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Past and current sediment dispersion pattern estimates through numerical modeling of wave climate: an example of the Holocene delta of the Doce River, Espírito Santo, Brazil

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ABSTRACT

This paper presents a numerical modeling estimation of the sediment dispersion patterns caused by waves inciding through four distinct coastline contours of the delta plain of the Doce River during the Late Holocene. For this, a wave climate model based on the construction of wave refraction diagrams, as a function of current boundary conditions, was defined and was assumed to be valid for the four coastlines. The numerical modeling was carried out on basis of the refraction diagrams, taking into account the angle of approximation and the wave height along the coastline. The results are shown to be comparable with existing data regarding the directions of net longshore drift of sediments estimated from the integration of sediment cores, interpretation of aerial photographs and C₁₄ datings. This fact apparently suggests that, on average, current boundary conditions appear to have remained with the same general characteristics since 5600 cal yr BP to the present. The used approach may prove useful to evaluate the sediment dispersion patterns during the Late Holocene in the Brazilian east-northeast coastal region.

Key words: Past and current sediment dispersion, wave refraction, numerical modeling, Holocene, Brazil.

INTRODUCTION

Based on a numerical modeling carried out using wave refraction diagrams, Bittencourt et al. (2005) present a sediment transport model that reproduces, on a regional scale, the sediment dispersion patterns along a coastal section approximately 3,000 km long in the east-northeast Brazilian region. These patterns were shown by the authors to correspond, on a large scale, to those proposed by Dominguez et al. (1992), based on paleogeographic reconstructions, as having persisted on the east-

northeast Brazilian coast since the Late Quaternary. In general, such persistence seems to be basically related to the marked stability of the high pressure South Atlantic cell, which determines the trade winds system generated in it to be also markedly stable. This result in a great stability in the direction and velocity of these winds and, consequently, in dispersion of sediments along the east-northeast Brazilian coast (Dominguez et al. 1992). Thus, the methodology and boundary conditions used by Bittencourt et al. (2005), seem to be adequate to reproduce past sediment dispersion patterns in the Brazilian east-northeast region during the Late Quaternary, which will be evaluated in the present paper.

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The Quaternary plain of the Doce River mouth (Fig. 1), in the eastern Brazilian region, has been object of several studies (Bacoccoli 1971, Suguio and Martin 1981, Suguio et al. 1982, Dominguez 1987, Dominguez et al. 1981, 1987, Martin and Suguio 1992, Martin et al. 1997). A detailed map showing the various absolute datings (Suguio and Martin 1981, Suguio et al. 1982, Dominguez 1987, Dominguez et al. 1987), shows that the coastal plain was developed against Miocene deposits of the Barreiras Formation (Suguio and Nogueira 1999) where the following types of deposits can be distinguished (Fig. 1): a) Pleistocene marine terraces associated to the subsequent regression of a transgressive maximum dated 123,000 yr BP, and b) Holocene deposits associated to the subsequent regression of a transgressive maximum dated from 5600 cal yr BP, where lagoon and river deposits of an intra-lagoon delta, and two generations of sandy marine terraces can be identified. A diachronic vision of the coastline positioning during the Holocenic evolution of the coastal plain is also available, for which the directions of net longshore drift of sediments active in each period were reconstructed, based on the integration of sediment cores, interpretation of aerial photographs and C_{14} datings (Dominguez 1987, Dominguez and Wanless 1991, Dominguez et al. 1992, Martin and Suguio 1992, Martin et al. 1997). Along the current coastline, there are geomorphic indicators of the net longshore drift obtained from aerial photographs.

Regarding the Holocene evolution of the coastal plain, the deposition started with the formation of a barrier-island/lagoon system that reached its final position around approximately 5600 cal yr BP. At that time, the barrier-island formed an ample bight on its north side, where the first generation of sandy terraces were deposited between approximately 5600 and 3800 cal yr BP. After this, a second generation of marine terraces was deposited.

The objective of the present paper is to develop a simulation to verify the applicability of the method used by Bittencourt et al. (2005), as well as the current boundary conditions, in order to reproduce the sediment dispersion patterns defined along different positions of the coastline from the Holocene to the present, in the coastal plain associated with the Doce River mouth.

PHYSIOGRAPHIC ASPECTS

The coastal plain of the Doce River mouth has a length of 150 km and a maximum width of 40 km (Fig. 1). The Doce River has a 750 km course and a watershed basin of approximately 83,000 km², located in a hot and humid tropical climate region with summer rains and a dry fall-winter season.

The continental shelf has a variable width, ranging from 50 km in the south to 220 km in the north, being relatively uniform in its southern half and irregular in the northern half. (Fig. 1).

ATMOSPHERIC CIRCULATION SYSTEM

The area under study is entirely located within the South Atlantic trade winds belt (NE-E-SE) that is related to the high-pressure cell, which exists in this region (Bigarella 1972, Martin et al. 1998). Another important atmospheric circulation element in this region is the periodic advance of the Atlantic Polar Front during the autumn and winter, generating SSE winds (Dominguez et al. 1992, Martin et al. 1998). It should also be noted that, on an inter-annual scale, the high-pressure cell normally shows a tendency to remain relatively stationary. Seasonally, however, this cell tends to expand and contract. In the coastal zone, this movement of the high-pressure zone controls the position of the Divergence Zone (DZ) between the trade winds *sensu-stricto* (SE) and the return trade winds (NE). During the winter, the DZ is located at approximately 20°S, while in the summer the position changes to approximately 13°S (Bigarella 1972, Dominguez et al. 1992, Martin et al. 1998).

WAVE CLIMATE MODEL

Significant direct measurements of the wave regime in the study area are not available. Wave statistics (height and period) used in this study were extracted from Hogben and Lumb (1967) (Area 37), which registered data obtained from visual observations taken on the open sea from ships. On the other hand, considering that along the east Brazilian coastal region, the sea-type waves are much more common than the swell-type waves (Davies 1972) – which is also confirmed by wave statistics given in Hogben and Lumb (1967) – local trade wind data were used to derive the frequencies regarding wave fronts

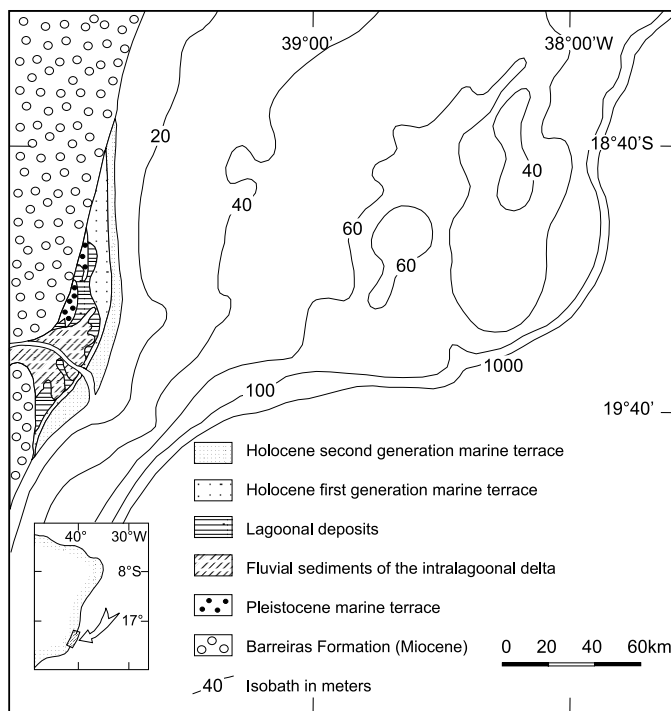


Fig. 1 – Schematic geological map of the coastal plain associated to Doce River mouth and morphology of the continental shelf.

reaching the coastline. Following are the average annual directions and frequencies of winds (the latter re-dimensioned to 100%) (DHN 1993), regarding a time series from 1951 to 1972, that can generate waves directed to the coastline: NE (N45°) – 39%, E (N90°) – 28%, SE (N135°) – 18% and SSE (N157.5°) – 15%. For these wave directions, the predominant periods and heights associated to them were considered to be, according to Hogben and Lumb (1967): period of 5 sec and height of 1 m for NE and E waves and period of 6.5 sec and height of 1.5 m for SE and SSE waves.

Based on these data, wave refraction diagrams were constructed manually, in accordance with the procedures described in CERC (1984), resulting in a generic wave climate model for the area under study. The bathymetric data used in the construction of these diagrams were extracted from a Brazilian Navy nautical chart on an approximate scale of 1:300,000. The waves were not propagated to water depths less than 10 m, which is the closest limit to the coastline on the nautical chart. In addition

to the present coastline (Fig. 2), refraction diagrams were constructed for three other distinct Holocene scenarios for the coastline position described by Dominguez (1987) and Dominguez and Wanless (1991) (Fig. 3): a) around approximately 5600 cal yr B.P., corresponding to the barrier-island coastline (Fig. 4), b) immediately after 5600 cal yr BP, corresponding to the coastline position during the deposition of the first generation of marine terraces (Fig. 5), and c) around approximately 3800 cal yr BP, corresponding to the coastline position after the end of the deposition of the first generation of marine terraces (Fig. 6). The current position of the coastline corresponds to the second generation of marine terraces, with the Doce River discharging into the ocean through a single channel (Fig. 2A). The refraction diagrams constructed based on current boundary conditions, had their wave-rays refracted to the 10 m isobath and, from there, the last propagation direction was maintained, extending to the coastlines mentioned above (Figs. 2B and 4B to 6B).

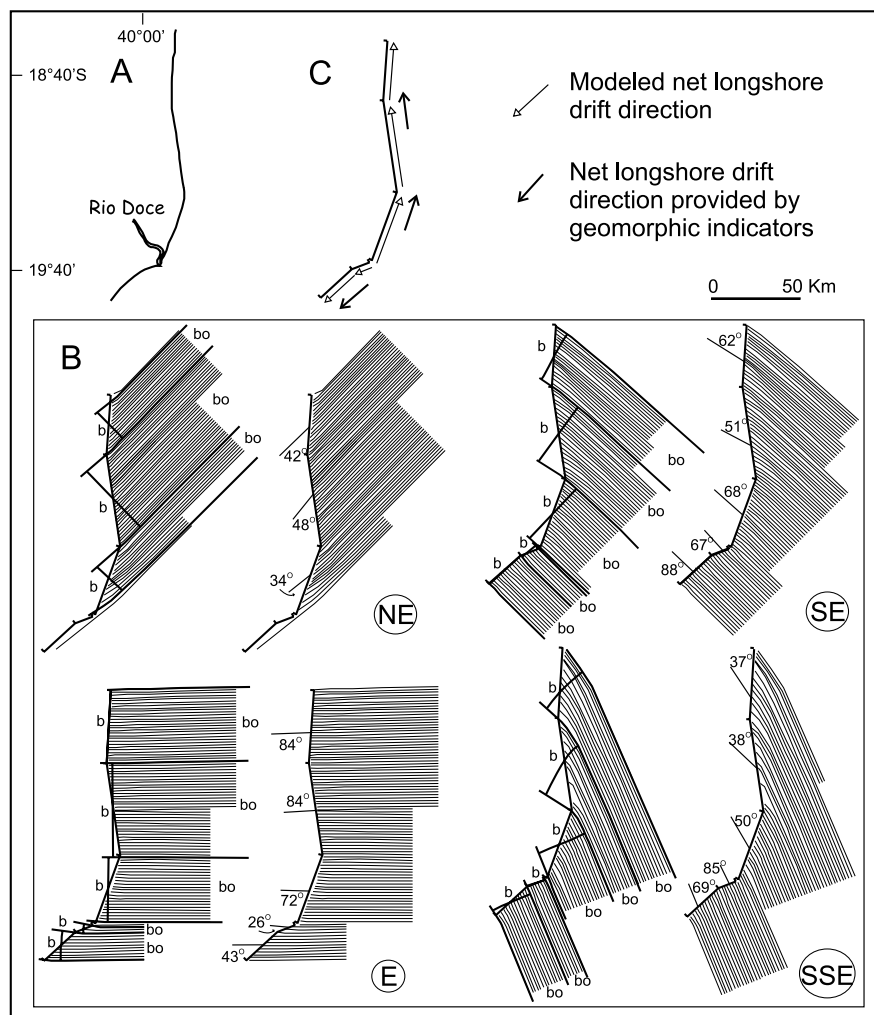


Fig. 2 – (A) Current coastline in the Doce River mouth. (B) Refraction diagrams for waves with a 5-s period, coming from NE and E, and 6,5-s period, coming from SE and SSE. Here are also shown: 1) different segments into which the shoreline was rectilinearized, 2) incidence angles formed by the wave-rays in relation to the coastal segments and 3) measurements of b and b_o (see text) used to estimate wave height along the shore segments. (C) Rectilinearized shoreline showing the directions of net longshore drift of sediments estimated from numerical modeling and from geomorphic indicators.

DETERMINATION OF THE NET LONGSHORE DRIFT DIRECTION

The direction of net longshore drift of sediments was determined by the calculation of potential intensity of longshore drift for each of the different wave-front directions, according to the method described in Bittencourt et al. (2005). Thus, the potential longshore drift

intensity, for each wave-front was expressed by a non-dimensional number, considering the function:

$$x = \sin \alpha \cdot \cos \alpha \cdot H^2, \quad (1)$$

where x is the longshore drift intensity, α is the incidence angle of the wave-front to the coastline, and H is the normalized height of the wave (*ie.*, the results were divided by a constant with the value of 1 m). The height of the

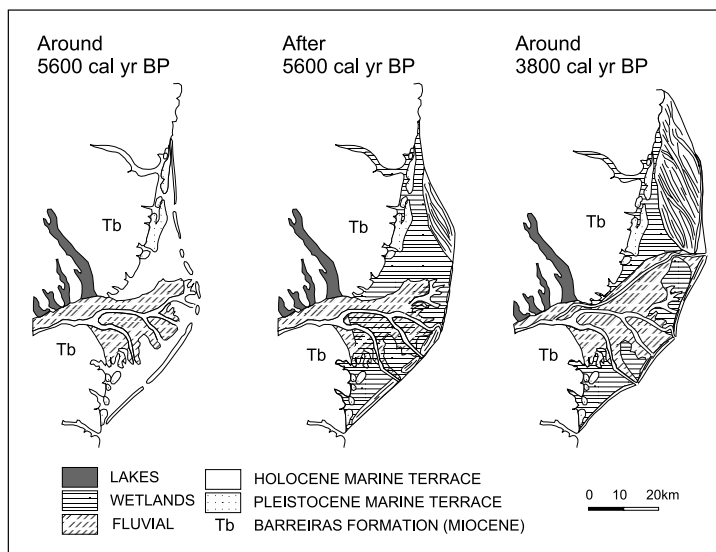


Fig. 3 – Paleogeographic maps of the coastal plain associated to Doce River mouth from 5600 to 3800 cal yr BP. (according to data from Dominguez 1987, Dominguez and Wanless 1991).

wave along the coastline was estimated in accordance with the equation (Bascom 1954):

$$H = H_o \left(\frac{b_o}{b} \right)^{1/2}, \quad (2)$$

where the subscript zero designates the conditions of deep waters and, b , the distance between adjacent sets of wave-front orthogonal. The coastline was divided into segments each of which approximated to a straight line, in accordance with the orientation of the coastline (Figs. 2B and 4B to 6B). Later, the value obtained for drift intensity was multiplied by the percentage of the annual frequency of wind direction to which the wave-front under consideration is associated. In the coastal sections presenting opposing drift directions during the year, the direction of net longshore drift was defined considering the predominant direction given by the difference of intensity between opposing drifts.

RESULTS AND CONCLUSIONS

Figures 2C and 4C to 6C present the directions of net longshore drift of sediments estimated in the present paper, as well as of those reconstructed by geological indicators, where it can be seen that they are comparable

among themselves. Thus, it can be concluded that, in spite of the limitations inherent to the methodology used herein (see Bittencourt et al. 2005), in addition to the uncertainties regarding the boundary conditions and to the simplified suppositions incorporated in the model, the model showed its usefulness for reproducing past and current sediment dispersion patterns during the evolution of the coastal plain associated with the Doce River delta in the Late Holocene. This fact may mean that, on average, regarding the Brazilian east-northeast region, current wave conditions, as well as the morphology of the continental shelf, seem to have remained with the same characteristics from approximately 5600 cal yr BP to the present time. However, in certain limited periods, for example, between 5600 and 3800 cal yr BP, phases of localized erosion can be seen, testifying to modifications in the coastal dynamics. It seems that these erosions are a consequence of the existence of periods of some decades of years during which the waves from the SSE were weakened or absent (Martin and Suguio 1992). A time reconstruction of these anomalies may furnish valuable information concerning modifications in the characteristics of the atmospheric circulation with durations of several decades of years. This type of in-

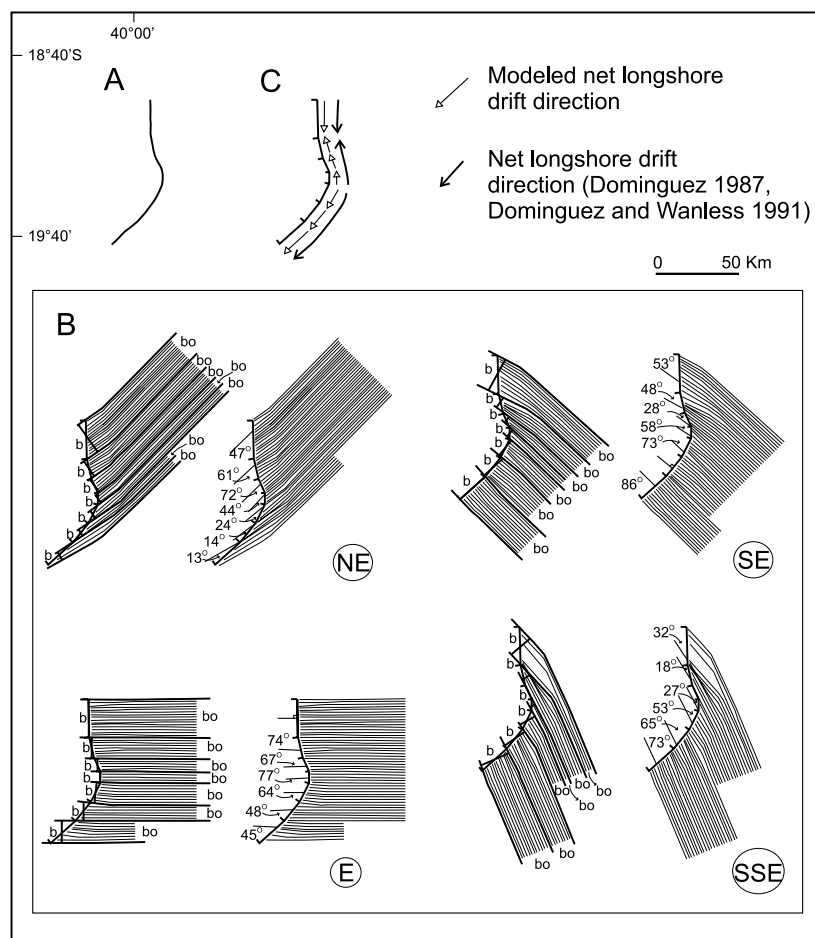


Fig. 4 – (A) Coastline in the Doce River around 5600 cal yr BP (see Fig. 3). (B) Refraction diagrams for waves with a 5-s period, coming from NE and E, and 6,5-s period, coming from SE and SSE. Here are also shown: 1) different segments into which the shoreline was rectilinearized, 2) incidence angles formed by the wave-rays in relation to the coastal segments and 3) measurements of b and b_0 (see text) used to estimate wave height along the shore segments. (C) Rectilinearized shoreline showing the directions of net longshore drift of sediments estimated from numerical modeling and from Dominguez (1987) and Dominguez and Wanless (1991).

formation may be very important for the simulation of future situations.

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RESUMO

O presente trabalho apresenta uma estimativa, por modelagem numérica, dos padrões de dispersão de sedimentos causados por ondas ao longo de quatro distintos traçados da linha de costa durante o Holoceno Tardio na planície deltaica do Rio Doce. Para tanto, foi definido um modelo de clima de on-

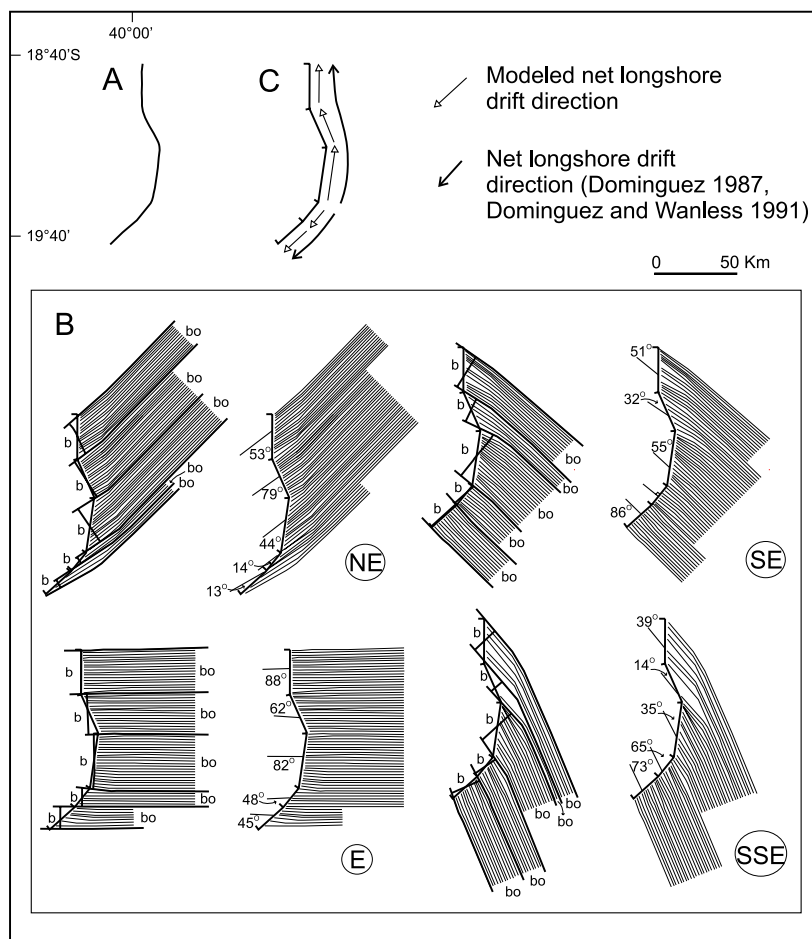


Fig. 5 – (A) Coastline in the Doce River immediately after 5600 cal yr BP (see Fig. 3). (B) Refraction diagrams for waves with a 5-s period, coming from NE and E, and 6.5-s period, coming from SE and SSE. Here are also shown: 1) different segments into which the shoreline was rectilinearized, 2) incidence angles formed by the wave-rays in relation to the coastal segments and 3) measurements of b and b_o (see text) used to estimate wave height along the shore segments. (C) Rectilinearized shoreline showing the directions of net longshore drift of sediments estimated from numerical modeling and from Dominguez (1987) and Dominguez and Wanless (1991).

das baseado na construção de diagramas de refração de ondas, em função das condições de contorno atuais, que foi assumido como válido para as quatro linhas de costa. A modelagem numérica foi realizada a partir dos diagramas de refração, levando-se em conta o ângulo de aproximação e a altura da onda ao longo da linha de costa. Os resultados obtidos mostraram-se compatíveis com os dados existentes relativos aos sentidos da deriva litorânea efetiva de sedimentos estima-

dos a partir da integração de testemunhos de vibração, interpretação de fotos aéreas e datações por C_{14} . Esse fato aparentemente sugere que, em média, as condições de contorno atuais parecem ter permanecido com as mesmas características gerais desde 5.600 cal yr BP até o atual, bem como que a abordagem aqui utilizada poderá ser útil para a avaliação de padrões de dispersão de sedimentos durante o Holoceno Tardio na região costeira leste-nordeste brasileira.

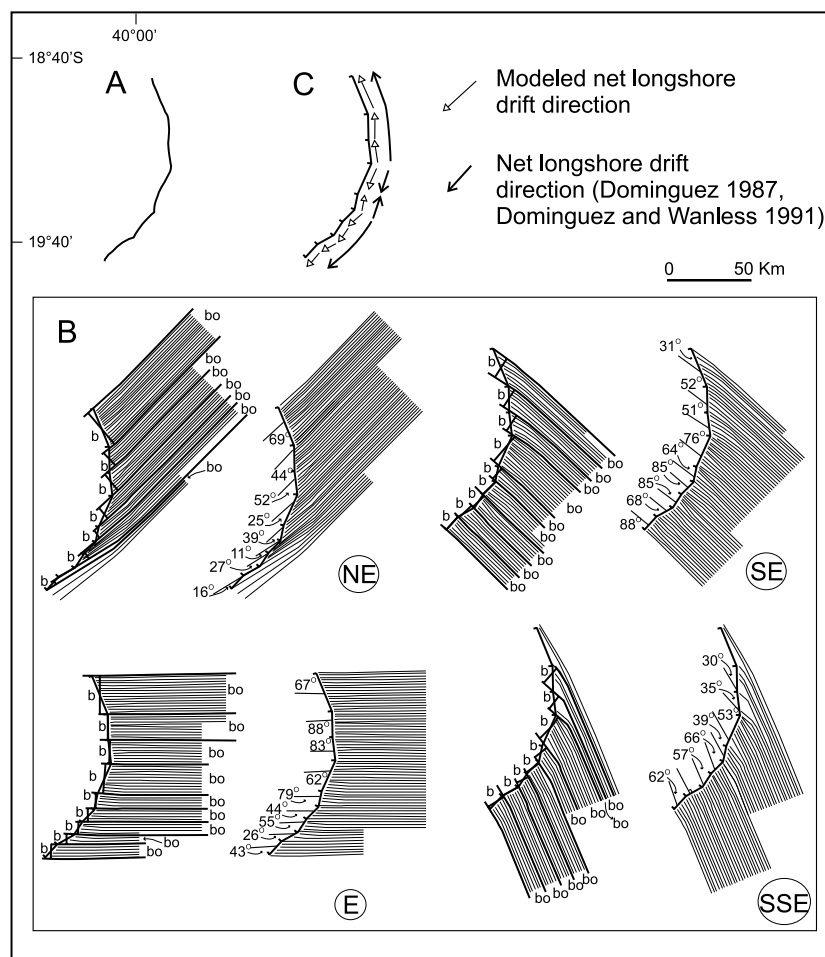


Fig. 6 – (A) Coastline in the Doce River around 3800 cal yr BP (see Fig. 3). (B) Refraction diagrams for waves with a 5-s period, coming from NE and E, and 6,5-s period, coming from SE and SSE. Here are also shown: 1) different segments into which the shoreline was rectilinearized, 2) incidence angles formed by the wave-rays in relation to the coastal segments and 3) measurements of b and b_0 (see text) used to estimate wave height along the shore segments. (C) Rectilinearized shoreline showing the directions of net longshore drift of sediments estimated from numerical modeling and from Dominguez (1987) and Dominguez and Wanless (1991).

Palavras-chave: padrões pretéritos e atuais de dispersão de sedimentos, refração de onda, modelagem numérica, Holoceno, Brasil.

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