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DISTINCTIVE SEDIMENTARY PROCESSES IN GUANABARA BAY – SE/BRAZIL, BASED ON THE ANALYSIS OF ECHO-CHARACTER (7.0 kHz)

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ABSTRACT. Guanabara Bay bottom sediments and seabed characteristics were analysed using high-resolution (7 kHz) sub-bottom profiles associated with particle size analyses of 92 bottom sediment samples. Eight types of echo-characters were identified revealing the strong relation with the particle size distribution. Sandy bottom areas presented strong echo reflections, without sub-bottom penetration (Echo types I and III), while in muddy areas sub-bottom reflections showed the acoustic basement delineating buried sugar-loaf hills and infilled-valley features (Echo type IV). The presence of shallow gas within the sediments is indicated by acoustic blanket and a series of bottom-multiple reflections (Echo types Va and Vb). Erosion by bottom currents and artificial mechanical dredging are suggested by truncations of sub-bottom reflections and a wrinkled seabed surface (Echo types VI and VII). Crystalline basement outcrops on the seabed are recognized by multiple or single hyperbolae with varying elevations above the bay bottom (Echo type II).

Keywords: echo-character, dynamics of sediments, seismic of high resolution.

RESUMO. O presente trabalho faz uma descrição geral das caracteristicas de fundo da Baía de Guanabara com base na descrição de 92 amostras de sedimentos de fundo e na interpretação de perfis de perfilador de sub-fundo de alta freqüência (7 kHz). Os oito tipos de ecocarater identificados revelam uma forte relação com as variações sedimentológicas. Nas áreas de fundo arenoso observa-se uma forte reflexão do eco no fundo, impedindo a penetração em subsuperficie (Tipos de eco I e III), enquanto que nas áreas de fundo lamoso é possível observar, abaixo dos refletores de sub-fundo, o embasamento acústico fomando feições de morros tipo “pão-de-açucar” e vales preenchidos (Tipo de eco IV). A presença de gás nos sedimentos foi associada a uma série de múltiplas e cortinas acústicas (Tipos de eco Va e Vb). Nas áreas de erosão, por correntes de fundo e dragagem mecânica, observa-se uma superfície irregular, com truncamentos dos refletores de sub-fundo (Tipos de eco VI e VII). Em regiões de afloramento do embasamento cristalino ocorrem hipérboles múltiplas ou simples, com elevações variadas acima do fundo submarino adjacente (Tipo de eco II).

Palavras-chave: eco-carater, dinâmica de sedimentos, sísmica de alta resolução.

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INTRODUCTION

High-frequency (3.5, 7.0 and 12 kHz) sub-bottom profiling has served as an important tool for deciphering near-bottom sedimentary processes in marine environments as demonstrated by several workers (e.g. Hollister & Heezen, 1972; Damuth, 1975; Embley, 1976; Flood, 1980; Jacobi & Hayes, 1992; Baptista Neto et al., 1996; Reddy & Rao, 1997; Dowdeswell et al., 1997; Zaragosi et al., 2000; Hong & Chen, 2000; Quaresma et al., 2000; Lee et al., 2002). The types and distribution of the echo-character can be used as basis for the interpretation of depositional and erosional processes, since the echo types are mainly controlled by surface topography, subsurface geometry and sedimentary texture of the superficial and sub-superficial sediments and rocks (Damuth, 1975, 1980; Embley, 1976; Damuth & Hayes, 1977).

This study investigates sedimentary processes in the Guanabara Bay (Rio de Janeiro - Brazil) (Figure 1), focusing on the bottom morphology and sediment characteristics distribution, integrating the geomorphologic, sedimentary and geophysical characteristics of the bay bottom.

The Guanabara Bay is one of the most polluted bays on the Brazilian coastline, and great effort has been spent in order to de-pollute the bay. The development of studies to understand its hydrodynamics and bottom sediment characteristics in order to provide informations for environmental and water quality management projects devoted to the re-vitalization of Guanabara Bay.

ENVIRONMENTAL SETTING

Guanabara Bay is one of the largest bays along the Brazilian coastline, located in Rio de Janeiro State ($22°40'$ to $23°00'$ S and $043°00'$ to $043°18'$ W) (Figure 1). The bay has an area of approximately 384 km^2 including its several islands and presents a coastline of 131 km long and a mean water volume of 1.87×10^9 m^3 (Amador, 1980). It measures 28 km west to east and 30 km north to south, with a narrow entrance (1.6 km wide) (Kjerfve et al., 1997). Guanabara Bay shows a complex bathymetry with a relatively flat central channel, 400 m wide, stretching from the bay's mouth to more than 5 km into the bay more or less defined by of 30 m isobath. The deepest point of the channel is 58 m, near the bay's entrance, towards the bay head, the channel becomes wide and shallow, averaging 5.7 m in water depth (Kjerfve et al., 1997) (Figure 2). The observed diminishing relief and present depth of the central channel is in part explained by sedimentation rates, which increases towards the bay interior, and was accelerated in the past century by anthropogenic activities in the catchment area.

The area lies within the tropics of southeastern Brazil, but because its coastal location, a humid sub-tropical climate prevails between December and April with 2,500 mm (high altitudes) and 1,500 mm (low land) of rainfall. The mean annual temperature is between 20 and $25°$C (Nimer, 1989). The drainage basin has an area of 4080 km^2, consisting of 32 separate sub-watersheds with 91 rivers and channels (Kjerfve et al., 1997). Only six rivers, however, are responsible for 85% of the total mean fresh water input, in the order of 100 m^3 s^{-1} (JICA, 1994).

Nowadays, 11 million inhabitants live in the greater Rio de Janeiro metropolitan area, which is responsible for tons of untreated sewage directly discharged into the bay. Rio de Janeiro metropolitan area also includes the second largest Brazilian industrial region, with more than 12,000 industries dispersed along the Guanabara Bay drainage basin, accounting for 25% of the organic pollution released to the bay (FEEMA, 1990). Two oil refineries located along the bay's shores are responsible for the processing of 7% of the national oil. At least 2,000 commercial ships dock in the port of Rio de Janeiro every year, making it the second largest harbour in Brazil. The bay is also the homeport to two naval bases, a shipyard, and a large number of ferries, fishing boats and yachts (Kjerfve et al., 1997).

In the last 100 years the catchment area around Guanabara Bay has been strongly modified by human activities, in particular deforestation and uncontrolled settlement, which increased river flow velocities and sediment load and transport to the bay. Consequently the average rates of sedimentation increased to 1 to 2 cm year^{-1} (Godoy et al., 1998).

METHODOLOGY

Surface sediments were collected in November 1999 with a van Veen grab sampler at 92 stations (Figure 3), providing an almost complete geographic coverage of the bay area. The exact position of each sample was recorded using a Global Position System (GPS). The geophysical equipment, RYTHEON RTT 1000A, operates simultaneously in 200 kHz frequencies for the depth detection, and 7.0 kHz for penetration through the sub-bottom. Grain size analysis of sediment samples was carried out using standard sieve techniques (for $> 62\mu$m, Wentworth scale) and pippete ($< 62\mu$m) after destruction of organic matter with H_2O_2. The total organic carbon content was determined using an equipment CS infrared analyser model Eltra Metaly 1000CS.

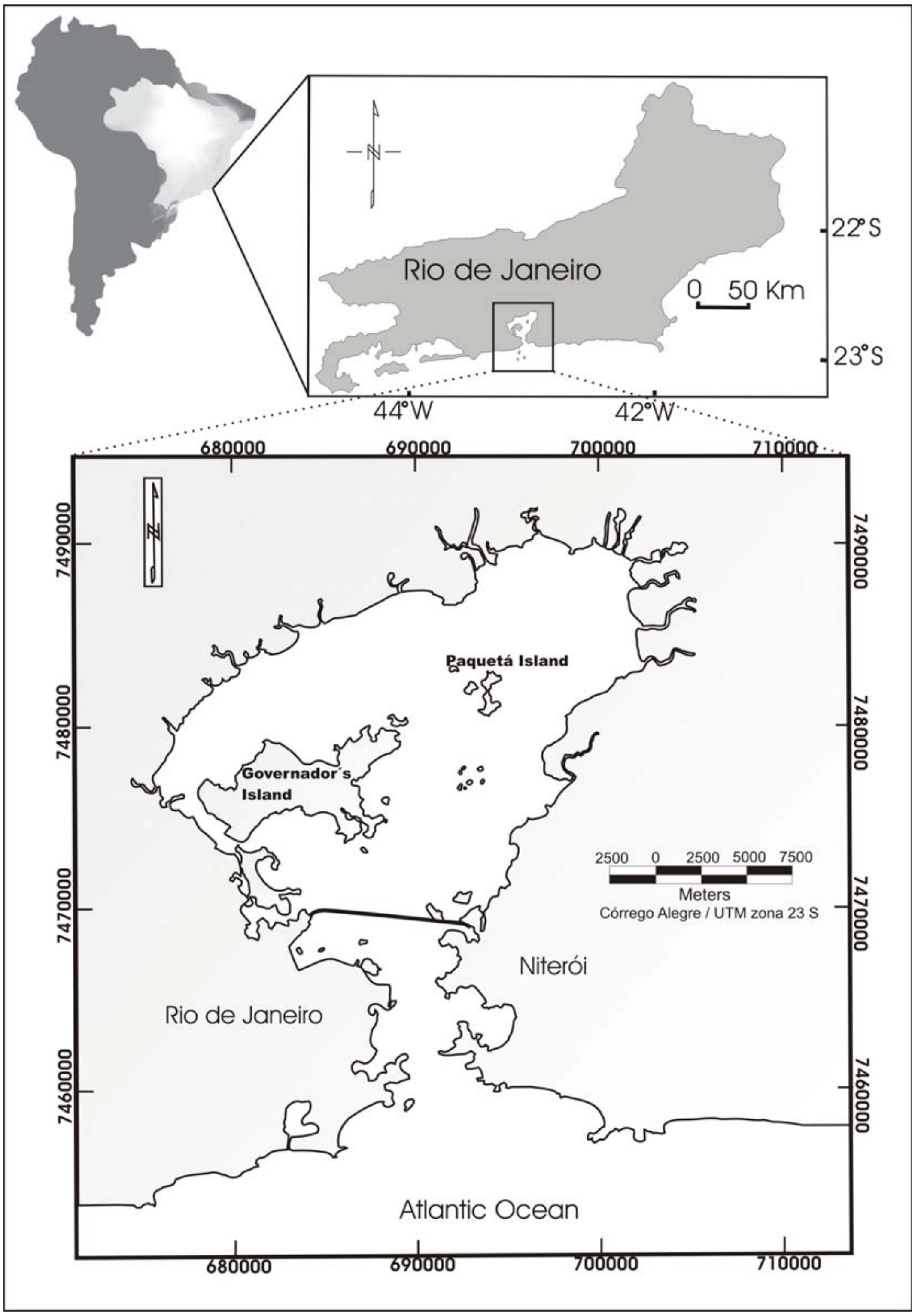

Figure 1 – The location map of the studied area.

Figura 1 – *Mapa de localização da área de estudo.*

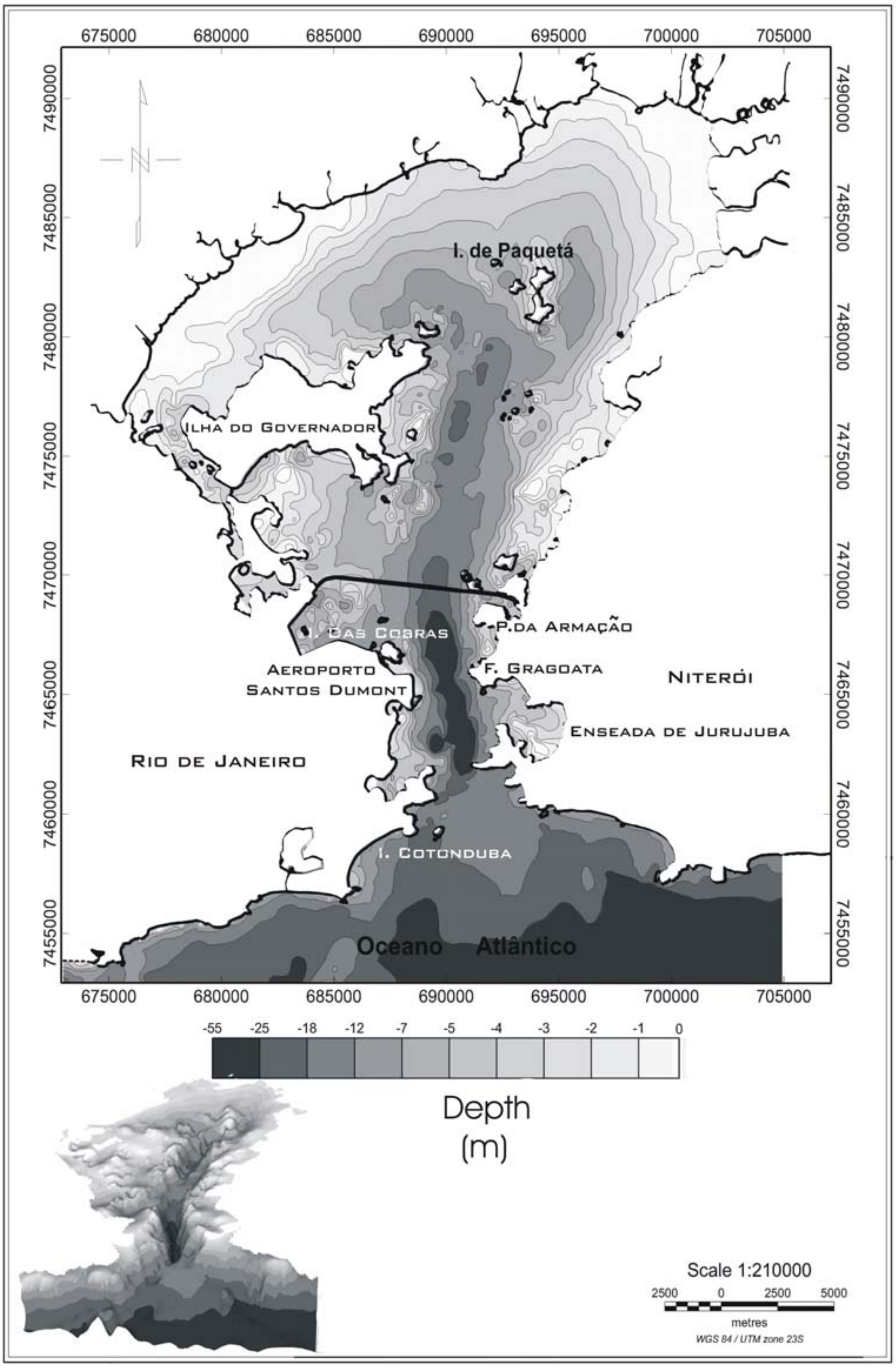

Figure 2 – The bathymetric map of the Guanabara Bay.

Figura 2 – *Mapa batimétrico da Baía de Guanabara.*

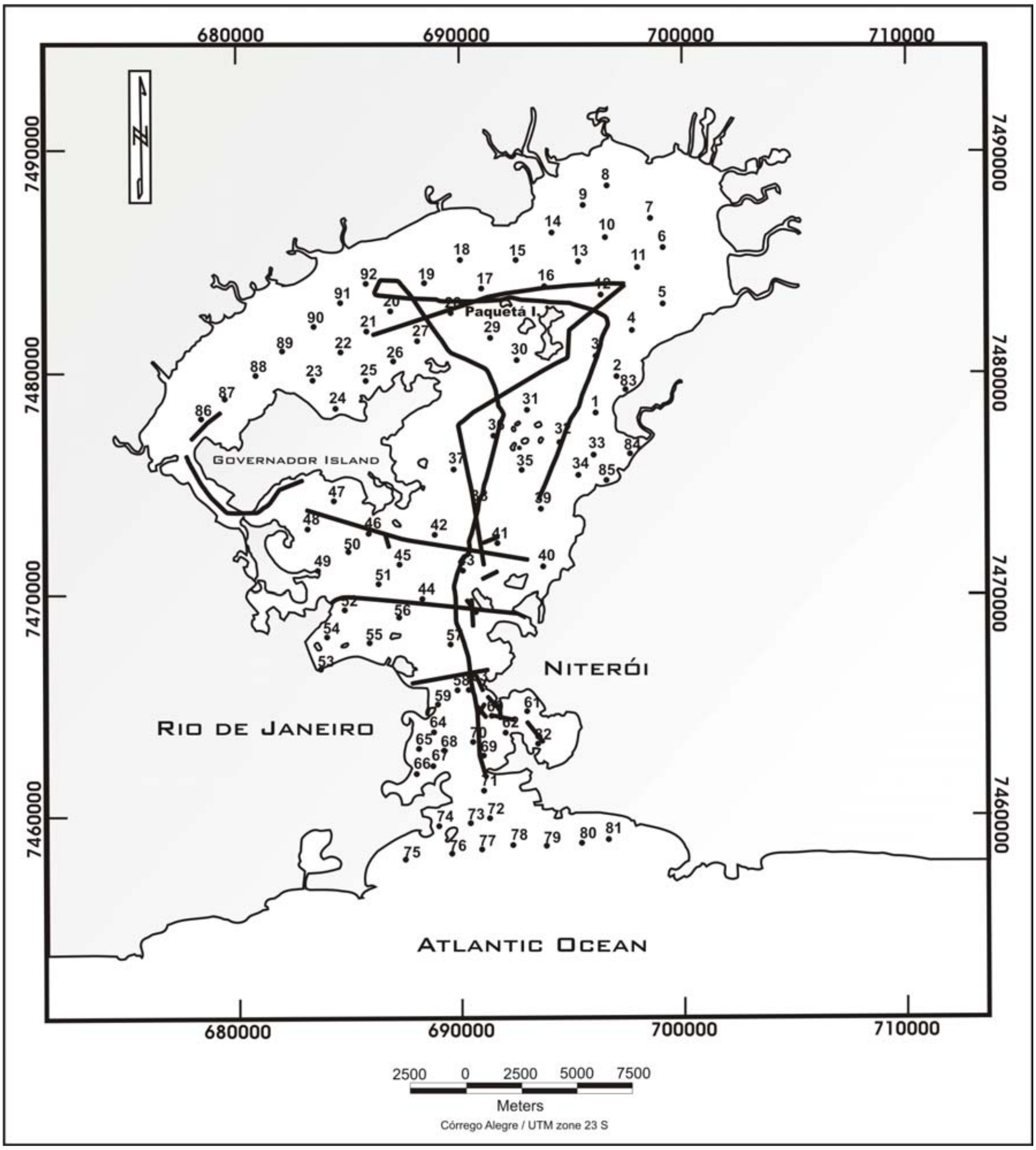

Figure 3 – The map with the position of the superficial samples and the seismic lines.

Figura 3 – *Mapa com a posição das amostras superficiais e linhas sísmicas.*

RESULTS AND DISCUSSION

Particle size and organic carbon content

The grain size distribution reflects the tidal current energy near the bottom, which is directly influenced by bottom morphology and the Guanabara Bay shoreline contour. The bottom sediment of the bay ranges from clay to coarse sand (Figure 4), sedimentary textures can comprise from 0% to 100% of sand, 0% to 92% silt and 0% to 85% of clay. The samples from Guanabara Bay were classified into four principal groups: clay, sand, clayey silt and clay-silt-sandy, by it median.

The sand sediment occurs from the entrance of the bay and follows the main channel, which is the deepest part of the bay. This area is subject to intense hydrodynamic action from waves

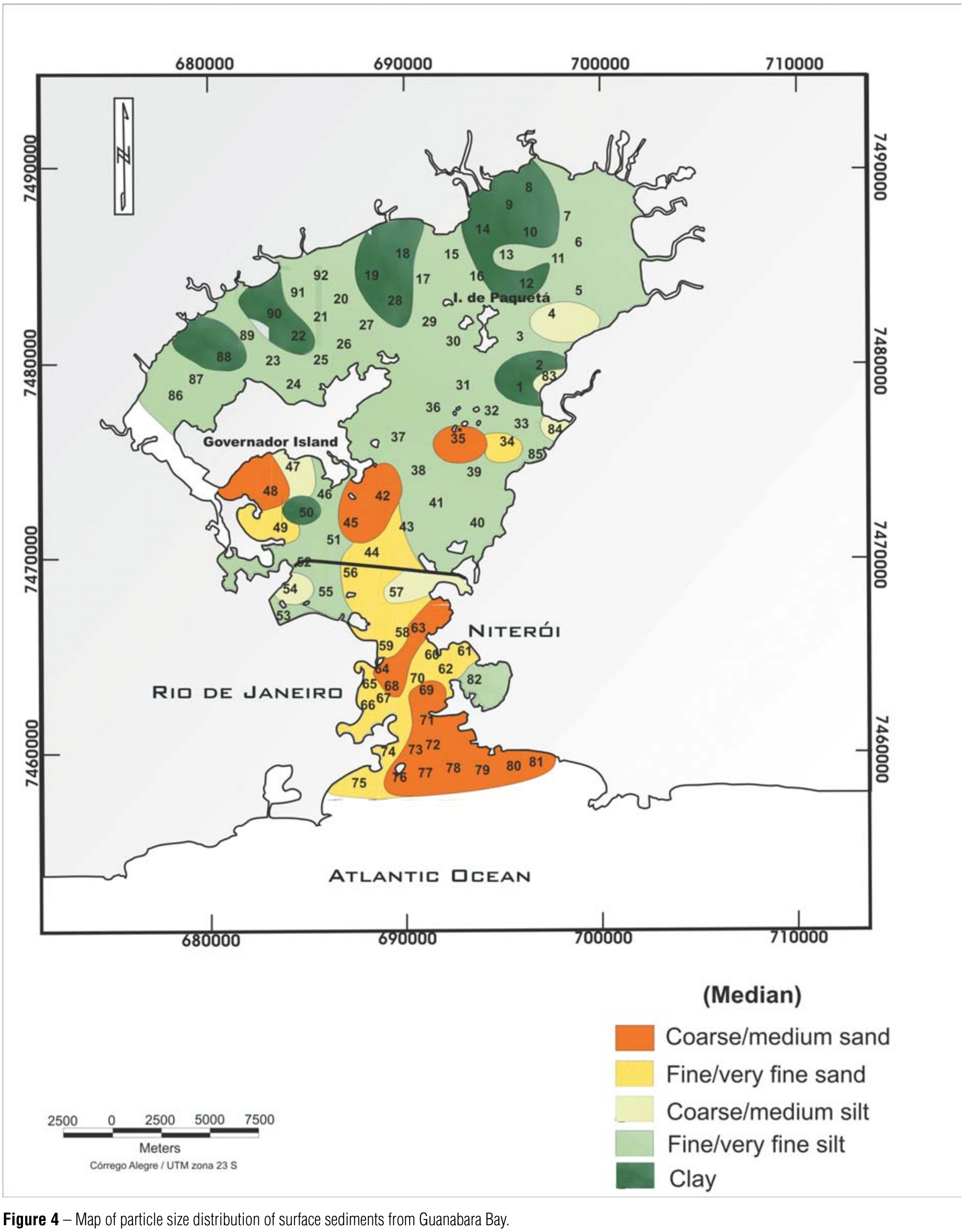

Figure 4 – Map of particle size distribution of surface sediments from Guanabara Bay.

Figura 4 – *Mapa de distribuição da granulometria dos sedimentos superficiais da Baía de Guanabara.*

and tidal currents, indicated by the presence of sandwaves. According to Quaresma et al., (2000) and Kjerfve et al. (1997) these sandwaves occur along the eastern margin of the central channel between the 10 and 6 m isobaths between Morro do Morcego and Gragoatá. These sand waves have heights of 0.5-2.5 m, lengths of 18-98 m, and decrease in both height and wavelength from the ocean into the bay in response to decreasing tidal energy. The sandwaves have steeper slopes facing the bay, indicating wave progression and bottom sand transport into Guanabara Bay. The sandwaves and their characteristics results from energetic ocean swells associated with meteorological frontal passages and the tidal flood-dominance of bottom current. From the alignment of Forte Gragoatá and Aeroporto Santos Dumont, the bay experience a widening in the main channel, which reflects in the reduction of the currents speeds, making possible the deposition of the fine sediments in the both side of the channel, as clayed-silt and silt-clay. The north and the centre of the bay is also characterises by the presence of the muddy sediments. In the region most internal of the bay, after the Ilha do Governador (NW), observes the predominance of clay-silts, a sedimentation coarser than the NE in the same region, this probably occurs in function of that in this part of the bay the rivers that input in this area, are strongly impacted by the mans activities, therefore has a significant population density in this place. On the other hands, in the muddy sediments of the NE part of the bay predominates clays. Such sedimentation can be explained as product of the combination of a lower hydrodynamics in this area, and the presence of mangrove vegetation, which act as a trap, where only the finest sediment bypass to the bay.

Fine sediments of Guanabara Bay show high levels of organic carbon (Figure 5) the higher value is 7.05%, which occurs in the NW side of the bay, and the lower value, less than 1% occur at the entrance and central part of the bay. According to Fulfaro & Ponçano (1976), organic carbon is a very good indicator of bottom zone dynamics. Tucker (1991) suggested that in many depositional environments organic carbon is decomposed and destroyed at the sediment surface, but if the rate of organic productivities is high, the organic carbon can be preserved. The high concentration of organic carbon in the bottom sediments in the internal part of Guanabara Bay, are associated with the bottom morphology, the particle size of the sediments, the restricted water circulation in the internal areas and mainly related with the high productivities as well as great amounts of untreated sewage discharge in the bay. According to Carreira et al. (2002), the bay is amongst the most productive marine ecosystems with an average net primary production (NPP) of 0.17mol cm^{-2} day^{-1} (Rebello et al., 1988). According to the same authors the high productivity is supported by the availability of intensive sunlight and elevated temperature throughout the year and by an estimated annual input of 3.2×10^9 mol P and 6.2×10^{10} mol N (Wagener, 1995) derived mainly from untreated sewage discharge.

Classification of Echo types (7.0 kHz)

Echo types were classified mainly on the basis of the acoustic character and micro topography of the bay bottom. Seven distinct echo-character types were identified and its nature and distribution throughout the bay are shown on Figure 6. The echo-character are studied and classified following the classification of Baptista Neto et al. (1996) and Quaresma et al. (2000).

Echo character type I

This type of echo is characterized by very sharp surface reflector with no sub-bottom echoes (Figure 7), reflecting the dominance of superficial sands (Damuth and Hayes, 1977). This echo-character occurs at the entrance of the bay, where the sandwaves were observed (Figure 6). Quaresma et al. (2000) and Kjerfve et al. (1997) had already described the occurrence of these bedforms at the bottom of the Guanabara Bay entrance. These authors suggested that the occurrence of such bedforms results from both very energetic ocean swell, which regularly enter the bay from the south-southwest during frontal passages, and the dominance of flood-directed tidal bottom currents. It is possible to observe the gradual reduction of the length and the height of the sandwaves towards the interior of the bay.

Echo character type II

Formed by large single or irregular overlapping hyperbolae with widely varying vertex elevations above the seafloor (Figure 7). Each hyperbolae generally show very strong surface echo and prolonged sub-bottom echoes.

These large hyperbolic echoes are suggestive of basement highs or outcrops as was also suggested by Damuth (1980) and Lee et al. (2002). These echo types do not depend on the hydrodynamic conditions of the environment, being exclusively structurally controlled. It occurs mainly close to the islands and in the central channel of the bay as was already observed by Quaresma et al. (2000).

Echo character type III

This type of echo is characterized by the presence of a wrinkled reflector, which represents small ripple marks, with no subbottom

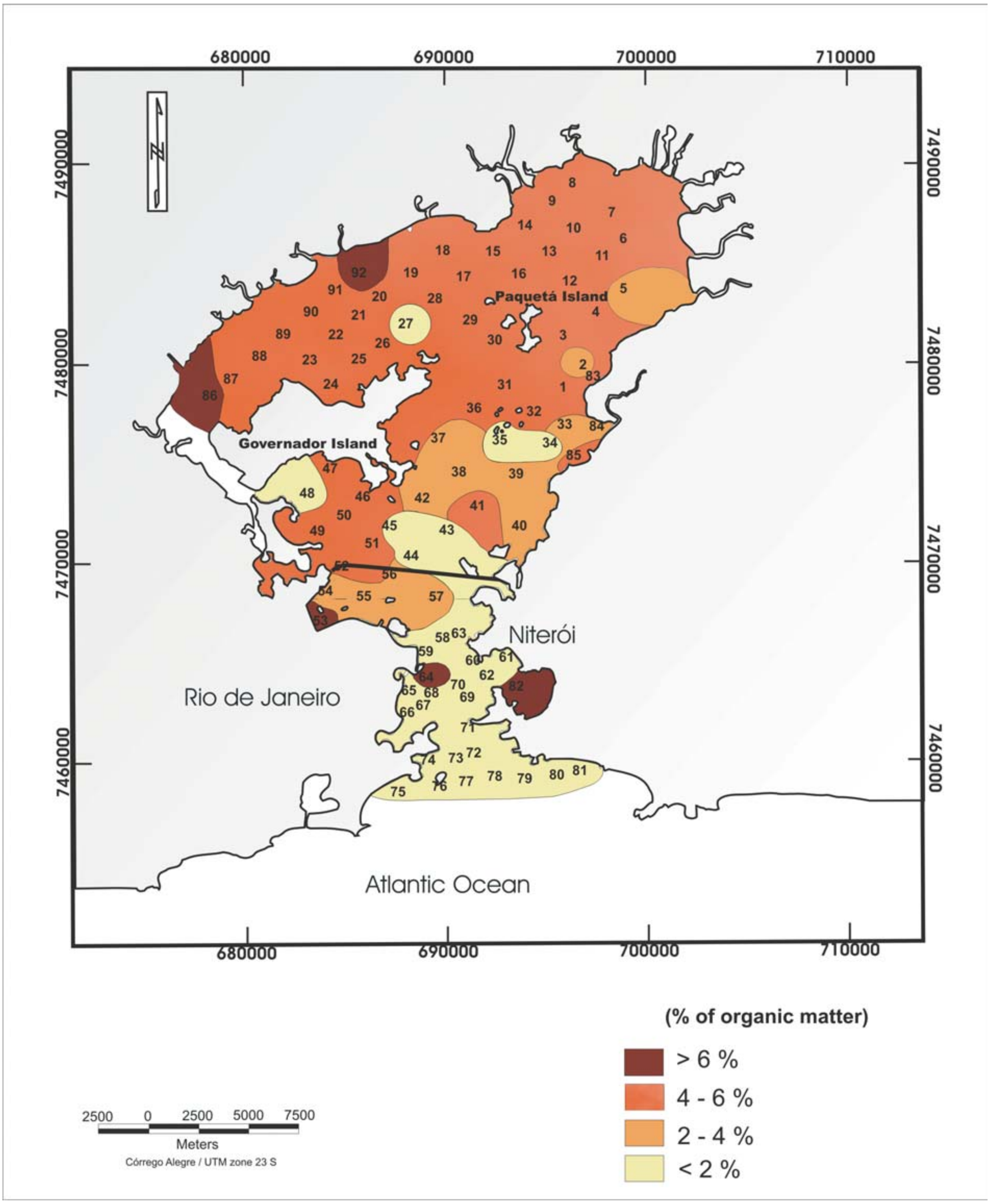

Figure 5 – Map of the organic carbon content (%) distribution in Guanabara Bay surface sediments.

Figura 5 – *Mapa de distribuição do conteúdo de carbono orgânico (%) em sedimentos superficiais da Baía de Guanabara.*

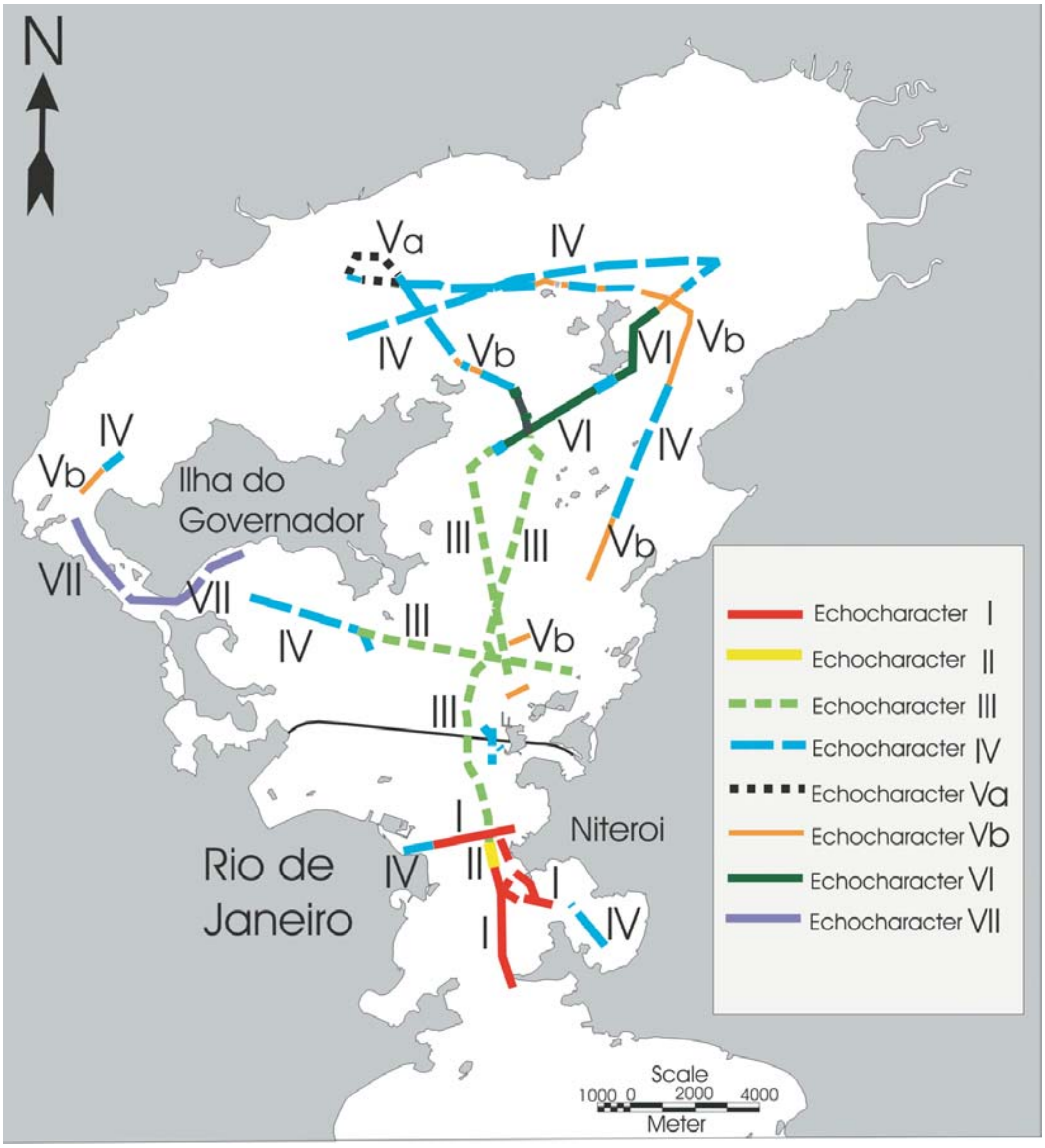

Figure 6 – Map of the Echocaracter (7.0 kHz) distribution in the Guanabara Bay.

Figura 6 – *Mapa de distribuição de ecocarater (7.0 kHz) na Baía de Guanabara.*

reflectors. This type of echo occurs preferentially in the central channel of the bay (Figure 7), also appearing, perpendicular to this, indicating a transitional zone between coarse and fine sediments. This echo character occurs mainly in the areas of coarse to median sands. The local strangulation or a canalization of the flow due to the bathymetric characteristics is generally responsible for the occurrence of the ripple marks, this bedforms occur in a transitional zone between the areas affected by marine processes and the areas affected by fluvial sedimentation (Kjerfve et al., 1997; Quaresma et al., 2000).

Echo character type IV

The type IV echo comprises a distinct bottom echo and several continuous, parallel internal reflectors, that are conformable to the surface topography (Figure 7) indicating muddy (clay and silt) sedimentation above the acoustic basement, in areas of reduced hydrodynamic conditions. The palaeo-relief of the acoustic basement observed below the transparent mud layers shows sugar-loaf forms characteristic of the crystalline basement onshore, buried incised valleys and palaeo-channels covered by sands of probable Pleistocene age (Amador, 1997; Oliveira, 2000).

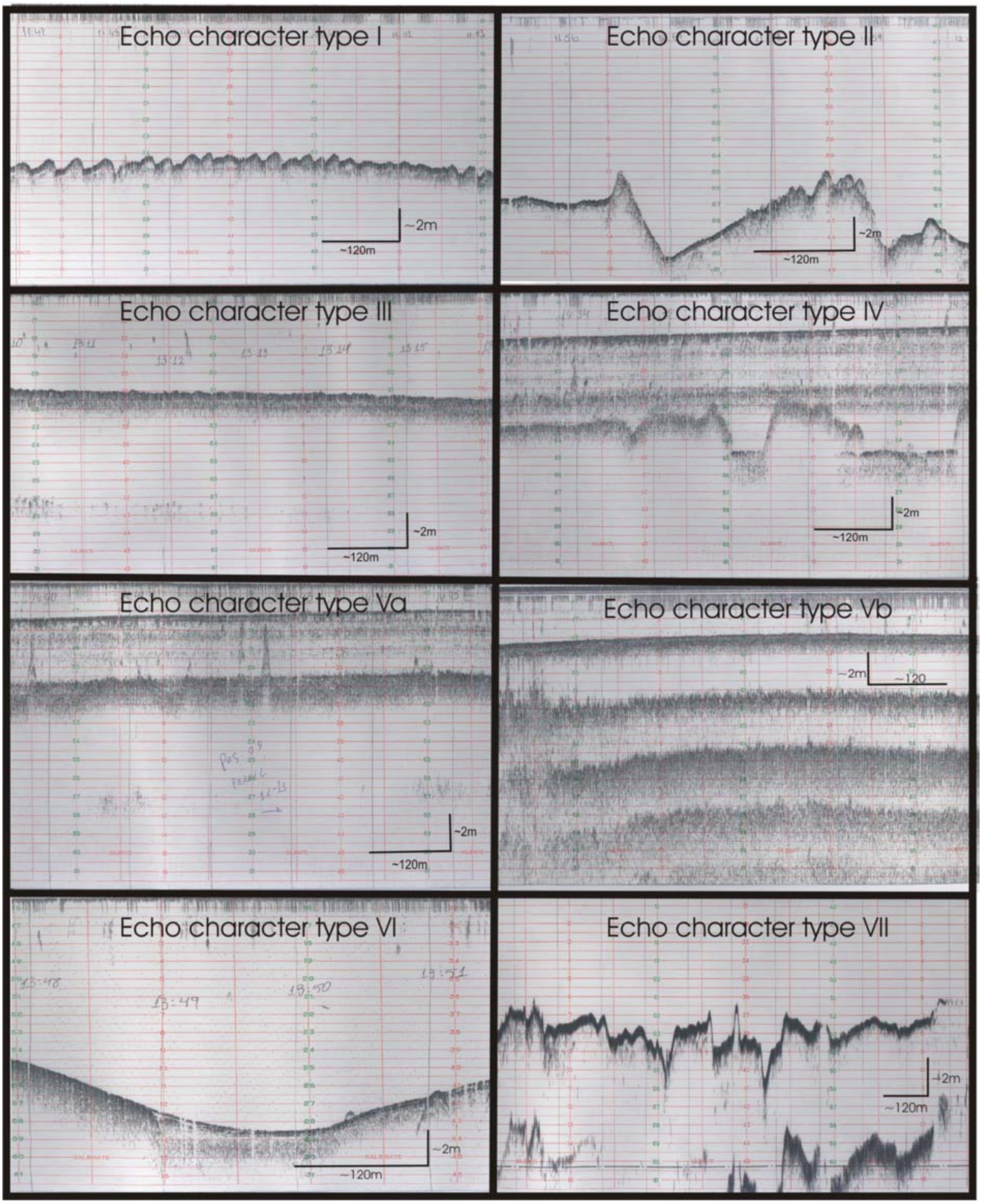

Figure 7 – The different types of echocaracter observed in Guanabara Bay.

Figura 7 – *Diferentes tipos de ecocarater observados na Baía de Guanabara.*

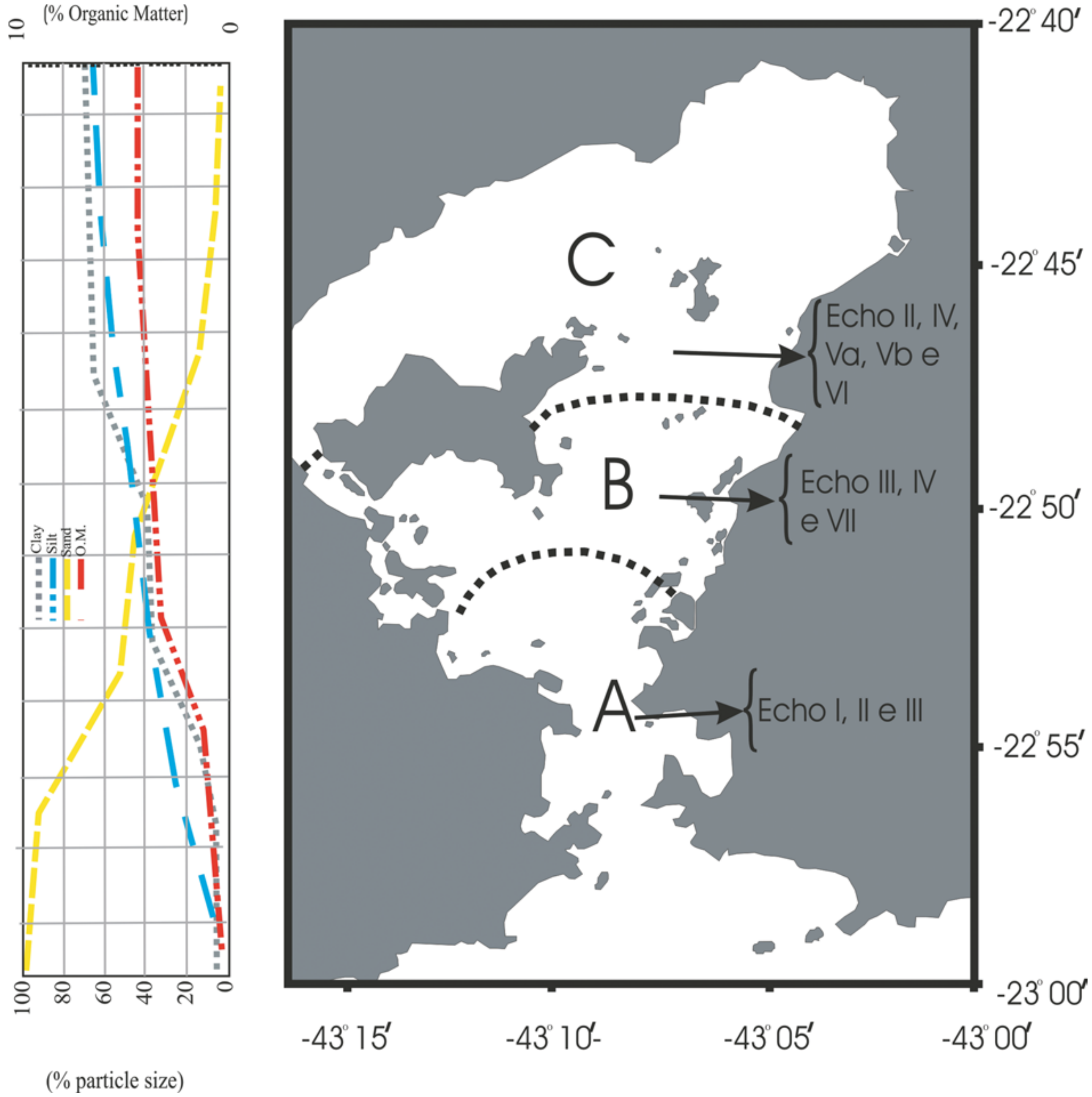

Figure 8 – The syntheses map of all data analyzed.

Figura 8 – *Mapa síntese de todos os dados analisados.*

Echo character type V

Echo character type V is associated with the presence of shallow gas within the sediments appearing as two distinct types named Va and Vb (Figure 7). Floodgate & Judd (1992) discuss on the origin of gas in flat areas, attributing two forms of gas origin: thermogenic and biogenic. The thermogenic origin requires gradients of pressure and temperature whereas the biogenic gas is formed by the reduction of organic matter by anaerobic bacteria activities, being methane (CH_4) the most common gas. The latter origin is probably due to the main source for the gas encountered in Guanabara Bay, considering the elevated content of organic matter available for bacterial reduction especially within the bottom sediments of the bay's interior.

Gas escape features, forming an acoustic blanket in the upper sedimentary layers characterizes type Va (Figure 7), similar to the occurrences described by Garcia-Garcia et al. (1999), Judd &

Hovland (1992) and Costa & Figueiredo Jr (1998) elsewhere and by Oliveira (2000) in Guanabara Bay, near the Paqueta Island. Echo-character type Vb (Figure 7) presents a series of multiple bottom-parallel subsurface reflectors as observed by Baptista Neto et al. (1996) in Jurujuba Sound.

Echo-character type V occurs in areas of low hydrodynamic conditions within the bay, where clay and silt sediments with high concentrations of organic matter are found (Figure 6).

Echo character type VI

Echo type VI is characterized by truncation of reflectors and slightly wrinkled surface (Figure 7), representing conditions of erosion or non-deposition of sediments in areas affected by bottom-currents. This echo type occurs on the northern extremity of the central channel, to the east of Paqueta Island. Based on the current information collected by JICA (1994), Oliveira (1996) and Amador (1997) suggest that tidal currents are capable to erode and impede deposition of fine-grained sediments in this area.

Echo character type VII

Echo-character type VII is characterized by irregular and wrinkled bottom surface (Figure 7), It may represent dredging in the channel area between Governador Island and Ramos Beach. Dredging of access channels and port areas is a very usual activity in Guanabara Bay aiming to maintain the navigability in spite of the extreme sedimentation rates estimated to be as high as 100 cm/century in some areas by Amador (1997).

SUMMARY OF ECHO-CHARACTER DISTRIBUTION AND SEDIMENTARY PROCESSES IN GUANABARA BAY

The main characteristics of the echo-character found in Guanabara Bay are synthesized on Table 1. Based on the main types of echo-characters in association with the bottom sediments and with the main hydrodynamic compartments of Guanabara Bay, it is possible to recognize three distinct regions reflecting the dominant sedimentary processes within the bay. These regions reflect the decreasing marine and tidal influence towards the bay's interior (Figure 8).

Near the entrance, the dominance of the tidal energy, conjugated with the waves results on the predominance of sand deposits, highly reflective with characteristic sandwave bedforms. A transition zone in the upper part of the central channel presents a mixture of muddy and sandy sediments representing the decreased tidal current velocities. The acoustically transparent, flat and predominantly muddy bottom of the bay's interior is dominated by sediment settling reflecting the low energy environment, where fine clastic particles are deposited with fine particulate organic matter. In these low energy areas where conditions for bacterial degradation of organic matter occurs, shallow gas can be formed, obliterating the penetration of the acoustic waves, and generating characteristic echo types presenting acoustic blanket and multiple bottom reflectors.

CONCLUSIONS

The association between the geophysical and sedimentological data is a very useful tool to understand the hydrodynamic conditions of the Guanabara Bay bottom.

The grain-size distribution reflects the tidal current energy near the bottom, which is directly influenced by the bottom morphology and the Guanabara Bay shoreline contour.

The geophysical data analyses revealed a strong relationship with the sediments permitting the distinction of seven types of echo-character distributed within Guanabara Bay. These echo-character types are useful to discriminate the higher energy areas, dominated by sand deposits on the entrance of the bay and on the central channel, from the lower energy regions located on the interior of the bay, covered by silts and clays. The presence of biogenic gas within the bottom sediments was also detected by the echo-character type, in areas of organic-rich mud deposits located on the interior of the bay.

The recognition of the different hydrodynamic compartments of Guanabara Bay, as reflected by the sediment distribution and echo-character types can be used as subsidiary information to the diagnostic of the environmental quality and de-pollution programs, helping to identify areas of deposition of fine sediments which usually tend to accumulate pollutants and areas of erosion, sediment by-pass or non-deposition which normally are less impacted by pollution.

ACKNOWLEDGEMENTS

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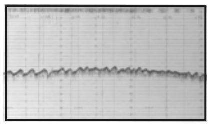
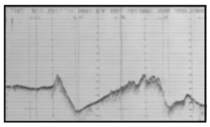
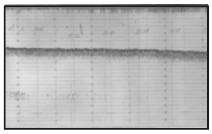
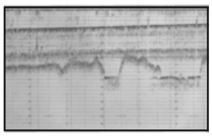
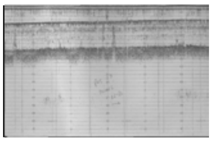
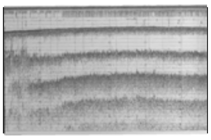
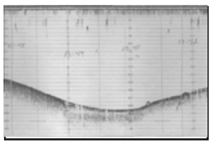
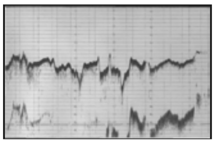
Table 1 – Types of echocharacter found in Guanabara Bay, and it´s main characteristics

Tabela 1 – *Tipos de ecocarater encontrados na Baía de Guanabara, e suas principais características.*

Echo type	Sediment	Description	Forms of bottom and subbottom	Processes	Local and depth of occurrence	Profile
Type I	Predominantly sandy	Strong bottom reflectors, absence of subbottom reflectors	Sandwaves	Transport by current near the bottom	Entrance of the bay, with an average depth of 20m	
Type II	—	Basement highs or outcrops	Irregular bottom	Structural and lithological control	Varied	
Type III	Transitional zone between coarse and fine sediment	Strong reflection, absence of subbottom reflectors	Flat bottom with little ripple marks	Transport by current near the bottom	Between Paquetá Island and the Bridge, between the depth of 10 to 20m.	
Type IV	Predominantly muddy	Strong prolonged surface echo, with the presence of internal reflectors and the acoustic basement	Flat bottom with the presence of the acoustic basement – sugarloaf type	Calm sedimentation	Inner part of the Bay, in the protected and calm condition, depth average of 5 to 10m.	
Type Va	Muddy	Transparent subbottom reflector with evidence of gas escape	A plain bottom surface with acoustic blanket in the subbottom	Sedimentation by vertical aggradation	The inner part of the bay, with depth between 1 to 5 m.	
Type Vb	Muddy	Bottom-multiple reflection with a blurred aspect, without strong contrast suggesting the presence of gas	A plain bottom surface, with the presence of a plain-parallel subbotom	Sedimentation by vertical aggradation	Predominantly in the NE of the Bay, close to the coast	
Type VI	Muddy	Truncations of subbottom reflection	A plain bottom in the form of channel, with a surface slightly wrinkled	Erosion by bottom current	Between Governador and Paqueta Islands, with depth between 10 to 20m	
Type VII	Sandy	Strong reflection of a irregular and wrinkled bottom surface suggesting dredging	Extremely irregular and wrinkled bottom surface	Artificial mechanical dredging	Between Governador Island and The continent, with depth between 1 to 5m.	

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