

## INTERPRETATION OF SEDIMENTARY PROCESSES USING ECHO-CHARACTER DISTRIBUTION: CASE STUDY OF PIRAQUÊ-AÇU AND PIRAQUÊ-MIRIM ESTUARINE SYSTEM, ARACRUZ – ES (BRAZIL)

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**ABSTRACT.** This research aimed to map distinct types of echo-character in order to recognize estuarine sedimentary processes along the Piraquê-Açu System, in Aracruz, Espírito Santo State, Brazil. Echo-character mapping was undertaken using high frequency sub-bottom profiling data. Four echo-character (EC1, EC2, EC3, EC4) patterns were recognized by combining sub-bottom and surficial sedimentological data. These EC patterns defined three distinct areas within the system that are characterized by the predominance of a specific echo-character and a seabed type: i) estuarine mouth, where sand beds with low penetration prevail; ii) a transition zone, where sandy-muddy and muddy-sandy beds are associated with a high penetration echo-character; and, iii) the rivers/estuary Piraquê-Açu and Piraquê-Mirim with sandy-muddy and muddy beds with high penetration echo pattern. The interpretation showed that the association of EC and surficial sediment may represent modern sedimentary processes within the estuary. Three sedimentary processes were recognized: a) marine dominated processes showing sand transport by tidal currents; b) estuarine processes with fine sediment input, resuspension and deposition; and c) erosive estuarine processes or scour lags, exposing possibly relict deposits.

**Keywords:** estuarine sedimentation, shallow geophysics, sub-bottom profiler.

**RESUMO.** Esse estudo busca reconhecer os tipos de ecocaráter existentes para o melhor entendimento dos processos sedimentares do sistema estuarino do Piraquê-Açu e Piraquê-Mirim, localizado no município de Aracruz, Espírito Santo. O reconhecimento e o mapeamento dos tipos de ecocaráter foram realizados a partir de registros de perfilador de subfundo de alta frequência. Através da associação dos dados geofísicos com dados sedimentológicos foram reconhecidos e definidos quatro padrões de ecocaráteres (EC1, EC2, EC3, EC4) associados a tipos de fundo distintos. A distribuição espacial dos tipos de eco permitiu a divisão do estuário em três áreas distintas que diferem pela predominância de diferentes tipos de ecocaráter e sedimento: i) A foz do sistema estuarino, interpretada como região de dominância marinha, onde predomina o fundo arenoso e a baixa penetração do sinal; ii) A zona de confluência, onde predomina sedimentos areno-lamosos a lamo-arenosos com penetração do sinal acústico; iii) Os braços Piraquê-Açu e Piraquê-Mirim de domínio de fundo areno-lamoso a lamoso, com penetração do sinal. Estas áreas estão associadas a distintos processos sedimentares, sendo eles: a) processos marinhos com transporte de sedimentos arenosos por correntes de maré (foz do sistema até a confluência dos braços); b) processos estuarinos com aporte, resuspensão e deposição de sedimentos finos, típicos da região interna do sistema; e c) processos estuarinos erosivos ou de ravinamento, ocorrendo localmente nos braços.

**Palavras-chave:** sedimentação estuarina, geofísica rasa, perfilador de subfundo.

**INTRODUCTION**

Studies involving sedimentary and morphological characterization of the seabed (Flood, 1980; Cooke et al., 2007; Veronez Júnior et al., 2009a) are important not only to scientific purposes but also to support the planning of various human activities such as construction of coastal/marine structures, mapping of mineral deposits, identification of marine habitats, definition of navigation channels, and others. Studies about the acoustic response from echo-characters (EC) are a widely applied tool to recognize sedimentary facies and sedimentary processes. This technique can be applied not only to map the seabed, but also to infer the hydrodynamic and sedimentary processes acting in the environment (Laine et al., 1986; Quaresma et al., 2001; Belo et al., 2002; Catanzaro et al., 2004; García-García et al., 2004; Palomino et al., 2009).

Each type of identified echo-character is associated with a different type of seabed and/or sub-bottom (Souza, 2006), responding differently to sedimentary parameters such as particle size, layer thickness, porosity, compaction, and density, among others.

Damuth (1975) was the first author to associate echo-character types with sedimentary processes, and although this author studied deep regions, several others applied this principle to shallow marine/coastal areas (Quaresma et al., 2001; Nitsche

et al., 2004; Veronez Júnior et al., 2009b). It is noteworthy that when analyzing echo-characters in shallow waters, the geomorphological and hydrodynamic factors of the area should be considered in order to accomplish a more accurate interpretation (Palomino et al., 2009).

Thus, this study aims to associate high-resolution sub-bottom profiler echo-character with surface sediment distribution in order to recognize patterns of dominant sedimentary processes existing in an estuarine system.

The Piraquê-Açu and Piraquê-Mirim Estuarine System (PAPMES) is located in Aracruz, Espírito Santo State (Fig. 1). The PAPMES crosses an area classified as sector 3 by Martin et al. (1996), where narrow coastal plains are located adjacently to the tablelands of the Barreiras Formation. It is a typical Y-shaped estuary, of drowned valley, formed during the last post glacial marine transgression. The proximity of the Barreiras Formation to the main channel imposes special conditions for sediment distribution, morphology and extent of mangroves (Silva et al., 2013). This system is of great scientific interest, since it is typically the first transgressive feature south of a prograding coast represented by the Rio Doce Delta, and has been the subject of various geo-environmental studies since 2010. The system is subjected to a micro-tidal regime.

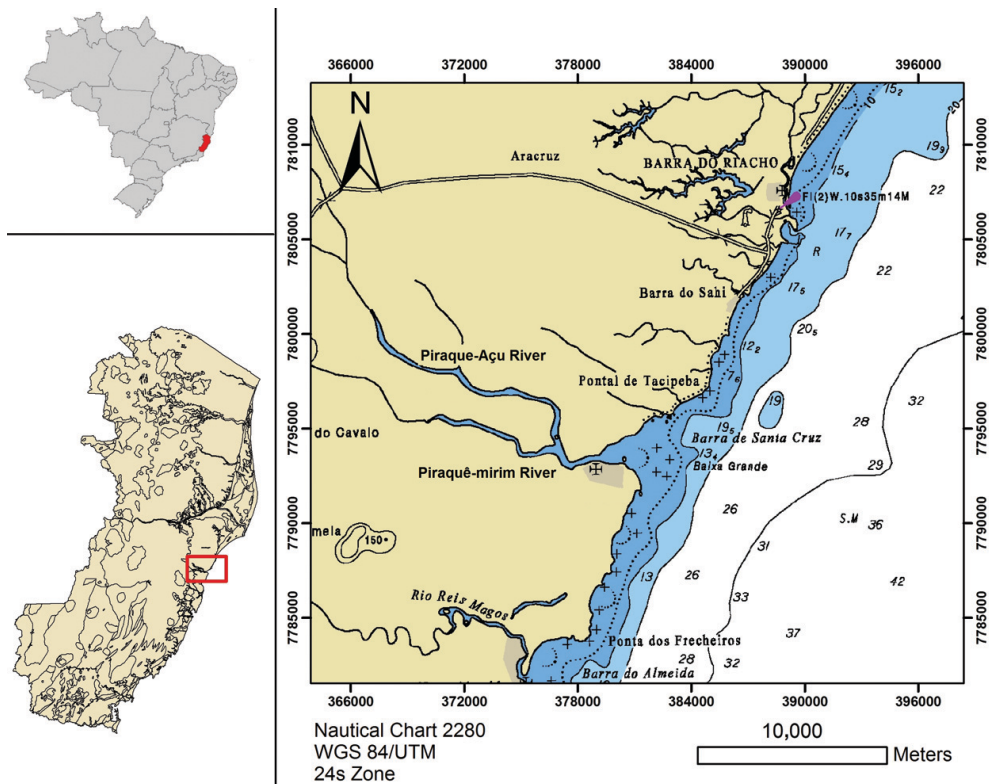


Figure 1 – Study area location.

## METHODOLOGY

The research consists of correlating acoustic data with textural properties of bottom sediments.

The geophysical surveys were carried out along the estuary using a high frequency (10 kHz) Stratabox sub-bottom profiler. A total of 42 km of seismic lines were collected. The data was processed and interpreted using SonarWizMap-5 software, from Chesapeake Technology. The echo-characters were determined by:

- i) considering the degree of penetration and reflection;
- ii) occurrence of sub-bottom reflectors and
- iii) geometry of the reflectors (occurrence of hyperboles).

A total of 90 surface samples were collected (Fig. 2) and analyzed to determine the distribution pattern of the surface sediment. Grain size distribution was determined by dry sieving analysis at 1/2 phi intervals. Qualitative and direct correlation between echo-characters, mean grain size and sand/mud ratio were performed.

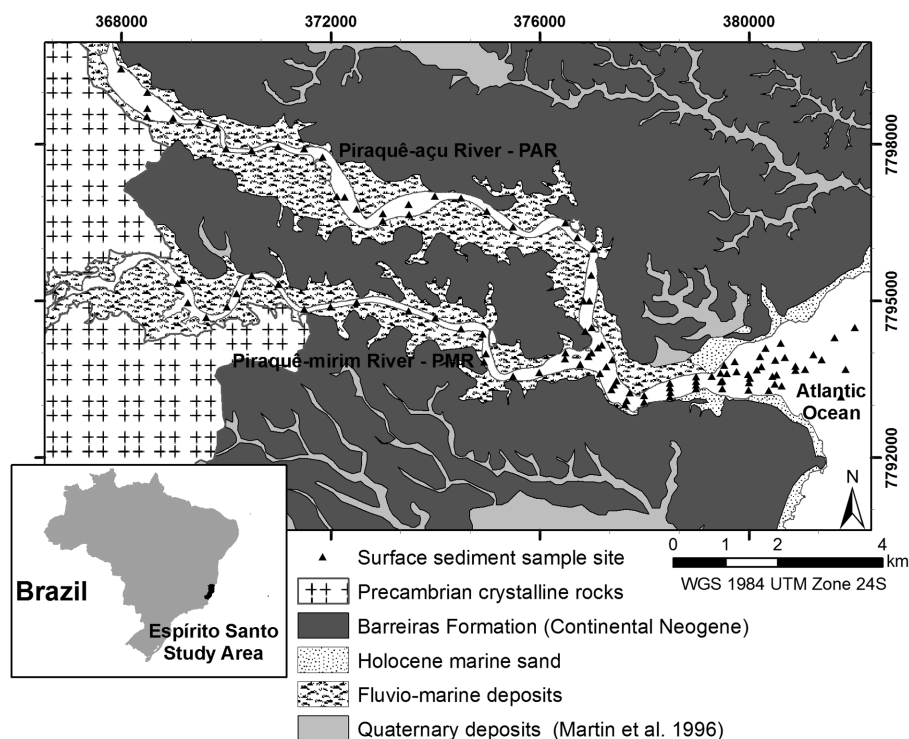
Data was overlapped and grouped seeking to relate directly the backscatter signal and the properties of the seabed sediment, recognizing patterns of distribution and variability of sediments and depositional processes.

## RESULTS AND DISCUSSION

### Sedimentology

The distribution of the mean sediment grain size along the estuary (Fig. 3) showed a change from medium to coarse sand near the mouth and the head of the estuary, ranging from fine to very fine sands up to the bifurcation of the system. Sandy sediments (coarse and medium) predominate near the mouth and the head of the Piraquê-Açu, areas of higher energy due to both tidal and river currents. The intermediate portion of the Piraquê-Açu branch has predominantly muddy-sand sediments (mud associated with fine and very fine sand), suggesting a zone of lower energy, in which marine and fluvial processes are counterbalanced. This distribution corresponds to the classical model of estuarine facies proposed by Dalrymple et al. (1992).

On the other hand, the Piraquê-Mirim branch displayed different deposition patterns, with predominance of medium and coarse sands after a muddy area at the riverhead. This sandy characteristic is possibly associated with a higher current flow as a function of the local geomorphology (lower width between the river banks) (Silva et al., 2013). The coarse and medium sand sediments observed in the upstream portion of the Piraquê-Açu River suggest greater fluvial influence, because they are outside



**Figure 2** – Geomorphological map of the study area showing the surface sediment sampling locations (modified from Silva et al., 2013).

the areas where sediment is reworked by waves and tides, while mud deposits in the estuary appear to be associated with stretches where the channel depth is greater. However, there is a sandy stretch (medium sand) that requires further investigation for an appropriate environmental interpretation.

The sedimentary pattern, which is predominantly sandy near the mouth, suggests the influence of tidal forcing. The distribution of mean size grain (Silva et al., 2013) (Fig. 3) shows that, in general, the inner estuary has extensive coverage of fine sediments, which contributed to a good penetration of the acoustic signal since it has low penetration in sand beds.

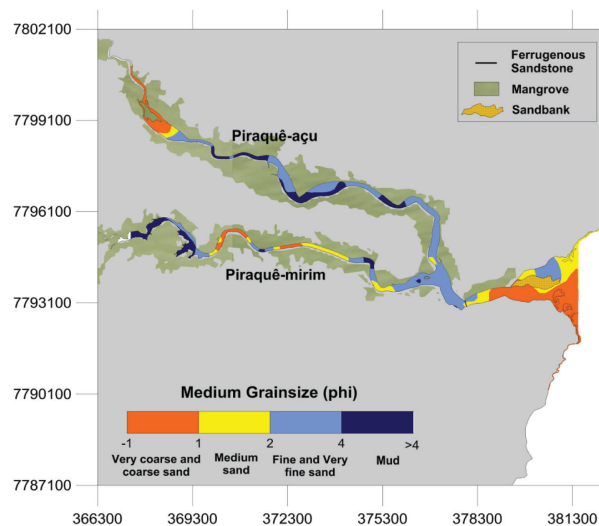


Figure 3 – Mean sediment grain size distribution (after Silva et al., 2013).

### Sub-bottom profile

Four echo-characters (EC) were recognized using the sub-bottom profiler data (Fig. 4):

- Echo-character type 1 (EC1) is characterized by the high reflectivity of the bottom surface and the low penetration of the acoustic signal. It is possible, sometimes, to observe the presence of bed forms.
- Echo-character type 2 (EC2) was distinguished by the low penetration pattern, which enabled to identify the subsurface reflectors and acoustic basement near the bottom.
- Echo-character type 3 (EC3) presented a high reflectivity surface, with high penetration of the acoustic signal. It is possible to observe the plane or irregular acoustic basement, and also diffuse acoustic expressions which have been interpreted as the presence of gas in the sediment, similar to the acoustic turbidity observed by Garcia-Gil et al. (1999).

- Echo-character type 4 (EC4) is characterized by high penetration and limited by high reflectivity subsurface reflectors, with irregular/hyperbolic geometry, which indicate the basement.

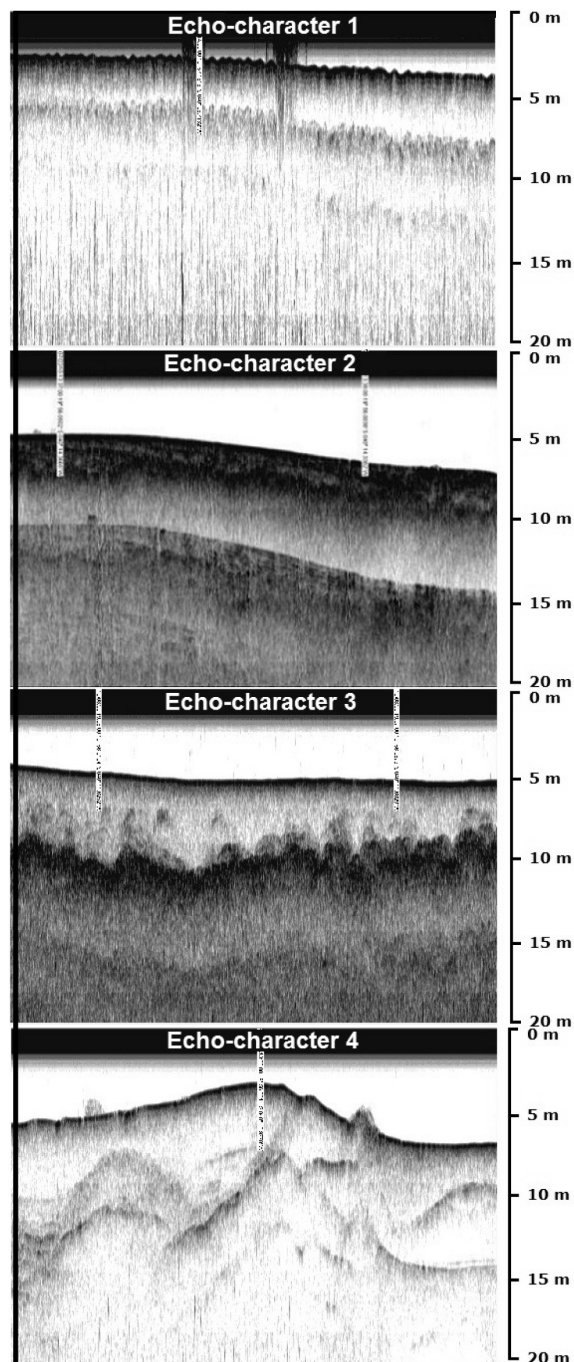


Figure 4 – Different types of echo-character identified in the PAPMES. EC1 – high reflection and low penetration; EC2 – low penetration and acoustic basement near the bottom; EC3 – high reflectivity and penetration; EC4 – high penetration and irregular/hyperbolic geometry.



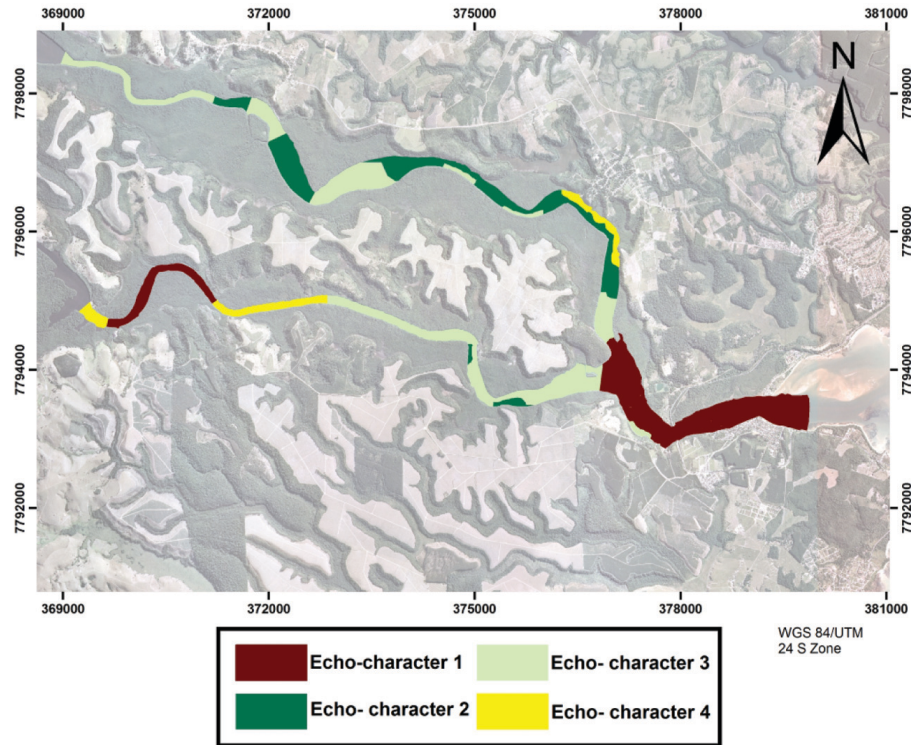


Figure 5 – Distribution of different echo-character patterns along the estuarine system.

The spatial distribution of echo-character types (Fig. 5) shows a pattern of low penetration near the mouth of the estuary; with the highest signal penetrations where the fine material is most concentrated, i.e., the inner portion of the estuary. This analysis showed distinct patterns associated with Piraquê-Açu and Piraquê-Mirim branches. In the Piraquê-Mirim branch, near the confluence EC3, and upstream, the echo-characters EC4 and EC1 predominate, where signal penetration is defined by the geomorphology and grain size, respectively.

EC2 prevails in almost all the Piraquê-Açu River extension, except near the confluence where EC3 appears. The EC2 record is interrupted locally; where the occurrence of deposits from the Barreiras Formation along the banks allows the emergence of EC4. EC1 predominates from the confluence of the branches up to the mouth of the estuarine system, associated with a sandy bottom and higher energy sedimentary processes influenced mostly by the sea.

These observations showed that EC1 is associated with higher energy sedimentary processes while EC2 and EC3 types prevail especially in areas classified by Silva et al. (2013) as estuarine domain. The difference lies in the fact that the EC3 type occurs where the sediment distribution is dominated by mud beds. Finally, EC4 type always appears in areas nearby Pre-

Cambrian coastal massifs (according to the geomorphology shown on the map of Fig. 2), which may explain the presence of hyperbolic reflectors.

### Recent sedimentary processes

A sedimentary processes map is shown in Figure 6. This was produced by combining the distribution of mean particle size and echo-character types in the estuary. In addition to the echo-characters and particle size distribution, the compartmentalization of areas (fluvial, marine and estuarine) proposed by Silva et al. (2013) and the analysis of hydrodynamic circulation of this estuarine system (Neves, 2010; Melado, 2011) were also taken into account to produce the map. Table 1 shows a summary of the associations observed in this study.

Figure 6 shows that near the mouth, toward the confluence, the associated processes are mostly marine, according to the low estuary definition by Dalrymple et al. (1992). This interpretation was supported by the fact that sand beds predominate in this portion of echo-character type 1 (low penetration and the possible presence of bottom shapes). Another indication is the high current speeds found in this stretch of the estuary (up to 1.75 m/s), primarily associated with ebb tide currents (Melado, 2011). Franco et al. (2011) mapped subaqueous dunes in this stretch of

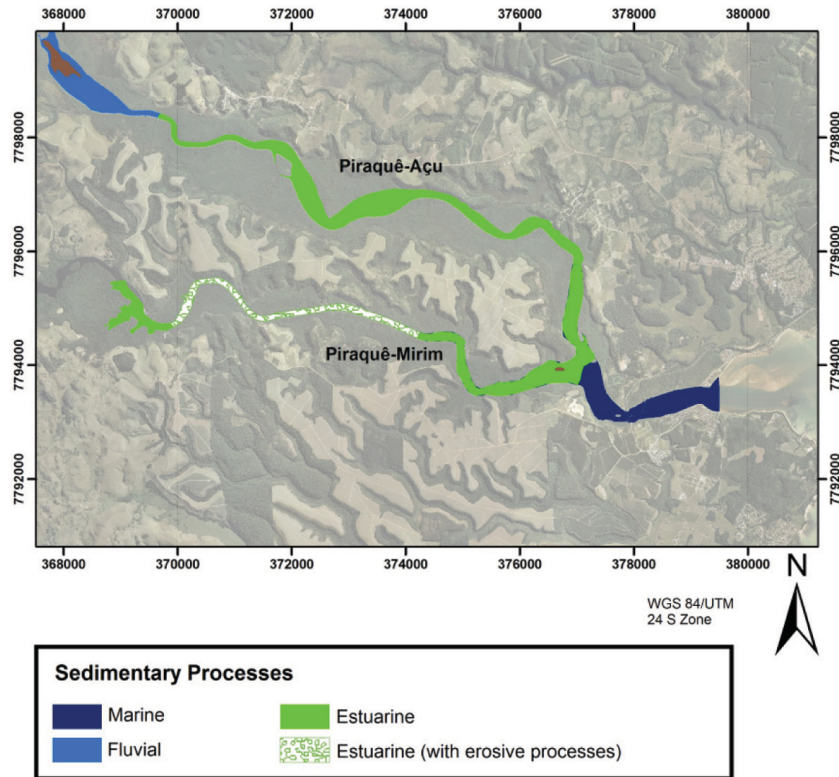


Figure 6 – Modern sedimentary processes along the PAPMES.

the estuary, which are bed forms associated with currents. Thus, this sector of the estuary was interpreted as an area of modern sedimentary processes related to tidal currents.

In the central portion of the Piraquê-Mirim branch, there is a stretch where interpretation shows the occurrence of bottom erosion, exposing relict sediments. The sand sediments may be related to regressive fluvial sands. This part of the estuary presents more intense current speeds than the northern branch (0.75 m/s), with hydrodynamic characteristics closer to the mouth of the estuary (Neves, 2010). These current speeds found in this sector of the estuary can be explained by the narrowing of the Piraquê-Mirim canal banks. This pattern is consistent with the data already presented, and allows, therefore, to classify this area as estuarine dominance with erosive sedimentary processes. It is noteworthy that a similar pattern – predominantly muddy estuarine sedimentation with eroded areas with sandy bottom – was reported by Veronez Júnior et al. (2009b) in the estuarine system of Vitória Bay, further north from the PAPMES.

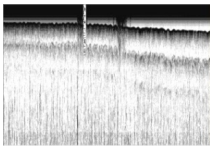
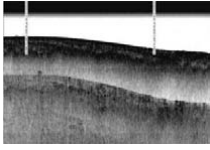
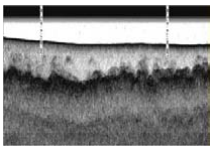
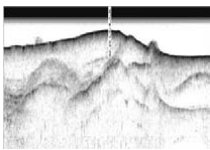
In the northern part of the estuarine system, the tidal flat appears more developed, which allows storage of large amounts of water in the inter-tidal period. In addition, the current speeds are lower. Thus, recent sedimentary processes were interpreted as a

low energy estuarine dominance.

The occurrence of different echo-character types (EC2 and EC3, respectively) in areas classified as of estuarine dominance in Piraquê-Açu and Piraquê-Mirim indicates that particle size is not the only property influencing the response of the acoustic signal. Although the sedimentary distribution of the northern branch shows finer sediments than that of the southern branch, echo-character EC2 is characterized by a lower penetration than that observed in echo-character EC3. Thus, other sediment properties – such as density, porosity and compaction – are possibly influencing the sub-bottom profile data. Other studies have pointed out that the grain size is not the only property that defines the echo type (Belo et al., 2002).

Fluvial dominated sedimentary process was observed at the head of the Piraquê-Açu branch. As the sub-bottom survey did not cover this stretch, this interpretation was based on the occurrence of sandy beds in this area, indicating a higher energy fluvial action, which approaches the characterization of an estuarine head as proposed by Dalrymple et al. (1992). Furthermore, the salinity distribution in this local of the system (Leite et al., 2011) presents low values, limnetic zone, typical of areas with little tidal influence.

**Table 1** – Characteristics of the echo-characters types observed in the PAPMES.

Echo	Description	Sediment	Associated processes	Location occurrence	Sub-bottom profile
EC1	Surface reflector with high reflectivity, low penetration, with/without bed forms	Sand	Sea dominance - tidal currents	Mouth of the estuary	
EC2	Pattern with the presence of subsurface reflectors with high reflectivity and acoustic basement near the bottom	Sandy-Mud/Muddy-sand	Estuarine dominance	Predominates along the Piraquê-Açu	
EC3	Surface reflector with high reflectivity, internal reflectors and/or diffuse gas structures, with flat/irregular highly reflective acoustic basement	Mud/Muddy-sand	Estuarine dominance	Predominates along the Piraquê-Mirim; some and in some portions of Piraquê-Açu	
EC4	High signal penetration, followed by an acoustic basement with irregular/hyperbolic geometry	Sandy-mud, associated with rocky bottom	No associated characteristic process	Portions near the crystalline basement	

## CONCLUSIONS

Four echo-character patterns were identified. The spatial distribution associated with these bottom sediment patterns allowed us to recognize active sedimentary processes in the Piraquê-Açu and Piraquê-Mirim Estuarine System. These processes can be defined as: i) marine processes with transport of sandy sediments by tidal currents that shape the bottom (mouth of the system up to the confluence of both rivers); ii) estuarine processes with input, deposition and resuspension of fine sediments characterized by sandy-mud deposits with high signal penetration, typical of the system inner region; and, iii) erosion or scour lags estuarine processes, with relict sediments exposure. Fluvial processes were only observed in the sediment distribution since no sub-bottom survey was performed in these areas.

The variation in the penetration degree of the acoustic signal depended on the bottom sediment of the estuary. Higher penetration was observed in areas with finer materials. However, the penetration of the signal as well as aspects of echo-characters

(penetration and geometry of reflectors) depended on the morphology/geology of the estuary, which showed rocky outcrops and deposits limited by the tertiary sediments of the Barreiras Formation sometimes present in direct contact with the estuarine waters. In the Piraquê-Açu River, the signal penetration was limited by other physical characteristics of the sediment, possibly density.

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