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Sedimentary Dynamics of the Southern Shelf of Madeira (Portugal)

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ABSTRACT

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In order to investigate the sedimentary dynamics of the Madeira's southern shelf several aspects of this North Atlantic island shelf were studied. The principal goals of this work are: identification of the major sediment sources to the shelf; understand the sedimentary patterns and obtain further insight into the governing mechanisms of the shelf. To fulfil these objectives, high-resolution sea-floor mapping, heavy mineral distribution maps, wave and current information and sedimentary data were used. It was possible to identify four different sectors of the shelf, each one with different characteristics. Those characteristics are: sediment transport direction and magnitude; major suppliers of sediment (creeks and/or sea cliffs); distribution factors (currents, waves); and a energy gradient. The westernmost part of the shelf is very wide (9 km) and is characterized by high energy parallel to shore sediment transport. Sea cliff erosion plays a major role in supplying the shelf with sediment in this sector and creek contribution is negligible in comparison. The easternmost sector is narrow (about 1.5 km wide) and shows normal to shore sediment transport with a slight component towards the east. Wave energy is very low, thus, the transport gradient in this sector is also low. Creeks are the major suppliers of sediment in this sector, more so than sea cliffs. The mid-sectors show a high transport gradient, which is parallel to shore near the western end and tends to become normal to shore towards the eastern end. Sea cliffs and creeks have similar importance in shelf sediment supply.

ADDITIONAL INDEX WORDS: *Sediment sources; heavy mineral dynamics; swath bathymetry.*

INTRODUCTION

The island of Madeira is located in the Atlantic Ocean between the 30º01'-33º08' N parallels and the 15º51'-17º16' W meridians (Figure 1) and has an area of 736,75 km2. It is part of a chain of islands that were formed due to the activity of a mantle plume over 5.2 Ma ago (MATA, 1996).

Madeira, as most volcanic islands, is formed by multiple and variable growth volcanic structures, as suggested by the island's elongated and irregular shape. The island, when viewed from sea, has the shape of a flat shield with trimmed edges. It shows a marked dissymmetry in its profile because the rate of erosion on the north side of the island is higher that on the south side. Because of this, the northern slope has a concave shape and the south slope is convex. Even though it has a small area, Madeira has a high mean altitude, with almost 25% of its surface over 1000 meters above sea level. In addition, the island has an irregular relief in which slopes show high mean dip values (CEEETA, 1989). Madeira's high mean altitude and its high precipitation grant the island's hydrographic network a high erosion potential. The island's morphology is characterized by very deep valleys that were formed by temporary creeks of torrential nature. Because of this, valleys have a U-shaped transversal profile in most cases. Despite the fact that the island is made up of multiple cones, the hydrographic network is radial in nature. The creeks that are the essential part of this network are short and have a normal-to-shore orientation converging to the centre of the island. The hydrographic network shows signs of great youth which is confirmed by the absence of capture elbows or the regularization of the creeks longitudinal profiles (NASCIMENTO, 2000). Almost all the coast is characterized by the occurrence of high sea cliffs that are vertical (when the bedrock is basalt) to sub-horizontal (when the bedrock is made up of pyroclasts). This line of sea cliffs is only interrupted in the Funchal amphitheatre, Machico bay and in the mouth of major creeks. Because of the vertical nature of most sea cliffs, some of the streams are suspended and form waterfalls.

As a consequence of the very unstable profile of most sea cliffs, landslides and rock falls are very common along the coast. These landslides sometimes form extensions of land called "fajãs" and important submarine deposits.

Regarding this geographic setting, some questions have to be considered when facing the dynamics of the shelf adjacent to the exposed island: what are the main sources of sediment? Where are the pathways between particles sources and shelf deposits? What is the stability of the shelf deposits and how is that stability affected by oceanic dynamics?

In order to understand some of the above questions and because there is a considerable lack of knowledge concerning marine dynamics in the Portuguese islands, a multidisciplinary approach was recommended. In this paper the major results regarding morpho-dynamics will be presented.

METHODS

The recommended approach to tackle the complexity of the system includes a full bathymetric survey (between the coastline and the 100 m isobath), sediment samples (using the Smith-McIntyre grab), suspended particulate matter (SPM) samples, CTD and nephelometer profiles, and finally current measurements in three locations.

The multibeam survey was made using the Simrad EM3000 system and the area was fully covered. Sedimentary analyses include grain-size (using the MALVERN, 2000, laser grain sizer), carbon content and geochemistry (heavy metals, PCB and hydrocarbons). In addition, the heavy minerals were used as tracers of the sedimentary dynamic processes occurring in the bottom sediments.

The heavy mineral content of the collected samples was separated using heavy fluids of known density, bromoform (2.80 g/cm^3) and Sodium-polytungstate (2.82 g/cm^3). Heavy mineral separation was conducted on four grain fractions, 2-2.5ϕ , 2.5-3ϕ , 3-3.5ϕ and 3.5-4ϕ . Each fraction was later examined using a petrographic microscope, where the heavy mineral species were identified and counted leading to the acquisition of numerical data. After the application of principal component analysis (PCA, DAVIES, 1986), the heavy mineral

data was projected in distribution maps using a krigging interpolation method.

Since this paper is only concerned to morpho-sedimentary dynamics, only morphologic data and bottom sediments characteristics will be focused.

RESULTS AND DISCUSSION

Morphology

Madeira´s southern shelf is very narrow, as depicted by the multibeam data reproduced in Figure 1. Since the medium length is less than 5 Km, the shelf break is located very close to the shoreline.

Generally speaking, the morphological complexity of the shelf is the result of alternating volcanic extrusive periods, and periods where the conditions were calmer (when sediments were deposited). The equilibrium between these two alternating mechanisms is expressed in the morphological map.

During the most recent times of the Quaternary, thick sedimentary bodies were formed, due to the erosion of the land mass; these sedimentary deposits occur in volcanic paleo-troughs, filling the available accommodation space. Today, these sediments form areas of smooth and planar morphology.

The multibeam data, together with the morphological characteristics, allow the identification of four distinct sectors in the southwestern shelf: Ponta do Pargo/Fajã da Ovelha, Fajã da Ovelha/Calheta, Calheta/Ponta do Sol and Ponta do Sol/Cabo Girão.

A - Ponta do Pargo / Fajã da Ovelha

This sector is characterised by an underdeveloped sedimentary cover. At the surface, it is possible to identify remnants of volcanic structures. These outcrop near the shore, and have conspicuous WNW-ESE (in the inner part) and NE-SW to E-W (in the central part) lineaments. These lineaments are related to volcanic dykes (ZBYSZEWSKI *et al.,* 1975) that have survived to erosion periods (both sub-aerial when sea-level was at 100 m and marine when sea-level attained its present position). The permanent action of these high-energy processes near the bottom is the major shaping factor of this shelf sector, precluding the accumulation of significant sediment volumes. In fact, even the deposits that result from the coastal erosion processes (i.e. major land slides or continuous marine erosion) are absent in this sector. As such, the morphological aspects of this area seem to indicate that it should act as a major sedimentary source.

B - Fajã da Ovelha / Calheta

The slope break that characterises the edge of the sedimentary accumulation is at different depths (below 100 m depth in the area farther from the coast), and at 20 m depth (at the heads of the Calheta submarine valleys). Actually, these submarine valleys are arranged in a broad amphitheatre, and present important indexes of sedimentary transport; therefore, they are grouped in this study and referred to as Calheta submarine canyon.

The innermost part of this canyon system is characterised by rocky outcrops and sedimentary fans that were the result of important collapses, when the slopes were exposed to erosion agents throughout the Quaternary (ZBYSZEWSKI *et al*., 1975).

The main tract of this sector is the significant presence of prograding sedimentary bodies; these tend to be shallower from the meridian of Ponta da Fajã do Pargo towards Calheta (eastern limit of the sector). For instance, near Ponta do Pargo the progradational edge is small and it is located at 100 m depth; between Jardim do Mar and Calheta, the prograding front is roughly E-W, and its depth varies, from 80 m (south of Jardim do Mar), to 60 m, and then to 40 m (Calheta canyon). Finally, as stated before, the slope break near Calheta is located close to the shore, at 20 m depth.

From the observation of the multibeam images (Figure 1) it is possible to note that the bottom sediments are very mobile; these sediments are arranged in broad wavelength sedimentary structures (sometimes in excess of 100 m), and are also perpendicular to the walls of the valleys. The sediments are transported from the heads to the toes of the canyons, towards the basin areas, with the concomitant and progressive incision of the canyon heads. This stepping back of the canyon head, and its associated morphology, only takes place because such head is located in a prograding sedimentary prism.

C - Calheta / Ponta do Sol

This sector is different from the previous one, since the large

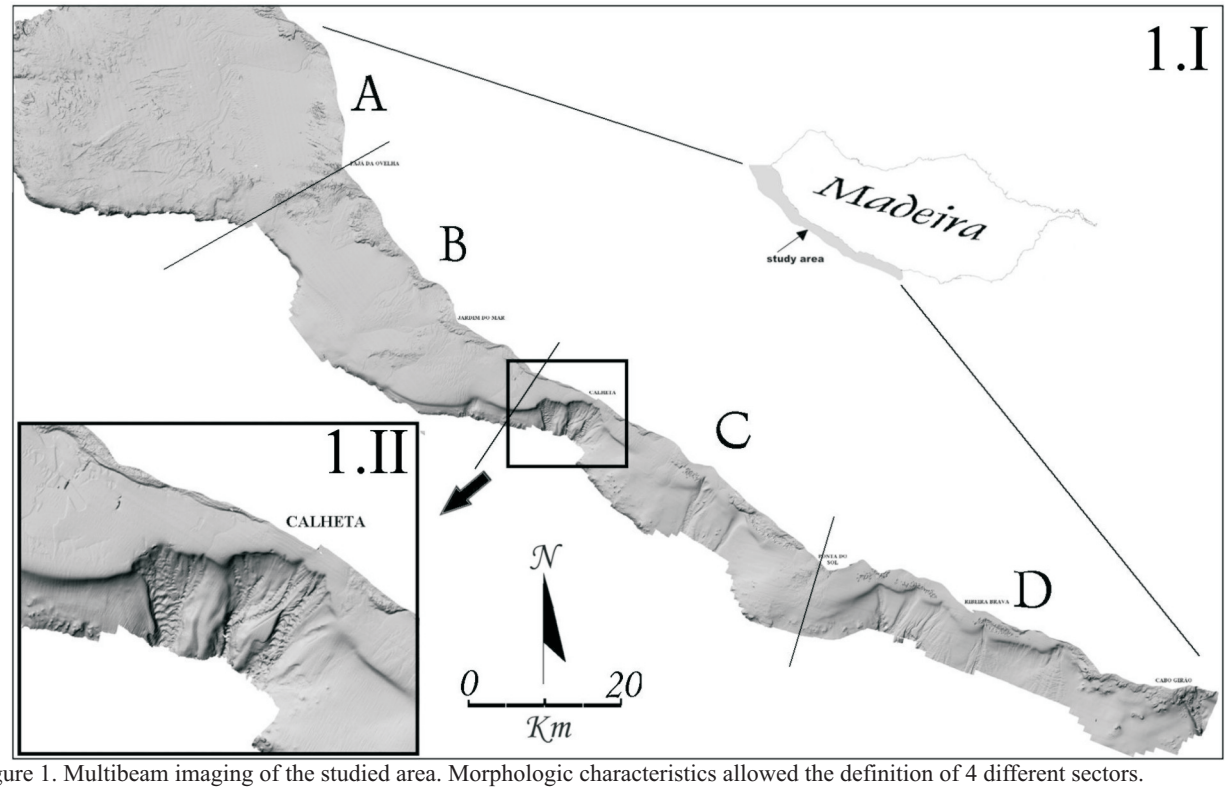

Figure 1. Multibeam imaging of the studied area. Morphologic characteristics allowed the definition of 4 different sectors.

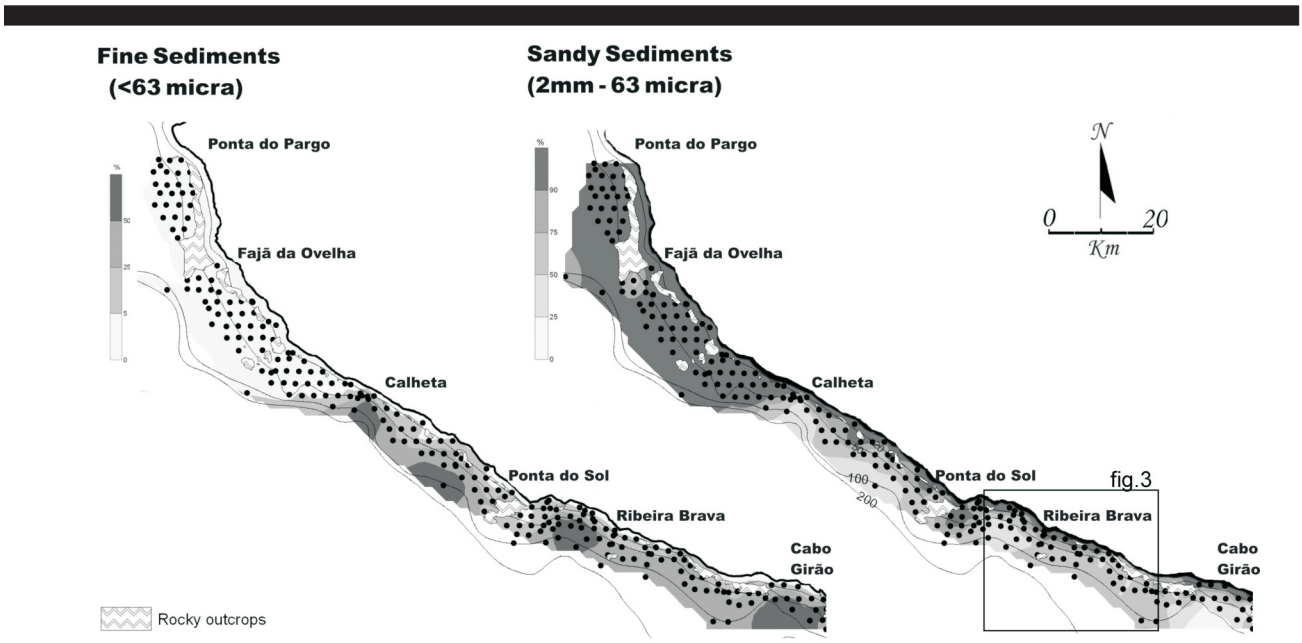

Figure 2. The sedimentary cover of southwestern Madeira shelf. Distribution of fine sediments and sandy sediments. Black dots indicate sample locations.

sedimentary bodies that were observed are absent. Instead, the geophysical data acquired in the offshore of Madalena do Mar points out towards the presence of a relatively thick sedimentary basin (sometimes over 30 m thick). Most likely, these sediments are filling in a structural trough (INSTITUTO HIDROGRÁFICO, 2000; 2001). On the other hand, it is possible to observe the influence of the exploitation and extraction of sediments in the coastal deposits. Finally, it is also worth mentioning the presence of two submarine valleys that affect the shelf break offshore Madalena do Mar. The first valley is located to the west of this village and its upper part deeply cuts the progradational front; in this regard, it is similar to the Calheta canyon, because it also shows important sediment transport in its bottom. The second valley, although following the same orientation and geometry of the first one, does not show any signs of sediment transport, and as such it is not active. This is probably because it is currently undergoing burial, as suggested by its morphology. Also, this inactivity may be due to the fact that, during its incision, it has encountered more competent and/or rocky formations, instead of softer postgradational sediments.

This seems to be supported by the presence of a major rock outcrops that are located between the shoreline and 40 m depth, in the area where this valley's head abuts.

D - Ponta do Sol / Cabo Girão

The profile for this area shows a well-developed sedimentary platform that ends abruptly at 20 m depth. The exception is the eastern area.

In this sector it is possible to observe different sedimentary geometries. When the sediments occur inside conduits or troughs, they are well organised, otherwise, they display irregular and disorganised geometries (e.g. in slope settings, where the sediment is displaced more slowly). Whatever the case, both are the result of near-surface processes of sediment transport.

The cross-shelf profile of the area between Ribeira Brava and Cabo Girão, is very different from the previous one.. The sedimentary platform of the previous sector gives place to a highly irregular coastal stretch. This is composed of rocky outcrops and/or accumulations of very immature deposits that extend down to 25-30 m of depth. At greater depths, it is possible to identify, underneath the sedimentary cover, a highly irregular rocky substrate that is almost present in the deepest parts of the studied area. In the area near Cabo Girão, there is an important submarine valley that acts as a conduit for the coastal sediments, transporting them from the coast (less than 20 m depth) to greater depths.

From the analysis of the morphological characteristics of the several aforementioned sectors, it is possible to stated that the main sedimentary sources are : coastal erosion, slope instability, erosion of submarine outcrops, and fluvial input (particularly Ribeira Brava).

Oceanography

In the Madeira island, swells arrive predominantly from NW to NE. Some but not so frequent SE SW events can affect the southern coast. Mean wave period is 7 s and wave heights are less than 1.5 m. During NW-WNW storms the significant wave height can reach 3.0 m and the mean wave period is 11 s.

Regarding the thin water column, the bottom current is strongly affected by meteorological forcing (wind and wave regime). During the observational period (03 Juin-27 July), meteorological forcing was very weak since waves have maximum height less than 0.8 m and s mean wave period. The current meter, deployed atEast Calheta, indicates that longshore currents are predominant with values ranging between 8 and 12 cms^{-1}. Cross shore currents are negligible.

Bottom Sediments

Madeira Island is an excellent case study to the understanding of sedimentary dynamic processes, namely the interplay between oceanic currents and sediment inputs from cliff erosion and rivers. Due to the volcanic nature of Madeira, shelf sediments are mainly comprised of heavy minerals (around 50%), containing a low percentage of bioclastic carbonates (1.2% on average).

As it is shown in the textural sedimentary distribution map (Figure 2), silt and fine sands are mainly located in the eastern part of the area. Assuming that cliff retreat and rivers are the major particle sources, this distribution highlights the deposition in the medium and outer shelf after the net SE transport. Also reflecting the high energy levels induced by NW wave climate, the sediments collected on the western area are very coarse (medium sand, coarser sand and gravel); fines are only deposited in the outer shelf and slope (deeper than 100 m).

An integrated analysis of different textural distribution patterns defines 2 major areas with distinct textural characteristics, the borderline being the Calheta canyon. This system seems to be a morphologic barrier to the WE-SE longshore sediment transport. Westwards particles are very coarse (less than 5% of particles sized minor than 63im), moderate to well sorted (standard deviation <1); eastward the

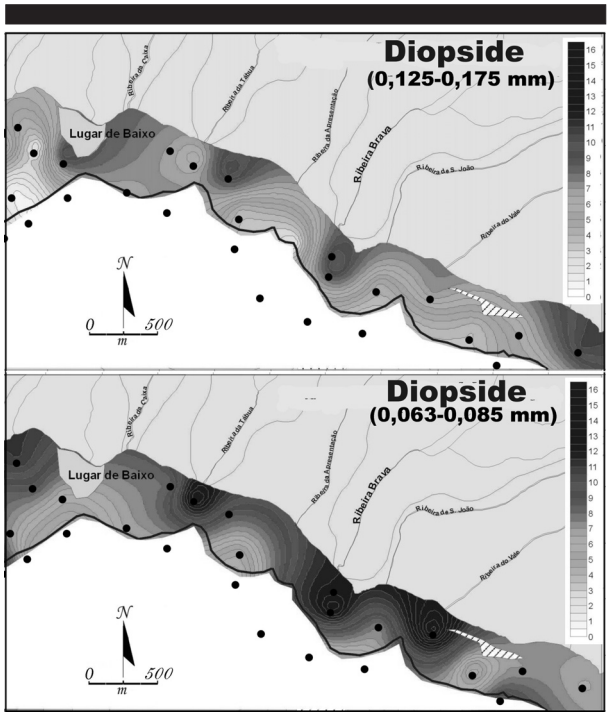

Figure 3. Diopside distribution in the 2-2,5 ϕ fraction and in 3,5-4 ϕ fraction. Black dots indicate sample locations (FONSECA *et al*, 2003).

medium grain size increases and particles become poorly sorted (standard deviation >1).

Distribution patterns indicate that west of Calheta Canyon there is no clear relation between grain size patterns and depth while eastward there is a clear control of depth (or distance to the coastline) in the sediment grain size characteristics.

Heavy minerals

Heavy minerals analysis was only conducted in the easternmost sector of the shelf, a low energy shelf zone where creek influence is felt and is not buffered by sea cliff erosion.

The collected samples are mostly fine sand with a high mean heavy mineral content (around 40%). The identified minerals reflect the inland petrology described by MATA (1996) and NASCIMENTO (2000) showing the presence of alkali basalts with olivine and pyroxene phenocrysts.

A total of 9 heavy mineral species were identified. The most abundant species are lithoclasts (43.89%) and oxides (magnetite and ilmenite, 36.36%) and to a lesser extent, diopside (7.22%), Ti-diopside (5.36%), olivine (3.90%) and kaersutite (1.13%).

The observed high percentage of some heavy minerals near creek mouths and some sea cliffs (Figure 3) indicates that these are major sources of sediment. Brava Creek is believed to be a major point source of sediment to the shelf, also the Lugar de Baixo feature, which consists of a landslide deposit that resulted from the dismantling of the sea cliff nearby, appears to be another major source of sediments. The diopside distribution pattern shows a decreasing content behavior with increasing depth. This shift is the result of proximity to the source, and usually the gradation is perpendicular to the shore, even if it is locally deviated (due to local action of creeks, rocky outcrops and in the vicinity of sea cliffs).

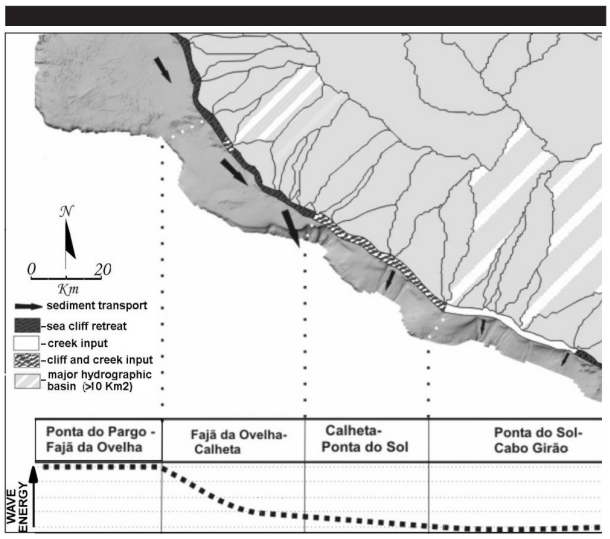

Figure 4. General conceptual model for the sediment dynamics of the Southwestern shelf of Madeira.

CONCLUSIONS

All of the above observations lead to the following conclusions:

There is active marine erosion in the southwestern shelf of Madeira. Despite the protection provided by the island, there is a strong energetic gradient related to the influence of the Atlantic wave energy. The westernmost sector is the one that is directly exposed to the Atlantic wave energy, while the eastern one is much more protected. This energy, together with inland sedimentary sources (such as fluvial inputs and coastal mass movements) is the main factor controlling the morphodynamics of the Madeira shelf. Regarding these considerations four main provinces with distinct morphology and sedimentary processes can be defined in the studied area.

A - Ponta do Pargo / Fajã da Ovelha

This sector is affected by the highest wave energy. The energetic field is expressed in the grain size distribution of bottom sediments. These are coarser and correspond mainly to residual deposits of sand and gravel. Waves and currents transport finer particles to the southeast. The main sediment source is related to cliff erosion, while fluvial contribution should be of secondary importance.

B - Fajã da Ovelha / Calheta

The energy gradient in this sector is very high. The mean diameter of bottom sediments decreases to the southeast and there is also evidence for an increase in sedimentation rate in the same direction. In fact, the fine sands that are deposited near Calheta (SE) are transported from the NW by shore parallel currents. Morphologically, the E-W front of the prograding deposit has an orientation concordant with this NW-SE transport. A well-developed canyon, observed south of Calheta, is covered by sedimentary structures that indicate a rapid sediment transfer from the inner shelf to deeper zones. Probably this area is the one that has the highest long-shore transport rates.

C - Calheta / Ponta do Sol

This is a less energetic sector within the Madeira shelf and the sedimentary cover is finer than in the western sectors. The sandy sediments of the inner shelf are very fine and have a homogeneous composition and regular spatial distribution. Despite the slight displacement to the west of the valley's head, the spatial geometry of the prograding deposits indicates that the net sediment transport is cross-shore. However, there seems to be a minor long shore component as well. This conclusion is also corroborated by the distribution pattern of the heavy minerals and the available current meter data. Despite the existence of some significant hydrographic basins there are no evidences of fluvial inputs to the continental shelf. The above observations lead to the conclusion that cliff erosion is the main source of particles into the shelf.

D - Ponta do Sol / Cabo Girão

The morphology of this sector is very similar to the previous one, but some indentations can be recognised at the river mouths, indicating that fluvial input plays an important role. Regarding the effect of the wave regime, the coastal physiography indicates that this sector is even less energetic that the others.

A general conceptual model for the sediment dynamics of the Southwestern shelf of Madeira can be envisaged based on the above description and can be seen in Figure 4.

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