maximum. Martin et al. (1993) attribute the Holocene climatic variations in South America to long-term changes in the wind dynamics in SE Brazil.

CONCLUSIONS

The alkenone-based temperatures, sedimentological and bulk organic parameter variations in box-cores were used to better understand long-term upwelling oscillations off the Cabo Frio region, Southeastern Brazil. Despite the identification of a trend of increasing upwelling conditions for the last ca. 700 years, most of the sedimentological parameters did not show significant trends for the same period.

Due to the importance of the wind regime in the present-day upwelling conditions we can assume that its oscillation is the major factor for the water temperature variability over the last centuries.

The intensification in the upwelling regime for the last ca. 700 years can be associated with the strengthening of the NE winds off the area and a possible increase of the Brazil Current mesoscale activity.

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RESUMO

As análises de $U_{37}^{k'}$ paleotemperaturas e de parâmetros sedimentológicos em amostras de box-core da zona de ressurgência de Cabo Frio, sudeste do Brasil, foram usadas para compreender os processos de sedimentação moderna na área, bem como avaliar o papel desempenhado pela ressurgência no estabelecimento dos padrões sedimentológicos principais.

Como observado em três box-cores localizados nas proximidades da área de ressurgência, é possível verificar uma tendência geral de resfriamento das águas nos últimos 700 anos (idade calibrada). Uma vez que o processo de ressurgência é dependente do regime de ventos local e remoto, uma fase de ventos predominantes de NE favorece um deslocamento mais efetivo das águas frias da Água Central do Atlântico Sul em direção à costa.

Por outro lado, a falta de correlação significativa entre as paleotemperaturas e a maioria dos parâmetros sedimentológicos indica que a ressurgência não é o mecanismo prevalente na sedimentação da área. Além disso, a comparação dos parâmetros sedimentológicos entre os testemunhos revela que eventuais variações temporais são superimpostas pela variabilidade geográfica.

As taxas de sedimentação variam de 0,26 mm.ano^{-1} a 0,66 mm.ano^{-1}.

Palavras-chave: sedimentação, alquenonas, matéria orgânica total, ressurgência, Brasil, Atlântico Sul.

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