Journal of South American Earth Sciences 31 (2011) 110–123

Contents lists available at ScienceDirect

Journal of South American Earth Sciences

journal homepage: www.elsevier.com/locate/jsames

Controls of heavy minerals and grain size in a holocene regressive barrier (Ilha Comprida, southeastern Brazil)

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ARTICLE INFO

Article history:
Received 25 February 2010
Accepted 20 July 2010

Keywords:
Heavy mineral indices
Sedimentary transport
Beach ridges
Foredunes
Provenance
Hydraulic sorting

ABSTRACT

Ilha Comprida is a regressive barrier island located in southeastern Brazil that was formed essentially by Quaternary sandy sediments. Ilha Comprida sediments were analyzed to assess heavy mineral indices and grain size variables. The spatial variation of heavy minerals and grain size was interpreted in terms of the present barrier dynamics and the barrier's evolution since the Middle Holocene. These analyses allowed for the identification of the main factors and processes that control the variation of heavy minerals and grain size on the barrier. Rutile and zircon (RZi) and tourmaline and hornblende (THi) are significantly sensitive to provenance and exhibit the contributions of the Ribeira de Iguape River sediments, which reach the coast next to the northeastern end of Ilha Comprida. In addition to the influence of provenance, TZi responds mainly to hydraulic sorting processes. This agrees with a sediment transport pattern characterized by a divergence of two resultant net alongshore drifts southwest of the barrier. The sediments from the Ribeira de Iguape River reach the barrier directly through the river mouth and indirectly after temporary storage in the inner shelf. The combination of grain size and heavy mineral analyses is a reliable method for determining sediment transport patterns and provenance.

1. Introduction

Heavy mineral analysis (e.g., denser than 2.85 g/cm^3) and grain size analysis are classic methods of characterizing sedimentary rocks and sediments. These methods have been used in studies examining stratigraphical correlations, sediment transport pathways and sedimentary provenance. Although the analysis of heavy minerals and grain size is used less commonly than the description and interpretation of sedimentary structures, these methods still remain an important source of information in situations where sedimentary structures and/or outcrops are inaccessible, slightly apparent or monotonous. These characteristics occur frequently in coastal Quaternary deposits, where grain size analysis has been successfully tested and applied as an auxiliary tool for sedimentary facies discrimination (Miller, 1956; Martins, 1965; Chappell, 1967; Bigarella et al., 1969; Taira and Scholle, 1978; Tucker and Wacher, 1980; El-Ella and Colleman, 1985; Ponçano, 1986) and sediment transport pathway definition (Evans, 1939; Russel, 1939; Self, 1977; Greenwood, 1978; McCave, 1978; Bryant, 1982; McLaren and Bowles, 1985). Heavy mineral analysis has been widely used in sedimentary provenance studies (Krynine, 1942, 1946; Stanley et al., 1988; Morton et al., 1991, 2005, 2007, 2009; Morton and Hallsworth, 1994).

Studies on the processes controlling heavy mineral assemblages have been conducted since the 1940s (Pettijohn, 1941; Dryden and Dryden, 1946; Allen, 1948; Van Andel, 1959; Morton and Smale, 1990). A synthesis of heavy mineral assemblages was presented by Morton and Hallsworth (1999). According to these authors, heavy minerals within sandstones are controlled by different factors: parent rocks, weathering in the source area, mechanical abrasion during transport, post-depositional weathering, hydraulic processes, burial diagenesis and weathering at an outcrop (telodiagenesis). These factors can be categorized as four main processes: weathering, mechanical abrasion, hydraulic sorting and diagenesis. These factors determine the availability and initial size of heavy minerals.

Changes in the relative contributions of different source rocks and the intensity of the four processes give a compositional signature within the heavy mineral assemblage. These signatures have a complex genesis, which makes their interpretation challenging. As a quantitative method to analyze and to interpret the influence of each process on heavy minerals, Morton and Hallsworth (1994)

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doi:10.1016/j.jsames.2010.07.007

proposed a comparison of pairs of transparent minerals with similar characteristics of two aspects of provenance, hydraulic equivalence and chemical stability. Thereby, indices based on the ratio between minerals with similar chemical and physical characteristics and contrasting source rocks have allowed for the identification of relative changes in sedimentary provenance (Morton and Hallsworth, 1994; Morton et al., 2005, 2007, 2009). However, other reliable applications of heavy minerals such as sedimentary transport, weathering and diagenesis remain incipient and scarce (Flores and Shideler, 1978; Stanley et al., 1988; Morton and Johnsson, 1993; Xiubin et al., 1997; Frihy, 2007). The Brazilian Quaternary deposits are similar, and this technique has rarely been applied to determine relative age (Giannini, 1987, 1993; Giannini and Suguio, 1994; Angulo et al., 1994, 1996; De Mio and Giannini, 1997; Giannini et al., 1997; Lessa et al., 2000) or the dynamics of depositional systems (Tessler, 1982, 1988; Giannini, 1987, 1993; Giannini et al., 2004). Furthermore, these applications do not use the quantitative index approach of Morton and Hallsworth (1994).

The aim of this study was to analyze factors controlling the heavy mineral assemblage and grain size distribution of the Ilha Comprida sediments, which are part of a Brazilian Holocene regressive barrier (Giannini et al., 2003, 2009; Guedes, 2003, 2009). The heavy mineral analysis emphasizes the use of source area indices (Morton and Hallsworth, 1994), an approach that has never been applied to the Ilha Comprida barrier. Additionally, a new index for sedimentary transport that was established analogously to the Morton and Hallsworth (1994) source area indices is proposed here. The Ilha Comprida barrier has well-preserved geomorphological features that allow for the identification of barrier growth patterns and facilitate the understanding of its sedimentary history. Grain size statistics and heavy mineral indices were used to evaluate changes in sediment source areas and sediment transportation patterns during the evolution of the barrier. Based on this case study, we evaluated the efficiency of heavy mineral and grain size analyses to generally describe the evolution of Holocene wave-dominated coastal systems.

2. Regional setting

The Ilha Comprida barrier is located on the southern coast of the São Paulo State (southeastern Brazil). The barrier has a length of 63 km (southwest to northeast) and a width ranging from 0.5 to 5 km (Fig. 1). It is separated from the adjacent coastal zones by the Icapara inlet at the northern end and by the Cananéia inlet at the southern end. It is separated from the continent by the Cananéia–Iguape lagoon system (Tessler, 1982). The mouth of the Ribeira de Iguape River is the major drainage area in the region and is located near the northern end of the barrier.

The Ilha Comprida is a prograded barrier (sensu Roy et al., 1994) formed by multiple coast parallel beaches and foredune ridges. The barrier was divided into three morphological units by Sawakuchi et al. (2008): inner, middle and outer. The inner unit is composed of beach ridges, the middle unit is a belt of blowouts (high paleodunes), and the outer unit consists of foredune ridges. Giannini

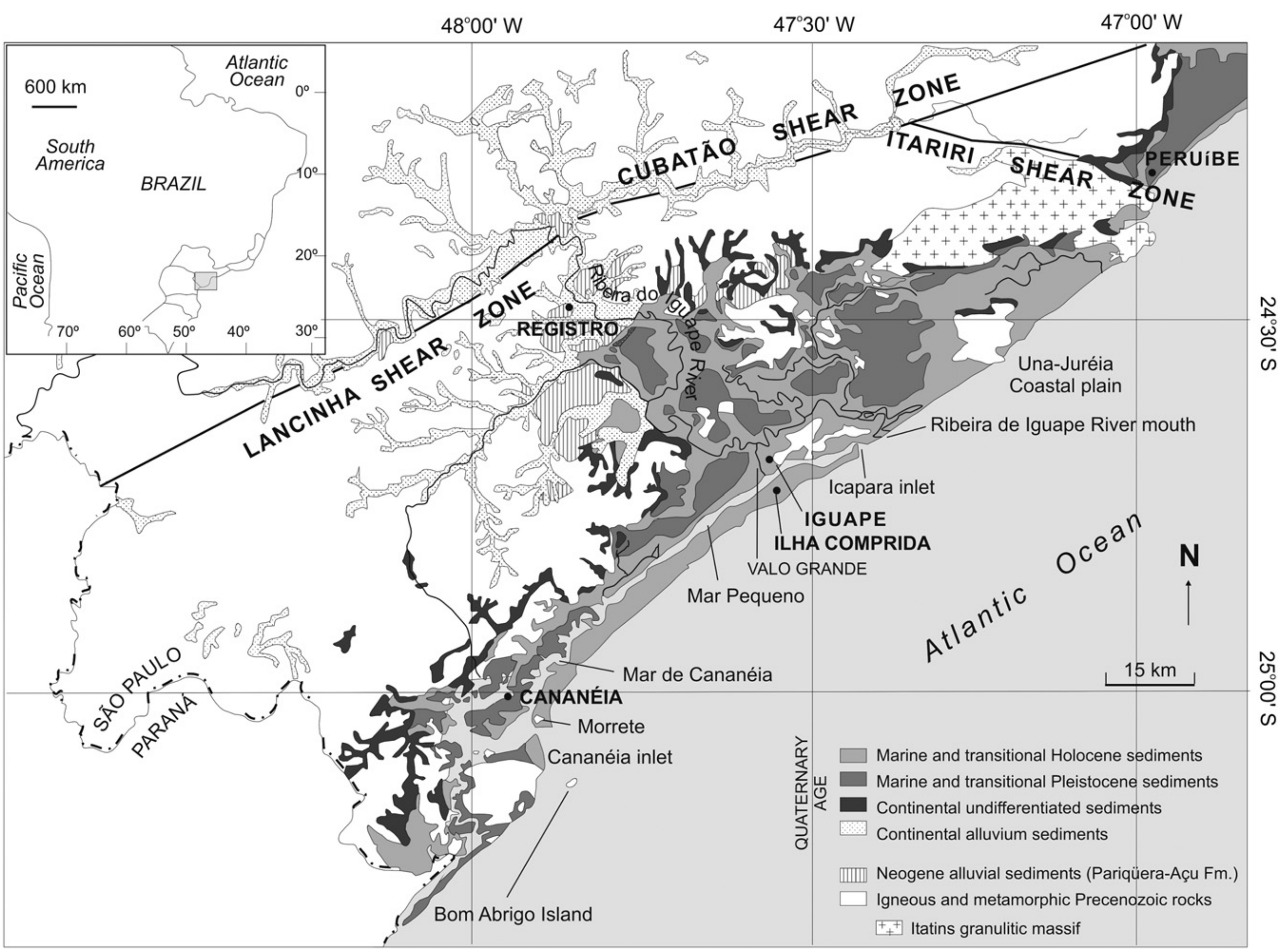

Fig. 1. The Cananéia–Iguape lagoonal system and the Ilha Comprida barrier. Location and geological maps modified from IPT. (1981), Nascimento et al. (2008) and Giannini et al. (2009).

et al. (2009) studied the sedimentology and morphological evolution of the island during the Holocene and divided the barrier evolution into four main phases with different levels of importance for alongshore growth components (running toward the northeast) and transverse growth components (running toward the southeast).

The dominant climate in the Ilha Comprida region is the Cfa type (wet subtropical climate with a warm summer) according to the Köppen classification. There is an annual average temperature of 20.7 °C, a relative air humidity average higher than 80% and an absence of a well-defined dry season (Lepsch et al., 1990). The average tidal range varies between 1.2 m during the spring tide and 0.25 m during the neap tide (Mesquita and Harari, 1983). This tidal range characterizes the system as microtidal (Davies, 1964). Two wave systems operate in the region: one from the east and northeast that is associated with trade winds and another from the south and the southeast that is related to cold fronts (Tessler, 1988). Wave heights of up to 2 m prevail in both systems, with 50% of wave heights between 1 and 1.5 m (Geobrás, 1966). The average period of the waves related to the southeast swell is 8.8 ± 1 s. The two wave systems are responsible for alongshore transport systems with opposite directions and predominant transport to the northeast. The predominance of transport to the northeast is shown by deviations of little inlets and patterns of variation in sedimentological properties (Tessler, 1988). Grain size trends and heavy mineral distributions in the present beach and dune sediments (Barcelos, 1975; Tessler, 1982, 1988; Souza, 1997; Tanaka et al., 2005; Nascimento, 2006; Nascimento et al., 2008; Giannini et al., 2009), as well as in older deposits of the Ilha Comprida barrier (Tessler, 1988; Giannini et al., 2009), have been interpreted as a result of the action of this predominant alongshore drift to the northeast.

The Pleistocene Cananéia Formation (Petri and Suguio, 1973) and the Holocene marine sandy deposits occur in the coastal plain around the lower portion of the Ribeira de Iguape River (Suguio and Martin, 1978). The coastal plain is surrounded by granitoid igneous rocks and pre-Cenozoic metamorphic rocks with green schist and amphibolite facies. There is a small hill in the southern portion of the island called "Morrete." Morrete has a height of 42 m and is composed of Late Cretaceous alkaline rocks (Spinelli and Gomes, 2008).

Sedimentary studies in Ilha Comprida have provided knowledge about the grain size distribution and barrier evolution (Geobrás, 1966; Barcelos, 1975; Landim et al., 1977; Suguio and Barcelos, 1978; Landim and Castro, 1981; Tessler, 1982, 1988; Guedes, 2003; Giannini et al., 2003, 2009; Nascimento et al., 2005; Tanaka et al., 2005; Nascimento, 2006). A grain size pattern of fine and well sorted sediments toward the northeast was detected by these studies. Using the criteria of McLaren and Bowles (1985) to infer sediment transport, Nascimento (2006) assumed the existence of two alongshore drift directions, with a divergence zone located in the southwestern region of the beach. This divergent pattern may be related to the influence zone of the hydraulic shadow effect exerted by the Cananéia inlet and respective ebb tidal deltas that blockade the main littoral drift toward the northeast (Giannini et al., 2009).

Previous studies in the Cananéia and Iguape regions used heavy mineral analysis to determine the primary provenance of the mineral assemblage and trends of spatial variation (Petri and Suguio, 1973; Barcelos, 1975; Suguio and Barcelos, 1978; Tessler, 1982, 1988; Guedes, 2003; Giannini et al., 2003, 2009; Nascimento, 2006). The heavy mineral assemblages found by these studies are very similar but have small variations in minor components (Table 1). The results permit the identification of a spatial trend for decreasing mineralogical maturity (ZTR index) from southwest to northeast in the present beach, foredunes, stabilized beach ridges and dune ridges (Tessler, 1988; Guedes, 2003; Giannini et al., 2003, 2009; Nascimento et al., 2008).

3. Methods

3.1. Sampling

This study presents heavy mineral and grain size results for 245 sand samples. Of these samples, 153 were from previous studies (27 from Giannini et al., 2003 and Guedes, 2003 and 126 from Nascimento, 2006 and Nascimento et al., 2008) and 92 were previously unpublished (Fig. 2). Sediment samples from old beaches and stabilized dune ridges were collected in outcrops and pits. The upper horizons with pedogenesis were avoided to minimize the possible effect of weathering on mineralogy. Sediments from the active beach (swash zone) dune system were sampled from the surface up to 0.1 m deep.

Table 1
Heavy minerals identified in Quaternary sediments of the Cananéia–Iguape region by previous studies. X = abundant, TR = trace.

Minerals	Petri and Suguio (1973)	Barcelos (1975)	Tessler (1988) Beach and coastal plain	Tessler (1988) Inner shelf	Guedes (2003), Giannini et al. (2009)	Nascimento (2006), Nascimento et al. (2008)
Anatase		TR	TR	TR		
Andalousite		TR	TR	TR		X
Apatite	X	TR				
Kyanite		X	TR	TR	X	X
Clinopyroxene				TR	TR	TR
Chlorite	X					
Dumortierite		TR				
Epidote		X	X	X	X	X
Staurolite		X	X	X	X	X
Garnet			TR	X	TR	X
Hypersthene		TR	TR	TR		X
Hornblende		X	X	X	X	X
Monazite			TR	TR		TR
Perowskite			TR	TR		
Rutile	X	X	X	X	X	X
Sillimanite	X	X	TR	TR	X	X
Titanite		TR	TR	TR	TR	
Tremolite		TR	TR	TR		TR
Tourmaline	X	X	X	X	X	X
Zircon	X	X	X	X	X	X

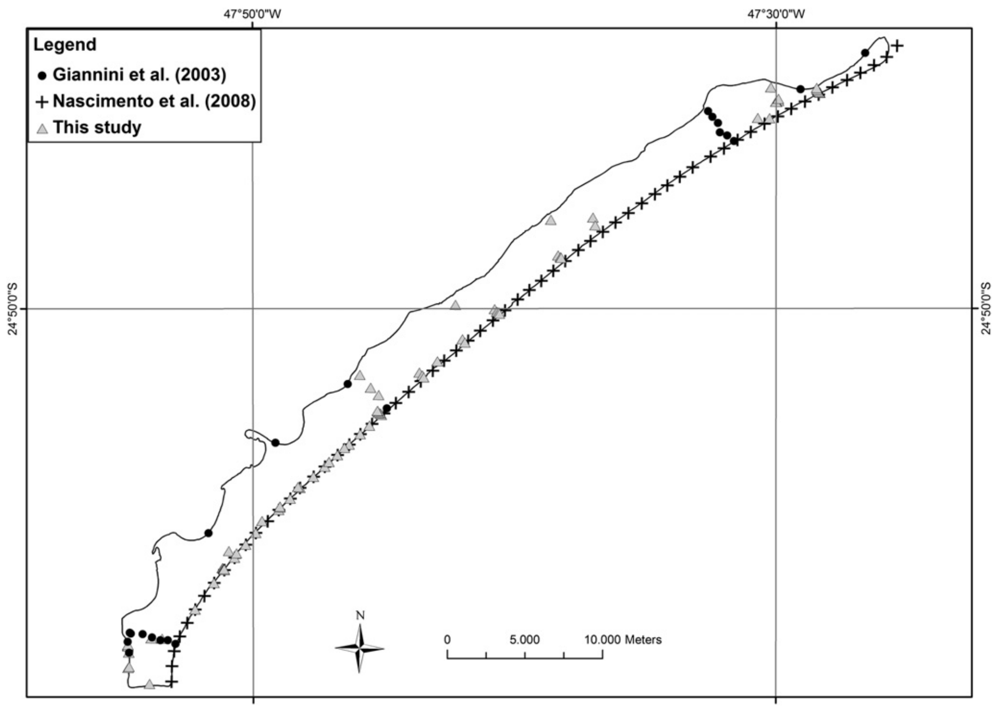

Fig. 2. Map of sampling locations.

3.2. Grain size analysis

The sand samples (approximately 60 g) were dry sieved in 0.5 phi intervals. Descriptive statistics (mean diameter, standard deviation and skewness) of the sand intervals were calculated using the Pearson moment method. Folk and Ward (1957) criteria were used to nominally classify the samples based on their standard deviation values. The samples were grouped in three different ways for comparison. The first criterion for grouping considered the sedimentary process (wind-deposited sediments versus wave-deposited sediments). The two other criteria for grouping were based on morphological facies. The first morphological facies criterion separated the samples into five categories: 1) foredunes (active and stabilized), 2) active features of a dunefield in the northeastern region of the island (parabolic and barchans), 3) paleodunes (middle unit sensu Sawakuchi et al., 2008), 4) active beaches and 5) beach ridges. The second facies criterion subdivided the samples into beaches (4 and 5), dunes (1 and 2) and paleodunes (3). The second facies grouping aimed to provide a more homogenous spatial distribution of the samples than the first grouping, with the purpose of preparing interpolation maps based on the inverse weighted distance method. The inverse weighted distance method is a straightforward and robust interpolation method implemented as a standard in many GIS software packages (Longley et al., 2001). The maps were made in ArcGIS software using a 200 m × 200 m cell size and a power of two for the interpolation method.

3.3. Heavy mineral analysis

The very fine sand fraction was chosen for the separation of heavy minerals using bromoform ($CHBr_3$; $\rho = 2.85$ g/cm^3). All samples were submitted to heavy mineral quantification following the "ribbon counting" method (Galehouse, 1971; Mange and Maurer, 1992), which consists of the counting of non-opaque and non-micaceous grains (ranging from 100 to 200 grains) in randomly selected bands along a microscope slide. Heavy mineral indices based on pairs of minerals were determined as suggested by Morton and Hallsworth (1994). These authors proposed counting a minimum of 100 and a maximum of 200 grains per pair (A and B) of minerals. These indices were obtained for 33 samples with homogenous spatial distribution. The *AB* indices (*ABi*) were calculated using Equation (1) (according to Morton and Hallsworth, 1994).

$$ABi = \frac{A}{(A+B)} \times 100 \quad (1)$$

The heavy mineral indices were used to evaluate patterns of sediment transport, changes in sediment sources and the influence of weathering since the epoch of deposition of the heavy mineral assemblage. For this reason, the physical characteristics (e.g., density and shape) and chemical stability (i.e., resistance to dissolution) of the most common minerals occurring in the region (Table 2) were tabulated to define pairs of minerals. They were then classified by sensitivity to transport, source and age (post-depositional dissolution).

Two contrasting mineral groups were defined based on density: a less dense group (hornblende, tourmaline, sillimanite, epidote and kyanite) and a denser group (rutile, zircon and garnet). Minerals with a high frequency of occurrence and intermediate densities, such as staurolite, were excluded from this grouping.

The minerals composing the *ABi* must have a high frequency of occurrence and as many similar or contrasting physical and/or chemical properties as possible in order to isolate the influence of a specific control factor. Thus, rutile and zircon (RZi) were selected to determine source area variation because they have similar physical and chemical behaviors, but different source rocks (there is a preferential association of rutile with high-grade metamorphic rocks; Force, 1980). Tourmaline and hornblende (THi) were chosen to verify the chemical maturity and relative ages of the sediment samples due to their similar physical properties (density and shape) but contrasting chemical persistences. However, if the dissolution

Table 2
Physical and chemical properties of the most common heavy minerals described in the Ilha Comprida sediments. Data based on Pettijohn et al. (1987) and Mange and Maurer (1992). E = equidimensional, P = prismatic.

Mineral	Minimum Density	Maximum Density	Shape	Mineral Stability
Anatase	3.82	3.97	E	Ultrastable
Andalusite	3.13	3.16	P	Metastable
Kyanite	3.53	3.65	P	Metastable
Clinopyroxene	2.96	3.96	P	Unstable
Epidote	3.38	3.49	E	Metastable
Staurolite	3.74	3.83	E and P	Metastable
Garnet	4.2	4.3	E	Metastable
Hypersthene	3.21	3.96	P	Unstable
Hornblende	3.02	3.5	P	Unstable
Monazite	5	5.3	E	Metastable
Perowskite	5.17	5.17	E	–
Rutile	4.23	5	E	Ultrastable
Sillimanite	3.23	3.27	P	Metastable
Titanite	3.45	3.55	E	Metastable
Tremolite	3.02	3.44	P	Unstable
Tourmaline	3.03	3.25	E and P	Ultrastable
Zircon	4.6	4.7	E and P	Ultrastable

effect between the two was negligible, THi was used to determine source area variation. Tourmaline and zircon (TZi) were chosen for the determination of sediment transport pathways because they have similar chemical stabilities but different shapes and densities and, consequently, distinct hydraulic equivalences.

Maps of heavy mineral concentrations and *ABi* were created with the inverse weighted distance interpolation method. The same method was also used to present the grain size data.

3.4. Statistical methods

Descriptive statistics (mean, standard deviation, first quartile, median, third quartile, minimum and maximum) created a summary of the grain size data and allowed for a preliminary comparison between the different groups of samples. Groups of sediment samples were compared by their grain size arithmetic means using the Student's *t*-test with a significance level of 0.05. A Student's *t*-test is adequate to compare two independent groups of samples (e.g., wave-deposited sand versus aeolian) using their means and variances (Witte and Witte, 2003).

The Pearson product moment coefficient (r) was used to measure the degree of linear correlation between grain size and heavy mineral variables. A two-tailed hypothesis test evaluated the significance of the correlation coefficients. P-values less than 0.05 were used to accept significant correlations.

4. Results

4.1. Grain size

In general, the grain size results agreed with previous studies conducted in the region. Samples classified as fine sand (84% of the samples) and very fine sand (14%) predominated, with sorting degrees varying from very well sorted (58%) to well sorted (43%). The sediment samples grouped by morphological facies or depositional processes were compared by their grain size statistics (Table 3). Skewness was the only grain size statistic that differentiated wave deposits from aeolian sands, apparently without any spatial influence. For the other grain size statistics, no significant granulometric differences were observed between different morphological- or process-based groups. The main factor controlling the grain size variability of the studied samples is the spatial distribution within the barrier. When grouped by sedimentary processes as well as by morphological facies, the sand samples presented a remarkable trend of becoming finer and more sorted from southwest to northeast, parallel to the coastline (Figs. 2 and 3).

Despite the relative grain size homogeneity, the mean diameter of the sand fraction displayed a remarkable pattern of longitudinal variation within the Ilha Comprida barrier (Fig. 4). However, there

Table 3
Descriptive statistics of the grain size of the sediment samples grouped by morphological facies and sedimentary process: 1) foredunes (active and stabilized), 2) active features of a dunefield at the northeastern region of the island (parabolic and barchans), 3) paleodunes (middle unit; sensu Sawakuchi et al., 2008), 4) active beaches and 5) beach ridges.

	Beach Ridge (5)	Dunefield (2)	Foredune (1)	Paleodune (3)	Beach (4)	Aeolian (1,2,3)	Wave Deposited (4,5)
Mean diameter (phi)							
N	41	4	88	47	65	139	106
Mean	2.79	2.96	2.82	2.62	2.77	2.76	2.78
StDev	0.15	0.07	0.22	0.22	0.25	0.24	0.22
Minimum	2.49	2.88	2.23	2.00	2.18	2.00	2.18
Q1	2.67	2.89	2.72	2.48	2.55	2.58	2.62
Median	2.78	2.96	2.83	2.61	2.80	2.79	2.80
Q3	2.93	3.02	2.97	2.77	2.99	2.94	2.95
Maximum	3.07	3.03	3.50	3.00	3.13	3.50	3.13
Standard Deviation							
N	41	4	88	47	65	139	106
Mean	0.33	0.29	0.33	0.35	0.37	0.34	0.35
StDev	0.05	0.03	0.06	0.05	0.08	0.06	0.07
Minimum	0.22	0.25	0.19	0.24	0.23	0.19	0.22
Q1	0.29	0.26	0.29	0.32	0.31	0.29	0.30
Median	0.33	0.30	0.33	0.35	0.36	0.34	0.34
Q3	0.36	0.31	0.37	0.38	0.41	0.38	0.39
Maximum	0.45	0.31	0.52	0.49	0.57	0.52	0.57
Skewness							
N	41	4	88	47	65	139	106
Mean	−0.12	0.49	0.24	0.42	−0.14	0.30	−0.13
StDev	0.58	0.34	0.53	0.30	0.74	0.47	0.68
Minimum	−2.17	0.01	−1.29	−0.11	−3.76	−1.29	−3.76
Q1	−0.44	0.13	−0.04	0.20	−0.52	0.05	−0.47
Median	−0.05	0.60	0.25	0.35	−0.08	0.30	−0.07
Q3	0.11	0.75	0.54	0.64	0.46	0.58	0.35
Maximum	0.93	0.76	1.97	1.03	1.32	1.97	1.32

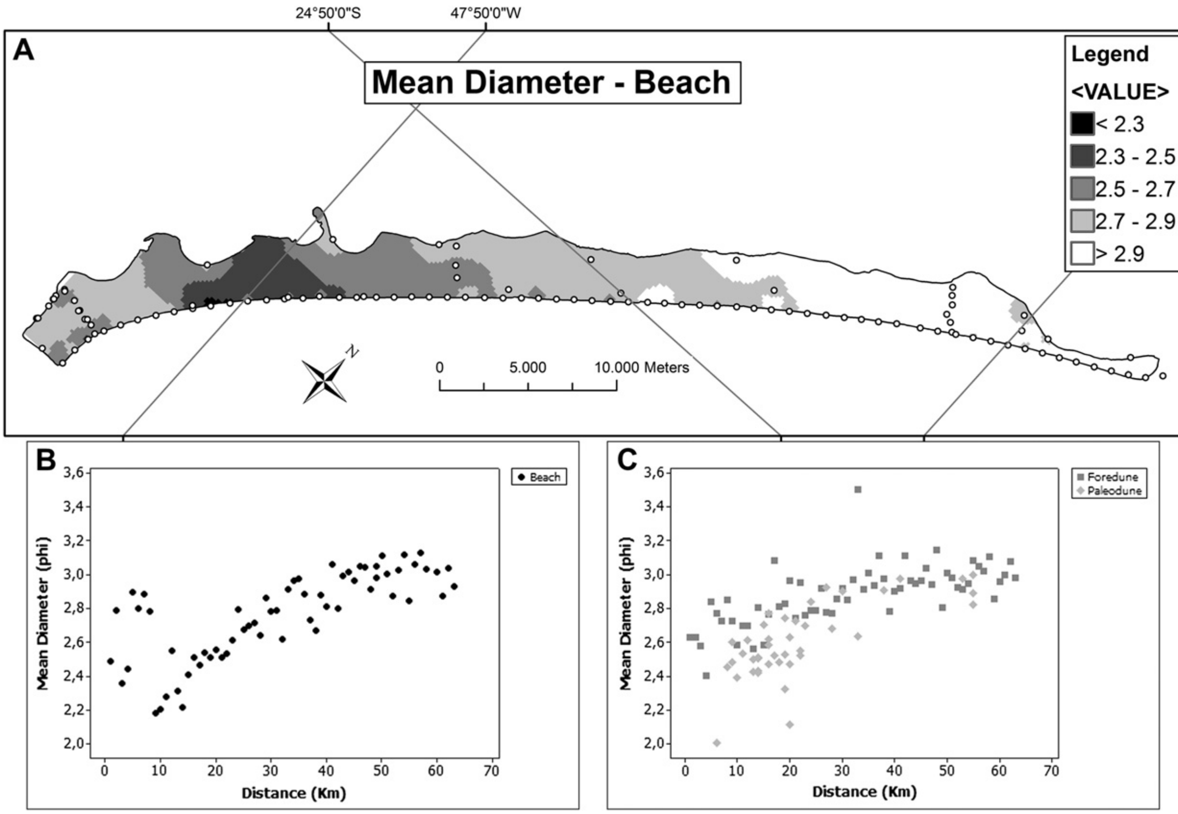

Fig. 3. Spatial variations in the mean diameter (phi units) of the sand fractions in the beach and paleobeach sediments (A). Graphics of mean diameters for beach sands (B), dune sands and paleodune sands (C). Distances are relative to the southwestern end of the barrier. White points represent the locations of samples used in the interpolation.

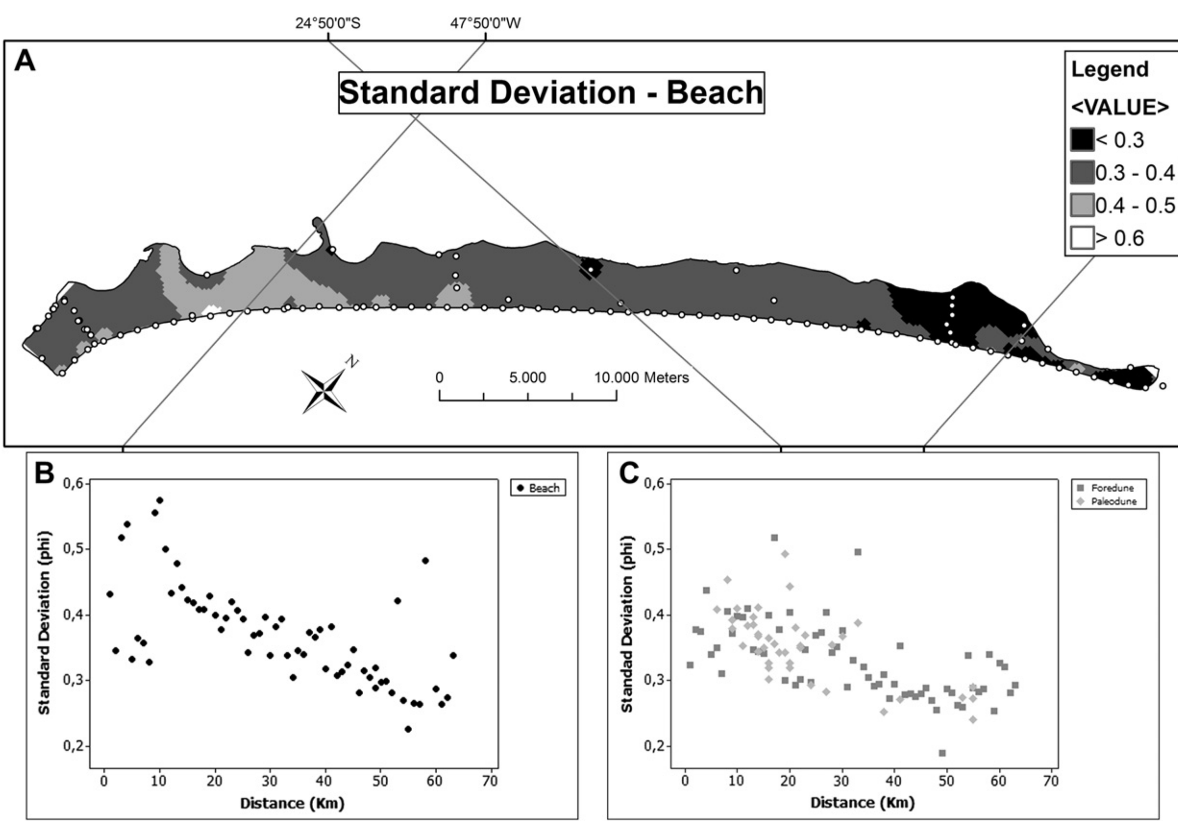

Fig. 4. Spatial variations in the grain size standard deviation (phi units) of beach and paleobeach sediments (A). Graphics of grain size standard deviations for beach sands (B), dune sands and paleodune sands (C). Distances are relative to the southwestern end of the barrier. White points represent the locations of samples used in the interpolation.

was no significant grain size variation across the barrier. Recent beach sands, old beach ridges, active dunes and stabilized dunes presented a tendency for coarser sediments toward the central, southern portion of the island. This pattern was previously described for the recent beach sands (Tanaka et al., 2005; Nascimento, 2006; Nascimento et al., 2008; Giannini et al., 2009). Within the aeolian samples, paleodune sands were approximately 0.2 phi coarser than foredune sands (Fig. 4 and Table 3), which suggests either a higher wind energy/sediment input ratio in the past relative to the present or a coarser and/or less reworked source (beach sands) under different morphodynamic conditions in the past relative to the present.

The spatial variation in the standard deviation of the sand fraction was similar to the pattern presented by the mean diameter, with significant variation along the barrier and higher values (lower sorting) in the mid-southwestern portion of the Ilha Comprida barrier (Fig. 3). Thus, the sorting of beach, dune and paleodune sands increased along barrier from the southwest to the northeast. There was no significant variation transverse to the coast.

The skewness of 16% of the analyzed samples was approximately symmetric, whereas 28% had negative and 56% had positive skewness. The skewness of the sand fraction was not significantly affected by the geographical localization, which differentiated it from the two other moment statistics (Fig. 5). The divergent trend from the mid-southwest, also found in the mean diameter and standard deviation data, was only observed by skewness for wave-deposited samples (beach and paleobeach). The trend was diffuse and almost unrecognizable in the aeolian dunes and paleodunes maps. There was a general predominance of negative to zero skewness for wave-deposited samples. In contrast, aeolian samples had zero to positive skewness. The distinction between the two groups was confirmed by a Student's *t*-test, with a *t*-value of 5.54 and 243 degrees of freedom. This t-value (*P*-value <0.01) rejected the null hypothesis of a similar behavior between wave-deposited and aeolian sands and confirmed that the positive skewness was an aeolian signature.

4.2. Heavy minerals

The mean heavy mineral concentration within the very fine sand fraction was 6.7%, with the aeolian sands (mean = 8.8%) presenting a heavy mineral concentration almost three times higher than that of the wave-deposited sands (mean = 3.1%). However, the effect of spatial variation of heavy mineral concentrations was greater than the variation due to the mode of deposition (wind-deposited sands versus wave-deposited sands). This finding was widely present across the barrier. The spatial variation of heavy mineral concentrations agreed with the alongshore circulation pattern proposed by Nascimento (2006), Nascimento et al. (2008), and Giannini et al. (2009). This pattern is characterized by divergent alongshore currents that start at the mid-southwestern portion of the island. The mid-southwestern portion of the island had a higher heavy mineral content, which decreased toward the two island extremes (Fig. 6). Since this trend was also found with grain size, these results illustrate that the distance of sediment transportation is more effective than the mode of deposition in defining heavy mineral concentration.

Because rutile and zircon have similar physical and chemical properties, the RZi can be used as a robust indicator of sediment source (Morton and Hallsworth, 1994). In addition, the RZi is also useful to interpret the geological significance of the THi and TZi. The THi is sensitive to post-depositional dissolution and source area, while the TZi is affected mainly by source area and hydraulic

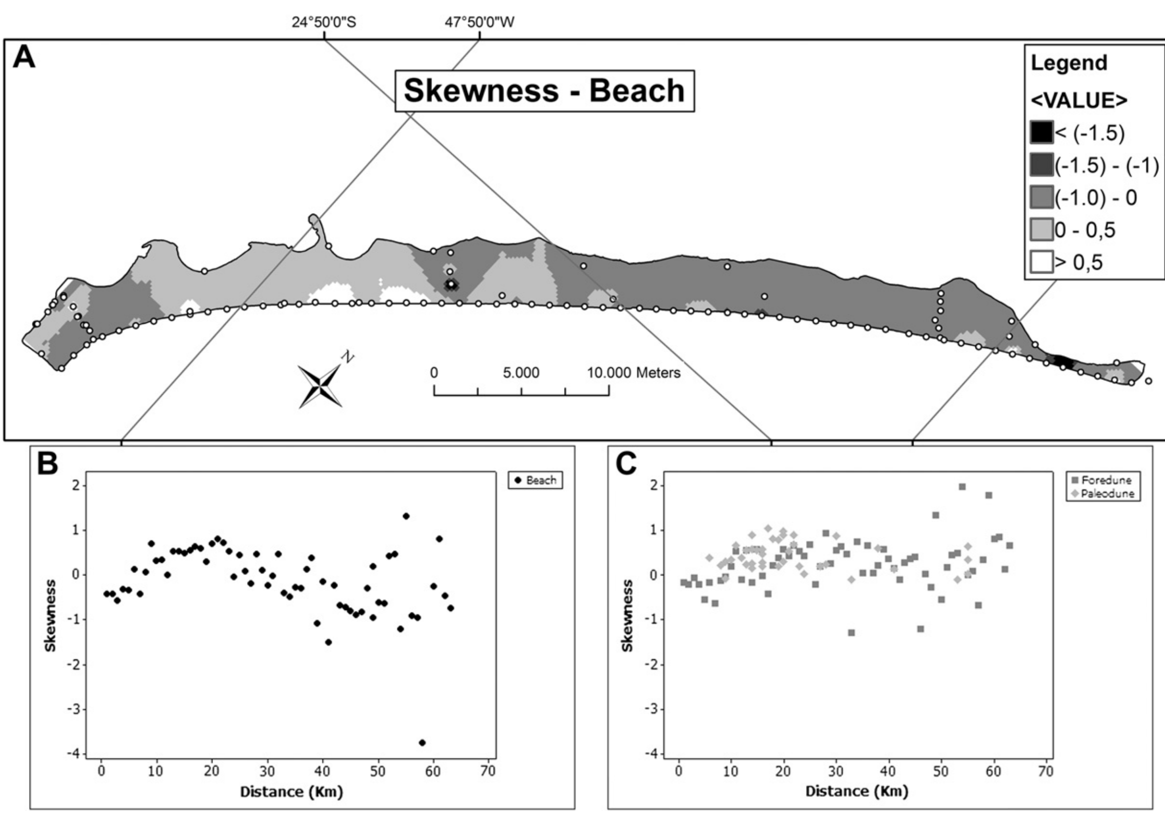

Fig. 5. Spatial variations in the grain size skewness of beach and paleobeach sediments (A). Graphics of grain size skewness for beach sands (B), dune sands and paleodune sands (C). Distances are relative to the southwestern end of the barrier. White points represent locations of samples used in the interpolation.

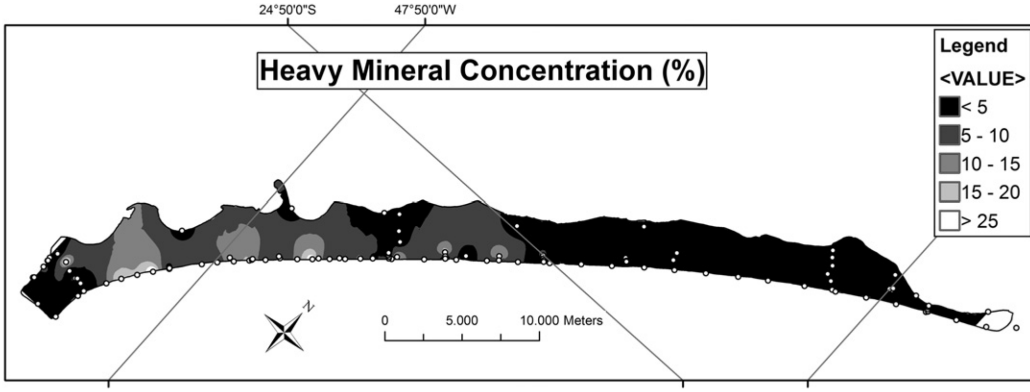

Fig. 6. Variations in heavy mineral concentrations (very fine sand) in the Ilha Comprida barrier (all samples grouped). The highest values were concentrated in the mid-southwestern portion of the island as a response to a residual lag effect. White points represent locations of samples used in the interpolation.

sorting. Thus, the RZi allows for the evaluation of the possible effect of source area on TZi and THi.

The interpolation map of RZi (Fig. 7) shows variations in source area between the northeastern and southeastern portions of the barrier, with a relatively higher content of rutile in the northeastern portion. The lack of significant differences in RZi transverse to the island (i.e., crossing timelines) suggests the absence of important shifts in provenance during the evolution of the Ilha Comprida barrier.

The THi is composed of heavy minerals (tourmaline and hornblende) with similar hydraulic behaviors and contrasting chemical and physical stabilities. Thus, the THi was calculated with the initial objective of determining the influence of post-depositional dissolution on the heavy mineral assemblage. The influence of post-depositional dissolution, initially thought to be the most important factor controlling the THi, can be re-evaluated through the comparison between ancient and recent sediments. The absence of significant changes in the THi across the barrier suggests that the post-depositional dissolution, which is proportional to the age of the beach ridges, is not the main factor controlling this index (Fig. 8). In contrast, significant changes in the THi values occurred along the barrier, with an increase in the relative abundance of hornblende in the northeast. Without the influence of post-depositional dissolution, the THi can be used as an index for source area.

The TZi (Fig. 9) was used in combination with the distribution of heavy mineral concentrations (Fig. 6) and the proportions of various densities of heavy minerals (Fig. 10) to interpret patterns of sedimentary transport through hydraulic sorting. All indicators showed the same pattern, with an increase in the proportion of less dense minerals near the ends of the island and lower values in the mid-southwestern region. This pattern fits with the interpretation of a zone of divergence resulting from alongshore drift currents.

5. Discussion

5.1. The influence of the mode of sediment transport (wind versus wave) on grain size and heavy minerals

Skewness was the grain size measure that best discriminated aeolian sands from wave-deposited sands. This discrimination was a result of the variation in skewness of wave-deposited sands in comparison to their aeolian counterparts (dunes and paleodunes, Fig. 5). It confirmed the previously proposed differentiation between foredunes and beach sands (Nascimento et al., 2005; Nascimento, 2006). The more positive skewness of aeolian sediments can be explained by the reduced competence of the local wind to transport coarse sand from the beach fractions. This results in a higher relative concentration of the finer fraction on aeolian sediments. According to Bagnold (1941), the very fine and fine sand fractions present the minimum threshold wind velocity for transportation. The lag concentration of coarser fractions left at the beach, along with the major competence of water in transporting sediments toward the sea, creates a negative skewness for wave-deposited sands.

Beach ridge samples that were interpreted as wave-deposited sands based on geomorphology (despite the absence of sedimentary structures) had a negative skewness. Thus, grain size skewness

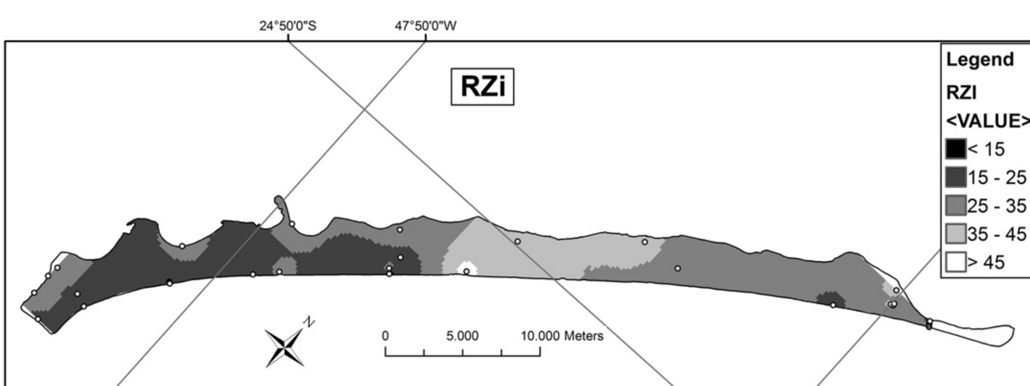

Fig. 7. Variations in RZi within the Ilha Comprida barrier. Changes throughout the barrier indicate provenance variations. White points represent locations of samples used in the interpolation.

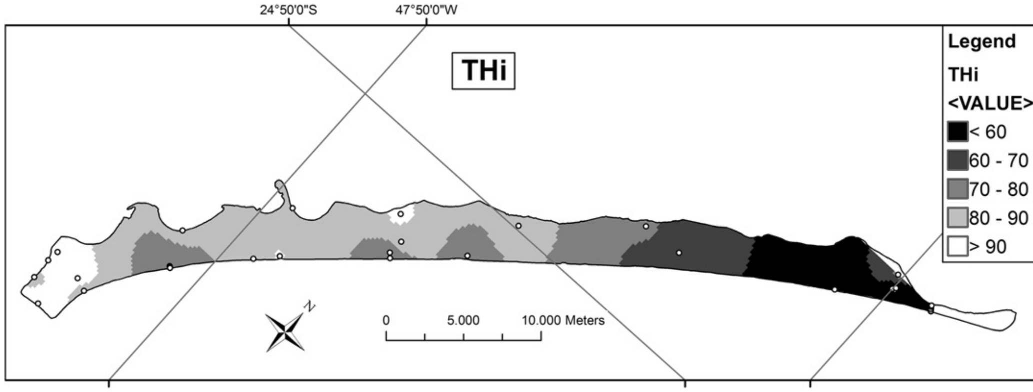

Fig. 8. Variations in THi within the Ilha Comprida barrier. The lowest values of THi were attributed to the Ribeira de Iguape River contribution. White points represent locations of samples used in the interpolation.

is a good criterion to differentiate between aeolian sediments and wave-deposited sediments on the Ilha Comprida.

In the studied sediments, the relationship between grain size and heavy minerals (Table 4 and Fig. 11) had two main characteristics: 1) the linear correlation of the heavy minerals (specific percentages) with the mean diameter of grains had the opposite sign of the correlation between the heavy minerals and grain size standard deviation and 2) the correlation coefficients between heavy minerals and grain size statistics were higher for aeolian deposits than for wave deposits. The first characteristic was related to the sedimentary transport along the island. In areas of longer transport, there were finer, more sorted sediments and higher concentrations of less dense heavy minerals, such as hornblende and tourmaline. Additionally, coarser and poorly sorted sands with higher concentrations of heavier minerals, such as zircon and rutile, were concentrated in the opposite direction of transport. The second characteristic was related to the transport of sand by wind. The higher concentration of heavy minerals in aeolian sediments and the preferential transport of the finer fraction by the wind probably increased the correlation between heavy minerals and grain size statistics.

5.2. Direction of sediment transport and source areas

The trends of finer grains, better sorting and more negative skewness for both recent and old beach sands from the mid-southwestern portion of the island toward its extremities agree with the hypothesis of a grain size trend of sediment transportation as proposed by McLaren and Bowles (1985). Based on the assumptions of McLaren and Bowles, two directions of resultant alongshore drift might be interpreted with a zone of divergence at the mid-southwestern portion of the barrier. This coastal circulation pattern was previously recognized by Nascimento et al. (2005, 2008) and Giannini et al. (2009) in recent foreshore sediments. Thus, our results suggest that this recent pattern of coastal circulation has been present throughout the entire evolutionary history of the island.

The negative correlation between the less dense minerals (tourmaline and hornblende) and the heavier minerals (zircon and rutile) (Table 5) confirms the strong influence of hydraulic sorting on the distribution of heavy minerals along the Ilha Comprida barrier. Despite source area variation, rutile and zircon had a positive correlation ($r = 0.529$ and $p = 0.000$). This correlation demonstrated that proportions of rutile and zircon are controlled by another factor, such as hydraulic sorting, despite source area changes.

The absence of significant correlations between hornblende and tourmaline (Table 5), which have similar hydraulic characteristics, suggests the dominance of provenance and/or post-depositional controls on the distribution of these minerals. Theoretically, post-depositional dissolution can significantly reduce the content of hornblende (which is chemically unstable) in relation to the content of tourmaline (which is chemically ultrastable). However, low variations of THi between recent and old beach ridges (in transects across the barrier) indicated little influence of post-depositional dissolution on the heavy mineral assemblage during the evolution of the Ilha Comprida barrier. The correlation between hornblende and tourmaline contents for recent sediments (e.g., beaches and foredunes) that are not supposed to be affected by post-depositional dissolution was insignificant ($r = -0.18$ and

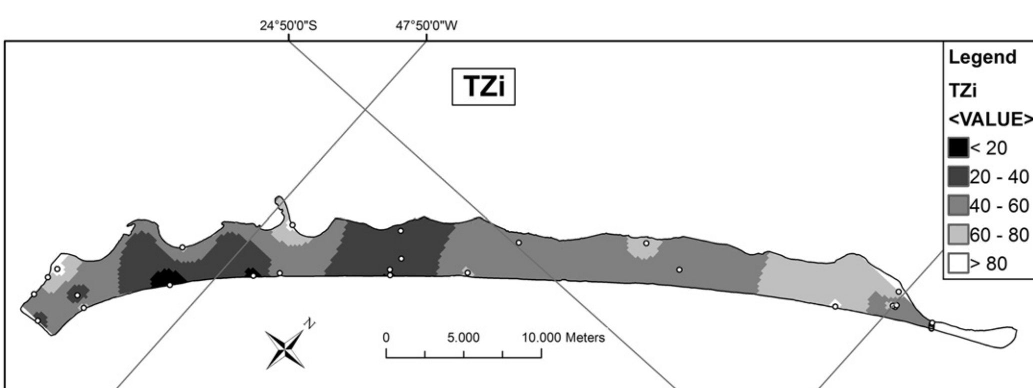

Fig. 9. Variations in TZi within the Ilha Comprida barrier. The high concentration of zircon (low TZi) at the mid-southwestern portion of the island indicates a sedimentary transport pattern to the barrier's extremities. White points represent locations of samples used in the interpolation.

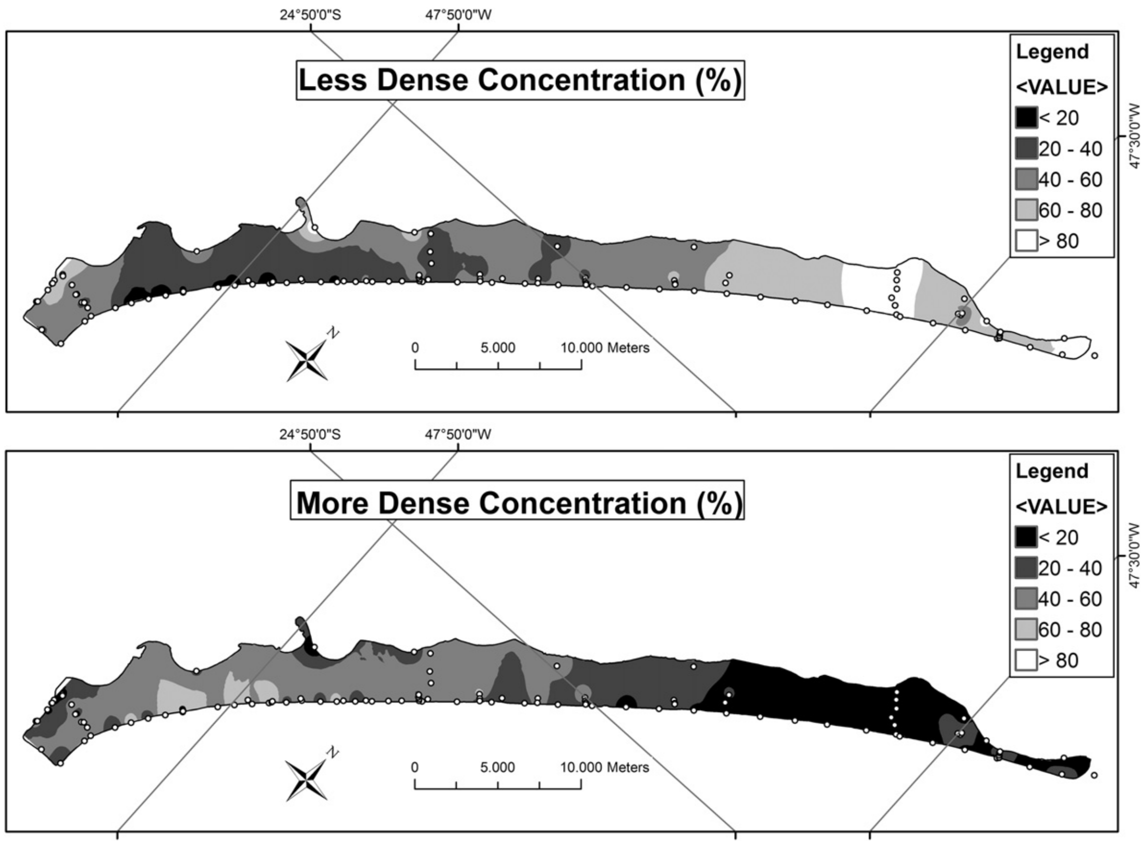

Fig. 10. Variations in the proportion of the denser and less dense heavy minerals within the Ilha Comprida barrier. This variation shows a similar pattern to the other sedimentary transport indices (TZi, heavy minerals concentration and grain size). White points represent locations of samples used in the interpolation.

$p = 0.127$). Thus, variations of THi can mainly be attributed to changes in the sediment provenance. The high alongshore and low across-shore variations of RZi and THi (Fig. 8) emphasize that the spatial shifts of sediment provenance surpass the temporal ones. The Ribeira de Iguape River is likely the source of sediments enriched in hornblende grains (Tessler, 1988). Indeed, high concentrations of hornblende grains (up to 56%) were found by De Maman (2006) in sandy sediments from Holocene terraces of the lower Ribeira de Iguape River in Registro (Fig. 1). Additionally, sediments from inland areas drained by the Ribeira de Iguape River have been stocked at the continental shelf as a result of the last post-glacial relative sea-level rise. Hence, sediments with low THi (i.e., a high content of hornblende) in the Ilha Comprida barrier were sourced directly from the Ribeira de Iguape River and further dispersed through the subordinate littoral drift from the northeast or by the cross littoral drift from the ancient Ribeira de Iguape River sediments stocked in the inner shelf. Sediments with high THi (i.e., a low content of hornblende) were supplied by the littoral drift from the southwest.

Table 4
Pearson correlation coefficients and *P*-values of heavy mineral concentrations and grain size statistics of aeolian and wave-deposited sediments.

	Mean Diameter		Standard Deviation	
	Aeolian	Wave Deposited	Aeolian	Wave Deposited
Zircon	−0.707	−0.269	0.571	0.071
P-Value	0.000	0.020	0.000	0.548
Rutile	−0.334	−0.235	0.249	0.056
P-Value	0.001	0.044	0.011	0.634
Hornblende	0.522	0.369	−0.533	−0.010
P-Value	0.000	0.001	0.000	0.930
Tourmaline	0.380	−0.003	−0.343	−0.153
P-Value	0.000	0.977	0.000	0.193
Epidote	0.684	0.343	−0.527	−0.278
P-Value	0.000	0.000	0.000	0.016
Staurolite	0.232	−0.309	−0.122	0.023
P-Value	0.018	0.007	0.219	0.051
More Dense	−0.709	−0.277	0.569	0.068
P-Value	0.000	0.017	0.000	0.566
Less Dense	0.676	0.352	−0.578	−0.229
P-Value	0.000	0.002	0.000	0.049

The strong correlation between groups of heavy minerals of low and high densities suggests a high interdependence between these two variables ($r = -0.898$ and $p = 0.000$). This interdependence is a result of the hydraulic sorting by the resultant alongshore drift. Tourmaline and zircon had a correlation coefficient of −0.482 ($p = 0.000$). This result was probably a response to the hydraulic sorting control in the dispersion of these minerals. The trends of the spatial variations found for TZi, the heavy mineral concentrations and the content of heavy minerals of various densities was the same. This trend was characterized by little variation across the barrier and an increase in the content of less dense minerals from the mid-southwestern portion of the island toward the northeast and southwest. This pattern can be attributed to hydraulic sorting control and suggests a divergence of resultant alongshore drifts in the mid-southwestern region. These findings agree with previous studies that described features indicative of sedimentary supply starting from this region (e.g., Nascimento, 2006; Nascimento et al., 2008; Giannini et al., 2009).

The heavy mineral assemblages identified in the analyzed sands are compatible with the rocks cropping out in the area of the Ribeira de Iguape River basin. Almost all minerals are found in sediments from the inner continental shelf and coastal plain

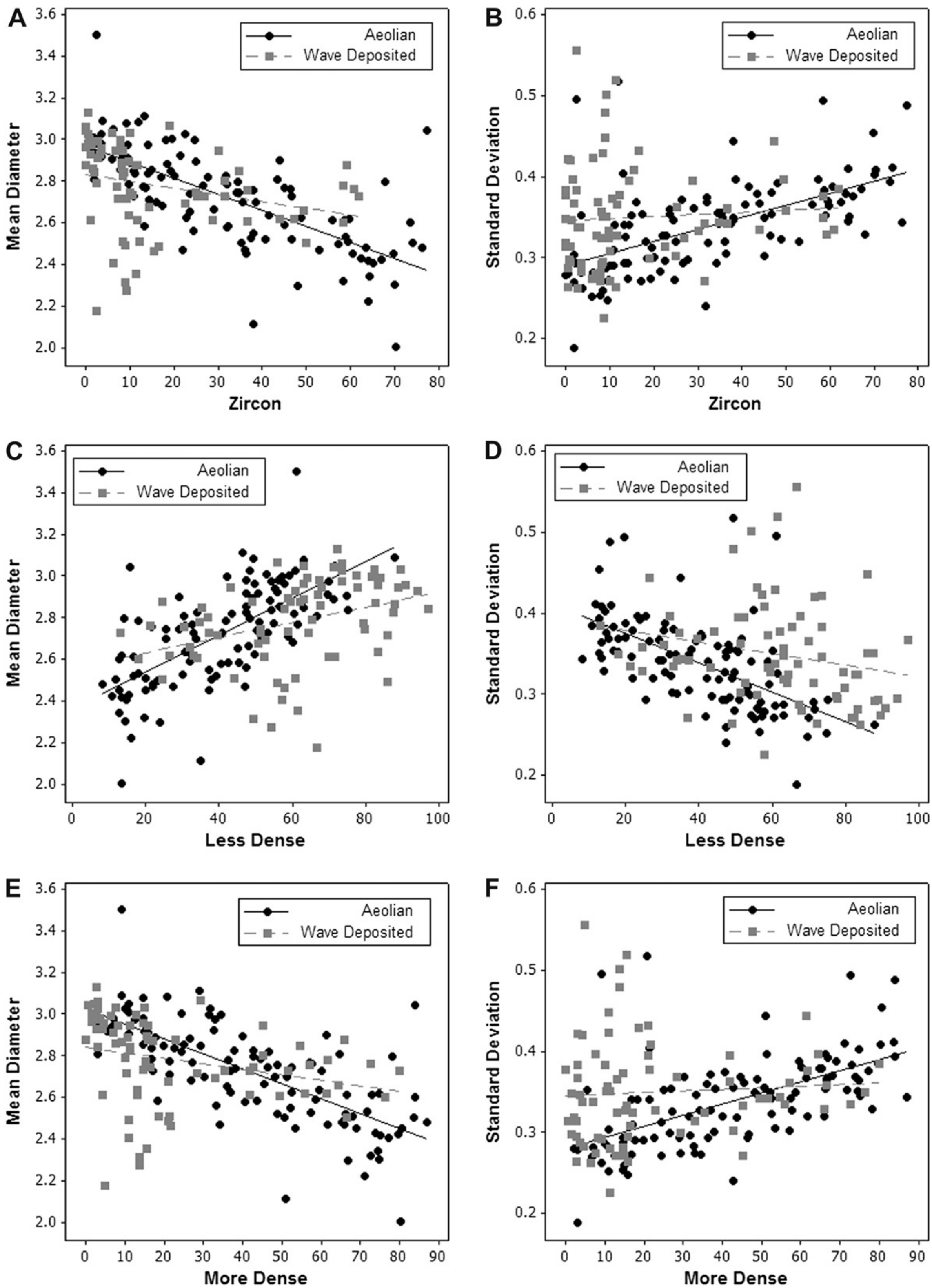

Fig. 11. Scatterplots of zircon concentration (%) versus grain size mean diameter (phi) (A), zircon concentration (%) versus grain size standard deviation (phi) (B), less dense heavy minerals (%) versus grain size mean diameter (C), less dense heavy minerals (%) versus grain size standard deviation (D), denser heavy minerals versus grain size mean diameter (E) and dense heavy minerals versus grain size standard deviation (F). The correlations observed for the aeolian samples were absent for wave-deposited sediments.

(Tessler, 1988). Thus, the estimation of the relative contribution of sediments from each source area is a very complex task. However, hornblende appears to be a good signature of the sediments from the Ribeira de Iguape River due to the spatial behavior of the THi. Similarly, the RZi seems to be an indicator of source area changes linked with the river sedimentary supply. There is a preferential association of rutile with high-grade metamorphic rocks (Force, 1980), and the increase in its relative abundance in the northeastern

Table 5
Pearson correlation coefficients and *P*-values of the heavy minerals used to compute the RZi, THi and TZi indices.

	Tourmaline	Zircon	Hornblende	Rutile	Less Dense
Zircon	−0.482				
P-Value	0.000				
Hornblende	0.004	−0.622			
P-Value	0.963	0.000			
Rutile	−0.307	0.529	−0.536		
P-Value	0.000	0.000	0.000		
Less Dense	0.675	−0.879	0.625	−0.617	
P-Value	0.000	0.000	0.000	0.000	
More Dense	−0.487	0.982	−0.661	0.677	−0.898
P-Value	0.000	0.000	0.000	0.000	0.000

region may be related to the increase of sediments derived from high-grade metamorphic rocks drained by the Ribeira Iguape basin.

A model for the various sediment sources of the Ilha Comprida is illustrated in Fig. 12. The Ribeira de Iguape River contribution occurs at the river mouth as an indirect reworking of ancient deposits stored in the inner continental shelf. This last contribution is associated with the secondary northeast to southwest alongshore drift related to the trade winds and the east/northeast wave systems. Other important regional sources are the reworked sediments in the coastal plain, which are mainly of Pleistocene age (related to the Penultimate Interglacial). These sediments are furnished by the Icapara and Cananéia inlets and are dispersed by the predominant southwest to northeast alongshore drift linked with cold fronts and the south/southeast wave systems. The evidence of sedimentary reworking by alongshore drift, even to recent beach ridges (Nascimento et al., 2008) and inner beach ridges, indicates that the coastal circulation and the Ribeira de Iguape River sedimentary supply has not experienced major changes over the last 6000 years. The budget between the supply of the Ribeira de Iguape River (triggered by trade winds) and that of southern regional sources (through the cold fronts) remained nearly the same. Even small climatic changes with a beach-dune system effect, as detected in the Ilha Comprida barrier during the Little Ice Age climatic event (Sawakuchi et al., 2008), would not affect the Ribeira de Iguape River discharge. Indeed, periods of high frequency of cold fronts and storm weather conditions are related to erosion and/or stable coastlines (Sawakuchi et al., 2008). Thus, stormy periods would be poorly recorded or not even registered in the strictly sedimentary record. In fact, Giannini et al. (2003, 2009) found storm evidence at the Ilha Comprida that were comprised of a 0.3 m thick heavy mineral concentrated sand layer that was associated with hummocky and swalley cross stratification. This evidence was not recurrent in the sedimentary record of this barrier. Rather, the occurrence was limited to the inner part of a profile across the southern portion of the barrier.

6. Conclusions

- The combination of grain size and heavy mineral analyses is a useful tool to determine sedimentary transportation patterns, especially in systems with strong hydraulic and aerodynamic sorting.
- Heavy mineral indices proved to be reliable for discrimination between contributions from rivers, draining primary rocks and sediment reworking. This finding suggests a great potential for use in similar geological settings of wave-dominated systems in humid climates.
- The TZi is a good indicator of the direction of sediment transport. Both tourmaline and zircon are also commonly found in sandstones and Holocene sediments. Thus, the TZi index can be applied to a wide range of studies. Other mineral pairs with similar stabilities and sources but different hydraulic behaviors could be used when tourmaline and zircon are absent or are not abundant.
- The stillstand behavior of heavy minerals and grain size patterns from outer to inner beach ridges suggests that climate changes in the past 6000 years were not enough to modify the Ilha Comprida costal circulation pattern and the Ribeira de Iguape River fluvial discharge.

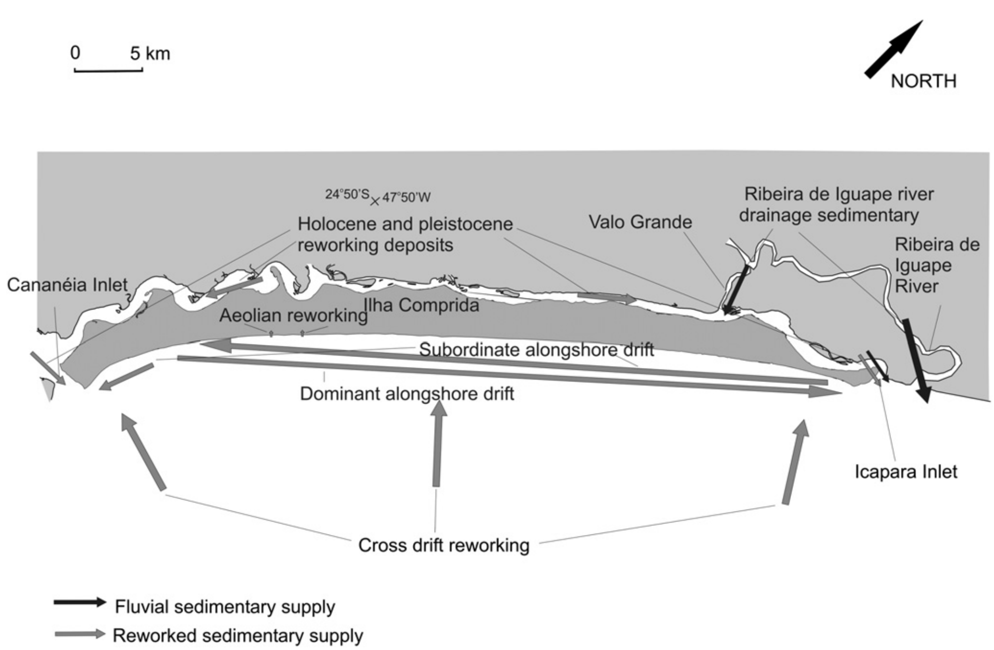

Fig. 12. Model of sediment source and transport in the Ilha Comprida barrier system. The Ribeira de Iguape River is the main source of sediments derived from primary source rocks. Reworked sediments are supplied from the coastal plain and inner continental shelf by inlets and alongshore and across-shore littoral drifts.

Acknowledgements

The authors would like to thank Professor Moyses Gonsalez Tessler for helpful discussions, M.Sc. Mariane Brumatti for comments on the text and Dr. James N. Kellogg and two anonymous reviewers who provided constructive comments on the manuscript. This work was funded by the Fundação de Amparo à Pesquisa do Estado de São Paulo (FAPESP 2001/01732-8, 2002/01016-3, and 2007/51511-4) and the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq 135013/2007-0).

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