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Marine substrate response from the analysis of seismic attributes in CHIRP sub-bottom profiles

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ABSTRACT

This paper presents an evaluation of the response of seismic reflection attributes in different types of marine substrate (rock, shallow gas, sediments) using seafloor samples for ground-truth statistical comparisons. The data analyzed include seismic reflection profiles collected using two CHIRP subbottom profilers (Edgetech Model 3100 SB-216S), with frequency ranging between 2 and 16 kHz, and a number (38) of sediment samples collected from the seafloor. The statistical method used to discriminate between different substratum responses was the non-parametric Kruskal-Wallis analysis, carried out in two steps: 1) comparison of Seismic Attributes between different marine substrates (unconsolidated sediments, rock and shallow gas); 2) comparison of Seismic Attributes between different sediment classes in seafloors characterized by unconsolidated sediments (subdivided according to sorting). These analyses suggest that amplitude-related attributes were effective in discriminating between sediment and gassy/rocky substratum, but did not differentiate between rocks and shallow gas. On the other hand, the Instantaneous Frequency attribute was effective in differentiating sediments, rocks and shallow gas, with sediment showing higher frequency range, rock an intermediate range, and shallow gas the lowest response. Regarding grain-size classes and sorting, statistical analysis discriminated between two distinct groups of samples, the SVFS (silt and very fine sand) and the SFMC (fine, medium and coarse sand) groups. Using a Spearman coefficient, it was found that the Instantaneous Amplitude was more efficient in distinguishing between the two groups. None of the attributes was able to distinguish between the closest grain size classes such as those of silt and very fine sand.

Descriptors: CHIRP, Seismic attributes, Shallow seismic.

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RESUMO

O presente trabalho tem por objetivo apresentar uma avaliação da resposta dos atributos sísmicos (Amplitude Instantânea, Amplitude RMS, Energia e Frequência Instantânea) em diferentes tipos de substratos marinhos, correlacionando-os com características sedimentológicas das amostras coletadas. Foram analisados perfis sísmicos obtidos com um perfilador de subsuperfície com sinal do tipo CHIRP modelo SB-216S da marca EdgeTech, com frequência de trabalho de 2 e 16 kHz. O método se deu a partir da análise estatística não-paramétrica de Kruskal-Wallis foi aplicada para comparar o comportamento dos atributos com as diferentes classes dos grãos das amostras (subagrupadas segundo o grau de seleção) e com diferentes feições. Com base na análise dos resultados, foi possível distinguir dois grupos distintos nas amostras, o grupo SAMF (silte e areia muito fina) e o grupo AFMG (areia fina, areia média e areia grossa). Como conclusão, pode-se dizer que os atributos não foram capazes de distinguir entre as classes mais próximas dos grãos. Utilizando o coeficiente de Spearman foi verificado que o atributo "Amplitude Instantânea" mostrou-se mais eficiente em separar os dois conjuntos. Comparando sedimentos, gás e rocha, os atributos que utilizaram o atributo "amplitude" foram eficazes em separar os sedimentos do gás e da rocha, porém não os distinguiram entre as duas feições, visto que elas apresentaram amplitudes muito altas, mas semelhantes entre si. O atributo "Frequência Instantânea" mostrou-se eficaz na diferenciação entre sedimento, rocha e gás, o sedimento apresentou uma maior banda de frequência, a rocha uma faixa intermediária e o gás a menor delas.

Descritores: CHIRP, Atributos sísmicos, Sísmica rasa.

INTRODUCTION

The geophysical methods applied to the solid Earth consist of indirect investigations of the subsurface of our Planet to infer the physical properties of the rocks (JONES, 1999). Using seismic reflection profiles it is possible to obtain information on the substrata, such as the thickness and internal geometries of the layers, the presence of faults and fractures, as well as the accumulation of shallow biogenic gas and the presence of landslide deposits (AYRES, 2000).

The study of sediments involves the analysis of a number of properties, which is essential to define their acoustic behavior. The main features and properties sensitive to the acoustic (seismic) behavior of the sedimentary rocks are: grain size, morphology and roundness of grains, texture, porosity, packing, and permeability of the whole rock (DIAS, 2004; JACKSON, 2007).

An important parameter for the acoustic characterization of strata is the acoustic impedance, i.e., the product of sound speed and density (JACKSON, 2007). More specifically, the acoustic impedance contrasts between two strata is proportional to the amount of energy reflected at their interface. Sediment densities and velocities depend on their mineralogy, porosity and water content, and these properties can be highly variable within a wide range of values (AYRES, 2000).

The acoustic response will vary according to interaction and combination of sediment properties; each sediment sample produces a different acoustic response, so the acoustic wave's behavior is different for each substrate (FALCÃO; AYRES, 2010). As stated by DAMUTH (1978), an eco-character can be classified using the different responses and characteristics of the acoustic signal. The sea floor's sedimentary nature will determine the behavior of the reflected sound wave as a function of the transmission and reflection coefficients (appearance of the primary reflector), and these can be used to define an eco-character.

An echo-character can be defined as a set of return signal characteristics. Analyzing the existence of reflectors, seismic facies (thickness, roughness, continuity), presence of diffraction hyperbolas, acoustic signal penetration, is a tool which can theoretically be used to discriminate between different types of eco-character associated with distinct seafloor types (DAMUTH, 1975). In this way, each type of sediment sample or substrate interacts differently with the seismic wave evidencing different characteristics, and thus a different eco-character. Combining this analysis with the use of seismic attributes (i.e., Instantaneous Amplitude and Frequency) can further improve the accuracy of the bottom classification.

Seismic Attributes include all the information obtained from seismic data by direct measurement, experiment or logical reasoning (TANER, 2001). The analysis of Seismic Attributes as part of seismic reflection profile interpretation has been used since the 1920s (CHOPRA; MARFURT, 2005) and their evolution and proliferation are closely related to the development and advance of computer technology, as in the digitization of records and introduction of color scales. The same authors also noted that seismic attributes can be considered a good tool for visualization, classification, identification and interpretation of seismic records.

In this paper was chosen CHEN and SIDNEY's (1997) classification. This autors considered two broad categories of Seismic Attributes, those that use a specific time window (RMS amplitude and energy) and the "instantaneous" ones (Instantaneous Amplitude and Frequency).

The RMS amplitude attribute may be described as a type of average reflectivity in a specific time window. This attribute is linked to characteristics of a layer lying between two interfaces (TANER, 2001).

The Energy attribute is generally used to analyze amplitude anomalies in layers of interest (CHEN; SIDNEY, 1997).

Instantaneous attributes were developed around the 80s as a way of calculating the potential energy component by developing a proceeding to calculate the seismic trace envelope (CHOPRA; MARFURT, 2005). Also called complex seismic trace analysis, instantaneous attributes are composed of a real and an imaginary part that constitute the seismic signal. The imaginary component is calculated using a special type of Fourier transformation (TANER et al., 1979). Using the Instantaneous Amplitude it is possible to obtain information on the intensity of the reflection, which is sensitive to changes in acoustic impedance, lithology and porosity (CHOPRA; MARFURT, 2005). Instantaneous Frequency provides information on the abnormal attenuation and layer thickness (CHOPRA; MARFURT, 2005).

The aim of this paper was to test the potential of Seismic Attributes evaluated in marine seismic reflection data (Amplitude RMS, Instantaneous Amplitude, Energy, and Instantaneous Frequency) in differentiating substrates with different sediment types (38 collected samples were used during statistical analyses) using a CHIRP-SBP as seismic source.

MATERIAL AND METHODS

The methodology consisted of 3 parts: 1) the granulometric parameters were determined for the samples collected; 2) the seismic profiles were analyzed, and 3) the seismic attributes were calculated from these profiles. After the creation of the attributes it was necessary to delimit a horizon (to trace a line at the interface between the seafloor and the water) at the seismic profiles (already containing the respective seismic attribute). After the delimitation of the horizons the 3D form was derived from them, because they could thus be exported in a .xyz file which contained the coordinates and the values of the attribute. This .xyz file was converted into a table and the particle size parameters were added to it. The statistical analyses were undertaken on the basis of this table. Figure 1 presents a short description of the steps taken during the undertaking of the study.

CHIRP signal

The data were obtained using two Edgetech sub-bottom profilers, models 3100 SB-216S and 3200 SB-512I. Model 3100 has 3 frequency bands within a range of 2-16 kHz. Seismic profiles with a shallow gas feature were obtained with model 3200 SB-512I - with a frequency range between 0.5 and 12 kHz. The CHIRP signal is generated by the stimulation of piezoelectric crystals and received by hydrophones mounted on the vehicle which also carries the acoustic source (MCGEE, 1995).

Distribution of samples

Sediment and rock samples were provided by the CB&I company and the Coastal Oceanography Laboratory (LOC) of the Federal University of Santa Catarina; the locations are along the Brazilian coast, offshore of five cities in four states (Figure 2). Seismic lines were selected on the basis of the location of available sediment and rock samples. The description of the sediment samples was made using FOLK and WARD’s (1957) classification and the granulometric parameters according to the Moments Method proposed by BLOTT and PYE, 2001 (Table 1 and Figure 3).

Attribute evaluation

To calculate seismic attributes from the available data, the open source software OpendTect 4.6.0. was used.

RMS amplitude is defined as the square root of the arithmetic mean of the squares of the values (LANDMARK, 2004).

$$RMS = \sqrt{\tfrac{1}{n}\sum_{i=1}^{n} Ai^2} \qquad (1)$$

where *N* is the number of interval samples and *A* is the amplitude value.

Energy attribute is the square of the sum of the sample values within a specific time window divided by the total number of samples in the set time interval. The Energy Attribute is obtained using the following formula (LANDMARK, 2004):

$$Energy = \frac{A_1^2 + A_2^2 + A_n^2}{N} \qquad (2)$$

where *N* is the number of interval samples and *A* is the amplitude value.

According to TANER et al. (1979), the complex seismic trace is composed of two parts: a real and an imaginary one. The imaginary component is calculated

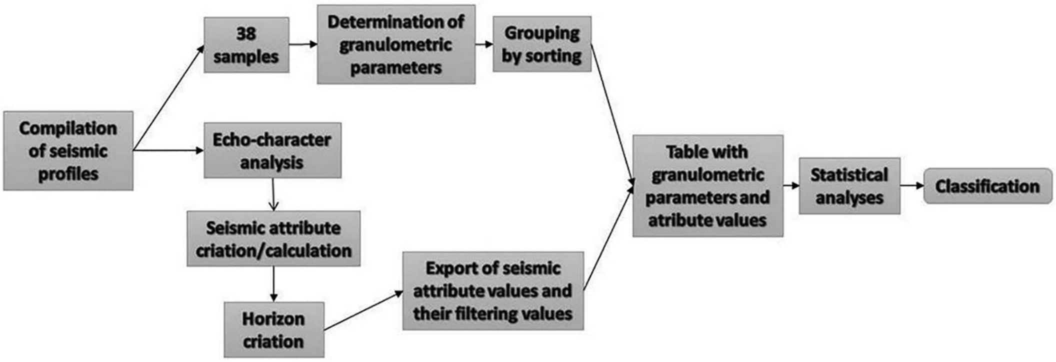


Figure 1. Description of material and methods.

using the Hilbert transform. By undertaking this procedure it is possible to separate amplitude and phase, and derive Instantaneous Frequency from phase. Equation (3) shows the result of the complex trace analysis, indicating the instantaneous amplitude and phase.

$$F(t) = A(t)\,e^{j\theta(t)} \qquad (3)$$

where A *(t)* is the Instantaneous Amplitude and θ *(t)* is the Instantaneous Phase.

Instantaneous Amplitude can be calculated using equation 4.

$$A(t) = \sqrt{f^2(t) + f^{*2}(t)} \qquad (4)$$

A (t) indicates the Instantaneous Amplitude, f^{2} *(t)* the real trace, and f^{*2} *(t)* the quadrature trace.

Instantaneous Frequency can be calculated from the instantaneous phase attribute, illustrated by equations 5 and 6.

$$\theta(t) = \tan^{-1}\left[\frac{f^{*}(t)}{f(t)}\right] \qquad (5)$$

$$\omega(t) = \frac{\mathrm{d}}{\mathrm{d}t}\tan^{-1}\left[\frac{f^{*}(t)}{f(t)}\right] \qquad (6)$$

where θ *(t)* indicates the Instantaneous Phase and ω *(t)* gives the Instantaneous Frequency.

HORIZONS

After the calculation of the attributes, it is necessary to draw a horizon (2D) on the seismic profile and then derive the 3D horizons from it. Only a 3D horizon can be transfered to the.xyz file, this file being necessary for the statistical analyses and comparisons.

For this step it was necessary to choose the respective attribute for the seismic profile and add the samples collected to it (the seismic profile containing the previously calculated attribute) and draw a horizon at a distance of 15-20 meters on each side of the sample (Figure 4), respecting the reflection's strength, geometry and profile information indicating the corresponding eco-character. The 2D horizon was marked at the interface between seafloor and water, including the profiles with shallow gas.

The conversion from the 2D to the 3D horizon was undertaken using the Extension algorithm. This 3D horizon was transfered to the .xyz file and the file converted into a table containing coordinates and attribute values for each seismic line analyzed with each seismic attribute. The attribute values of these tables (this table?) were filtered and outliers excluded. A moving average filter (applied every 4 or 5 values) was also applied to remove unwanted noise (ROSA, 2010). This final table was used for the statistical analyses.

STATISTICAL ANALYSIS

The sedimentological parameters, such as grain class, grain size, sorting, skewness and kurtosis, were

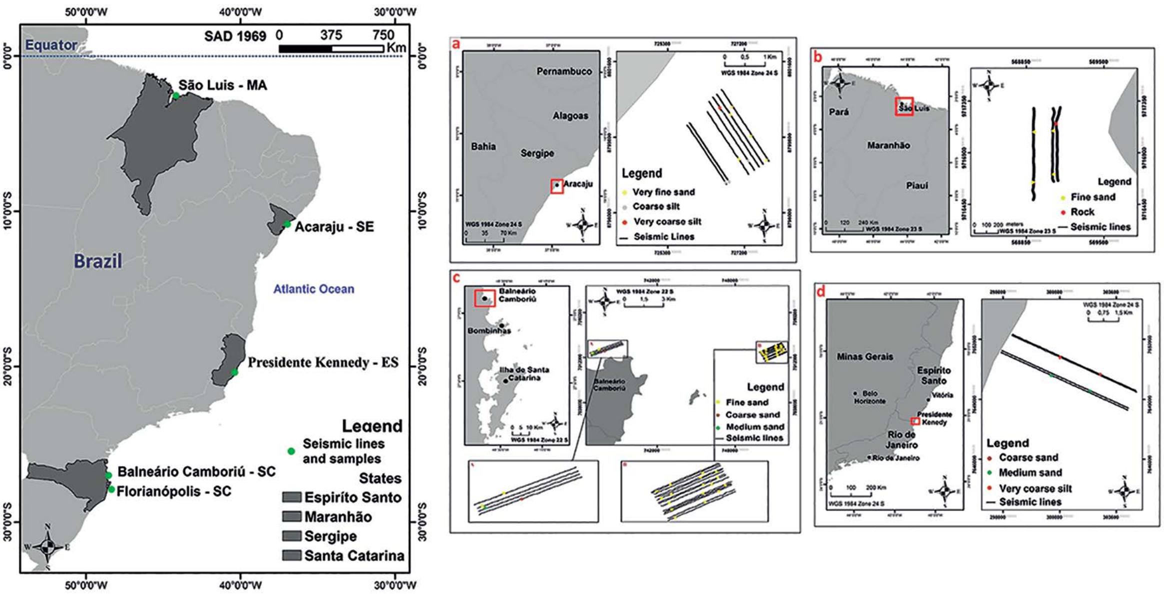


Figure 2. Distribution of the samples and the seismic lines. On the left side is the Brazilian coast, on the right are a, Aracaju city, b, São Luis city, c, the Balneário Camboriu and Florianópolis cities, d, Presidente Kennedy city.

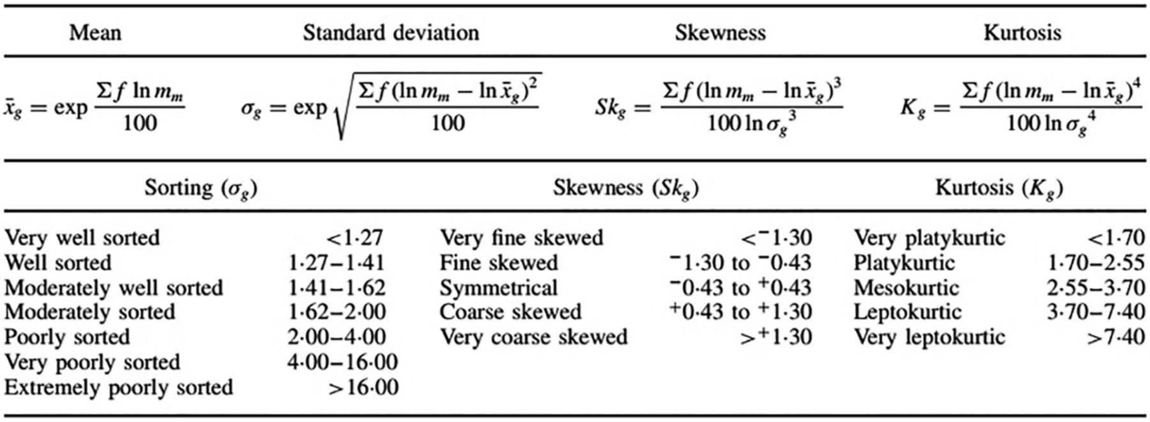
Table 1. Sample, rock and shallow gas coordinates. Grain class by FOLK and WARD (1957). Datum WGS 1984.

Place	Number Sample	Coordinate x	Coordinate y	Grain Class
Aracaju - SE	1	727297.8	8799237	Coarse silt
Aracaju - SE	2	726729.3	8798718	Coarse silt
Aracaju - SE	3	726813	8798745	Coarse silt
Presidente Kennedy - ES	4	300813	7651082	Very coarse silt
Aracaju - SE	5	726591.1	8800498	Very coarse silt
Aracaju - SE	6	727751.5	8799252	Very fine sand
Aracaju - SE	7	726858.1	8800337	Very fine sand
Aracaju - SE	8	727062.5	8799274	Very fine sand
Aracaju - SE	9	726886.8	8800514	Very fine sand
Aracaju - SE	10	727362.4	8799818	Very fine sand
Balneário Camboriú - SC	11	750388	7011975	Fine sand
Balneário Camboriú - SC	12	750011	7012506	Fine sand
Balneário Camboriú - SC	13	750355	7012698	Fine sand
Balneário Camboriú - SC	14	750480	7011740	Fine sand
Balneário Camboriú - SC	15	751169	7013035	Fine sand
Balneário Camboriú - SC	16	751115	7012903	Fine sand
Balneário Camboriú - SC	17	751515	7013064	Fine sand
Balneário Camboriú - SC	18	751180	7012440	Fine sand
Balneário Camboriú - SC	19	751223	7012204	Fine sand
Balneário Camboriú - SC	20	751572	7012509	Fine sand
Balneário Camboriú - SC	21	751180	7012693	Fine sand
Balneário Camboriú - SC	22	751546	7012903	Fine sand
São Luís - MA	23	569078	9716711	Fine sand
São Luís - MA	24	568906	9716642	Fine sand
Balneário Camboriú - SC	25	751736	7012681	Fine sand
Balneário Camboriú - SC	26	751399	7012700	Fine sand
Balneário Camboriú - SC	27	750384	7012418	Fine sand
Balneário Camboriú - SC	28	750136	7012312	Fine sand
Balneário Camboriú - SC	29	750327	7012167	Fine sand
Balneário Camboriú - SC	30	737001	7012375	Fine sand
São Luís - MA	31	569076	9717091	Fine sand
São Luís - MA	32	568917	9717080	Fine sand
Balneário Camboriú - SC	33	737519	7012723	Fine sand
Balneário Camboriú - SC	34	737074	7012318	Medium sand
Presidente Kennedy - ES	35	300390	7650187	Medium sand
Presidente Kennedy - ES	36	302290	7649413	Medium sand
Presidente Kennedy - ES	37	302805	7650241	Coarse sand
Balneário Camboriú - SC	38	737947	7012563	Coarse sand
São Luís - MA	39	569100	9717152	Rock
Lagoa da Conceição - Florianópolis - SC	40	752573	6944115	Shallow gas

calculated using the GRADISAT (BLOT; PYE, 2001) by the Moments Method and according to the textural classification proposed by FOLK and WARD (1957).

The normality test of Shapiro-Wilk W (SHAPIRO; WILK, 1965) was applied to the Seismic Attributes values. The result of this analysis defined the statistical method, whether parametric or nonparametric, to be used in the table containing attribute values, grain classes sub-grouped by sorting. Due to the non-normality of the sample distribution, the lack of homogeneity of the attribute values, and the relatively small number of samples (38), a non-parametric statistical analysis, using the Kruskal-Wallis method, was chosen.

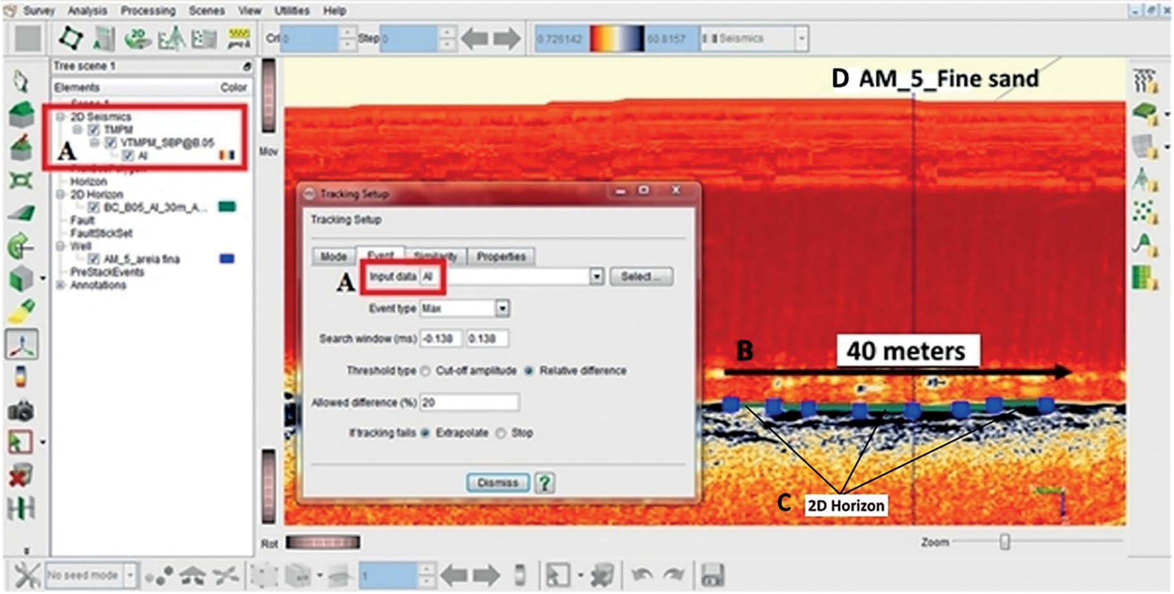
According to SIEGEL (1956), the Kruskal-Wallis analysis is very useful to test whether independent k samples belong to different populations. The analysis tests the null hypothesis as to whether the k samples come from the same population or population groups with identical averages. Multiple comparisons are used to complement the Kruskal-Wallis test, checking the difference between the two groups chosen. This analysis is appropriate



Mean	Standard deviation	Skewness	Kurtosis
$\bar{x}_g = \exp \dfrac{\Sigma f \ln m_m}{100}$	$\sigma_g = \exp \sqrt{\dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^2}{100}}$	$Sk_g = \dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^3}{100 \ln {\sigma_g}^3}$	$K_g = \dfrac{\Sigma f (\ln m_m - \ln \bar{x}_g)^4}{100 \ln {\sigma_g}^4}$

Sorting (σ_g)		Skewness (Sk_g)		Kurtosis (K_g)	
Very well sorted	$<1{\cdot}27$	Very fine skewed	$<{}^{-}1{\cdot}30$	Very platykurtic	$<1{\cdot}70$
Well sorted	$1{\cdot}27–1{\cdot}41$	Fine skewed	${}^{-}1{\cdot}30$ to ${}^{-}0{\cdot}43$	Platykurtic	$1{\cdot}70–2{\cdot}55$
Moderately well sorted	$1{\cdot}41–1{\cdot}62$	Symmetrical	${}^{-}0{\cdot}43$ to ${}^{+}0{\cdot}43$	Mesokurtic	$2{\cdot}55–3{\cdot}70$
Moderately sorted	$1{\cdot}62–2{\cdot}00$	Coarse skewed	${}^{+}0{\cdot}43$ to ${}^{+}1{\cdot}30$	Leptokurtic	$3{\cdot}70–7{\cdot}40$
Poorly sorted	$2{\cdot}00–4{\cdot}00$	Very coarse skewed	$>{}^{+}1{\cdot}30$	Very leptokurtic	$>7{\cdot}40$
Very poorly sorted	$4{\cdot}00–16{\cdot}00$				
Extremely poorly sorted	$>16{\cdot}00$				

Figure 3. Geometric method of moments. Adapted from BLOTT and PYE (2001).



Tracking Setup

A Input data: AI

Event type: Max

Search window (ms): -0.138 0.138

Threshold type: ○ Cut-off amplitude ● Relative difference

Allowed difference (%): 20

If tracking fails: ● Extrapolate ○ Stop

Figure 4. Example of seismic profile in A, the seismic attribute selected (in this case the Amplitude Instantaneous attribute); in B, the length of the 2D horizon; in C, the 2D horizon; in D, the sample of this profile.

when there are more than three independent groups to be compared (SIEGEL, 1956), where the independent variables are grain classes (sub-grouped by sorting) and the dependent variable is an attribute value.

A correlation test, comparing attribute values (amplitude and frequency attributes) and mean PHI was applied to calculate the significance of each attribute related to grain size. The correlation was performed using the Spearman coefficient, by which values near 0 indicate minimum correlation.

RESULTS

Table 2 shows the sedimentological parameters determined for each sample. In general, the collected samples are poorly sorted and asymmetry and kurtosis are varied. The samples were obtained from different locations (with different types of environment), near to and far from the coast, within port areas, and from environments characterized by different sedimentary covers and hydrodynamic regimes - which factors alter the samples' particle size characteristics.

The mean grain size may not adequately represent a sample, because it can present more than one mode, so an additional parameter was chosen for the sub-classification of the samples. In the parameter mean phi, sorting was chosen as a grain class sub-divider. This parameter is important to describe the sample, since a more heterogeneous composition may present different packing and arrangements, varying density, porosity and permeability values of the material. The kurtosis

Table 2. Results of granulometric analysis. NS indicates Number of Sample, SD standard deviation, SKE skewness, KUR kurtosis, CS Coarse silt, VCS very coarse silt, VFS Very fine sand, FS fine sand, MS Medium sand and CSS Coarse Sand.

NS	Class	SD	Sorting	SKE Value	SKE	KUR Value	KUR	Mean PHI
1	CS	1.80	Poorly sorted	-0.23	Symmetrical	1.19	Very platykurtic	5.85
2	CS	1.77	Poorly sorted	0.05	Symmetrical	2.67	Mesokurtic	5.04
3	CS	1.80	Poorly sorted	-0.34	Symmetrical	1.19	Very platykurtic	5.96
4	VCS	1.55	Very poorly sorted	0.92	Symmetrical	2.63	Mesokurtic	4.42
5	VCS	1.69	Poorly sorted	0.93	Fine skewed	2.48	Platykurtic	4.55
6	VFS	1.85	Poorly sorted	-0.16	Very coarse skewed	5.03	Leptokurtic	3.91
7	VFS	0.36	Well sorted	0.36	Symmetrical	5.50	Leptokurtic	3.70
8	VFS	0.39	Well sorted	-0.63	Coarse skewed	14.98	Very leptokurtic	3.72
9	VFS	1.51	Poorly sorted	1.33	Very fine skewed	4.39	Leptokurtic	4.14
10	VFS	1.26	Poorly sorted	0.75	Fine skewed	8.75	Very leptokurtic	3.71
11	FS	1.18	Poorly sorted	-2.11	Very coarse skewed	6.82	Leptokurtic	2.34
12	FS	1.57	Poorly sorted	1.30	Fine skewed	7.08	Leptokurtic	2.51
13	FS	1.12	Poorly sorted	-0.27	Symmetrical	10.86	Very leptokurtic	2.23
14	FS	0.78	Moderately sorted	-1.66	Very coarse skewed	7.39	Leptokurtic	2.46
15	FS	1.29	Poorly sorted	1.69	Very fine skewed	10.25	Very leptokurtic	2.86
16	FS	1.06	Poorly sorted	-1.45	Very coarse skewed	5.30	Leptokurtic	2.35
17	FS	0.65	Moderately well sorted	-2.08	Very coarse skewed	10.24	Very leptokurtic	2.54
18	FS	0.92	Moderately sorted	-2.09	Very coarse skewed	8.40	Very leptokurtic	2.25
19	FS	1.09	Poorly sorted	-1.58	Very coarse skewed	5.77	Leptokurtic	2.17
20	FS	0.77	Moderately sorted	-1.68	Very coarse skewed	7.59	Very leptokurtic	2.31
21	FS	0.71	Moderately sorted	-1.97	Very coarse skewed	8.83	Very leptokurtic	2.44
22	FS	0.81	Moderately sorted	-2.29	Very coarse skewed	10.58	Very leptokurtic	2.46
23	FS	0.40	Well sorted	0.58	Fine skewed	7.58	Very leptokurtic	2.85
24	FS	0.40	Well sorted	0.49	Fine skewed	8.53	Very leptokurtic	2.90
25	FS	0.90	Moderately sorted	-2.39	Very coarse skewed	10.39	Very leptokurtic	2.48
26	FS	1.29	Poorly sorted	-0.87	Coarse skewed	3.01	Mesokurtic	2.04
27	FS	0.90	Moderately sorted	-2.13	Very coarse skewed	8.12	Very leptokurtic	2.44
28	FS	1.63	Poorly sorted	1.30	Very fine skewed	6.58	Leptokurtic	2.70
29	FS	1.26	Poorly sorted	2.23	Very fine skewed	10.47	Very leptokurtic	2.83
30	FS	1.14	Poorly sorted	1.09	Fine skewed	12.12	Very leptokurtic	2.61
31	FS	0.32	Very well sorted	0.05	Symmetrical	7.49	Very leptokurtic	2.74
32	FS	1.38	Poorly sorted	1.61	Very fine skewed	9.13	Very leptokurtic	2.56

parameters and asymmetry were not statistically analyzed using the Kruskal-Wallis non-parametric method, yet their values and behavior were considered during the discussion of the results.

A table containing attribute values and texture classes, sub-grouped by sorting (when the grain class had more than one sorting) was created (Table 2). This table was analyzed on STATISTICA software and the result of this analysis will be described in the next topic.

Analysis carried out over 40 seismic profiles led us to discriminate between 3 types of eco-characters of the seafloor: unconsolidated sediments, shallow gas sediments and rock (Figure 5). The rock and shallow eco-character have specific signatures. The rocky seafloor (Figure 5D) has hyperbolic or irregular geometry and presents an absence of seismic signal penetration, without sub-surface reflectors or strong bottom reverberation. The shallow gas facies (Figure 5C) has a strong reflection (at the interface of sediment and gas) and masks adjacent reflectors. The different sand classes have similar eco-characters, presenting poor visualization of adjacent reflectors. The eco-characters of silt classes present a better characterization of adjacent reflectors and have configurations similar to those of the sand class.

Figure 6 shows an example of a sandy seafloor. Figure 6A presents a raw profile and Figures 6B, 6C and 6D show the same profile with different Seismic Attributes applied. The energy attribute has a large range of attribute values, because this attribute raises the attribute values to the square so the profiles show a large range of values. The instantaneous frequency attribute is able to distinguish the thickness of the layers, as is illustrated in Figure 6E, where the attribute indicates the seabed clearly.

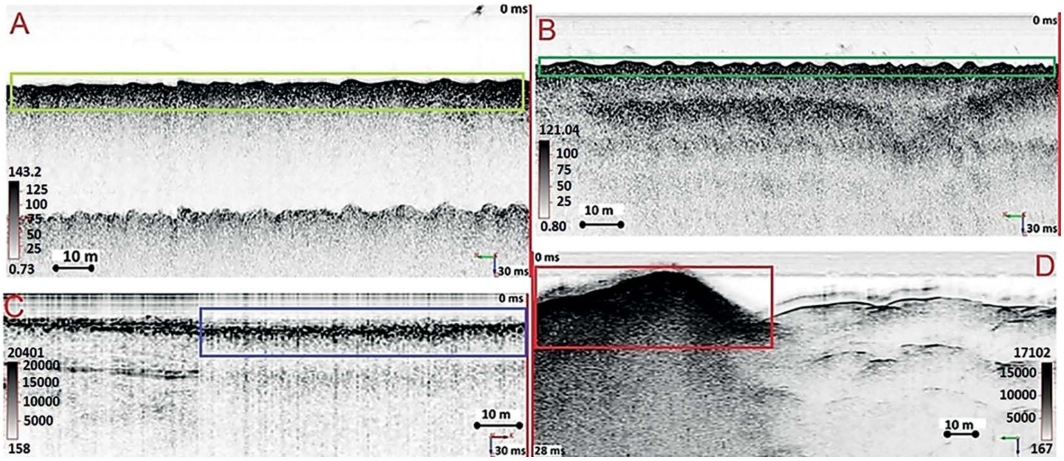


Figure 5. Description of some examples of eco-character analyses. In A - yellow - example of seismic profile containing sand located at Balneário Camboriu (SC); in B - green - example of seismic profile containing silt located in Presidente Kennedy (ES); in C - blue -example of seismic profile containing shallow gas located in the Lagoa da Conceição - Florianópolis (SC); in D - red - example of seismic profile containing rock located at São Luís (MA).

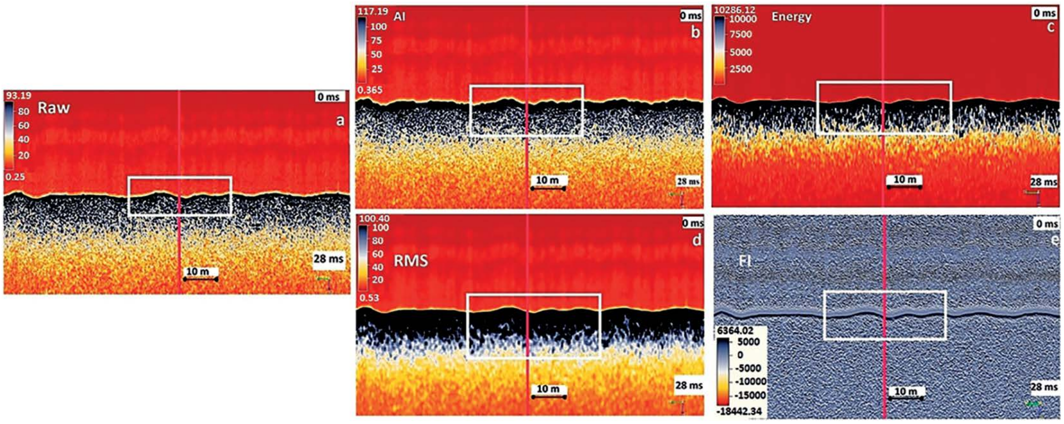


Figure 6. Example of seismic line with/without seismic attribute. In a, a raw record; b, with Instantaneous Amplitude attribute (AI); c, with Energy attribute; d, RMS Amplitude attribute; e, Instantaneous Frequency attribute.

COMPARING DIFFERENT SEAFLOORS COMPOSITIONS

Figure 7 indicates the comparison of different seafloors, characterized by the presence of rock, shallow-gas and unconsolidated sediments using Seismic Attributes, AI, RMS, Energy and FI, respectively. Note in the Amplitude Attribute that gas and rock have higher values, probably because rock and shallow gas are both characterized by strong reflection of the signal, resulting in high amplitude.

For the Instantaneous Amplitude attribute (Figure 7A) it may be noted that the rocky and gassy seafloors have much higher values (about 4,000-20,000 times higher) relative to unconsolidated sediments (with a range of values assigned to rock slightly lower than that obtained for the gas range feature). This is explained by the fact that rock has a characteristic strong reflection signal, resulting in high amplitude.

The Kruskal-Wallis analysis distinguishing between sediment, rock and gas using the RMS Amplitude attribute is shown in figure 7B. This attribute also effectively differentiated unconsolidated sediment from rock and gas, the gas feature having the highest amplitude values (between 11,000 and 21,000). The rock showed a greater range of amplitude values (between 6,000 and 20,000).

The Kruskal-Wallis analysis of sediment, gas and rock by Energy attribute (Figure 7C) is similar to that of the other attributes and also obtained a differentiation of unconsolidated sediment from rock and gas. Rock exhibited the highest amplitude value (between 52,000,000

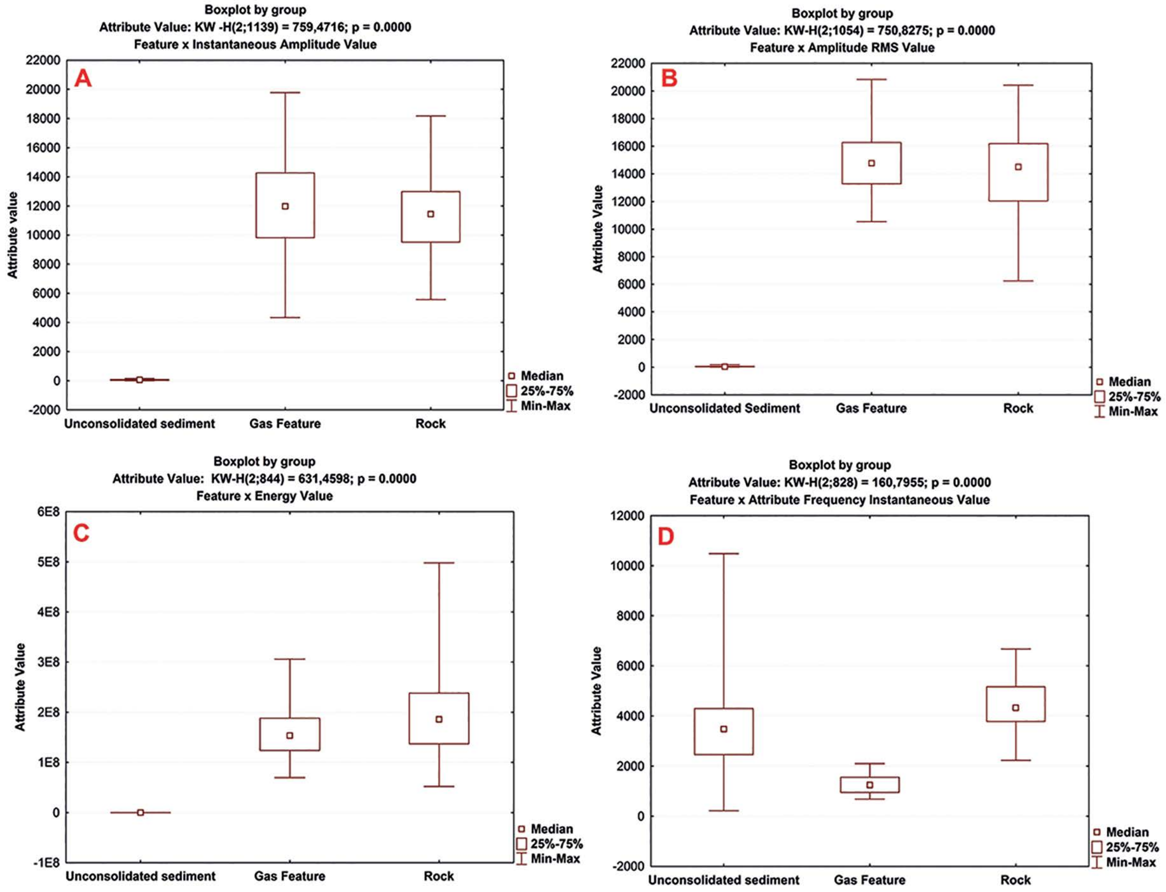


Figure 7. In A: boxplot analysis using rock, unconsolidated sediment and gas for Amplitude Instantaneous attribute; in B: boxplot analysis using rock, unconsolidated sediment and gas for Amplitude RMS; in C: boxplot analysis using rock, unconsolidated sediment and gas for Energy attribute; in C: boxplot analysis using rock, unconsolidated sediment and gas for Instantaneous Frequency attribute.

and 498,000,000). The energy attribute had a higher value range for rock (between 70,000,000 and 300,000,000) than shallow gas.

The Instantaneous Frequency attribute (Figure 7D) was the only one that showed a differentiation between the features analyzed. Sediments had a higher frequency range (between 0.20 kHz and 10.50 kHz). Rock features presented a frequency band between 2.25 kHz and 6.70 kHz, and gas features presented the lowest range - between 0.70 kHz and 2.10 kHz.

COMPARING DIFFERENT GRAIN SEDIMENT CLASSES

In general, the amplitude attributes enabled us to discriminate between fine and coarse sediments, but no analysis grading the fine class was, or course, apparent.

The Instantaneous Amplitude attribute (Figure 8A) shows the lowest values (ranging between 8 and 160) for fine-grained sediments. It is possible to note a tendency to increasing attribute value with increasing grain-size; this is also observed in the Spearman correlation coefficient. This parameter is significant at 0.62, i.e., a moderate positive relationship between the grain size (mm) and the attribute value.

Another consideration relates to the different attribute values assigned to the fine-sand. This class contains two sub-classes related to the sorting, poorly/moderate and well sorted. Analyzing these sub-classes in the light of Table 2 it can be said that a large proportion of fine poorly/moderately sorted samples present coarse skewed asymmetry, providing higher attribute values (ranging between 10 and 150).

According to the graph in Figure 8A, the smaller (average) grain-size may be differentiated from those of greater (average) size. It is possible to distinguish between two groups: 1) the coarse silt, encompassing very coarse silt and very fine sand (SVFS - silt and very fine sand); and

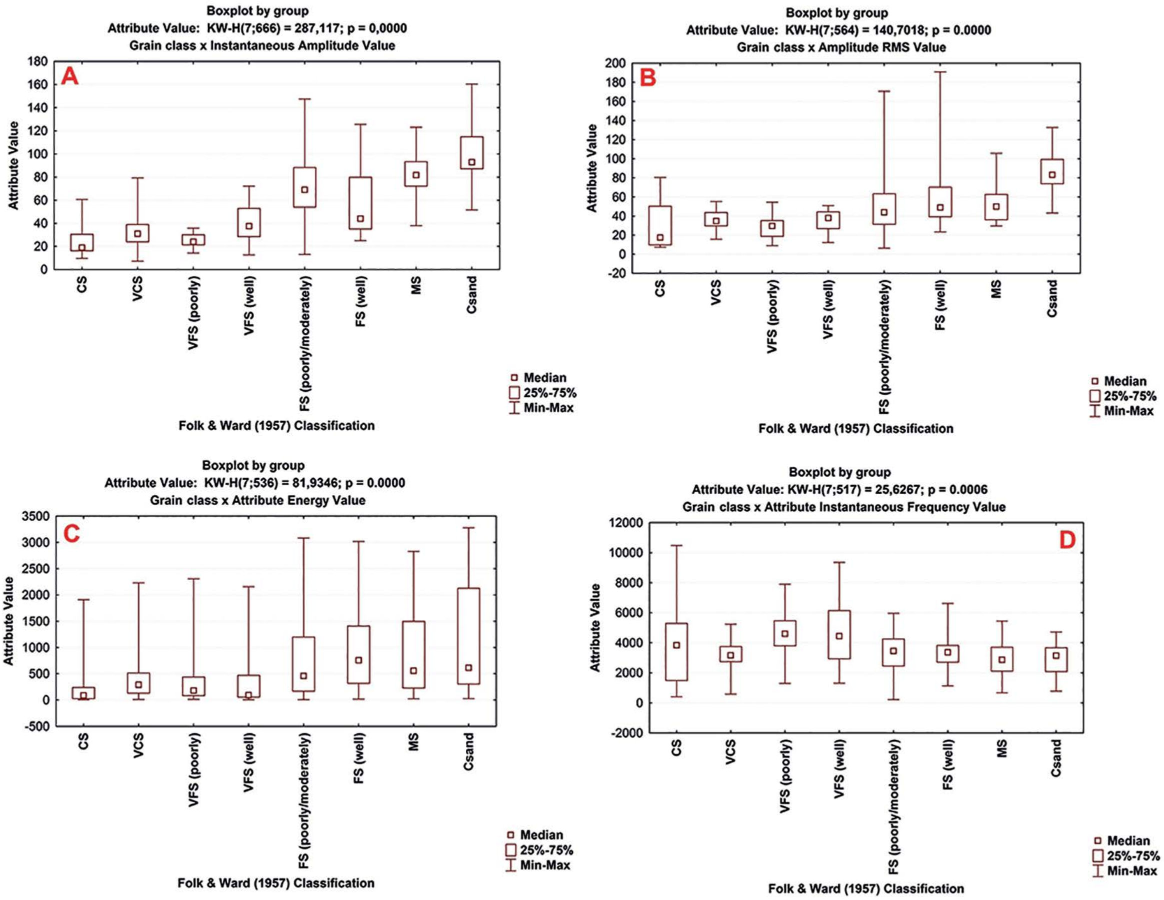


Figure 8. In A: boxplot analysis distributed in different grain classes sub-grouped according to sorting by Instantaneous Amplitude attribute; in B: boxplot analysis distributed in different grain classes sub-grouped according to sorting by Amplitude RMS; in C: boxplot analysis distributed in different grain classes sub-grouped according to sorting by Energy attribute; in C: boxplot analysis distributed in different grain classes sub-grouped according to sorting by Instantaneous Frequency attribute. CS=Coarse Silt; VCS=Very Coarse Silt; VFS=Very Fine Sand; FS=Fine Sand; MS=Medium Sand; CS=Coarse Sand.

2) the fine sand, including medium sand and coarse sand (SFMC - Sand fine, medium and coarse). However, it is difficult to obtain a more specific division between the classes.

According to Figure 8B, the RMS Amplitude attribute, ranging in value between 6 and 190, was less efficient in separating grain classes than the Instantaneous Amplitude attribute. In general, the classes of silt, very fine sand, fine sand and medium sand were different from that of coarse sand, but showed very little distinction among them. There was a significant difference between the silt-very fine sand and the coarse sand classes. Note in the graph that there is an increase in the value of the attribute with increasing grain size, a fact evidenced by the Spearman coefficient, which was significant and moderate with a value of 0.41.

This lower value of the Spearman coefficient (compared to the Instantaneous Amplitude) can be explained as due to the fact that the greatest attribute values are not assigned to the coarse sand class but rather to the fine sand class. As the asymmetry of the fine sand class is variable, and it is not possible to establish a trend in asymmetry whether towards coarse sediment or fine since the samples are from different locations, it can be said that the attribute value may be associated with the other characteristics of the sediment, for example composition and morphological properties.

As is shown in Figure 8C, the Energy Attribute, ranging in value between 6,000 and 20,000, is not efficient enough to discriminate between different grain classes, even though it does seem sensitive to the difference between the SVFS and SFMC groups. This attribute presented a low Spearman coefficient, showing a significant though weakly positive relationship - 0.30 - as between attribute value and grain size, because there are very significant high values assigned to all grain classes even in the finer grade ones such as silt and very fine sand.

In Figure 8D it may be noted that the Instantaneous Frequency attribute was not as effective as the amplitude attributes in discriminating between different grain classes. The Instantaneous Frequency displayed two distinct behaviors, the silt and very fine sand classes have a tendency to show increased attribute value, while the fine, medium and coarse sand classes have the opposite behavior. As a consequence, this attribute presented the low Spearman coefficient of 0.10.

DISCUSSION

As regards sorting, asymmetry and kurtosis, correlation between the first parameter and seismic attributes presented the best result. Sorting was investigated because it is an important parameter for describing the samples of more heterogeneous composition which may present different packaging arrangements, which influence the density, porosity and permeability of the material (JACKSON, 2007).

COMPARING DIFFERENT SEAFLOORS COMPOSITIONS

Figure 5 shows the 3 eco-characters observed in seismic profiles, including unconsolidated sediment, gas and rock. Considering the seismic records indicating sand, though these sediments usually have a higher density and thus greater impedance, this sediment has higher reflection amplitude as compared to the echo character of smaller sediment grain size (JACKSON, 2007). As described above, rock and gas eco-characters have specific characteristics, which can be easily identified in seismic profiles. Shallow gas was usually identified by multiple seismic attributes and causes the masking of adjacent reflectors. In the analyzed profiles the gas was a shallow feature, found at the interface between seafloor and water, and is formed from the decomposition of organic matter.

When analyzed in comparison with unconsolidated sediment, gas and rock show higher amplitudes when amplitude attributes are analyzed. This is because shallow gas is associated with fine-grained sediments (FRAZÃO; VITAL, 2007), and when the gas is close to the water/seabed interface it forms a strong impedance contrast, because the speed of the acoustic wave decreases considerably when it comes into contact with the gas (WILKENS; RICHARDSON, 1998), thus constituting a boundary that will reflect a great amount of energy.

It was not possible to determine which feature had higher amplitude attribute value, because each one presented a different behavior for each attribute. IA and RMS showed higher values for gas, while Energy indicated the highest values for rock. These differences may occur during the tracing of the horizon because in OpendTect the horizon is created manually, i.e., there might be uncertainties regarding the position of the amplitude peak.

The Instantaneous Frequency was the only attribute able to differentiate between rock, gas and unconsolidated sediment. The larger variability of this attribute observed in sedimented seafloors can be explained by differences in the compositions, characteristics and morphometric parameters of the particle size curve for selected samples.

COMPARING DIFFERENT GRAIN SEDIMENT CLASSES

No relationship between seismic attributes and the sorting of unconsolidated sediments was observed. When comparing well-sorted very fine sand and fine sand we did not observe any real distinction between them, indicating that sorting is not the main property that determines attribute value. In the literature, no such comparison is found. The most common use made of Instantaneous Amplitude is to emphasize the continuity of reflectors, to highlight the presence of channels, or to enhance deeper reflectors.

The RMS amplitude attribute gave a significant and moderate Spearman coefficient (0.41). This intensity can be explained as resulting from the fact that the highest attribute values were not assigned to the coarse sand class but to fine sand. Coarse sand is poorly sorted and symmetrical, while fine sand has varied sorting and symmetry; in this case, variability could be explained by changes in other sediment characteristics and properties such as, for example, composition and morphological properties.

Analyzing the Energy attribute (Figure 8C), it may be noted that all the grain size classes had a large range of attribute values, because all the samples had coarse grains and the values were squared, increasing the amplitude attribute range. So the Spearman coefficient, even though significant, indicates a weakly positive relationship of 0.30 between attribute value and grain size. This could be due to the fact that there are significant, high values assigned to all classes of grains even to the smaller-sized classes such as silt and very fine sand.

The Instantaneous Frequency attribute presented two distinct kinds of behavior. The silt and very fine sand classes have a tendency to increase attribute value (the value ranging between 0.4 kHz and 10.5 kHz), while fine, medium and coarse sand classes have the opposite trend (a value range of between 0.2 kHz and 6.6 kHz), resulting in a low positive Spearman's correlation (0.10). This might also be explained by the different frequency bands (and the different equipment used) of seismic sources and by the uncertainties involved in tracing the horizons.

MODEL VALIDATION

Before the analysis, two seismic profiles containing the samples collected were separated to validate the results. The attribute with the highest efficiency in discriminating between different seafloors, the Instantaneous Amplitude, was calculated for these two lines and the results analyzed. Considering the two groups proposed: SVFS (the silt and very fine sand group) and SFMC (the fine, medium and coarse sand group), the limits for the attribute values were defined: between 10-50 for the SVFS group; and between 50-175 for the SFMC group, taking as a reference the minimum value and variability range of between 25 and 75%.

Analyzing Figure 9A and Figure 9B, it may be seen that there are a large number of samples of the SFMC group characterized by a coarser grain size, and this may be confirmed by the number of samples located on the same profile. In Figure 9C the SVFS group was predominant and the silt and very fine sand classes can be confirmed by the number of samples collected on the same seismic line.

After the test with two seismic lines, the method was applied to a small area (containing a collected sample) in Ponta da Madeira Port Terminal in São Luís (Figure). Ponta da Madeira Port Terminal is part of the Maranhão Port, located in São Marcos Bay, on the west coast of São Luís Island.

The Instantaneous Amplitude attribute was calculated, eliminating the larger and applying a moving average filter (n=5 for the moving average). Figure 10 shows the application of the method to a small area of the São Luís port, from which it is inferred that the region has a sedimentary cover composed of the two groups. Samples from this region are well sorted (the reference sample is of fine sand) and the attribute values are lower. Figure 10 also shows the ratio of the average Instantaneous Amplitude

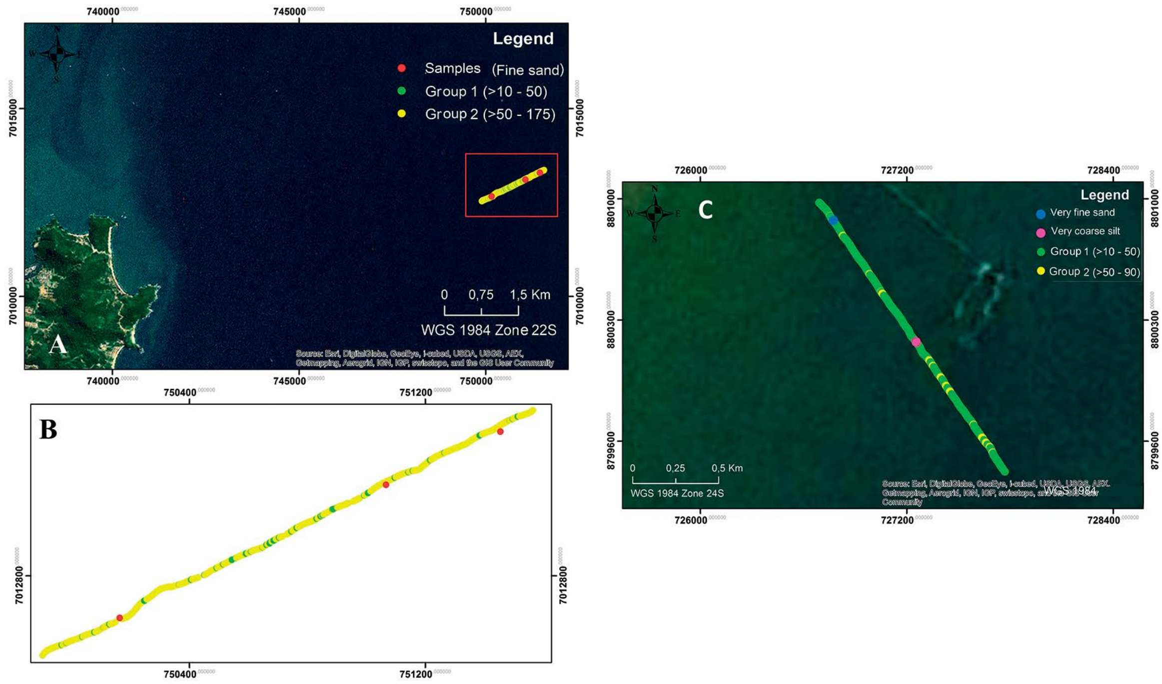


Figure 9. On the left may be seen the attribute values for Balneário Camboriu city, in B is the zoom of area A; the right side showing the attribute value for Aracaju city (C). Source: Google Earth.

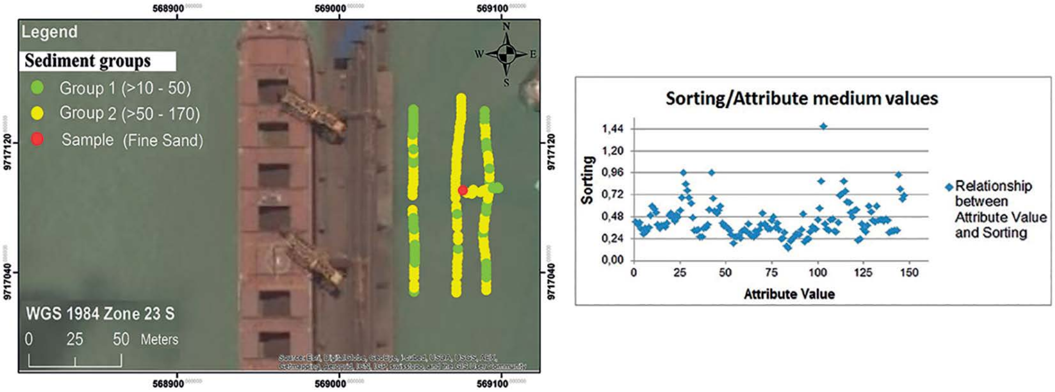


Figure 10. On the left: sample and attribute value distributions, where Group 1: SVFS and Group 2: SFMC. On the right: the ratio of the average Instantaneous Amplitude attribute values and sorting. Source: Google Earth.

attribute values and sorting. The range (minimum and maximum) of fine sand sample sorting, between 0.12 and 0.63, indicates that values above that range are composed of particles larger than fine sand and that below this range they would be even smaller than fine sand.

In this paper we tested the ability of Seismic Attributes to discriminate between different seafloors. Concerning the seafloors covered by unconsolidated sediments, we used Seismic Attributes to discriminate between different grain sizes, and were able to provide a division into two groups: the silt and very fine sand (SVFS) group and the fine, medium and coarse sand (SFMC) group. On the other hand, these attributes were not efficient in providing a finer discrimination. For this purpose, the Instantaneous Amplitude was more efficient in distinguishing between the two groups relative to the Energy attribute. The Instantaneous Frequency attribute showed a different behavior: in the SVFS group there was an increase in the frequency range, while in the SFMC group there was a decrease in the frequency range.

Comparing different seafloor types, i.e., those characterized by the presence of shallow gas and rock, the amplitude attributes were effective in distinguishing the sediments from shallow gas/rock, but did not differentiate between shallow gas and rock. The two features had very high, though similar, amplitudes. On the other hand the Instantaneous Frequency attribute was effective in differentiating between sediment, rock and gas, with sediment presenting a higher band, rock an intermediate band and gas the lowest one.

For a better development of the subject in future studies, it is suggested that other kinds of information should be considered to describe the behavior of the seismic waves - such as the material composition (the amount of carbonate, organic matter), parameters of the grading curve, structural and morphometric characteristics (angularity, tortuosity, rounding, arrangement, packing), porosity and density. In addition the conditions under which the survey was undertaken should also be considered.

These would include the sea conditions: a ripple can modify the stability of the equipment and thereby alter the angle of the beam striking the background from various angles, depending on whether the equipment has been attached to the vessel or is being towed. Even when the same equipment is used, different frequency bands can be selected, and thus modify the attributes that correspond to a particular frequency. Further, the equipment's power supply used during data acquisition directly influences the amplitude values obtained. The parameters such as sea water temperature, salinity and suspended material, for example, are responsible for attenuating the acoustic signal by changing the response of the attributes.

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