Acoustic evidences of along-slope processes associated with mass movement deposits on the Madeira Island lower slope (Eastern Central Atlantic)

Evidencias acústicas de procesos paralelos al talud asociados con depósitos de movimiento en masa en el talud inferior de la Isla de Madeira (Atlántico Central Oriental)

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Abstract: The Madeira Island lower slope has been build-up mostly by along slope-processes associated with mass movement deposits as seen in GEBCO bathymetry, multibeam bathymetry, Parasound echosounder profiles and multichannel seismic reflection profiles. A plastered contourite drift (Madeira Drift) developed on this lower slope, being composed of seismic units D1, D2 and D3. The most probable water mass responsible for its deposition is the Antarctica Bottom Water (AABW). The youngest sediments of seismic units D2 and D3 are affected by gravity-driven processes, probably slumps and debris flows, which moved downslope towards west. Parasound profiles show evidences of such mass movements on present-day seabottom (e.g. diffraction hyperbolae echoes) but also of past-events buried within the contourite sediments. These older debris flows are recognized by semitransparent/transparent acoustic facies and lenticular shape.

Keywords: *along-slope processes, mass movements, Madeira lower slope, Madeira drift, Central Atlantic*

1. INTRODUCTION

The knowledge of the sedimentary processes acting on the Madeira Island slope remains scarce. The idea that the deep marine realm was a quiet and steady place changed over the last decades, due to technological improvements. For instance, bottom-current activity is more important than thought before, being testified worldwide by the occurrence of thick contourite drifts. This is the case for instance of Argentina Basin (e.g. Hernández-Molina *et al*., 2009). The joint occurrence of contourite drifts and several types of mass movement deposits (MMD), such as debris flows and slumps, is recognized independently of the geological and oceanographic settings and at different time-scales (e.g. Bryn *et al*., 2005). Nevertheless, despite the studies done so far regarding these questions, little is known about the interaction between along-slope and down-slope processes in volcanic islands slopes. While several volcanic islands occur in the Eastern Central Atlantic, the majority of the works have been focused either on large landslides or broad turbidite systems (e.g. Wynn *et al*., 2000). However, an extensive contourite drift, the Madeira Drift, is located in western lower slope of the Madeira Island (Fig. 1). The Madeira Drift was scarcely studied in the pioneer work of Embley *et al*. (1978) and remained almost unknown since then. Recently, Hernández-Molina *et al.* (2011) predicted the presence of contourite drifts on the Madeira lower slope based on numerical modeling of water masses circulation. The present work shows new acoustic evidence of along-slope processes on Madeira lower slope and its association with mass movement processes.

2. DATA AND METHODS

The dataset used in this work is multiscale and includes GEBCO bathymetry, multibeam bathymetry, Parasound ecosounder profiles and multichannel reflection seismic profiles (Fig. 1). Multibeam bathymetry was acquired by EMEPC in the scope of the Portuguese project of Extension of Continental Shelf. A 100m cell-size grid was produced for this study.

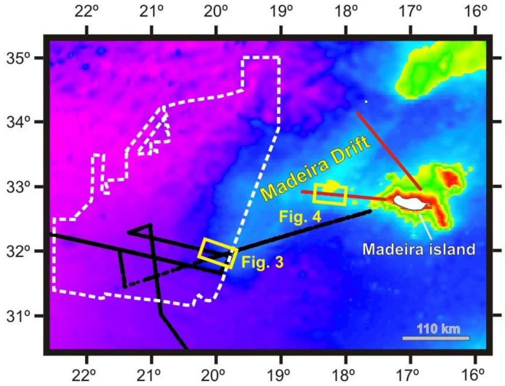

Fig. 1. Dataset used in this work: multichannel seismic profiles (red lines), Parasound echosounder profiles (black lines), multibeam bathymetry (white dashed polygon) and GEBCO bathymetry (outside the dashed polygon). Yellow boxes indicate the location of profiles shown in Figures 3 and 4. Location of Madeira Drift is also indicated.

Very high resolution profiles were acquired using the Parasound Echosounder System during the SUBVENT cruise in April of 2014 onboard the R/V Sarmiento de Gamboa. The Parasound system is a hull-mounted high-frequency sediment parametric echosounder using an operational signal of 4 kHz with beam angle of about 4º. Penetration depth on the Madeira lower slope ranges between ~8 and 83 m, depending on the type of sediment and attenuation. Seismic reflection profiles TM60 and TM64 (Fig. 1, red lines) were acquired by IFREMER in 2001 during the Tore-Madère scientific survey. A SISRAP system (by Genavir) composed of a 6 channels seismic streamer 590 m long with 50m groups was used. Two GI-GUN in harmonic mode (300 in^3) have been used as seismic source. The nearoffset was 213 meters and the shot interval 50 meters. Seismic record was 10 sec TWT with a 4 msec sample rate. SISRAP system is commonly used to acquire single channel profiles at high cruise speed (8-10 knots). Nevertheless it was possible to apply a slight processing on the data. Spherical divergence correction and a band bass filter have been applied to both of the lines and the six channels have been finally stacked in the scope to improve the signal/noise ratio.

3. RESULTS

1.1 Morphological domains

GEBCO bathymetry inspection allowed identifing an extensive NE-SW feature developed on the western lower slope of Madeira Island (Fig. 1). This feature is about 385 km long and over than 175 km wide and is located between >1500 and ~4800m water depth. Multibeam bathymetry acquired in its westernmost sector shows four distinctive morphological domains (Fig. 2), as follows: *Domain A* corresponds to a continuous and elongated NNE-SSW topographic high with a steep scarp ~90m high developed at ~4500 m water depth. It is affected by slope failure, testified by several amphitheater depressions interpreted as slide scars; *Domain B* corresponds to the area dominated by several lobate bodies elongated ~NNW-SSE to ~NNE-SSW, which are about 65 km long and 25 km wide and limited by channels flowing towards NNE-SSW; *Domain C* is located in the southernmost sector, where two channels trending WNW-ESE and flowing towards west can be observed. These channels are related to the distal part of the large turbidite system described by Wynn *et al*. (2000). This system constitutes the main pathway of sediments sourced in Madeira Island and also Morocco margin towards the Madeira abyssal plain.

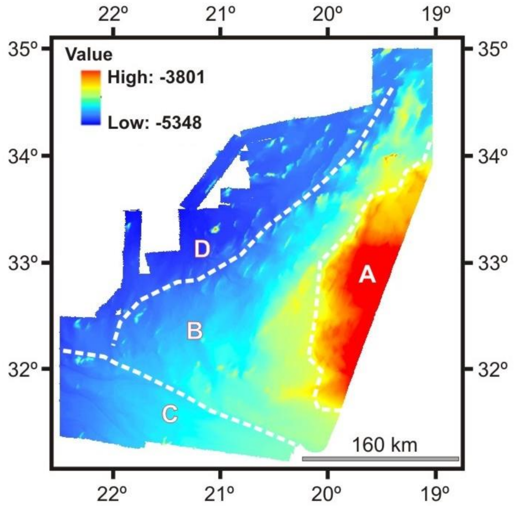

Fig. 2. Morphological domains (A to D) defined in the multibeam bathymetry mosaic. See the text for details.

Domain D corresponds to the westernmost sector, being characterized by a smoother sea bottom, although interrupted locally by elongated NNE-SSW terraces and isolated volcanic peaks.

1.2 Classification of echo types

Sediments echosouding provides important information about sediment types and sedimentary processes. Several echoes classifications based on 3.5 kHz echograms have been proposed since the 1960' of last century (e.g. Damuth, 1975). The acoustic characterization of sediments by Atlas Parasound system and their classification in four basic echo categories (prolonged, layered, diffraction hyperbolae, and wedging) was proposed by Kuhn & Weber (1993). This general classification is used in the present work, but other types are found in the Madeira's lower slope besides those four echo categories (Fig. 3). They are the following:

Prolonged type 1 echo (P1) – It is defined as high amplitude prolonged seafloor reflection with low penetration (maximum 8-13 m). Generally, subbottom reflections are few or absent. It is identified in morphological Domain C, where active processes are channel incision or bottom-current erosion.

Prolonged type 2 echo (P2) – It a high amplitude refection but weaker than echo P1 and occurs in steep slope areas of morphological Domain A. Acoustic penetration depth is < 5m. Subbottom reflections are rare or absent.

Layered echo (L) – It consists of a set of parallel to sub-parallel reflections defining a layered configuration laterally constant over a long distance. Acoustic penetration depth is in places up to 83 m. This type occurs in nearly flat to gently sloping areas. Two distinct reflections packages can be identified, (i) high amplitude and high continuity reflections package in the upper 20-28 m sub-bottom, (ii) lower amplitude discontinuous reflections package underneath, ranging between 19 and 35 m thickness. This echo category indicates the presence of fine-grained sediments with low compaction, as suggested by the deep acoustic penetration. It is found in morphological Domains A and B. Kuhn & Weber (1993) found a similar succession of echo sub-types on the Parasound record of contourite drifts in the Weddell Sea. Small scale (< 8m) lens of acoustically transparent material disrupt locally the layered pattern. This can indicate the presence of interbedded disorganized sediments due to slope failure events.

Diffraction hyperbolae echo (DH) – This type of echo consists of a downslope succession of small hyperboles, with similar amplitude and length. Penetration is low or absent. This kind of echo is usually interpreted as disturbed sediments due to gravity processes, such as debris flows. It can be recognized in morphological Domains A and B.

Semitransparent/transparent buried echo (T) - This echo type share certain similarities with the wedging echo category (W) defined by Kuhn & Weber (1993). However, on the Madeira lower slope it is identifyed within the sedimentary succession between the two sub-types of layered echo described above. It corresponds to buried sedimentary body with semitransparent or transparent acoustic facies, showing lenticular shape in some Parasound lines, whereas in others only the pinch-out termination towards east is seen. Its thickness ranges between ~10 m and 28 m. The basal reflection is high amplitude, irregular and discontinuous, suggesting an erosional origin. This echo type is in some places associated with a scarp about 40 m high. This type of acoustic facies is typically interpreted as slumps and proximal debris flow deposits (Damuth, 1975; Kuhn & Weber 1993; Antobreh & Krastel, 2007; Savini & Corselli, 2010). It is recognized in morphological Domain B.

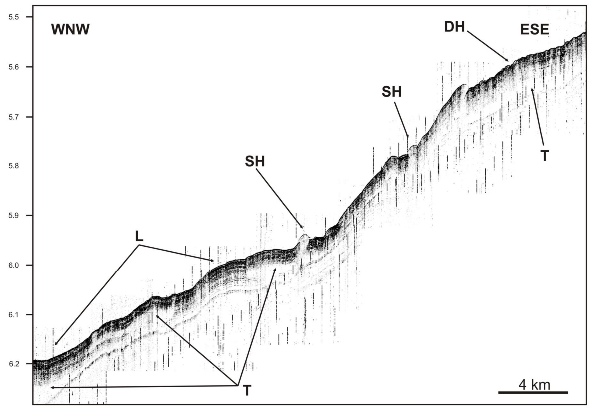

Fig. 3. Parasound profile showing a succession of several echoes categories on the Madeira lower slope. (T) Transparent buried echo; (DH) Diffraction hyperbolae echo; (SH) Single hyperbolae echo; (L) Layered echo. See Fig. 1 for location.

Single hyperbolae echo (SH) – It consists of small scale semitransparent isolated hyperboles rising about 8 m above the surrounding seafloor. This echo type is located between 4067 and 4460 m water depth in areas affected by slope failure and mass-movement. In some places there are diffuse acoustic sub-bottom echoes. Acoustically similar bodies have been found in other settings also affected by mass movements and bottom-currents and identified as carbonate mounds build-up by cold-water corals (e.g. Antobreh & Krastel, 2007; Savini & Corselli, 2010). Distribution of this echo-type is limited to small patches in morphological Domain A.

Chaotic/ disorganize echo (C) – This echo type consist of a high amplitude rough surface reflection and discontinuous, disorganized high amplitude sub-bottom reflections defining a chaotic acoustic facies. The shape of the sedimentary body is asymmetrical mounded and occurs at the base of steep slopes. Acoustic facies and its location suggest that this type of echo corresponds to slump deposits. It is identify in the morphological Domain A.

1.3 Seismic reflection record of contourite drifts

The occurrence and depositional architecture of the Madeira Drift is well imaged in multichannel seismic reflection profiles (Fig. 4). The Madeira Drift shows a plastered contourite configuration and developed against the Madeira lower slope. Four seismic units are identified: *Seismic Unit PD* corresponds to the pre-drift deposits that cover the basement. Acoustic facies change from semi-transparent near the base to stratified towards the top; *Seismic Unit D1* corresponds to the oldest contourite drift deposits and rests unconformably over unit PD. It is characterized by semi-transparent facies with low continuity and low amplitude reflections; *Seismic Unit*

D2 shows similar facies and is bounded by an irregular horizon that truncates Unit D1 (green horizon in Fig. 4); *Seismic Unit D3* corresponds to the youngest contourite deposits. Acoustic facies show low continuity and low amplitude reflections, defining a stratified configuration. An intra-Unit D2 high-amplitude and high continuity horizon (white horizon in Fig. 4) marks the base of mass movement deposits (MMD), which are composed of sediment from Unit D2 and Unit D3. These MMD show chaotic facies and probably consist of slumps and debris flows that moved downslope towards west.

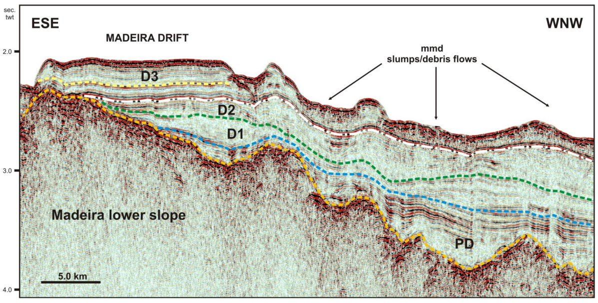

Fig. 4. Multichannel seismic profile crossing the Madeira Drift. (PD) Pre-drift seismic unit; (D1, D2, D3) Madeira drift seismic units. White horizon marks the base of mass movement deposits (mmd), probably slumps and debris flows. See Fig. 1 for location.

4. DISCUSSION AND CONCLUSIONS

The presence of contourite deposits derived from active along-slope processes on the Madeira lower slope opens the question regarding the identification of the water mass responsible for their development. Considering the water depths range of the Madeira Drift (below -1500 m and above -4800m) the best candidate is the Antarctica Bottom Water (AABW). It is generally accepted that this water mass reached the North Atlantic in the Eocene and enhancement of its circulation occurred at the Eocene-Oligocene transition (e.g. Goldner *et al.,* 2014). The age of the Madeira Drift edification can be constrained by the age of Madeira volcanic plateau edification. It probably started to build-up on old Cretaceous oceanic crust (located in the Cretaceous Magnetic Quiet Zone), during the Cenozoic and continued until Recent times. Thus, it is probable that the Madeira Drift developed on the Madeira lower slope from Eocene?/Neogene through present. The permanent or semi-permanent circulation of this water mass around the Madeira lower slope region allowed the edification of an extensive Contourite Drift System. It is well represented by the thick Madeira Drift but also by thinner drifts separated by channels in the southernmost part of the lower slope in the morphological Domain B. Down-slope processes play also an important role shaping the Madeira lower slope. Mass movements, represented by slumps and debris flows, affect the deposits of Madeira Drift deforming and displacing them downslope towards west. Several steep head scarps and amphitheater slide scars testified these mass movement events. Past events can be identified within the contourite layered sedimentary succession as buried semitransparent/transparent bodies with pinch-out terminations. Thus, the Madeira lower slope has been shaped mostly by along-slope processes but also with an important contribution and interaction with down-slope processes.

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