ACOUSTIC TEXTURES AND SEAFLOOR CHARACTERISATION OF SUBMARINE LANDSLIDES – AN EXAMPLE FROM THE SW IBERIAN MARGIN

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Seabed mapping has revealed the importance of submarine landslides in continental margins around the world. These areas are characterized by a large variety of terrains and the compound acoustic characteristics of the seabed often make geological interpretations a difficult task. Sonar backscatter is modulated at several spatial scales by the local slopes (surface processes), by the variable interface roughness and by the high variations in volume scattering processes. To address these problems, we are using marine geophysical data acquired in the SW Iberian Margin. The dataset includes high-resolution (3 m) TOBI sidescan sonar imagery complemented with Simrad EM-12S multibeam bathymetry. We focus on the recent Marques de Pombal mass-wasting complex. Our models and observations show that backscattering is heavily influenced by the geometry of insonification; for instance, seabeds rough at scales comparable to the acoustic wavelength (ca. 5 cm for TOBI) are more likely to exhibit facets scattering back to the sonar. The local distribution of backscatters creates textures, quantified with the *TexAn* software and associated to geological processes or terrains (e.g. landslides, background sediments). Textural entropy yields information related to the terrain roughness. Similarly, textural homogeneity provides details of the local organization of textures, which can be compared with terrain properties (relative importance of surface vs. volume processes). The results quantify the variability of geological processes along the slopes and for different parts of the submarine landslide. Combining different techniques from acoustic modeling, image processing, and geological interpretation makes a powerful tool to study mass-wasting areas in continental margins. A better appreciation of the complex acoustic interactions with the seabed, associated to awareness of the surveying constraints, provides better opportunities for the geophysical interpretation of sonar images in these challenging environments, whether in deep or in shallow water.

1 Introduction

The last decades of seabed mapping around the world have revealed that submarine landslides are widespread features [1]. They occur in the sedimentary successions of continental margins and within the basaltic edifices of volcanic islands. Their large number and the extensive amount of material involved make submarine mass wasting one of the most important geological processes shaping the continental margin

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architecture. Many of these slides are located within hydrocarbon exploration areas [2] and the bigger ones are also often associated with tsunamis. Interpreted with seismic data, when available, sonar maps can provide useful insights into the mechanisms associated with each landslide, and its probability of re-occurrence in geologically short terms. However, continental margins often present steep slopes and complex terrains (Fig. 1), modulating the acoustic returns at several spatial scales [3]. In addition, different terrains will present distinct surface roughness and volume scattering properties, depending on the imaging geomety, contributing to making traditional, visual interpretation a difficult task.

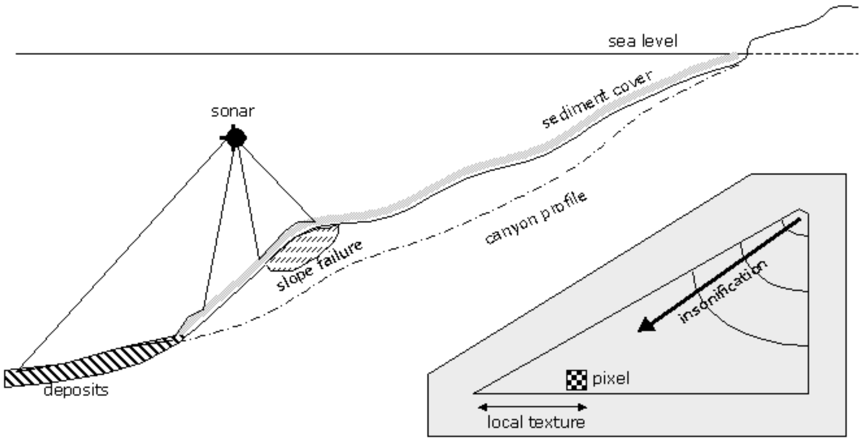

Figure 1. Sidescan sonar surveying of continental margins is affected by highly varying imaging geometries and seabed types. These will affect the interpretation of backscatter values (for individual pixels and for groups of pixels, as used for example to compute local textures).

This article focuses on quantifying and linking to geological processes the acoustic backscatter from a large submarine landslide, thought to be associated with the 1755 Lisbon tsunami and located in a region of high seismic potential [4]. Using the model of [5], we quantfied the expected returns at the local scale, for complex seabed types imaged at different altitudes on the highly varying slopes observed in the survey area. This demonstrated the necessity of accurately accounting the local angles of insonification, as the acoustic returns could be easily attributed to the wrong seabed types otherwise. This also quantified the relative importance of surface vs. volume processes for each region of the seafloor along the landslide. The acoustic textures of small groups of pixels were then quantified with the *Texan* software [6], and their interpretation was assisted with the knowledge of the more likely scattering processes. When available, localised ground truth was also integrated. By systematically and quantitatively mapping the variability of geological processes down the slope and across the landslide, these two approaches (backscatter model; texture analyses) constrain the geological interpretation and assist in the understanding of this region and its possible evolution.

2 The Marques de Pombal mass-wasting complex

Our study focuses on a large and fresh mass-wasting complex, recently imaged offshore Portugal in the Marques de Pombal fault area (Fig. 2). It was mapped during the HITS-2001 cruise on board the BIO *Hesperides* [7]. Most of this survey was devoted to the use of the high-resolution sidescan sonar TOBI. Operating 200-40 m above the seabed, this deep-towed instrument images the seabed at 30 kHz with a 6-km wide swath [8]. It is supplemented with a 6-7 kHz sub-bottom profiler and was used in conjunction with EM-12S multibeam bathymetry and TOPAS sub-bottom profiling along the track. These different instruments were selected to maximise the synergy between imaging techniques and map resolutions, fundamental to allow a detailed characterisation of the superficial and sub-seafloor structures.

The zone surveyed in the Marques de Pombal area, SW of Portugal, covers 31 x 108 km, from 36°29’N to 37°05’N and from 10°24’W to 9°33’W, in water depths from 1,500 to 3,500 m. Located at the limit of the SW Iberian margin, this area is mostly sedimentary. A fresh mass-wasting complex with steep slopes covers 20 km x 13 km, at depths between 2,500 and 3,500 m. The geological knowledge of this area builds up on the results from previous surveys (e.g. [4]). The mass-wasting complex was subdivided for processing into images of 3 x 3 km, with a resolution of 3 m for TOBI. The local topography was gridded from EM-12S measurements at 100-m resolution. The slope is continuously steep, with several large reliefs perpendicular to the sonar track.

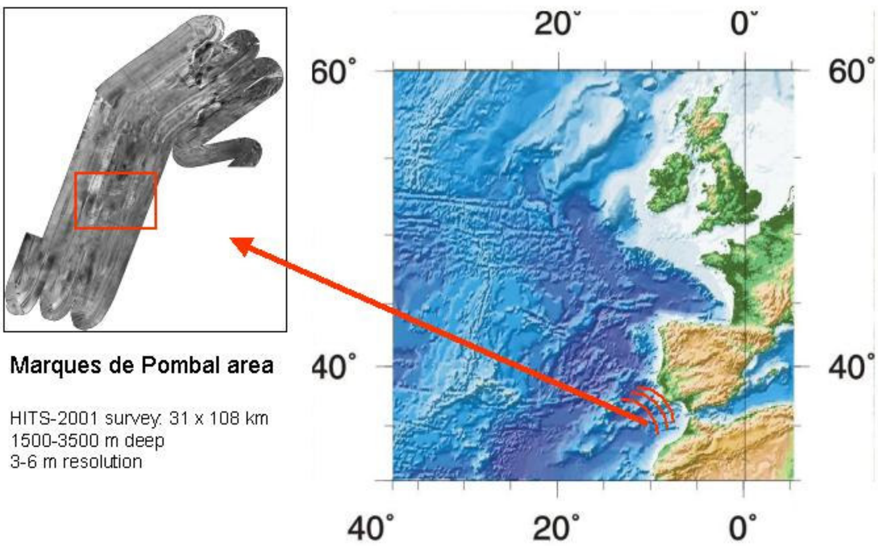

Figure 2. General location of the Marques de Pombal area. The sonar imagery acquired during HITS-2001 revealed this fresh mass-wasting complex, covering 20 km x 13 km approximately. The slopes are very important (1:20 over 18 km), significantly affecting possible interpretations.

The TOBI survey lines were processed with PRISM [9] to provide 3-m and 6-m resolution mosaics (Fig. 2), fully and accurately co-registered with the multibeam bathymetry. High backscatter returns are coded as high grey levels, following remote sensing conventions. The imagery shows varied and often mottled textures, more visible in Fig. 3. In this typical image, the sonar track (dashed line) delineates the two directions of insonification. The immediate effect is that angles of imaging downslope from the nadir will be higher than expected, and those upslope from the nadir will be considerably reduced. But what will be the influence on the interpretation of the different backscatter patterns?

3 Slopes and insonification angles

The large differences in depths between the upper and lower parts of the landslide are large (e.g. 600 m over 3 km in Fig. 3). This means there are important deviations in the imaging geometries. Traditional, visual interpretation by skilled geologists often assumes the angle of insonification is varying linearly away from the sonar track (nadir). The sonar position and attitude (i.e. the portion of seafloor actually imaged) are known from the length of towing cable out and from sensors on the TOBI platform itself (pitch and depth, mainly). The navigation and attitude files were filtered to remove outliers and spikes when the raw sonar data was processed with PRISM [9]. Calculating the actual angles of insonification on this complex seabed revealed significant discrepancies [3]. The angles can be misestimated by as much as 9°, in particular in the areas of higher relief upslope from the sonar track and in the depressions downslope. These differences induce important backscatter variations, exacerbated by localised reliefs, differences in micro-scale roughness and sediment properties along the slope. They can be quantified with the backscatter model of [5], validated at 30 kHz [10]. Geophysical parameters used in the simulations (e.g. mean grain size) were derived from available ground truth and we added plausible variations around their mean values to account for the intrinsic variability of any type of seabed. The backscatter model provides expected acoustic returns (in dB) as a function of the grazing angle, for each seabed type. Knowing the local imaging angle and the backscatter level, it would therefore be possible to deduce the terrain type. Unfortunately, the TOBI sonar is not calibrated, and it is not possible to associate definite seabed types to each pixel (coded in arbitrary grey levels).

It is possible however to deduce some information, as the simulated returns are divided into contributions from, respectively, surface processes (e.g. micro-scale roughness) and volume processes (e.g. sediment heterogeneity) [5]. Knowing that the acoustic return, for a series of similar generic seabed types (e.g. cobble/sandy gravel/very coarse sand), is dominated by surface processes, it is then possible to interpret local changes in the individual backscatters as, for example, due to variations in micro-scale roughness (at scales comparable to the acoustic wavelength of TOBI, ca. 5 cm). Conversely, knowing that acoustic returns are dominated by volume processes, one can then interpret local backscatter variations as changes in the sediment types or densities. These hints can assist other means of interpretation, such as the quantification of acoustic textures (Section 4) and the general geological context. The question is how sensitive this separation is to the accuracy of the angle of insonification. To this effect, we have compared simulations of the acoustic backscatters for several types of coarse sediments, using the actual angles and the assumed angles. The proportion of backscatter due to contributions from the seabed surface can be misestimated by as much as 15%, thus leading to wrong interpretations of the possible causes for backscatter variations. In the particular case of the image presented in Fig. 3, with steep slopes and coarse sediment types, surface processes are expected to contribute to more than 75% of the overall backscatter. Two areas only show lesser contributions: at nadir, where there is no useful TOBI data anyway, and at very far range, interpreted with caution in most cases. In this case, we can thus safely assume that all backscatter variations can be attributed to changes in the surface properties of the sediments imaged. For other parts of the mass-wasting complex (where the slopes are different), and for other images in general, the answer is not as straightforward. Some areas are more dominated by volume processes, and others by surface processes. A difference of 15% can adversely affect the interpretation of the backscatter returns.

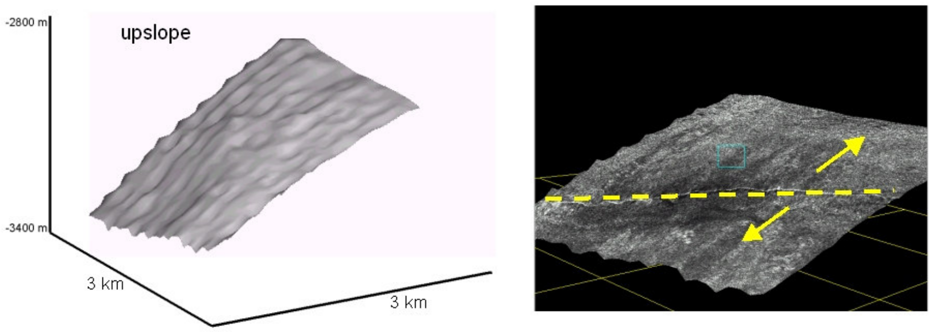

Figure 3. Bathymetry (left) and TOBI imagery (right, with no vertical exaggeration). Note the steep slopes, typical of the area, and the different insonification directions each side of the sonar track. The altitude and attitude of the TOBI platform will also vary along-track.

In the present case, where one is focusing on the general geological interpretation of the sonar imagery, individual pixels are assessed on their local variations. Acoustic simulations performed on local groups of pixels, and using the exact insonification geometry, show which areas in the image need to be interpreted differently, and how. The local variations in the backscatter returns are quantified through their textures.

4 Textural Analyses and their Interpretation

Textures can be intuitively described as smooth or rough, small-scale or large-scale, random or organised. Theoretical [11] and experimental studies [6] showed that textures are best quantified with stochastic methods, such as Grey-Level Co-occurrence Matrices (GLCMs). Suitably adapted, GLCMs have proved their worth for sidescan sonar imagery (e.g. [3,6]). They have been used successfully in another area of the HITS-2001 survey, south of Almería (Spain) [12]). GLCMs address the average spatial relationships between pixels of a small region, by quantifying the relative frequency of occurrence of two grey levels at a specified distance. Their properties are described by textural indices. Two indices are sufficient to describe the geological information [6]. Entropy measures the lack of spatial organisation inside the computation window. Homogeneity is directly proportional to the amount of local similarities inside this window. Smooth sediments will be associated to low entropies and high homogeneities, rough targets to high entropies and low homogeneities. Tectonised areas will present medium entropies and homogeneities proportional to the amount of faulting. These two indices are incorporated into a seafloor characterisation software called *TexAn* [6].

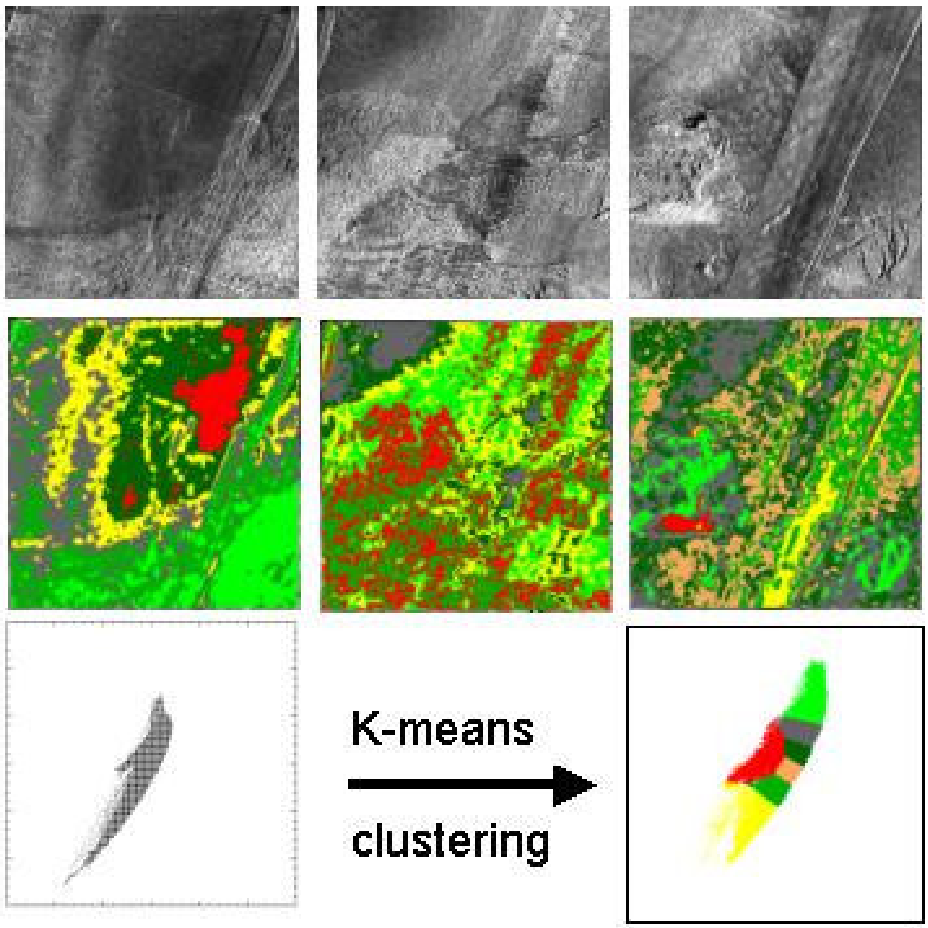

Figure 4. Textural analyses of 3 adjacent images along the slope of the mass-wasting complex. See text for explanation.

Fig. 4 presents 3 subsets of the TOBI imagery of the whole mass-wasting complex. The acoustic textures were computed with *TexAn*, using a computation window of 20 pixels, commensurate with the physical scale of the morpho-geological structures on the ground. Because of the grey-level dynamics in these images, the calculations could be run using 32 grey levels only (instead of 256). Fig.4 (top) shows the variations in sedimentary processes down the slope, with complex patterns and focusing of the landslide in some areas, constrained by the topography. For each pixel of each image, entropy and homogeneity were calculated, producing typical scatter plots like the one in Fig. 4 (bottom left). The (entropy; homogeneity) couples were clustered using the K-means algorithm (Fig. 4, bottom right). Through supervised classification, these clusters were associated to terrain types. Depending on the complexity of the images, 7 to 8 types were consistently recognised. By order of increasing entropies, they correspond to: dark, homogeneous sediments in the depressions (low entropies, low homogeneities); slightly brighter sediments, interpreted as slightly rougher (on the basis of the analysis in Section 3) (note the "tongues" coming down the slope into the depressions); coarse sediments with more mottled textures; rough sediments, marking the boundary with the next class, consisting of individual boulders and striated zones. The latter two classes have nearly the same entropies but different homogeneities. They correspond to the sediment gradation typical of underwater mass-wasting areas (e.g. [13]). Using the actual angles of incidence and knowing the overall contribution of surface processes to the local backscatter, we can confidently associate these geological interpretations to the different classes.

5 Conclusion

This study shows the synergy between two different approaches to process and interpret sonar data. First, a validated and recognised backscatter model was used to simulate the acoustic returns from a portion of a mass-wasting complex on the SW Iberian Margin. These simulations were informed by localised ground truth and used different types of coarse sediments. Our simulations showed the importance of accounting for the exact angles of insonification, and how the relative importance of surface vs. volume processes can then be quantified accurately throughout the sonar image. The knowledge thus gained can then be used to refine the interpretation of the acoustic textures, calculated with *TexAn*. Textural variations can then be confidently linked to variations in surface roughness or in volume properties. In some areas, he sediment gradation typical of mass-wasting complexes is linked to sediment "tongues", possibly associated to additional, localised slope failures.

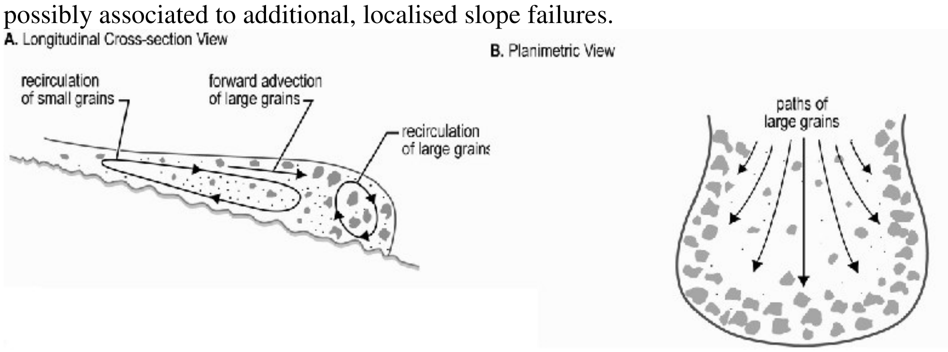

Figure 5. Schematic view of material entrainment in a mass-wasting event (adapted from [14]).

The mechanics of debris-flows and landslides is now well known (e.g. [13,14]). Fig. 5 shows typical material entrainment and the size segregation of the debris. The real case is of course more complex, because of the heterogeneity of the flowing material, the presence of underlying topography (e.g. outcrops, previous channels) and the volume and speed of the material. By knowing the relative local importance of surface and volume processes, and having assigned preliminary interpretations to the textural classes, it should be possible to analyse the different parts of a mass-wasting complex. One can also envisage the possibility of recognizing different types of events within the larger complexes. Combining different techniques from acoustic modeling, image processing, and geological interpretation makes a powerful tool to study mass-wasting areas in continental margins. A better appreciation of the complex acoustic interactions with the seabed, associated to awareness of the surveying constraints, can provide better opportunities for the geophysical interpretation of sonar images in these challenging environments, whether in deep or in shallow water.

Acknowledgements

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