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Principal component analysis (PCA) and mineral associations of litoraneous facies of continental shelf carbonates from northeastern Brazil

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ABSTRACT

The distribution of mineral phases according to the provenance of carbonate and terrigenous facies of carbonate sediments from a large area of the continental shelf of northeast Brazil was investigated using a major element multivariate analysis approach. Heavy minerals such as ilmenite are restricted to the litoraneous facies of the continental shelf of the states of Paraíba and Pernambuco, and clay minerals are found in distal facies of the continental shelf of the State of Ceará. In the carbonate fraction, composed essentially by Mg-calcite and aragonite, there is co-variation between CaO/MgO and bathymetry in part of the studied continental shelf from depths between 15 and 20 m, apparently due to influence of the seawater temperature, degree of oxygenation and luminosity. The terrigenous facies are mainly composed of quartz, clay minerals, K-feldspars and micro-micaceous minerals, having Fe and Ti oxide and hydroxide minerals as major accessory phases. Major element behavior attests to the presence of arenaceous quartz-rich relict sediments in the 35, 60 and 80 m isobaths of the continental shelf of the state of Ceará which is here interpreted as a proxy of ancient coast lines during the Flandrian transgression.

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1. Introduction

Principal component analysis (PCA) is a method of multi-variable analysis used in the interpretation of a many-variable data matrix by many authors (e.g. da Silva et al., 2005; Jolliffe, 2002; Sass-Kiss et al., 2008; Gil et al., 2008). The basic statistic procedure is based on the construction of new variables and reduction of large initial matrix. This simplification of data is done using linear combinations of the variables of the original matrix, which allow adequate visualization of the results that are grouped according to their similarities. This way, in a matrix of geochemical data, the chemical species are combined according to their provenance in the formation environment.

Therefore, new data from these linear combinations are derived, forming the principal components (PC) which can be

displayed as scores and weights in bi- or tri-dimensional diagrams as pointed out by several authors (e.g. da Silva et al., 2005; Mataragas et al., 2007; Polat and Günes, 2008; Azevedo et al., 2008). The scores and weights represent, respectively, sample distribution and influence of variables. The PC graph is formed by vectors that represent the variance coordinates.

PCA is broadly used in geochemical studies (e.g. Azevedo et al., op cit; Fernandes et al., 2008; Tavares et al., 2008; Cancès et al., 2008). In the case of a geochemical data matrix, each vector shows that the data spread according to their geochemical affinity and provenance. This way, these affinities can provide information about the provenance of the groups of oxides. For example, Yang and Youn (2007) and Foster et al. (2007) have pointed out that geochemistry is effective in the investigation of the origin of marine sediments, whose chemical variations depend on the nature of sediments dumped by rivers into the sea and lakes. Besides, according to Maloof et al. (2007) and Gingele et al. (2007), it can also help inferring climate conditions during sedimentary deposition.

Detailed geochemical studies of continental shelf carbonates of northeastern Brazil are still limited. With the scope of investigat-

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ing major oxide distribution and their geochemical affinities according to the provenance of the carbonate and terrigenous facies, PCA was applied to 208 chemical analyses of carbonate sediments from a large area of the continental shelf of north-eastern Brazil.

2. Study area

The study area is located in the eastern portion of the Brazilian continental shelf (Fig. 1) which encompasses sediments of the states of Piauí, Ceará, Rio Grande do Norte, Paraíba and Pernambuco, northeastern Brazil. The continental shelf, relatively narrow and shallow in this area, is 30 km wide, 50–80 m deep and has a steep continental slope (Behling et al., 2000). Its surface is slightly irregular and cut by well-developed channels (França et al., 1976). Sediments in this area are mainly in-situ biogenic carbonates and, at a less extent, continental terrigenous and relict sediments as reported by Coutinho (1992) and Summerhayes et al. (1975). The carbonate facies is mainly represented by Mg-calcite and aragonite. There is a lack of riverine sediment input in this area due to the fact that almost no small river-transported sediment reaches the ocean. Approximately 90% of the sediments transported by the São Francisco river, the major one in the region, is retained in its bottom (França et al., 1976).

The terrigenous facies is composed by reworked sediments from the Tertiary Barreiras formation, a widespread continental to shallow-marine sedimentary cover. This formation is composed by sand, red clays and conglomerates (Bezerra et al., 2008). The terrigenous facies of the continental shelf is also formed by Precambrian basement rock fragments predominantly of felsic composition, transported by rivers to the continental shelf (Freire, 1985).

3. Methods

This study includes a total of 208 bulk chemical analyses of platform sediments grouped into three sets: (1) one set from Mont'alverne (1982), from the state of Pernambuco, collected by dragging at depths from 0.5 to 56 m; (2) a second set (Freire, 1985) from the various states of northeastern of Brazil (Ceará, Pernambuco, Paraíba, Rio Grande do Norte, Alagoas), who analyzed samples collected by dragging during operations of the GEOMAR XVIII-Vitor Hense project (1981); GEOMAR XXI-REVISEE project (1983) in the oceanographic ship *Almirante Câmara* of the Brazilian Navy; and (3) a third set from the continental shelf of the state of Ceará, ceded by the Marine Geology Laboratory (LGMA) of the Federal University of Ceará.

All three set of samples have been collected by dragging with a van veen collector (device constituted by two articulated and open stainless steel shells that lock themselves as they touch the ground, storing sediments in its core). The three sets of samples have been washed using de-ionized water, dried at room temperature and stored in plastic bags. Before chemical analysis, they have been homogenized and split into four fractions, one of them ground in porcelain mortar and sieved in an 100-mesh sieve.

A 5 g aliquot from each LGMA samples was analyzed by X-ray fluorescence, at the Department of Geology, Federal University of Pernambuco. The other two sets of samples were analyzed by X-ray fluorescence at the Mineral Analyses Laboratory of SUDENE at Recife.

For determination of volatiles by loss in ignition (LOI), samples were dried at 110 °C during 6 h and placed into an oven at 1000 °C during 2 h. (LOI data are not available for Freire's samples). Each

dried sample was fused using Li-tetraborate as flush and fused discs were analyzed in a XRF Rigaku model RIX 3000, equipped with Rh tube, using the calibration curve method, prepared with certified reference materials and results are displayed in Table 1.

4. Results and discussion

4.1. Principal component analysis (PCA)

In PC1 versus PC2 diagram (Fig. 2), a clear distinction is made by PC1 values in relation to in-situ components (carbonates; PC1 values greater than +0.2) and allochthonous components (continental terrigenous facies; PC1 values, lower than –0.1).

4.1.1. Controlling factors of PCA in the study area

The data matrix used for the PCA include 12 parameters (major oxides, Mn and Sr). The first PC (PC1), or first auto-vector, is an axis in which the elements had maximum variance, or maximum scattering, but keeping chemical affinities. The second PC (PC2), orthogonal to PC1, represents the second largest variance axis, or the axis with maximum variance not explained by the first auto-vector. Matrix correlation of all data was done to look for correlation factors among the variables and provide supplementary data to those of PCA.

CaO, MgO and Sr are of carbonate affiliation and associated with them is P₂O₅, probably due to presence of autochthonous organic matter in the platform environment. Association of P with carbonate facies has been observed by Edwards et al. (2005), in the continental shelf of Mexico.

The terrigenous components are SiO₂, K₂O, Al₂O₃, TiO₂, Fe₂O₃ and Mn. Among these components, PCA allows identification of those related to coarser-grained detrital sediments, SiO₂ and K₂O (quartz and K-feldspar), and those related to finer-grained terrigenous sediments, Al₂O₃, Fe₂O₃, TiO₂, and Mn, which are related to clay minerals, pedogenic Mn and Fe, and ilmenite/rutile from the accessory fraction of heavy minerals.

Presence of K-feldspar in the inner platform is suggested by positive correlation between SiO₂ and K₂O, which indicates preferential paragenesis quartz and K-feldspar rather than quartz and clay minerals. The PCA statistical configuration shown in Fig. 2, probably reflects the dominance of a semi-arid climate of the continental area adjacent to the studied shelf, considering that climate plays an important role to the type of sediment transported to the continental shelf (Zecchin, 2007). Behling et al. (2000) have shown that a semi-arid climate has predominated in northeastern Brazil during the Late Quaternary, based on the study of pollens of oceanic sediments from the continental shelf of this area.

The PC1 value of the Mg/Ca ratios is at intermediate position between the other variables taken into account, associated both to carbonate and terrigenous facies, probably due to the fact that proximal carbonates contain more magnesium than distal ones due to temperature influence. The relationship between high-Mg calcite and environmental temperature has been already pointed by e.g. McArthur et al. (2007) and Kuhnert and Rathmann (in press).

4.2. Matrix of correlation

A correlation matrix with all available chemical data is shown in Table 1. Important factor correlations (*r*) are those between CaO and SiO₂ (–0.9); CaO and Al₂O₃ (–0.5); CaO and K₂O (–0.8); SiO₂ and Al₂O₃ (*r* = 0.6); Al₂O₃ and K₂O (*r* = 0.7), SiO₂ and K₂O (*r* = 0.8); Fe₂O₃ and TiO₂ (*r* = 0.7).

Table 1
Correlation matrix for major elements of all samples northeastern Brazil continental shelf in this study

	Depth (m)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	Ti	P ₂ O ₅	Mn (ppm)	Sr (ppm)	CaO/MgO
Depth (m)	1											
SiO ₂	-0.1	1										
Al ₂ O ₃	-0.2	0.6	1									
Fe ₂ O ₃	-0.2	0.1	0.6	1								
MgO	-0.1	-0.7	-0.3	0.1	1							
CaO	0.0	-0.9	-0.5	0.0	0.8	1						
K ₂ O	-0.1	0.8	0.7	0.1	-0.6	-0.8	1					
TiO ₂	-0.1	0.2	0.4	0.7	-0.1	-0.2	0.1	1				
P ₂ O ₅	0.2	-0.4	-0.3	-0.1	0.2	0.3	-0.3	-0.1	1			
Mn (ppm)	0.0	0.3	0.4	0.5	-0.3	-0.4	0.3	0.6	0.0	1		
Sr (ppm)	0.1	-0.7	-0.4	-0.1	0.4	0.7	-0.5	-0.1	0.2	-0.4	1	
CaO/MgO	-0.1	0.0	0.0	-0.1	-0.3	0.0	0.0	-0.1	-0.1	-0.1	0.2	1

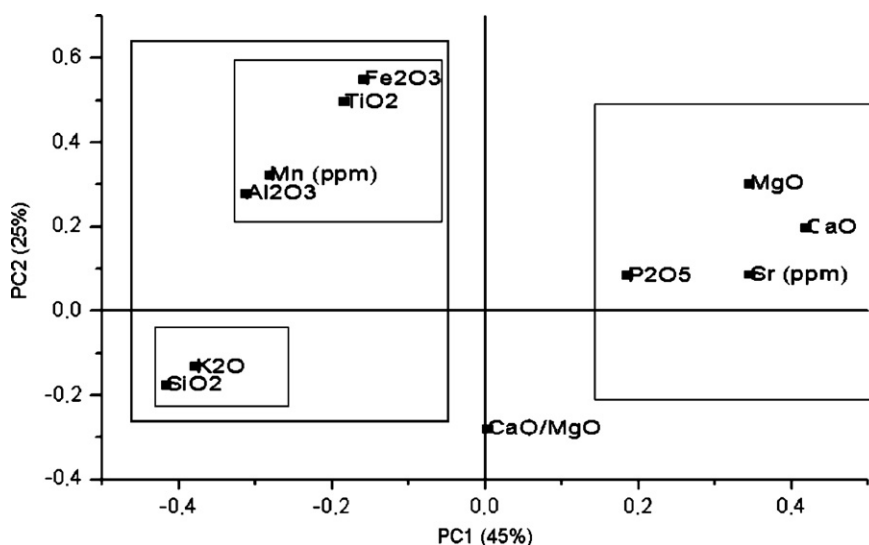


Fig. 2. PCA for sediments from the continental shelf of northeastern Brazil. PC1 shows 45% of explained variance. PC2 shows 25% of explained variance. Two vectors show 70% of explained variance.

Table 2
Correlation matrix for major elements from continental-shelf sediments, states of Paraíba and Pernambuco, northeastern Brazil

	Depth (m)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	TiO ₂	P ₂ O ₅	Mn (ppm)	Sr (ppm)	CaO/MgO
Depth (m)	1											
SiO ₂	-0.4	1										
Al ₂ O ₃	-0.3	0.6	1									
Fe ₂ O ₃	-0.4	-0.1	0.3	1								
MgO	0.6	-0.7	-0.3	0.1	1							
CaO	0.3	-1.0	-0.6	0.1	0.5	1						
K ₂ O	-0.2	0.7	0.8	0.0	-0.4	-0.7	1					
TiO ₂	-0.3	0.1	0.1	0.1	-0.2	-0.1	-0.1	1				
P ₂ O ₅	0.3	-0.4	-0.1	0.3	0.5	0.3	-0.2	-0.1	1			
Mn (ppm)	-0.4	-0.3	0.0	0.7	-0.1	0.3	-0.2	0.2	0.0	1		
Sr (ppm)	0.0	-0.6	-0.4	-0.1	-0.1	0.7	-0.5	0.1	0.1	0.2	1	
CaO/MgO	-0.2	0.1	0.0	-0.2	-0.5	-0.1	0.0	-0.1	-0.2	-0.1	0.2	1

The correlation matrix for the samples from the continental shelf of the states of Paraíba and Pernambuco is shown in Table 2. From this table, it becomes clear that there is no correlation between Fe₂O₃ and TiO₂ ($r = 0.1$).

4.2.1. Controlling factors of matrix of correlation in study area

This matrix shows an opposite behavior between the continental terrigenous facies and the biogenic carbonate facies in platformal environments (Fig. 3).

A positive correlation between SiO₂, Al₂O₃ and K₂O is indicative that the terrigenous facies is mainly formed by quartz, clay minerals, and K-feldspar, and disperse muscovite. The covariation between SiO₂ and Al₂O₃ ($r = 0.6$), in particular, reflects the partition of Si between quartz and aluminosilicate minerals (K-feldspar, clay minerals and muscovite). Strong correlation between Al₂O₃ and K₂O ($r = 0.7$) and SiO₂ and K₂O ($r = 0.8$) confirm the presence of significant amounts of K-feldspar in terrigenous fraction, according to paleoclimatic observations on the continental area next to the continental shelf.

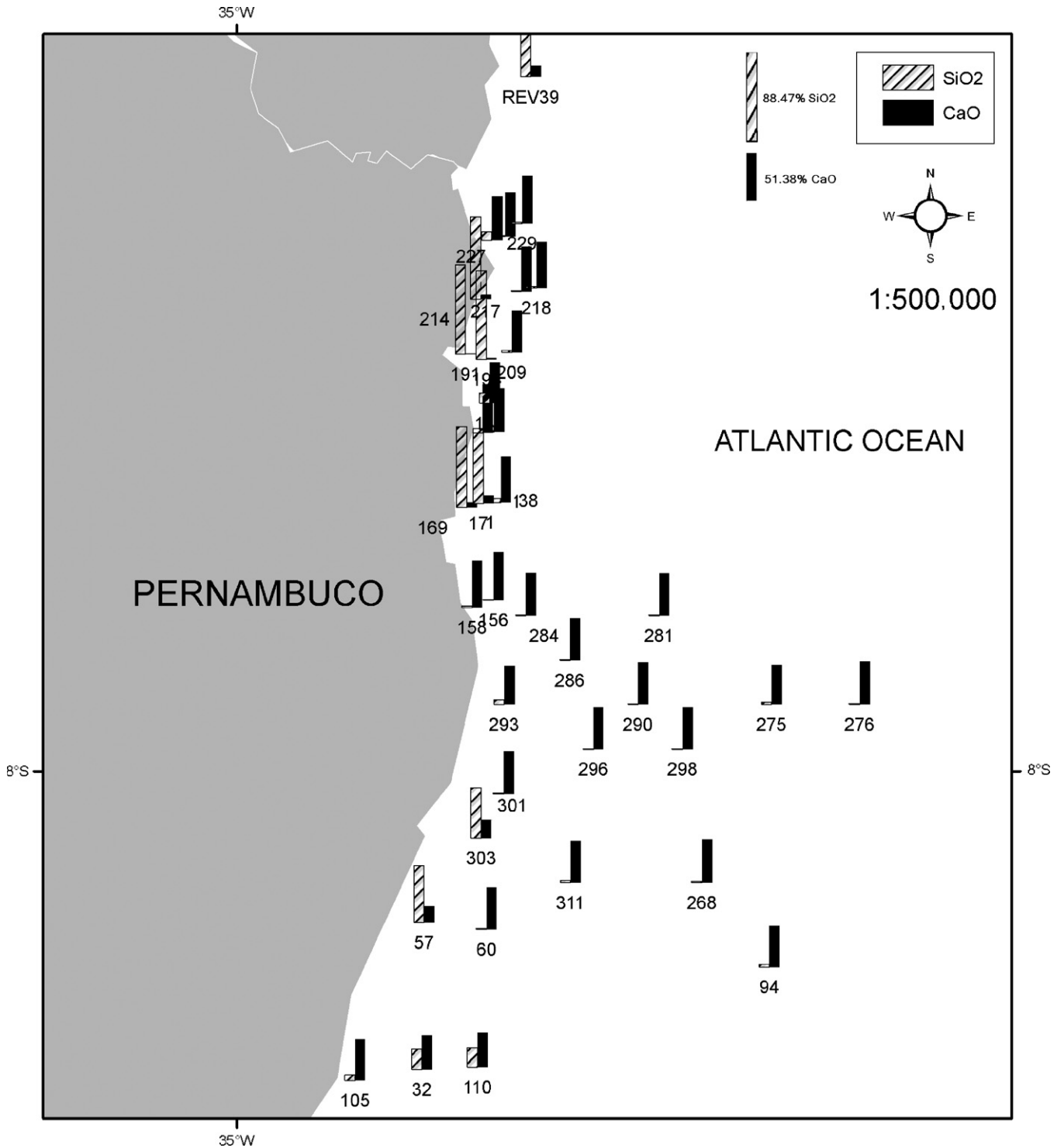


Fig. 3. Opposite behavior between the continental terrigenous facies and the biogenic carbonate facies in platformal environment. Horizontal line separates the fields for samples from above and below 20 depth.

The relatively good co-variation between Fe₂O₃ and TiO₂ ($r = 0.7$) points to ilmenite as the major Ti-bearing heavy mineral in the terrigenous facies, although weak correlation between SiO₂ and Al₂O₃ suggests low abundance of this mineral. Landing and Bruland (1987) suggest that the mechanical dispersion of an element in the platform depends, among other factors, of fluvial sources. This would imply in presence of ilmenite with variable grain size disseminated both in the proximal and distal facies of

the platform. The correlation between Al₂O₃ and Fe₂O₃ ($r = 0.6$) suggests dispersion of Fe-bearing minerals and that there is a very fine-grained pedogenic terrigenous component (goethite) together with clay minerals.

Ca, Mg, and Sr show good correlation to each other, in spite of the Mg and Sr competition for carbonate minerals (Mg-calcite and aragonite), being Sr preferentially incorporated into aragonite.

The correlation matrix for the samples from the continental shelf of the states of Paraíba and Pernambuco (Table 2) where a humid and warm climate predominates as opposed to the semi-arid climate in the state of Ceará, shows some differences relative to the carbonate facies of other states of northeastern Brazil. Differences are also observed in the chemical behavior of elements of accessory terrigenous minerals from the continental shelf, as in these shelves Ti shows random distribution and is not

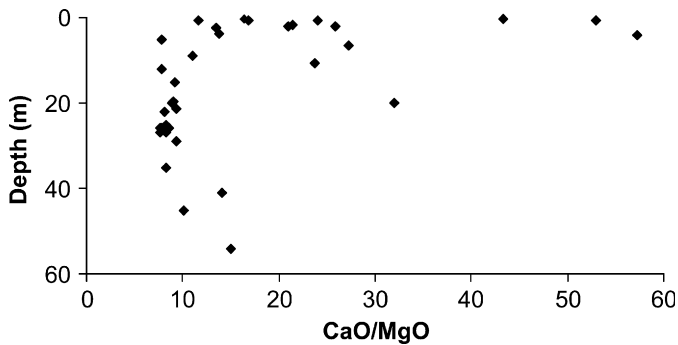


Fig. 4. Plot of CaO/MgO ratios against depth for continental shelf carbonates, state of Pernambuco.

related to clay minerals, while Fe_2O_3 and MnO show relatively good covariance ($r = 0.7$) with each other. Marin and Giresse (2001) suggested that Mn could enter into oceanic platforms through fluvial systems. In the studied continental shelf, the variation of Fe_2O_3 , Al_2O_3 and MnO is not related to the depth, suggesting that their mechanical dispersal has not reached distal facies.

In Table 2, Fe_2O_3 and TiO_2 show no co-variation ($r = 0.1$) suggesting that ilmenite, mined in placers at the coast of the state of Paraíba, is coarse-grained and better sorted than in the continental shelf of the state of Ceará, but it is restricted to the littoral facies at depths of less than 5 m. CaO/MgO ratios do not exhibit a well-defined co-variation with bathymetry, but there is a tendency of increasing ratios from 15 to 20 m depth, in the platform of the state of Pernambuco (Fig. 3). This could be related to temperature, as high-Mg calcite is more abundant in shallower, warmer waters, as suggested by some authors (e.g. McArthur et al., 2007; Kunhert and Hathmann, in press). Temperature, luminosity and oxygen availability imply on species distribution as low-Mg calcite and/or aragonite of skeleton of organisms predominate in deep water in this continental shelf, from 15 to 20 m depth. Mont'alverne (1982) has not mentioned details about phyla distribution but has observed a decreasing number of species in distal facies in this part of the continental shelf, where planktic and benthic foraminifera predominate over other organisms (Fig. 4).

Table 3

Chemical analyses of continental-shelf sediments of the state of Pernambuco (from Mont'alverne, 1982)

Samples	Depth (m)	SiO_2	Al_2O_3	Fe_2O_3 t	MgO	CaO	K_2O	TiO_2	P_2O_5	Mn	Sr	CaO/MgO	Lat S	Long W
169	0.50	87.14	1.18	0.36	0.36	5.88	0.53	0.14	0.06	45	125	16.33	07°48'09"	34°49'41"
214	0.50	88.47	1.65	0.18	0.11	4.76	1.00	0.00	0.03	40	200	43.27	07°38'46"	34°49'03"
225	0.60	9.50	0.56	0.26	0.90	47.70	0.06	0.16	0.05	70	5000	53.00	07°36'08"	34°48'33"
227	0.65	0.88	0.38	0.64	4.10	47.80	0.06	0.01	0.05	200	1500	11.66	07°35'58"	34°47'58"
193	0.70	95.74	0.52	0.18	0.07	1.68	0.21	0.04	0.04	12	25	24.00	07°41'29"	34°48'48"
171	0.75	81.00	0.90	0.29	0.53	8.96	0.60	0.01	0.06	42	175	16.91	07°47'58"	34°48'56"
179	1.40	0.20	0.28	0.16	0.14	53.15	0.03	0.00	0.06	27	6000	379.64	07°44'48"	34°48'58"
178	1.60	6.29	0.37	0.29	2.24	47.91	0.20	0.00	0.11	62	3500	21.39	07°44'46"	34°48'27"
191	1.90	96.50	0.52	0.13	0.05	1.05	0.18	0.03	0.03	10	50	21.00	07°41'15"	34°49'44"
158	2.10	1.71	0.28	0.35	1.95	50.54	0.04	0.00	0.12	92	4000	25.92	07°52'38"	34°49'27"
217	2.40	0.56	0.38	0.36	3.60	48.60	0.05	0.23	0.09	90	1800	13.50	07°38'26"	34°47'14"
181	3.70	11.24	0.37	0.47	3.25	44.67	0.15	0.04	0.13	75	1200	13.74	07°43'28"	34°48'39"
229	4.00	1.32	0.52	0.23	0.90	51.50	0.08	0.01	0.06	100	6200	57.22	07°35'22"	34°47'12"
209	5.20	2.14	0.52	0.66	5.80	45.00	0.10	0.00	0.11	100	1200	7.76	07°41'10"	34°47'40"
218	6.50	1.73	0.52	0.33	1.84	50.20	0.05	0.12	0.07	100	4700	27.28	07°38'17"	34°46'33"
105	9.00	6.17	0.56	0.58	4.09	44.86	0.10	0.03	0.33	92	2100	10.97	08°13'54"	34°54'42"
156	10.60	0.45	0.28	0.34	2.17	51.38	0.05	0.00	0.10	140	4000	23.68	07°52'17"	34°48'29"
303	12.00	54.56	1.60	0.58	2.53	19.74	0.55	0.04	0.09	72	500	7.80	08°03'00"	34°49'02"
57	13.00	61.50	0.71	0.20	0.05	18.20	0.31	0.00	0.05	40	500	364.00	08°06'48"	34°51'36"
284	15.00	0.84	0.35	0.37	5.05	46.06	0.17	0.00	0.12	60	2300	9.12	07°53'00"	34°47'02"
60	19.50	0.65	0.33	0.12	5.00	45.50	0.11	0.00	0.06	40	1400	9.10	08°07'06"	34°48'48"
138	20.00	4.43	0.37	0.35	1.57	50.11	0.11	0.03	0.00	120	420	31.92	07°47'55"	34°48'10"
293	20.00	5.40	1.51	0.64	4.74	42.39	0.30	0.02	0.15	80	1900	8.94	07°57'00"	34°48'00"
32	21.50	21.95	0.52	0.36	4.00	37.38	0.15	0.00	0.09	40	1100	9.35	08°13'24"	34°51'42"
301	22.00	0.56	0.47	0.11	5.62	45.92	0.11	0.01	0.09	20	2200	8.17	08°01'00"	34°48'02"
311	25.00	2.39	0.57	0.21	5.45	45.33	0.24	0.01	0.18	30	1700	8.32	08°05'00"	34°45'02"
94	26.00	3.08	0.28	0.10	5.90	44.74	0.09	0.00	0.11	12	1500	7.58	08°08'48"	34°36'06"
110	26.00	21.30	0.56	0.28	4.38	37.66	0.27	0.00	0.14	20	1300	8.60	08°13'18"	34°49'12"
286	26.00	0.75	0.23	0.37	5.80	45.50	0.08	0.01	0.10	40	2100	7.84	07°55'00"	34°45'03"
290	27.00	0.48	0.47	0.11	5.96	45.85	0.09	0.01	0.07	20	1700	7.69	07°57'00"	34°42'00"
296	27.00	0.58	0.38	0.10	5.54	45.50	0.11	0.01	0.09	20	1900	8.21	07°59'00"	34°44'00"
281	29.00	0.71	0.09	0.30	4.90	45.64	0.13	0.01	0.10	25	2400	9.31	07°53'00"	34°41'03"
298	35.00	0.58	0.38	0.10	5.54	45.50	0.13	0.01	0.11	30	1700	8.21	07°59'00"	34°40'00"
268	41.00	1.22	0.30	0.14	3.30	46.70	0.15	0.01	0.14	40	2900	14.15	08°05'00"	34°39'08"
275	45.00	2.66	0.30	0.09	4.30	43.26	0.23	0.01	0.13	30	2500	10.06	07°57'00"	34°36'00"
276	54.00	1.23	0.20	0.11	3.15	47.04	0.17	0.01	0.13	30	3100	14.93	07°57'00"	34°32'03"

Table 4
Chemical analyses for continental-shelf sediments from northeastern Brazil (Freire, 1985)

Samples	Depth (m)	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	K ₂ O	TiO ₂	P ₂ O ₅	Mn (ppm)	Sr (ppm)	CaO/MgO	Lat S	Long W
240	10	57.30	0.64	0.07	0.31	13.40	0.41	0.05	0.06	80	2940	43.23	03°48'05"	38°51'06"
241	10	6.60	0.13	0.02	2.00	33.90	0.11	0.02	0.10	48	3600	16.95	03°46'08"	38°48'09"
208	10	3.10	0.29	0.30	3.10	32.80	0.06	0.05	0.16	190	1570	10.58	03°32'05"	38°59'02"
209	10	2.30	0.05	0.02	2.50	35.00	0.04	0.02	0.14	73	2640	14.00	03°33'09"	38°81'07"
197	15	80.70	0.85	0.08	0.43	5.00	0.36	0.04	0.03	140	370	11.63	03°44'07"	38°19'02"
67	18	2.50	0.09	0.06	3.10	33.00	0.10	0.02	0.11	58	2100	10.65	02°33'00"	40°37'09"
58	19	0.51	0.06	0.07	3.00	34.80	0.04	0.01	0.12	65	2650	11.60	02°34'00"	40°52'09"
35	20	77.20	0.42	0.13	0.36	6.80	0.27	0.04	0.07	48	330	18.89	02°24'02"	40°37'07"
279	20	49.30	0.50	0.07	1.00	16.10	0.38	0.06	0.08	180	1100	16.10	04°10'09"	37°40'03"
59	20	0.07	0.07	0.10	3.10	34.30	0.04	0.01	0.13	84	1750	11.06	02°33'09"	40°52'00"
235	22	86.40	0.61	0.10	0.08	3.20	0.39	0.13	0.01	130	630	40.00	03°55'04"	38°01'00"
93	22	1.60	0.07	0.12	2.60	34.80	0.04	0.02	0.12	90	1680	13.38	02°31'06"	40°16'08"
247	22	42.10	0.50	0.04	0.56	19.80	0.41	0.03	0.09	58	3500	35.36	03°55'06"	37°55'05"
108	22	0.97	0.09	0.14	3.50	33.70	0.04	0.02	0.15	83	1760	9.63	02°35'09"	39°52'00"
91	23	57.50	0.66	0.18	0.84	12.40	0.53	0.06	0.10	76	1050	14.76	02°26'00"	40°17'02"
214	23	90.30	0.56	0.07	0.30	1.90	0.32	0.07	0.01	100	210	6.33	03°47'01"	38°11'06"
199	25	91.20	0.56	0.09	0.15	1.50	0.37	0.09	0.11	74	240	10.00	03°43'06"	38°16'00"
2	25	74.50	0.87	0.01	0.28	6.80	0.57	0.14	0.60	145	860	24.29	03°35'05"	38°28'00"
10	25	91.20	0.98	0.11	0.09	0.86	0.57	0.06	0.06	73	160	9.56	03°25'07"	38°42'00"
76	25	51.40	0.29	0.11	0.90	16.40	0.13	0.01	0.09	42	1360	18.22	02°25'06"	40°33'02"
51	25	0.83	0.06	0.04	2.30	35.60	0.04	0.01	0.13	40	2190	15.48	02°25'04"	40°59'05"
157	25	59.90	1.69	0.46	0.84	9.10	0.90	0.19	0.07	190	840	10.83	03°23'02"	38°48'02"
264	27	84.20	0.71	0.06	0.26	3.80	0.41	0.06	0.02	120	520	14.62	04°05'06"	37°49'04"
262	28	5.10	0.09	0.02	0.57	36.40	0.06	0.02	0.08	25	6310	63.86	04°01'09"	37°48'04"
75	30	0.85	0.07	0.06	3.60	33.60	0.04	0.02	0.11	76	2300	9.33	02°26'00"	40°33'04"
77	30	0.82	0.08	0.05	3.50	33.20	0.05	0.02	0.10	31	2650	9.49	02°22'08"	40°32'04"
135	30	53.20	0.53	0.21	1.30	15.10	0.39	0.07	0.09	160	850	11.62	02°56'00"	39°26'00"
182	30	76.20	0.56	0.05	0.27	6.90	0.45	0.05	0.03	48	1330	25.56	03°34'01"	38°14'05"
276	30	81.60	0.74	0.11	0.28	4.40	0.49	0.15	0.03	210	600	15.71	04°05'03"	37°43'01"
277	30	82.30	0.66	0.07	0.26	4.60	0.45	0.05	0.02	94	640	17.69	04°05'09"	37°43'09"
155	30	85.80	1.06	0.13	0.14	2.50	0.70	0.13	0.02	83	219	17.86	03°13'03"	38°48'05"
148	30	75.70	0.82	0.11	0.50	6.10	0.57	0.03	0.04	62	420	12.20	03°19'01"	38°49'08"
237	30	87.50	0.64	0.07	0.17	2.60	0.45	0.07	0.02	90	420	15.29	03°52'00"	37°56'01"
251	30	37.40	0.29	0.04	1.20	21.40	0.23	0.02	0.10	28	2370	17.83	03°53'09"	37°47'00"
272	30	82.70	0.71	0.05	0.26	4.30	0.53	0.03	0.03	120	480	16.54	03°59'04"	37°38'09"
283	30	1.00	0.04	0.02	3.20	33.90	0.04	0.02	0.14	15	2540	10.59	04°12'00"	37°33'04"
289	30	31.30	0.34	0.02	0.48	24.00	0.30	0.02	0.10	32	4650	50.00	04°16'05"	37°25'02"
274	33	34.80	0.48	0.05	0.35	21.80	0.37	0.04	0.09	32	4640	62.29	04°01'01"	37°40'00"
159	33	67.30	0.42	0.06	0.59	10.60	0.34	0.03	0.06	10	1030	17.97	03°20'03"	38°41'07"
246	33	59.00	0.69	0.07	0.24	12.80	0.49	0.06	0.05	120	3460	53.33	03°51'01"	37°53'04"
255	35	28.50	0.32	0.06	1.40	25.10	0.23	0.04	0.13	170	2250	17.93	03°49'04"	37°40'08"
97	35	50.20	0.50	0.18	1.30	15.70	0.36	0.04	0.11	150	850	12.08	02°24'00"	40°03'01"

In the continental shelf of the state of Ceará, there is an increase of silica contents in distal facies between the isobaths of 25 and 35 m, 40 and 50 m, and at 60 m depth, where contents are similar to those observed in the proximal facies (Tables 3–5). On the other hand, in these distal facies, TiO₂ and Fe₂O₃ contents are low. Freire (1985) reported irregular topographic relief from the 40 m isobath, associated to gravel and sand, as well as to biotrital mud, suggesting the existence of relict sediments as proxy of ancient coastal lines. This author had called, inappropriately, “shelf-border terrace” to the irregularities in the bottom topographic relief, between the isobaths of 20 and 30 m, 40 and 50 m, and 60 and 70 m. Finally, Behling et al. (2000) emphasized the presence of terrigenous matter in distal environment of the continental shelf of northeastern Brazil, as a proximal record of the latest post-glaciation period, when the sea level was well below its present level.

5. Conclusions

The PCA method together with matrix of correlation are useful tools in the study of continental shelf of northeastern Brazil, as they allowed defining mineral associations, geochemical affinity,

as well as in the provenance and partition of major elements and Sr in the sediments. In these environments of sedimentation on the continental shelf, biogenic carbonate minerals, of in-situ sedimentation are well distinguished from terrigenous continental minerals, which display an evident pedogenic contribution. The behavior of the chemical elements under consideration has defined two groups, Ca–Mg–Sr and Si–Al–K, in both, correlation matrix and PCA.

In the arrival of sediments transported by the rivers to the continental shelf, the relationship of groups of continental origin such as Si–Al–K and Fe–Ti–Mn is, apparently, governed by climate and hydrodynamics.

The presence of Fe oxide and hydroxide minerals, a very fine-grained Ti-bearing heavy fraction, and clay minerals towards open sea, are suggested by these statistical methods. In the platform of the states of Paraíba and Pernambuco, however, these minerals are more abundant in the proximal facies.

Mg-calcite producer organisms are inferred in the external continental shelf of the state of Pernambuco, as suggested by CaO/MgO ratios of the sediments. This may be due to the presence of planktic and benthic foraminifera in this area, as pointed out by Mont'alverne (1982) and Freire (1985).

Table 5
Chemical analyses for continental-shelf sediments from northeastern Brazil

Samples	Depth (m)	SiO ₂	Al ₂ O ₃	Fe ₂ O _{3t}	MgO	CaO	K ₂ O	TiO ₂	P ₂ O ₅	Mn	Sr	Loi	CaO/MgO	Lat (S)	Long (W)
Vh03157	10	68.68	3.00	2.62	1.61	8.46	0.23	2.81	0.04	549	820	10.98	5.25	05°45'12"	35°11'12"
Vh03146	15	1.05	0.31	0.16	6.89	43.30	0.04	0.19	0.06	46	2629	45.77	6.28	04°52'06"	36°22'48"
Rev88	18	0.00	0.00	0.03	5.97	48.39	0.01	0.03	0.07	16	3052	46.92	8.11	04°36'00"	37°14'24"
Vh03147	20	88.31	1.88	0.62	1.02	2.87	0.17	0.56	0.00	158	183	3.1	2.81	04°44'30"	36°19'12"
Rev74	20	25.61	0.65	0.05	3.90	34.56	0.18	0.04	0.05	16	3287	35.14	8.86	04°56'24"	35°19'30"
Vh03166	20	5.79	0.36	0.07	3.26	45.52	0.10	0.03	0.07	5	5301	43.58	13.96	06°45'12"	34°54'30"
G2 96	21	3.20	0.33	0.31	5.90	46.63	0.05	0.01	0.11	30	2940	43.57	7.90	02°29'05"	40°04'00"
Vh03171	23	14.63	0.38	0.08	3.90	41.11	0.04	0.02	0.07	18	3588	39.51	10.54	06°51'48"	34°46'30"
G2 95	25	9.27	0.60	0.37	5.50	42.85	0.23	0.01	0.10	31	2626	40.95	7.79	02°30'06"	40°07'00"
G1 32	25	70.18	3.17	0.47	1.74	12.11	0.90	0.23	0.03	90	1318	13.09	6.96	02°17'00"	40°27'30"
G2 71	25	8.53	0.50	0.29	5.42	43.85	0.14	0.02	0.10	36	2611	41.4	8.09	02°31'05"	40°35'00"
G2 27	25	12.43	1.39	0.33	4.31	40.56	0.35	0.08	0.09	40	3717	40.52	9.41	02°33'05"	39°47'03"
Rev12	25	87.78	1.97	0.25	1.04	3.52	0.22	0.28	0.00	51	217	4.85	3.38	03°52'48"	37°43'12"
G1 12	25	7.61	0.25	0.05	3.67	45.38	0.07	0.02	0.10	17	4086	42.51	12.37	03°36'30"	38°17'30"
G2 108	28	1.23	0.31	0.34	5.54	48.48	0.03	0.01	0.12	29	2689	44.6	8.75	02°35'09"	39°52'00"
Rev95	30	0.12	0.00	0.01	2.78	50.62	0.03	0.01	0.07	5	6482	45.93	18.21	03°17'24"	38°00'00"
Vh03134	30	0.67	0.21	0.07	3.86	49.17	0.04	0.02	0.08	14	5200	45.7	12.74	04°48'30"	36°37'42"
6	35	0.00	0.00	0.03	5.44	49.13	0.00	0.00	0.08	11	3611	45.34	9.03	02°31'05"	41°39'36"
90	35	0.00	0.00	0.02	4.52	50.88	0.00	0.03	0.08	18	4349	45.41	11.26	03°28'48"	38°04'48"
G1 31	35	61.05	2.32	0.96	2.21	16.55	0.56	0.12	0.06	111	1550	18.03	7.49	02°15'00"	40°30'30"
13	35	61.41	2.81	1.83	2.29	15.69	0.75	0.18	0.06	98	1226	16.73	6.85	04°15'00"	36°39'36"
Rev42	35	66.86	2.21	0.18	1.09	14.53	0.68	0.13	0.01	50	3326	16.19	13.33	09°06'00"	34°33'36"
89	35	0.39	0.01	0.02	2.78	50.13	0.05	0.01	0.08	16	6060	45.94	18.03	03°28'48"	38°04'48"
Rev90	35	0.05	0.05	0.04	3.52	50.58	0.00	0.00	0.08	12	4735	45.45	14.37	03°28'48"	38°04'48"
Rev121	35	16.83	1.83	1.55	3.41	36.59	0.28	0.11	0.12	71	3063	38.67	10.73	06°48'00"	34°39'36"
Rev72	35	63.70	2.90	0.59	1.58	14.97	0.76	0.08	0.01	53	2981	16.16	9.47	03°49'48"	37°22'12"
G 111	38	7.60	0.41	0.15	4.04	42.07	0.11	0.23	0.11	51	3174	42.49	10.41	03°54'30"	37°35'00"
Rev52	40	0.00	0.00	0.00	4.48	50.06	0.01	0.00	0.06	5	5133	45.72	11.17	05°18'00"	35°24'24"
G 46	40	0.60	0.16	0.16	5.68	49.08	0.00	0.00	0.11	14	2801	44.86	8.64	02°57'30"	39°16'30"
Rev75	40	0.15	0.01	0.04	5.47	46.21	0.30	0.00	0.07	15	3839	47.27	8.45	03°16'30"	35°06'00"
Rev41	43	0.33	0.03	0.02	3.11	50.42	0.01	0.00	0.07	16	4710	44.87	16.21	09°04'48"	35°01'12"
Rev39	55	70.31	2.75	0.15	1.72	12.20	0.73	0.04	0.02	29	2161	13.83	7.09	07°28'48"	34°46'48"

LGMA samples. REV: samples collected in GEOMAR XXI-REVISEE project (1983). VH: samples collected in GEOMAR XVIII-Vitor Hense project (1981). G: samples entitled only GEOMAR XXI.

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References

- Azevedo, D.A., Tamanqueira, J.B., Dias, J.C.M., Carmo, A.P.B., Landau, L., Gonçalves, F.T.T., 2008. Multivariate statistical analysis of diamondoid and biomarker data from Brazilian basin oil samples. *Fuel* 87, 2122–2130.
- Behling, H., Arz, W.H., Pätzold, J., Wefer, G., 2000. Late quaternary vegetational and climate dynamics in northeastern Brazil, inferences from marine core GeoB3104-1. *Quaternary Science Reviews* 19, 981–994.
- Bezerra, F.H.R., Neves, B.B.B., Corrêa, A.C.B., Barreto, A.M.F., Suguio, K., 2008. Late Pleistocene tectonic-geomorphological development within a passive margin—The Cariatá trough, northeastern Brazil. *Geomorphology* 97, 555–582.
- Cancès, B., Juillot, F., Morin, G., Laperche, V., Polya, D., Vaughan, D.J., Hazemann, J.-L., Proux, O., Brown Jr., G.E., Calas, G., 2008. Changes in arsenic speciation through a contaminated soil profile: a XAS based study. *Science of the Total Environment* 397, 178–189.
- Coutinho, P.N., 1992. Sedimentos carbonáticos da plataforma continental brasileira. *Revista de Geologia UFC* 6, 65–73.
- da Silva, J.B.P., Malvestiti, I., Hallwass, F., 2005. Principal component analysis for verifying ¹HNMR spectral assignments: the case of 3-aryl (1,2,4)-oxadiazol-5-carbohydrazide benzylidenes. *Química Nova* 28 (3), 492–496.
- Edwards, A.C., Hoz, L.R., Fucugauchi, J.U., Fortanel, A.S., Garza, E.M., Cruz, R.L.S., 2005. Geochemical distribution pattern of sediments in an active continental shelf in Southern México. *Continental Shelf Research* 25, 521–537.
- Fernandes, P.G., Carreira, P., Silva, M.O., 2008. Antropogenic sources of contamination recognition—Sines coastal aquifer (SW Portugal). *Journal of Geochemical Exploration* 98, 1–14.
- Foster, I.D.L., Boardman, J., Bright, K., 2007. Sediment tracing and environmental history for two small catchments, Karoo Uplands, South Africa. *Geomorphology* 90, 126–143.
- França, A.M.C., Coutinho, P.N., Summerhayes, C.P., 1976. Sedimentos superficiais da margem continental nordeste brasileira. *Revista Brasileira de Geociências* 6, 71–87.
- Freire, G.S.S., 1985. Geologia marinha da plataforma continental do Ceará. Dissertação de mestrado em Geociências. Universidade Federal de Pernambuco-UFPE. Recife, p. 132.
- Gil, M.V., Calvo, L.F., Blanco, D., Sanches, M.E., 2008. Assessing the agronomic and environmental effects of the application of cattle manure compost on soil by multivariable methods. *Bioresource Technology* 99, 5763–5772.
- Gingele, F., Deckker, P.D., Norman, M., 2007. Late Pleistocene and Holocene climate of SE Australia reconstructed from dust and river loads deposited offshore the River Murray mouth. *Earth and Planetary Science Letters* 255, 257–272.
- Jolliffe, I.T., 2002. *Principal Component Analysis*, second ed. Springer, New York, p. 502.
- Kuhnert, H., Rathmann, S., 2008. Carbonate ion effect on Mg/Ca, Sr/Ca and stable isotopes on the benthic foraminifera *Oridorsalis umbonatus* of Namibia. *Marine Micropaleontology* 66 (2), 120–133.
- Landing, W.M., Bruland, K.W., 1987. The contrasting biogeochemistry of iron and manganese in the Pacific Ocean. *Geochimica et Cosmochimica Acta* 51, 29–43.
- Malool, A.C., Kopp, R.E., Grotzinger, J.P., Fike, D.A., Bosak, T., Vali, H., Poussart, P.M., Weiss, B.P., Kirschvink, J.L., 2007. Sedimentary iron cycling and the origin and preservation of magnetization in platform carbonate muds, Adros Island, Bahamas. *Earth and Planetary Science Letters* 259, 581–598.
- Marin, B., Giresse, P., 2001. Particulate manganese and iron in recent sediments of the Gulf of Lions continental margin (north-western Mediterranean Sea) deposition and diagenetic processes. *Marine Geology* 172, 147–165.
- Mataragas, M., Skandamis, P., Nychas, G.J.E., Drosinos, E.H., 2007. Modeling and predicting spoilage of cooked, cured meat products by multivariate analysis meat. *Science* 77, 348–356.
- McArthur, J.M., Doyle, P., Leng, M.J., Reeves, K., Williams, C.T., Sanchez, R.G., Howarth, R.J., 2007. Testing palaeo-environmental proxies in Jurassic belemnites: Mg/Ca, Sr/Ca, Na/Ca, δ¹⁸O and δ¹³C. *Palaeogeography, Palaeoclimatology, Palaeoecology* 252, 464–480.
- Mont'alverne, A.A.F., 1982. Estudo dos calcários na plataforma continental de Pernambuco. Recife, Universidade Federal Pernambuco. Dissertação de mestrado em Geociências. Recife, Universidade Federal de Pernambuco, p. 197.

- Polat, K., Günes, S., 2008. Computer aided medical diagnosis system based on principal component analysis and artificial immune recognition system classifier algorithm. *Expert Systems with Applications* 34, 773–779.
- Sass-Kiss, A., Kiss, J., Havadi, B., Adányi, N., 2008. Multivariate statistical analysis of botrytised wines of different origin. *Food Chemistry* 110, 742–750.
- Summerhayes, C.P., Coutinho, A.P.N., França, M.C., Ellis, J.P., 1975. Uppon continental margin sedimentation of Brazil. *Contributions to Sedimentology* 4, 44–78.
- Tavares, M.T., Sousa, A.J., Abreu, M.M., 2008. Ordinary kriging and indicator kriging in the cartography of trace elements contamination in São Domingos mine site (Alentejo, Portugal). *Journal of Geochemical Exploration* 98, 43–56.
- Yang, S., Youn, J.S., 2007. Geochemical compositions and provenance discrimination of the central south Yellow Sea sediments. *Marine Geology* 243, 229–241.
- Zecchin, M., 2007. The architectural variability of small-scale cycles in shelf and ramp clastic systems: The controlling factors. *Earth-Science Reviews* 84 (1), 21–55.