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Submarine Mass Movements: Sedimentary Characterization and Controlling Factors

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1. Introduction

Marine geology studies about submarine mass-movements, especially during the last 20 years, have demonstrated their relevance in building and evolution of continental margins. This is because mass-movements represent the main mechanism of sediment transport from continent to deep-sea areas, and one of the most common geological hazards in submarine environments (Masson et al., 2011). They occur in all the sea and oceans of the world, and may develop in all the physiographic environments, from the shelf, slope, continental rise to deep sea areas. Their resulting deposits have variable dimensions, from metric to several hundreds of km in length, and from centimetric to severel tens meters of thick. Their sedimentary record informs about variations of glacioeustacy and hinterland sediment sources, occurrence of meteoceanic processes that can affect to seafloor, active tectonism and seabed fluid flow related processes.

Likewise, the study of mass-movement deposits is nowadays important for applied scientific, mostly related to hydrocarbon exploration and geological hazards. These deposits may represent important accumulations of clastic sediments for hydrocarbon accumulation. In spite of their important role in submarine environments their occurrence has never been directly observed (Hueneke and Mulder, 2011). Their occurrence has been detected due to injuries caused on infrastructures resting on or fixed to the seafloor and/or subbottom, as cables and pipelines. In this sense, mass-movement processes in marine environments, both at shallow and deep sea areas can represent a hazard for any marine infrastructure. During recent years there has been an important growth in the level of study of these processes and their deposits. This is due to the increasing development of deep water exploration activity and the joined scientist efforts, from geologists and engineers, on working in specific objectives to resolve unknowns about mass-movements. These efforts have produced an important collection of scientific literature about the variability of failures and their resulting sedimentary products as well as potential hazards, all based on indirect (acoustic and seismic analysis) and direct (sedimentological, geotechnical and geochemical) approaches.

The present work goes into deep the knowledgement of submarine sedimentary instabilities combining multidisciplinary and multiscale approaches. Four main topics for mass-movements investigations are presented: 1) characterization of continental margin and historic register of the instabilities on a continental slope; 2) definition of the dynamics of slope failures; 3) study of physical and mechanical properties of sediments; and 4) definition of forces that may trigger submarine mass-movements and determinate their evolution. These topics are studied with several direct and indirect techniques of different degrees of resolution (millimetric to decametric) and in different geological contexts.

2. Selected case studies in the Mediterranean, Atlantic and Antarctic Sea

Six case studies will allow discussing, using as thread the topics above mentioned, the different results obtained as well as their interrelation. Based on indirect, morphologic and acoustic evidences three case studies are presented: 1) Mass-movement on the Ebro continental slope (NW Mediterranean); 2) Evidence of gas in the continental slope of the Gulf of Cadiz; and 3) The dynamics of the Baraza Slide in the northern Alboran Sea (SW Mediterranean). Based on the combining morphologic and seismic facies analysis and direct (sedimentological, geotechnical analysis) techniques, three other cases are presented: 4) Physical-geotechnical properties and texture of the Pliocene-Quaternary sediments in the Madeira Abyssal Plain; 5) Sedimentary processes in sediments recovered from mud volcanoes in the Anaximander Mountains (Eastern Mediterranean); and 6) Sedimentary stability of the continental slope and adjacent deep sea areas in the Bransfield Basin (Antarctic Peninsula).

2.1 Methodology

The bathy-morphologic, seismic and acoustic facies analysis will allow to observe the tecto-sedimentary framework of the margin on which mass-movements occur or may occur, as well as to characterize in detail the resulting sedimentary products from the different types of mass-movement processes. Bathymetric data include multibeam records obtained with SIMRAD EM12 multibeam system and processed with NEPTUNE and CARAIBES softwares, combined with and information provided from GEBCO gridded bathymetry data. Seismic and acoustic facies analyses have done through the analysis of different single-channel seismic profiles. Those include: 1) very high resolution TOPAS (Topographic PArametric Sonar) profiles, with a penetration of the acoustic signal between 30 and 200 milliseconds (two way travel time –twtt-) and a decimetric resolution; 2) high resolution Sparker profile which provides a penetration of about 1.5 s (twtt) and a metric resolution; and 3) medium resolution airgun profile (sleeve guns, 120 c.i.) with a penetration of 2-3 s (twtt) and providing a resolution of tens of meters.

The sedimentological and physical and geotechnical analysis allow to ground truth information about the properties of nearsurface sediments, both failured/deformed and non-failured. A great diversity of techniques are involved in these analysis which allow characterizing grain size, composition, grain density, water content, porosity, shear strength etc. Physical properties of marine sediments are important variables to understand geological processes and events of marine environments. Physical properties (density, magnetic susceptibility and P-wave velocity) depend to a large extent on lithology, grain size and composition of sediment (Hamilton et al., 1982; Nobes et al, 1991). The bulk density, for example, is related to porosity, grain density and is partially controlled by grain size (Johnson and Olhoeft, 1984). The P-wave velocity is controlled by porosity, carbonate and clay contents (Hamilton et al., 1982; Mienert, 1984; Nobes et al., 1986). Physical properties are also influenced by diagenetic effects, not only decrease of porosity with increasing compaction, but also cementation and carbonate dissolution (Nobes et al., 1992).

2.2 Variability of mass-movement on the Ebro continental slope (NW Mediterranean)

The study of the mass-movement on the Ebro continental slope (Fig. 1) is a good example showing the great variety in scale and distribution of mass-movement features, both erosive and depositional, that can affect to slopes of continental margins (Casas et al., 2003a). They affect to any part of the slope. The triggering factors for this slope are variable, being the background factor the high sediment supply during the regressive sea-level falls of high amplitude.

Fig. 1. Map of location of the study area for case studies 2.2 (Ebro Margin), 2.3 (Gulf of Cadiz) and 2.4 (Alboran Sea).

The Ebro continental slope locates in the Spanish NW Mediterranean continental passive margin, off the Ebro River, the second largest rivers in the Western Mediterranean Basin. It extends between 160 ± 20 m and 1000 ± 200 m water depth, its width decrease southward from 20-25 km to 10 km, and its gradients increases southward from 2.5-4º to 3.8-5.8º. The Ebro is a prograding margin since the late Oligocene, mainly fed by the Ebro River, whose tectonic adjustments have been active as late as to the Upper Pliocene and the Quaternary (Dañobeitia et al., 1990). Seismicity is fairly moderate; magnitudes between 4 and 5 have been measured during the last century (Surinach and Roca, 1982). The oceanography is manly characterized by permanent flows along the continental shelf and slope resulting from wind-driven surface currents from northwest that extend to water depths of 150-200 m, interacting with upper slope topography (Castellón et al. 1990; Arnau et al. 2004).

About 37 % of the Ebro slope (Fig. 2) is affected by a great variety of mass-movement features, both erosive and depositional (Casas et al., 2003a). Erosive features predominate along the entire slope, whereas depositional ones are dominant on the lower slope. Submarine canyons and gullies eroding their heads and walls, are indicating removal of sediments through the continental slope. Their formation and enlargement are mostly related to the increase of sediment supplied that slope receives during high amplitude sea-level falls and lowstand stages in the Quaternary (Alonso and Maldonado, 1990). Slide scars, isolated or associated downslope to slide deposits, occur between canyons in the open upper slope (Fig. 3). They probably formed by the decreases in shear strength due to high sediment supply during those mentioned regressive falls in sea-level. Small-scale slides (tens ms thick, hundreds of meters to few kilometers in length) also occur locally on the canyon walls, due to oversteeping of seafloor (> 10º).

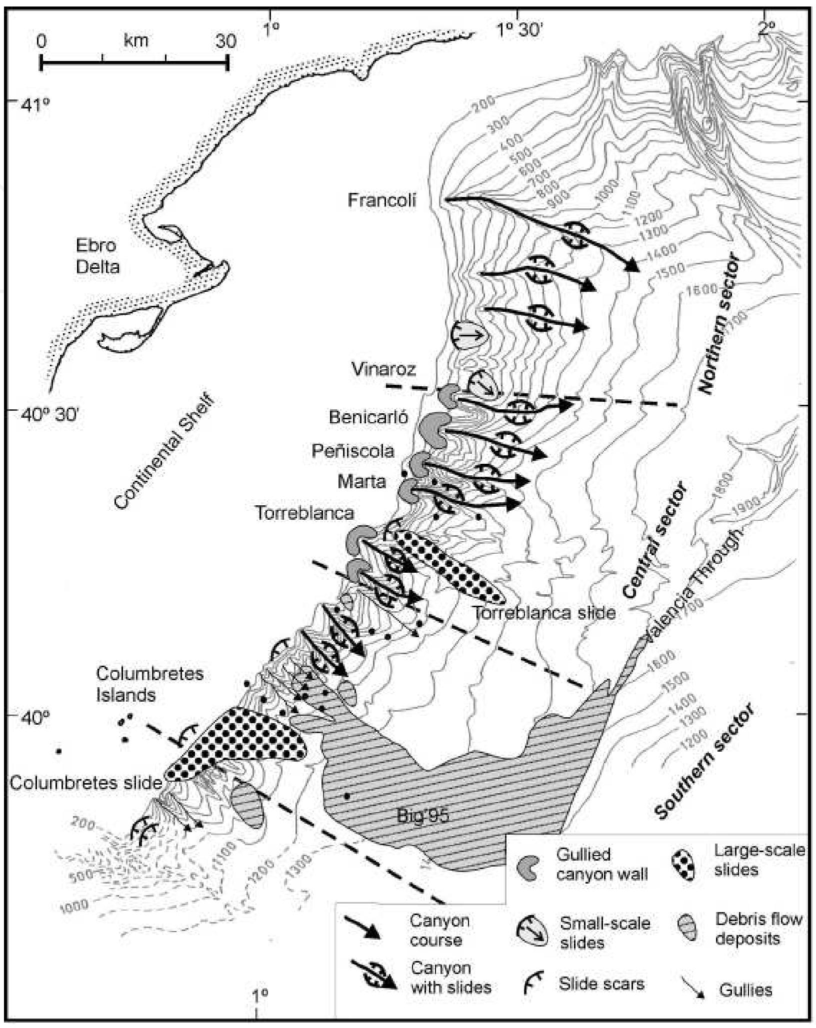

Fig. 2. Mass-movement features identified on the Ebro slope. From Casas et al. (2003a).

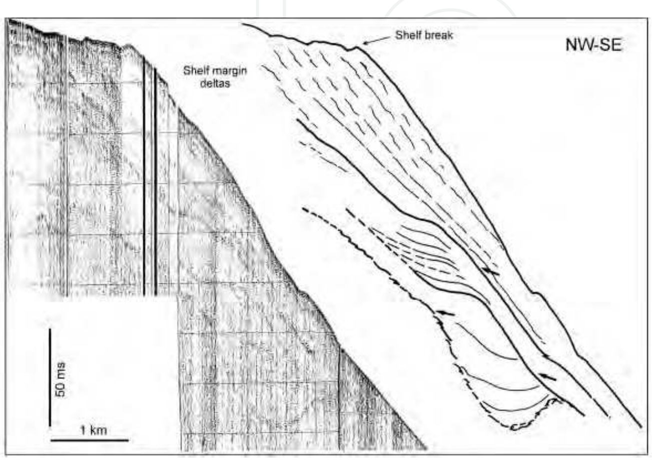

Fig. 3. Sparker profile showing the small-scale slides identified on the upper slope. The arrows indicate truncation of sediments. From Casas et al. (2003a).

The most prominent depositional mass-movement features occur on the open slope, and include three large slides, from north to south: Torreblanca (300 ms thick, > 40 km long), Big (< 135 m thick; 110 km long>; Lastras et al., 2002) and Columbretes (150 ms thick, 10 km long). They extend from the upper slope and enter into the base-of-slope where the Big Slide becomes to reach to the Valencia Channel, a mid-ocean valley crossing the Algero-Balear Basin. These slides represent slumps and associated mass-flows deposits with different post-failure behaviour. The main heads (unknown for the Big Slide) are defined by a main scar with an amphitheatre-like failure surface that evolves downslope to a depositional area defined by deformed stratified and chaotic facies with a rugged seafloor (Big Slide shows blocks metric in size). The Torreblanca and Columbretes slides represent frontal confined slides, whereas the Big Slide can be fit into the category of the unconfined frontally slides (Frey Martinez et al., 2005). In this sense, the Torreblanca Slide (Fig. 4), with a limited deformation and preservation of original stratification, and the Columbretes Slide (Fig. 5), more deformed and with a chaotic pattern, both display an increase of their thickness (few meters) at the distal end and do not rest upon the undisturbed sediments. Contrasting, the Big Slide, with a chaotic and transparent internal acoustic pattern, displays debris flow material over running the previous seabed. Addition to these large slides, on the lower slope of the south sector are also identified relatively small-scale debris flow deposits (< 8 km long, 0.26 s) interrupting the lateral continuity of the undisturbed stratified open slope deposits.

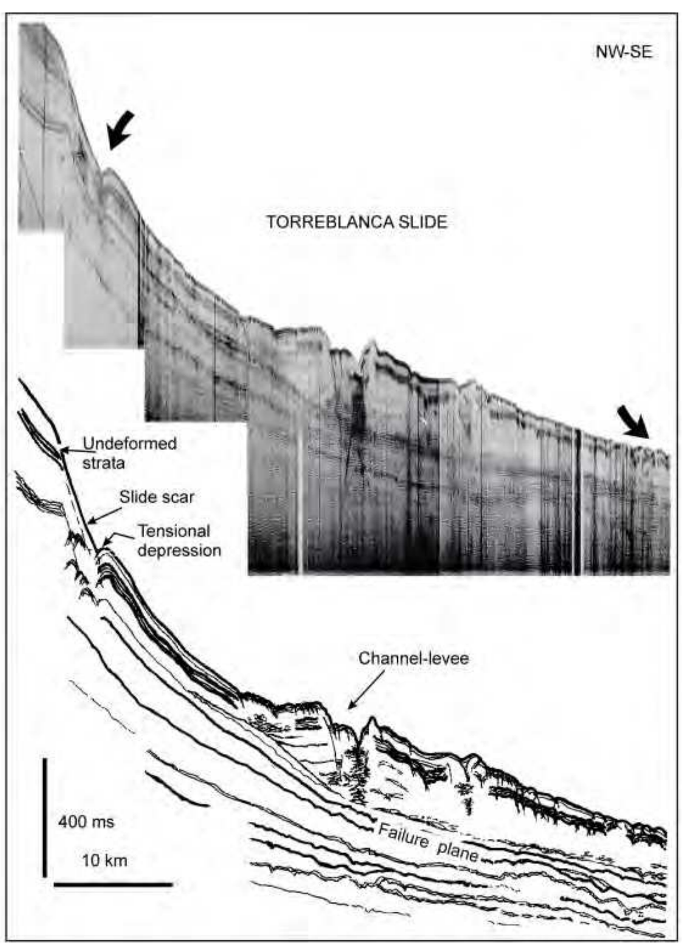

Fig. 4. Sparker profile along the Torreblanca Slide. From Casas et al. (2003a).

The distribution and variability of the mass movements in the Ebro margin are mainly conditioned by several factors: high sediment supply, oversteeping of the slope, sediment thickness involves in the failure, frequency of failures and structural location. The combination between high sediment supply and oversteeping of the sea surface favours the occurrence of small-scale slides and canyon incisions on the upper slope. The mass

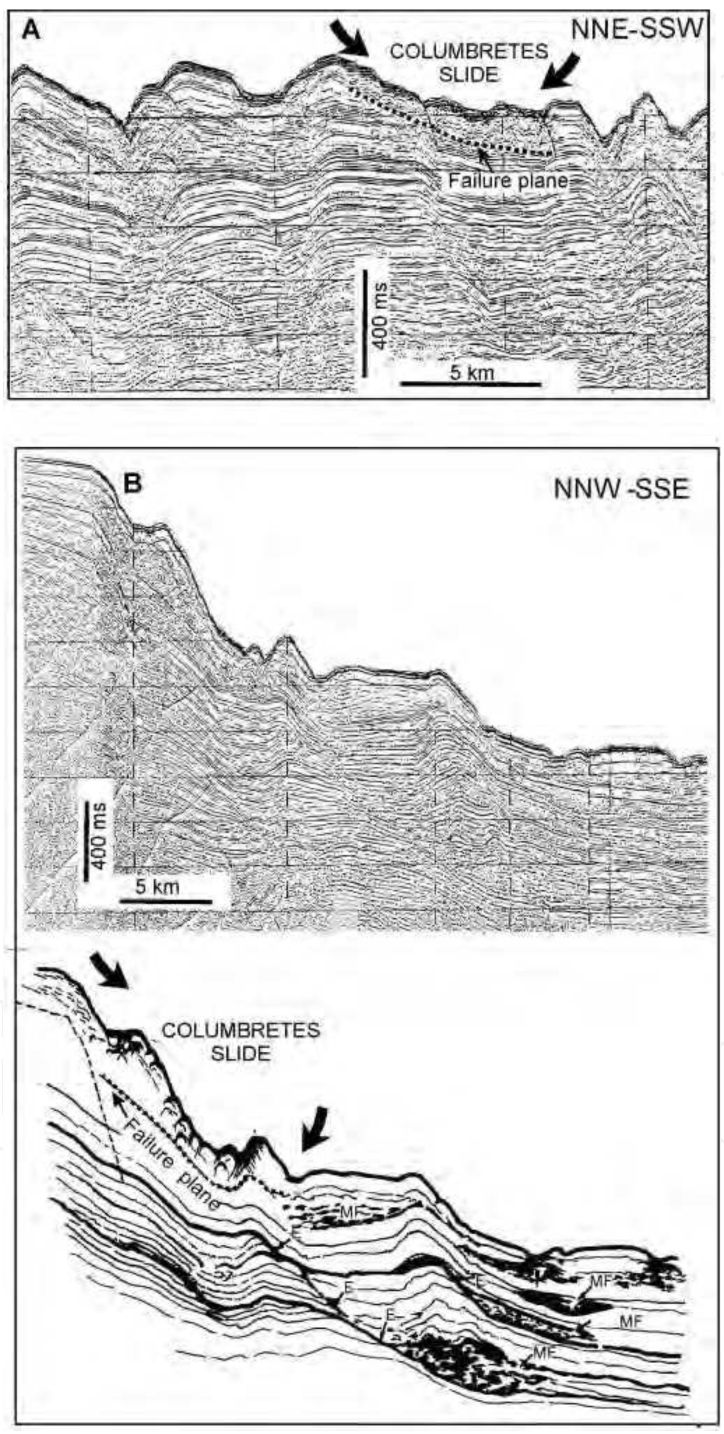

Fig. 5. Airgun profiles of Columbretes slide A) parallel to the slope; B) along the slide and line drawing. Legend: The thick arrows indicate the lateral extension of the slide; E, erosive surfaces; MF, mass-flow deposits. From Casas et al. (2003a).

movements forming both features, channelized and unchannelized (canyon vs. open slope), differ in the volume of sediment and occurrence frequency, being lower in volume and higher in frequency for the canyons and reverse for the small-scale slides. The failure style on the open slope involves short movements because those slides have not been transported over significant distances (few meters). On the other hand, the preferential location of the three large slides in the south sector of the Ebro slope, suggests a tectonic control in their triggering, specifically a seismic shacking related to volcanic activity (Field and Gardener, 1990). The timing occurrence of the two mass-movement groups seems to be different; during the regressive stages of sea level formed the small-scale slides and canyon incisions, being gravity loading plus storm and internal waves the possible triggering mechanisms; and whatever stage of sea-level for the three large slides, being the seismic activity their triggering. The distribution and variability of the mass movements on the Ebro slope also indicates that the depletive features of the mass movements are preferentially located on the upper slope whereas the accumulative features predominate in the lower slope.

2.3 A potential hazard for mass movement occurrence in the Gulf of Cadiz: Gas in slope sediments

Low to very high resolution seismic studies have revealed the presence of gas-charged sediments around the oceans and seas, from shallow to deep water depths (Judd and Hovland, 2007). Presence of gas in marine sediments, in its two versions as free gas and gas hydrate, is considered one of the main factors influencing on seafloor slope stability. Gas is considered a pre-disposition and triggering factor of mass movements. Although the direct evidence for the presence of gas in marine sediments can be only confirmed trough drilling and coring, it can be also identified indirectly by means of acoustic methods. The present study case has been chosen because the Gulf of Cadiz is a good example to show the great variety of acoustic evidences observed in marine sediments hosting gas, free and gas hydrate (Casas et al., 2003b). Its presence has to be always considered as potential geological hazard, of natural, induced or mixed type, and a predisposition factor to trigger mass movements (Judd and Hovland, 2007). Because of that the indirect interpretation of gas in marine sediments is essential in assessment of the factors controlling the occurrence of submarine mass-movements.

The Gulf of Cadiz (Fig. 1&6) is located in the southwestern Iberian, Atlantic Sea, and records a complex tectonic evolution because it occupies a focal position between the westernmost Mediterranean segment and the Iberian-African boundary (Bonnin et al., 1975; Dewey et al., 1989). This tectonic complexity is reflected by the seafloor morphostructure defined by a prograding margin with a continental slope (130 to > 900 m water depth) affected by numerous diapiric ridges and mud volcanoes separated by submarine valleys (Baraza et al., 1999; Maldonado et al., 1999). The Upper Miocene to Quaternary stratigraphic architecture of this margin corresponds to three main depositional systems (Maldonado et al., 1999). The main sedimentary systems comprise Plio-Quaternary shelf margin deltas on the proximal margin developed during the sea-level falls and rises and fed mainly from the two major rivers in the area (Guadiana and Guadalquivir); Upper-Pliocene to Quaternary mixed contourite-turbidite deposits on continental slope formed by the action of the Mediterranean outflow water after the opening of the Strait of Gibraltar (Hernández-Molina et al., 2003) ; and Upper Miocene fan lobe deposits in the distal continental slope fed by the two mentioned rivers. The above mentioned shelf margin deltas and fan lobe deposits contain substantial amount of gas, both in origin biogenic and thermogenic (Baraza et al., 1999; Leon et al., 2009).

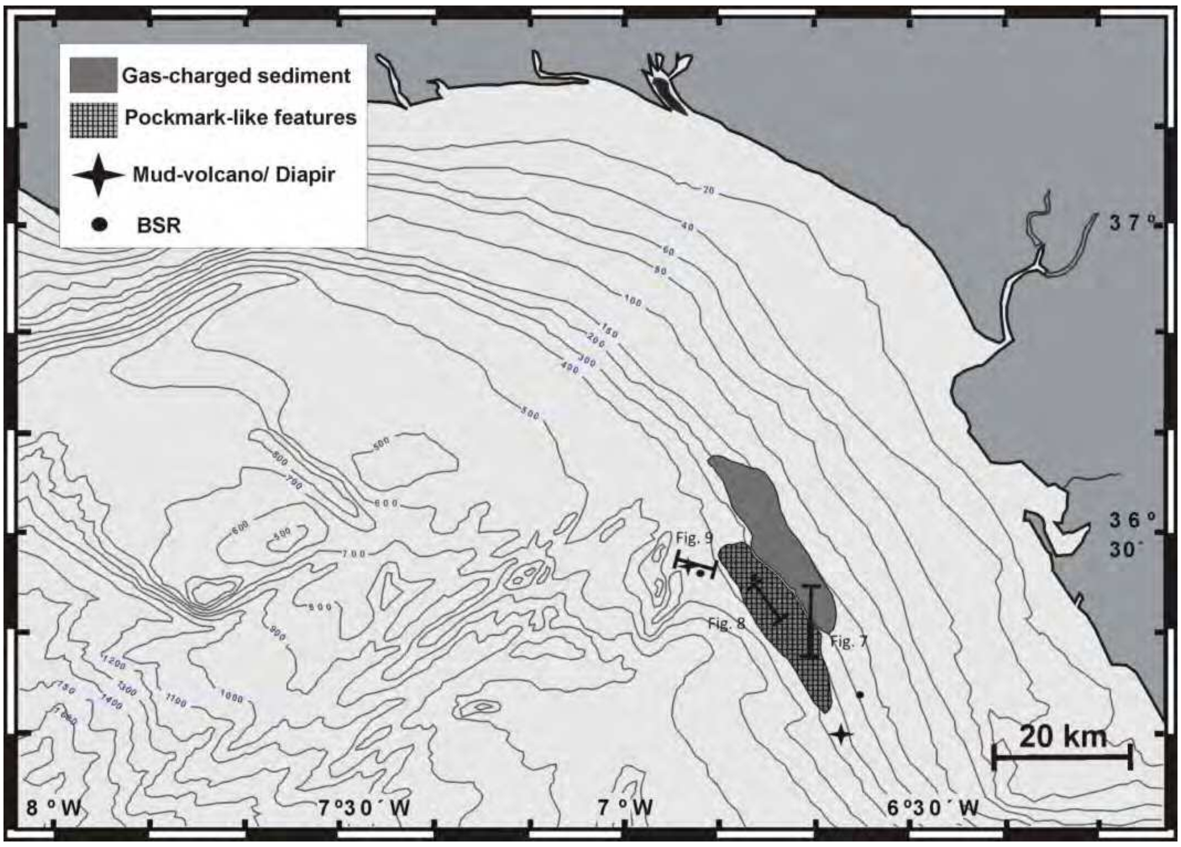

Fig. 6. Bathymetric map of the Gulf of Cadiz showing the location of the gas-related features observed in this study. Modified from Casas et al. (2003b). Location of Figs. 7, 8 & 9 are also displayed.

The presence of this gas has been defined in high resolution seismic profiles by a number of acoustic and morphological evidences: acoustic turbidity and blanking, bright spots, pockmarks, high amplitude refractions, acoustic plumes and turbidity in the water column, and bottom simulating reflectors (BSRs). These are the most typical gas related acoustic evidences defined in literature (Judd and Hovland, 2007). The acoustic turbidity and blanking features occur in the shelf margin muddy deposits on the uppermost slope (130 to 300 m water depth, area of 210 km^2), and reflects gas bubbles presence in the pore space on those deposits (Fig. 7). This gas is escaping to the immediately above water column, as it is suggested by the presence of acoustically reflective plumes. The mapped area with the free gas is locally affected by mass-movement deposits which tend to be rotational and are usually associated, forming multiple slides. They also occur immediately downslope of the area with free gas, and are underlined by acoustic turbidity and bights spots.
Modern and ancient pockmarks, hundreds meter in length and metric in relief, develop downslope from the gas-charged sediment area and surrounding diapirs (300 to 400 m water depth). These pockmarks are affected by high amplitude diffractions suggesting the escape of gas through them. Bright spots are also defined between pockmarks indicating gas concentrations trapped within sediment layers. The pockmarks shows a modern activity confirmed by the presence of acoustic reflective plumes above the pockmarks that indicate gas is ascending from the seafloor up to 50 m (Fig. 8). The expulsion processes implies a reworking of the subbottom and seafloor sediments that form dispersed craters whose steep walls can be affected by small scale mass movements. The pockmarks do not represent mass

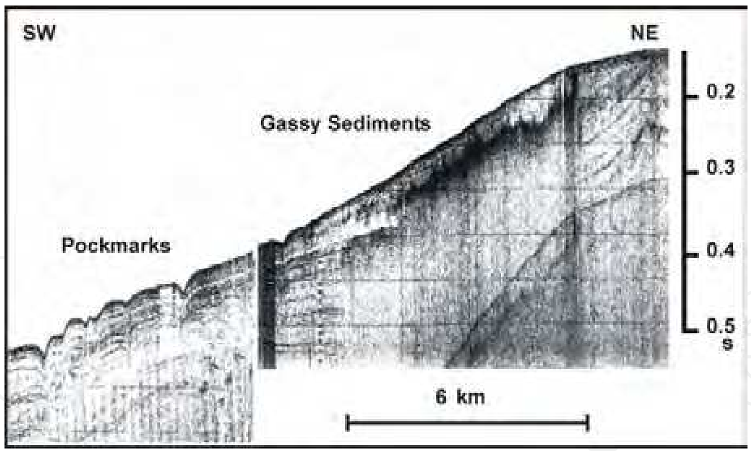

Fig. 7. GeoPulse seismic profile showing gas-charged sediment and pockmark-like features. From Casas et al. (2003b). See location in Fig. 6.

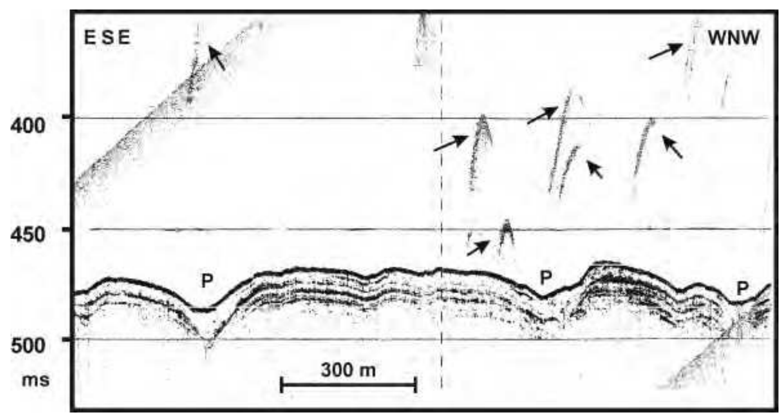

Fig. 8. GeoPulse seismic profile showing gas-charged sediment and pockmark-like features. From Casas et al. (2003b). See location in Fig. 6.

movements but they can be considered as geohazard because interrupt the lateral continuity of sediments and strata, becoming to rework sediment column "in situ". The BSR-like acoustic anomalies occur locally between 140 to 388 m water depth, and at 80 to 150 ms deep (Fig. 9). The gas saturated sediments that appear in the slope plus the diapiric activity have created the Pressure-Temperature conditions to form gas hydrate (Casas et al., 2003b).

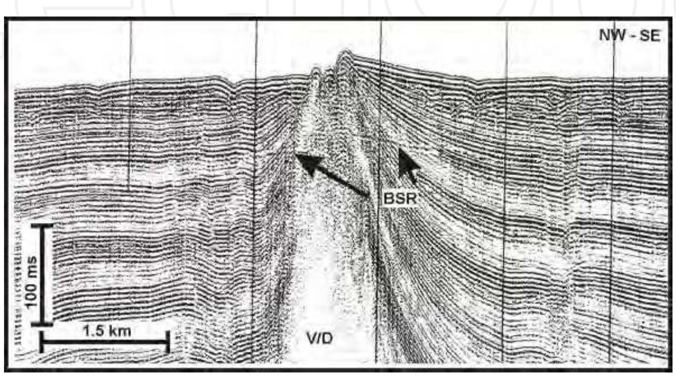

Fig. 9. BSR-like feature around the top of a mud volcanoe/diapir (V/D). From Casas et al. (2003b) Location of air-gun profile in Fig. 6.

It is evident a relationship between mass-movement occurrence and gas presence in the slope of the Gulf of Cadiz, but it is true that not elsewhere where gas exists there are mass-movements features. This means that gas alone cannot be responsible, but should be considered as a predisposition factor especially in tectonically active areas as the Gulf of Cadiz.

2.4 The dynamics of the Baraza Slide

The main objective of this case study is to show mass movement features imaged by multibeam systems on the seafloor should not be assumed to be recent alone and may have an instability history more complex than they seems. This study characterizes the Baraza Slide (Ercilla et al., 2009; Casas et al., 2011), located in the continental slope of the northern Alboran Sea (southwestern Mediterranean Sea; Fig. 1&10&11), between 590 and 830 m water depth, trough the analysis of their morphology, subbottom seismic facies and deformational features. The combined results indicate the Baraza Slide is a Late Pleistocene-Holocene sedimentary instability complex, that it has undergone repeated slope failures. The complex is formed by a mud flow system that changes to a slide system with time.

The mud flow system is characterized by the occurrence of a slope failure at the steepest (3 to 3.5º) sector of the open slope; the displaced mass moves down to the slope where gradients decrease sharply (0.5º to 1º). Mud flow is affected by a progressive dilution in flow concentration during its downslope movement. This dilution is suggested by the changes in acoustic facies of the mud-flow sediments, from chaotic to transparent, and also in the convexity of their cross-sections. It is inferred the occurrence of several mud flow events, at least 2 events based on multibeam mapping and seismic data, migrating from east to west and decreasing in their magnitude at the same time.

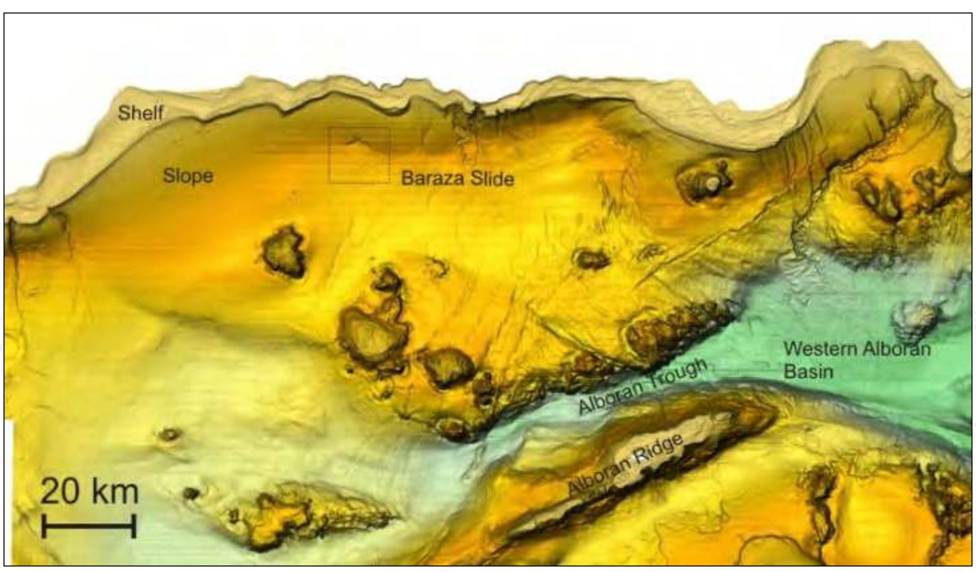

Fig. 10. Bathymetry of the Alboran Sea in the westernmost Mediterranean Sea showing the location of the Baraza Slide. The seafloor multibeam bathymetry, provided by the Spanish *Ministerio de Medio Ambiente y Medio Rural y Marino*.

The occurrence of mud-flow type movement ceases and the deformed resulting deposit is covered by a layer of late Pleistocene-Holocene sediments (Figs. 12&13). This level is affected by an unequal occurrence of structural (inverse faults, anticline folds) and outflowing

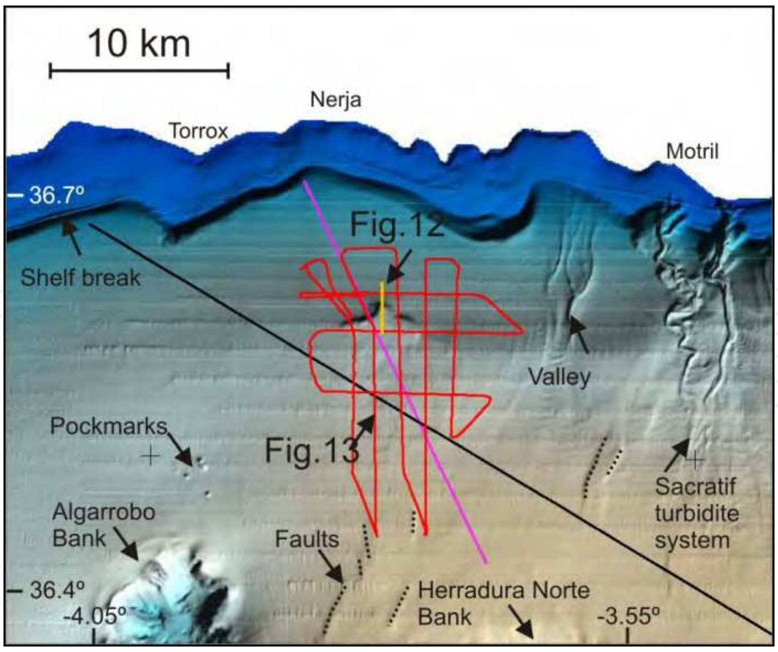

Fig. 11. Physiography of the present-day seafloor of the Baraza Slide area. Location of the Figs. 12 and 13 are also displayed.

features (water escape features). This fact suggest the occurrence of a slide-type movement at different time intervals up to recent times that affect different domains of the Baraza Slide although only the eastern sector of the slide still remains active. This type of movement affects to both the buried mud-flow deposits and to the overlying sediments. In fact, the slide scarp observed in the present day seafloor, results from the upslope propagation trough the overlying sediments of the ancient deeper scar that originated the mud-flow sediments. This

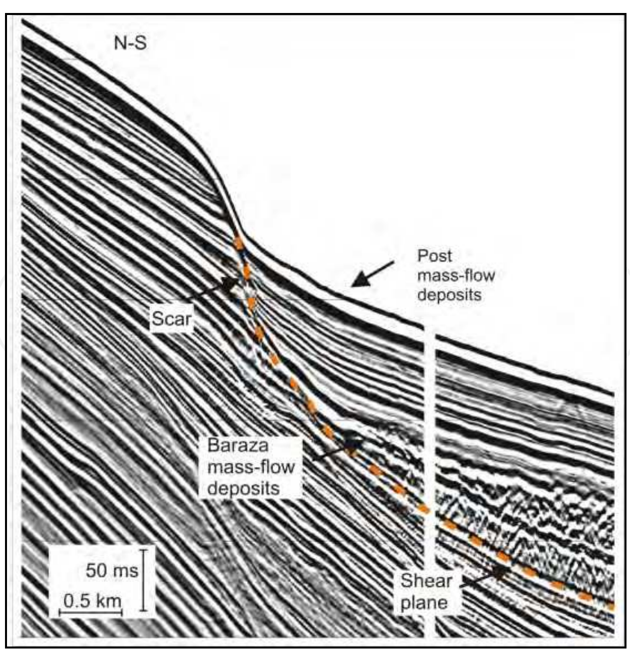

Fig. 12. Air-gun seismic profile illustrating how the scar plane extends downslope, going into subsurface sediments and joining with the shear plane. From Casas et al. (2011). See the location in Fig. 11.

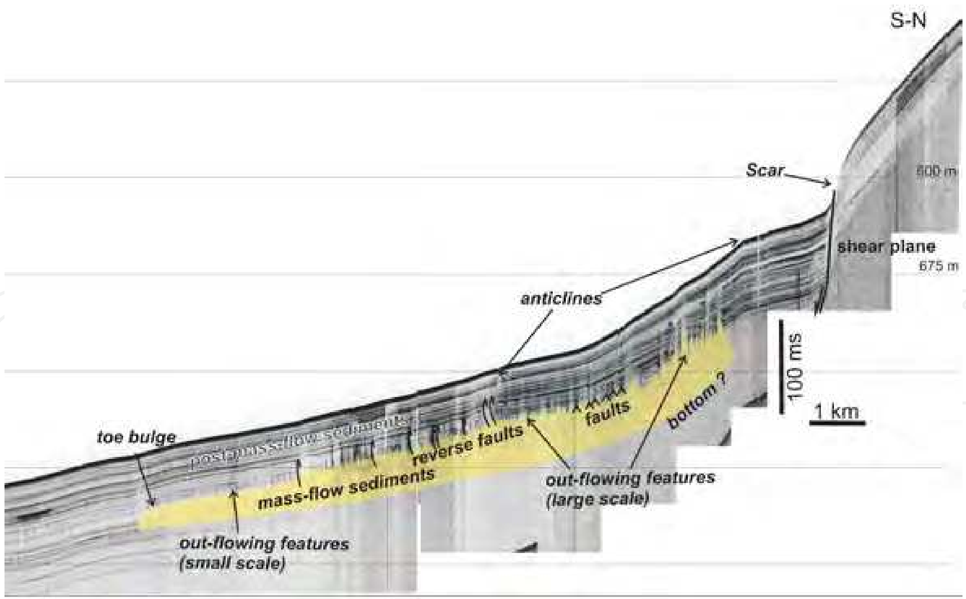

Fig. 13. TOPAS seismic profile which shows the main sedimentary structure and seismic facies of the Baraza Slide. From Ercilla et al. (2009). See the location on Fig. 11.

slide model combines extensional and compressional deformations. The extensional domain occurs at the slide scar where tensional failure occurs, and at foot of the scar where the post-mud-flow sediments are non-affected by outflowing features. The post-mud-flow level moves with a shear-dominated movement along the plane of the scar. Its stress originates the deformational an outflowing features; in fact, the anticline folds, water escape structures and their particular size distribution, the concomitant occurrence of slope breaks on the seafloor and upper surface of the mudflow deposits, all together would represent the structural criteria revealing the absorption of the compressional deformation.

2.5 Analysis of the physical-geotechnical properties and texture in the Pliocene-Quaternary sediments from the Madeira Abyssal Plain

This case study is centred on the analysis and the relationship of sedimentologic changes with the physical properties acquired on the upper 200 m of continuous coring at sites 950a to 952a of ODP Leg 157 (Baraza et al., 1996; Schmincke et al. 1995) which recovered more than 1000 m thick sediment sequence, from the deep floor of the Madeira Abyssal Plain (Fig. 14).
Four lithologic units define the Eocene to Quaternary sedimentary stratigraphy of the Madeira Abyssal Plain (Schmincke et al. 1995). The upper 200 m of cores studied corresponds to the Unit I (Pleistocene to middle Miocene). It consists of turbidite layers interbedded with pelagic nannafossil oozes. There are three primary types of turbidites (volcaniclastic, organic-rich and calcareous), originated from volcanic islands, the northwestern African margin and seamounts respectively. Results of grain-size analysis show homogeneity of grain-size distributions among all three sites. Attending to the percentages of the three main size-fractions, most of the analyzed samples are classified as silty-clays with only small amounts of sand (less than 17%).
Regarding the physical properties, they are controlled by the degree of compaction, rather than by changes in lithology. Differences in magnetic susceptibility (Fig. 15) appear to be related to changes in the mineralogical assemblage. Several high-amplitude peaks of magnetic susceptibility clearly differentiate between the highly magnetizable, volcanic-rich turbidites and the low magnetic organic and calcareous turbidites. Density and P-wave

velocity appear mostly related to consolidation effects, but at a detailed scale shows variations related to the presence of thin, coarser-grained (silty) bases of some calcareous or organic-rich turbidite intervals.

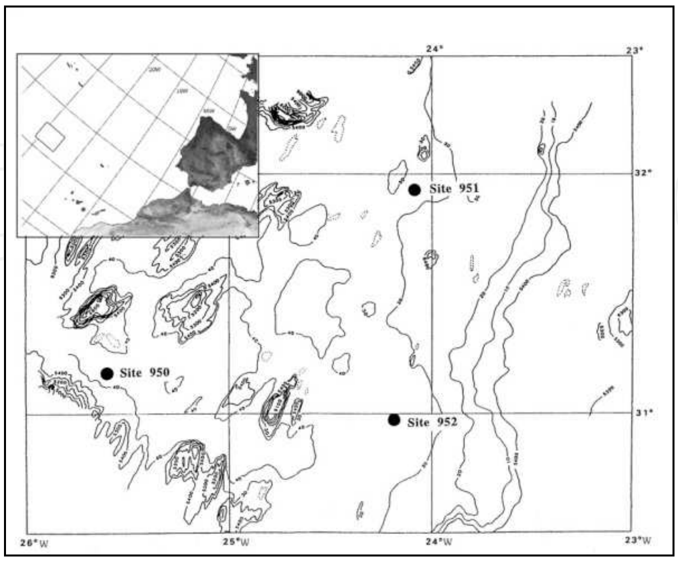

Fig. 14. Location map of ODP sites 950a, 951a and 952 in the Madeira Abyssal Plain.

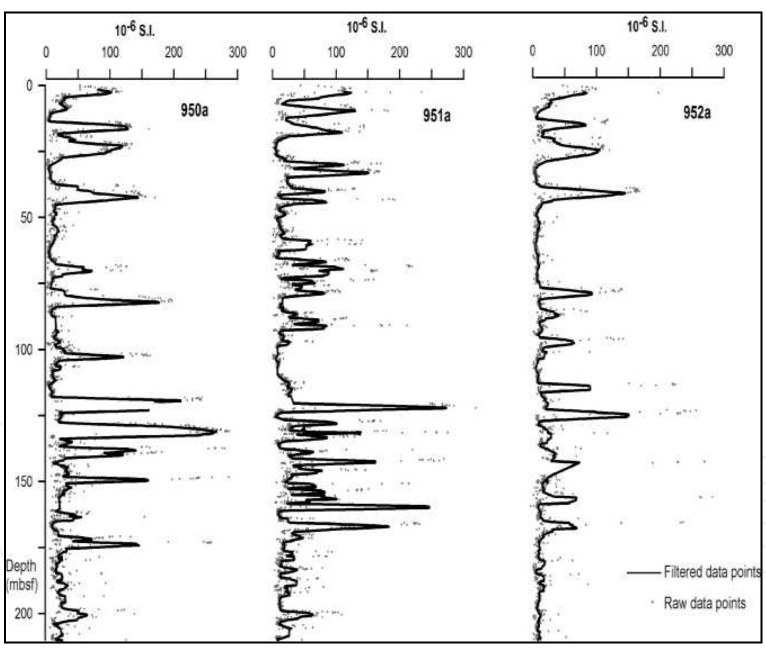

Fig. 15. Magnetic susceptibility profiles of the upper 200 mbsf for the three holes. From Casas et al. (2006).

Other properties as grain density, water content, porosity, undrained shear strength or calcium carbonate content show in general a range of variability associated to normally consolidated, fine-grained deep-sea sediments. Variations in grain density do not have a defined downcore trend, but they are mostly related to changes in composition (especially silica and carbonate) and primary bulk mineralogy. Grain densities are relatively higher in the volcanic turbidite intervals. The rest of index properties are mostly related to the decrease in porosity and increase in bulk density of the sediment due to compaction by overburden. Progressive consolidation due to overburden results in an expulsion of interstitial water and an increase of friction between particles on the sediment. The reduction of porosity and water content by progressive consolidation is the major factor controlling the increase in shear strength with depth (Schmincke et al., 1995). A plot of shear strength "versus" water content for samples from all holes (Fig. 16) shows the higher strength values for samples having water content around 40% and a sharp decrease in strength as water content increases to 60%. Nevertheless, changes in the rate of downcore increase/decrease of a given index properties may be related to compositional changes (carbonate and silica content).

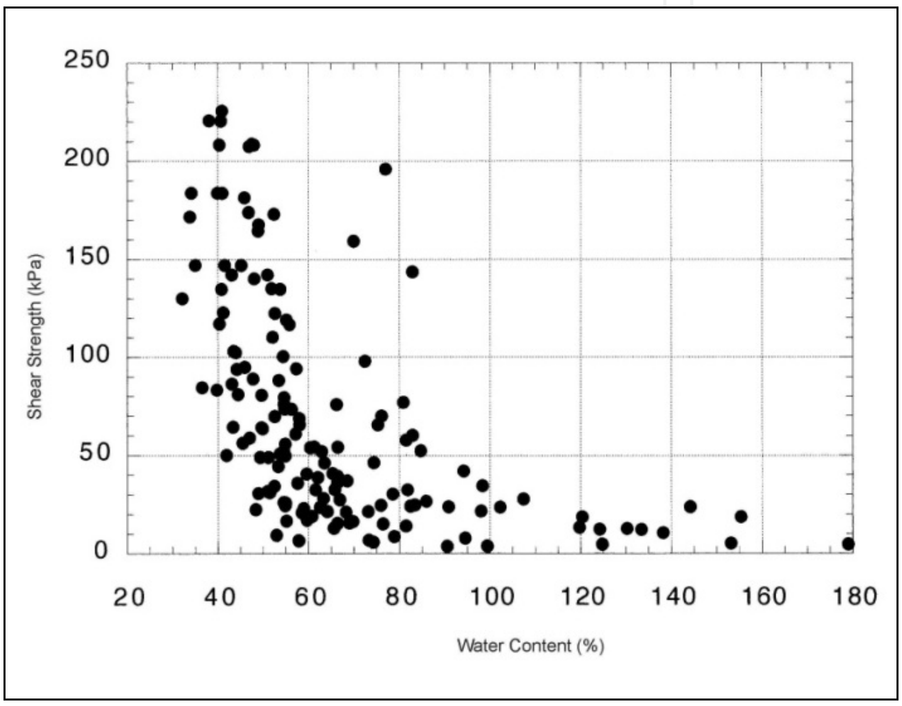

Fig. 16. Water content vs. shear strength for all samples studied. From Casas et al. (2006).

2.6 Sedimentary processes in sediments from mud volcanoes in the Anaximander Mountains (Eastern Mediterranean)

This case study focuses on the mud volcanoes Amsterdam, Kazan and Kula (Fig. 17) which are located in the Anaximander Mountains (SW Turkey continental margin) and are characterized by the presence of gas and gas hydrates (Woodside et al., 1998; Lykousis et al., 2004; Werne et al., 2004). A mud volcano is a positive relief constructed mainly of mud that typically emits a mixture of gas, water, and solid sediment derived from deep (Zitter et al., 2003). This sediment is usually composed by breccias comprising clasts of solid rock in a mud matrix (mud breccia). Mud volcanoes are dynamic and unstable sedimentary structures, accordingly sedimentary mass movements and gravitative flows may affect their flanks reworking the mud breccia.

Four cores with a maximum length of 131 cm were studied. Cores An05GC1, An07GC4 and An14GC1 are sited inside the crater of the Amsterdam, Kazan and Kula mud volcanoes respectively (2030, 1700 and 1636 meters water depth), and core An13GC1 at the outflowing masses that form the external flank of the Kula Volcano at 1636 meters water depth.

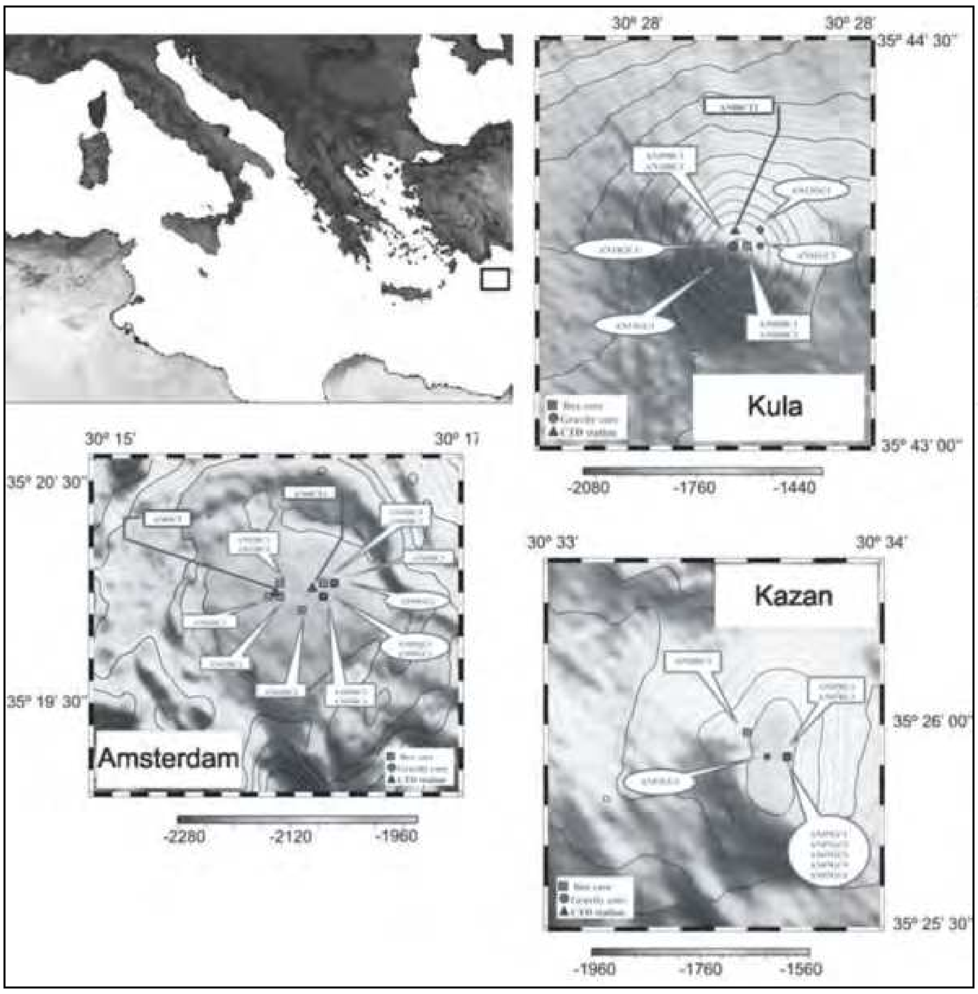

Fig. 17. Location of the Anaximander Mountains and mud volcanoes studied. Modified from Casas et al. (2006b).

The stratigraphy of cores An05GC1, An07GC4 and An14GC1 comprises the vertical stacking of mud breccia, whereas the core An013GC1 is defined by mud breccia that toward the top changes to hemipelagic mud (Fig. 18). Mud breccia is characterized by a high clay and silt content ranging between 67-56% and 19-30%, with a sand and gravel content of about 14%. Hemipelagic mud is characterized by high clay and silt content and a sand content lower than 3%.

Several correlations found between texture and density, magnetic susceptibility and P-wave velocity suggest that for the sediment cores located inside the mud volcanoes (An05GC1, An07GC4 and An14GC1) the physical properties are controlled by lithology and volcanic processes. This is supported for example by the correlations found between density and sand or silt (R= 0.47 and R=0.69 respectively) in core An07gc4 and between density and gravel or silt in core An14GC1(R=0.78, R=-0.75). The magnetic susceptibility of these cores seems to be controlled by the fine fraction. By contrast, the core located outside the Kula mud Volcano (An13GC1) displayed physical properties mostly related to consolidation effects and to the type of sediment at a detailed scale (hemipelagic mud vs. mud breccia), as occurs typically in deep sea fine-grained sediments. This is supported for example by the relationships found between density and core-depth (R=0.72). This suggests a restricted influence of volcanic processes outside the crater.

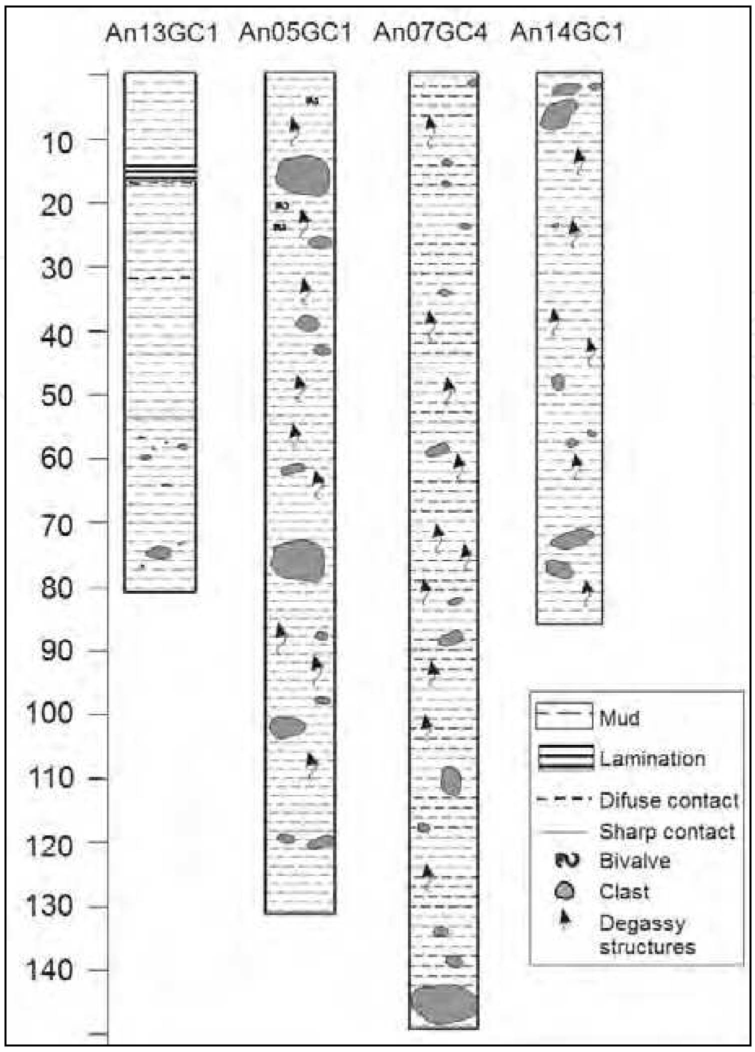

Fig. 18. Drawing of sediment logs showing the stratigraphy of the four cores studied.

Other variables measured as shear strength (Fig. 19) and its low or null correlation with, for example core-depth, could be reflect the effect of presence of porus gas-release structures resulting from depressurization after collection of samples containing gas. This could suggest recent fluid circulation, and therefore the possibility of current volcanic activity in the studied volcanoes. The depressurization may also be responsible for the relatively low strength values obtained. Mud breccia probably have greater absolute shear strength values because gas bubbles may affect sediment strength by decreasing grain-to-grain contacts (Briggs et al. 1996). However, the presence of gas hydrates could have the opposite effect.

2.7 Sediment stability on the Continental Slope and Basin of the Bransfield Basin (Antarctic Peninsula)

This case study is focused on the continental slope of the Antarctic Peninsula and adjacent deep sea areas, in the Bransfield Basin (Fig. 20). Type of sediments, sedimentary stratigraphy, and physical and geotechnical characterization of the sediments have been integrated. Four sediment gravity cores, located on the slope (at 1200 m water depth) and at the foot of the slope on the basin, at 1575 m water depth offshore the Antarctic Peninsula have been analysed (Fig. 20).

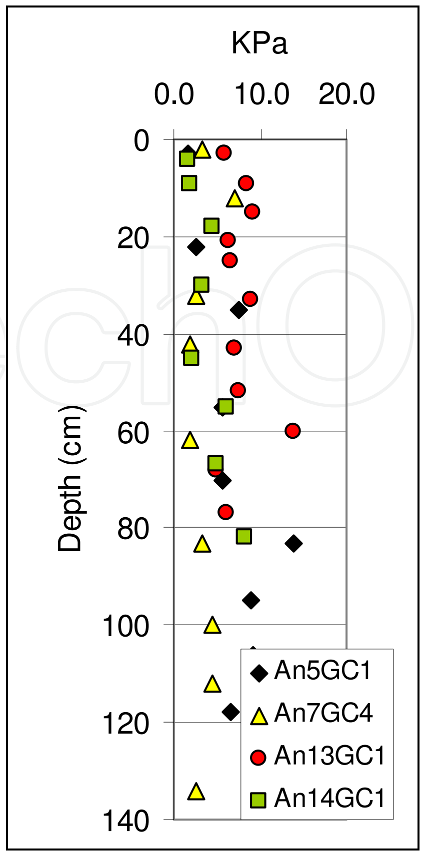

Fig. 19. Downcore variation of shear strength (kPa) for the Anaximander mud volcanoes sediments. From Casas et al. (2006b).

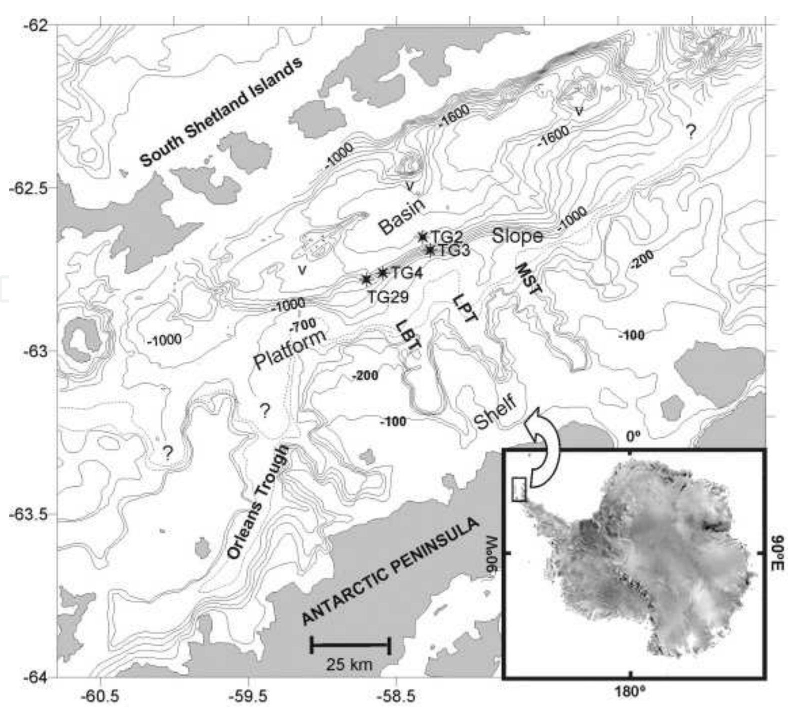

Fig. 20. Location of the study area and bathymetry of the Bransfield Basin. Black plots represent the position of studied sediment cores.

Based on the textural character and composition, the recovered sediments are defined as diamicton, unchannelised turbidite deposits (silty and clayey) and contourites which are associated to glacio-marine processes, gravitational flows and bottom currents, respectively. The stratigraphy indicates that sedimentation and related processes on the continental slope display lateral variations in short distances.
The physical properties, measured on the sediment cores (Fig. 21), appear to be controlled by textural differences and stratigraphy (sedimentary structures, vertical grain size trending). P-wave velocity decreases with increasing clay content (Fig. 22). Density and magnetic susceptibility values increase with the presence of gravel-size clasts or clusters of them. They also appear to be controlled by effects in two main macrofabric features: textural trend (vertical trending of grain size) and sedimentary structures (e.g. parallel and cross laminations). From a quantitative point of view, the statistical correlations found between textural and physical properties cannot explain some particular trends. This may imply that a secondary data set (e.g., microfabric, mineralogy, chemical activity, biological activity, or mechanical processes) is necessary to explain and understand variations in the physical properties.
Consolidation and shear strength properties are similar in all cores. Sediments in the Bransfield Basin are normally consolidated, except for slope core TG3, where lightly overconsolidation condition can be considered (Table 1). This overconsolidation results from the occurrence of mass wasting processes, a dominant process on the Bransfield slope (Ercilla et al., 1998; García et al., 2009). The loss of about 9 m of sediment overburden is suggested as the most probably cause. According to the stability under gravitational loading

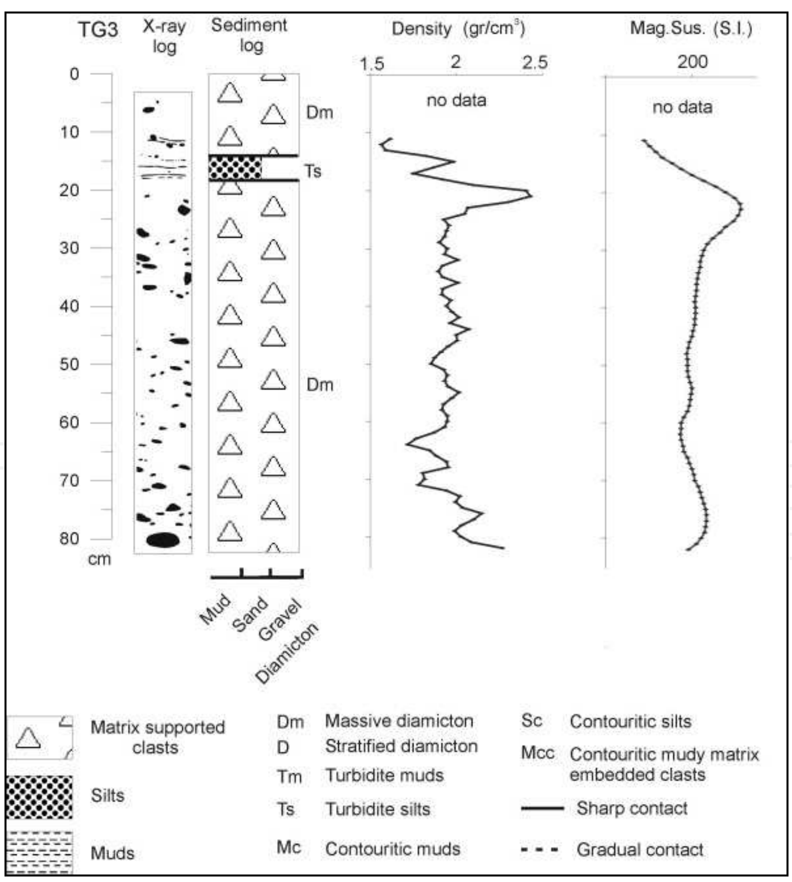

Fig. 21. X-ray log, sediment log, density and magnetic susceptibility records for the slope core TG3. From Casas et al. (2004).

concepts we can establish that the present slope with a maximum gradient of 20º is stable. This data is important because it could explain why the slope, as others in high latitudes are relatively steep with high gradients even when they have a sedimentary control. Nevertheless, different instability features have been seismically observed or deducted from the consolidation tests. To explain their presence we have to resort to external triggering since all sediments studied are stable by themselves.

Based on the geologic and oceanographic framework, volcanic activity, glacial loading-unloading, bottom currents and earthquakes are the triggers considered as potential mechanisms to induce sedimentary instability. Active mid-ocean ridge basalt volcanism characterizes the central Bransfield Basin (Gràcia et al., 1996). Volcanic emplacement may have caused earthquake shacking, triggering instability processes on the studied area. Ice sheet loading on a continental shelf may induce far-field pore-pressure effects (Mulder and Moran,1995), and the isostatic rebound related to the retreat of glacial loading could produce a crustal uplift with a probable influence on the instability processes (Anderson, 1999). Bottom-current-related processes have played a role in the most recent sedimentary history of the basin, favouring the formation of contourite drifts and associated moats (Fig. 23) at the foot of the continental slope (Ercilla et al. 1998). The formation of a moat at the foot of a slope as a consequence of an erosive current could become a trigger to initiate instability processes on the adjacent slope. Nevertheless the Bransfield Basin is considered to be a zone with moderate seismic activity with earthquake magnitudes varying between 4.8 and 6 (Ibáñez et al., 1997). Infrequent strong earthquakes with magnitudes greater than 6 can be tentatively considered as a major mechanism for instability features (Baraza et al., 1990). Likewise, the high activity of weaker earthquakes (Mb 2-4) registered in the area (Robertson et al., 2001) could be taking into account because they can reduce the sediment shear strength (Hampton et al., 1996).

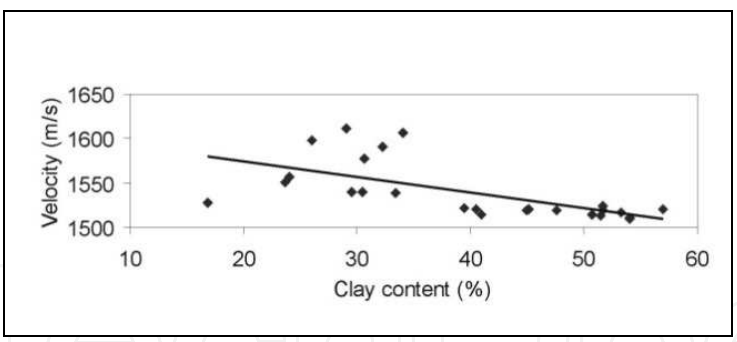

Fig. 22. Comparison of P-wave *vs* clay content. Vp = 1608-1.75 ∗ (% clay). From Casas et al. (2004).

Core	Depth (cm)	Density (gr/cm3)	OCR	σ′e
TG2	85	1.35	9.435	22.9
TG2	140	1.70	2.660	15.3
TG3	55	1.88	16.323	70.5
TG4	74	1.81	4.639	20.8
TG29	95	1.54	5.673	22.6

Table 1. Results of incremental consolidation tests. Legend: OCR (over consolidation ratio); σ'_e (excess maximum past stress).

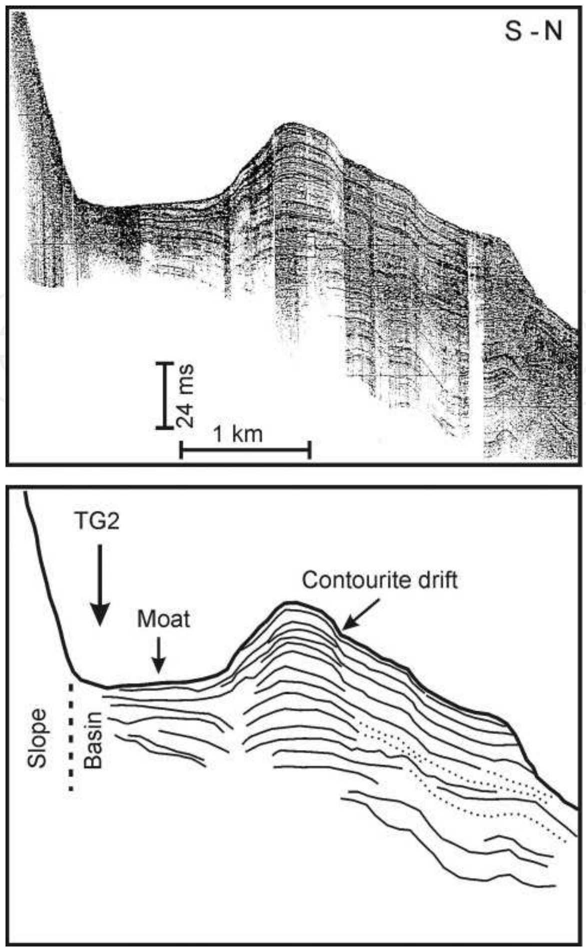

Fig. 23. Seismic profile illustrating the presence of a contourite drift and the associated moat at the foot of slope. Modified from Ercilla et al. (1998).

3. Contributions from multidisciplinary and multiscale analysis of mass-movement features and deposits

Each of the above case studies has been focused in one specific topic related to mass-movement processes and their resulting sedimentary products. They also represent multidisciplinary and multiscale approaches in different geological contexts. The integration of different study techniques is not an easy task because they have differences in relation to study scale, resolution and volume of data. In addition, commonly it must be considered the limited availability of the full range of data due to their economic cost or lack of technical and scientific development. Although this constraint, the overall integration of the main results obtained from the case studies give important inputs for the knowledge of submarine mass-movements:

Contribution 1. Characterization of a continental margin and historic register of submarine mass-movement features observed in a continental slope: The geologic characterization of a continental margin offers information about the potential key factors that may affect to sedimentary instability. The genesis of morpho-sedimentary and morpho-structural features or fluid dynamic in sediments can also explain the presence of mass-movements in an area surrounded by stable sediment. The study of continental margin also allows assessing the role played by mass-movements in the sediment transfer to deep sea areas as well as shaping the seafloor.

The complexity of failuring styles and evolution of sedimentary instabilities as well as the identification of triggering mechanisms require the joint analysis of all those geological parameters that characterize the area of study. In this sense, the above case studies establish that continental margin geological characterization provides information on those critical factors that can affect the stability of continental slope (bottom and sub-bottom), and allows defining essential key quantitative and qualitative parameters in the indirect study of the mass-movements. These parameters can be divided into five main groups, which comprise those critical factors to consider in any detailed analysis of seafloor and subbottom stratigraphy:

1. Physiographic parameters: gradients; width; water depth; type of boundaries between physiographic domains (sharp, gradual).
2. Morphologic parameters of mass-movements deposits (both plan view and dimensions): plan view and cross-sections shape measurements; water depth extension; curvature and/or irregularities of the downslope concavity of the scar and downslope convexity of the distal end of the slide; offset of the scar and lateral variations; seafloor relief.
3. Sedimentary parameters of mass-movements deposits: internal acoustic facies and their vertical and lateral variations; slide planes and their morphoacoustic characteristics in their both expression, plane or level; presence o lack of tensional depression; type of the distal end of the slide, frontal confined or unconfined.
4. Surrounding unfailed sedimentary systems: acoustic and seismic facies; sedimentary structure; growth pattern.
5. Deformational features of mass-movements deposits and surrounding unfailed sediments: structural, as folds and faults; fluid (water and gas)-dynamic features, and their lateral and vertical distribution.

On the other hand, the regional study of distribution, size and morphology of submarine sedimentary instabilities is also important to assess their effect on the slope sedimentary systems and their role as a mechanism to shape continental margins. Furthermore, they provide criteria for understanding the direction of travel, which is roughly perpendicular and sub-perpendicular to bathymetry. When quantifying the number of submarine mass-movements in terms of depth, it appears that they are more abundant on continental slope (Pratson and Laine, 1989, Booth et al., 1993). The case studies 2.2, 2.3, 2.5 and 2.7 also enable broadly to define two main areas on the continental slope: an evacuation or depletive area and a depositional or accumulative area. Depletive area is characterized by thinning of the sliding deposits, tensional structures, outflowing escape features, and formation of erosional surfaces such as canyons, gullies and scars. That is, upper slope are areas where erosive gravitational features predominate. The accumulative area is characterized by depositional features such as debrites, mass flow deposits, levees bordering channles, turbidite boulding up depositional lobes and the presence of compressional structures, and even outflowing escape features.

Contribution 2: Understanding the dynamics of failures: Regional studies of mass-movements indicate that similar sediments show differences in the potential stability and behavior. Distribution and variability of mass-movements and their related triggering should be studied individually in order to determine the local conditions of failure events. One way to explain differences is through the integration of the geotechnical models with the morphologic and sedimentary observations on seismic records.

Mass-movement is a common process in different margins, both in submarine canyons and open slope environments (e.g., case studies 2.2, 2.3, 2.6, 2.7). Seismic analysis offers indirect observations of the tectono-sedimentary framework where the mass-movement features occur and how we see them, being able to define slide plane, internal pattern, scale of failure, slide geometry, run-out distances, etc. Among the mass-movement deposits identified through the case studies, the Baraza Slide (Alboran Sea) and Torreblanca Slide (Ebro margin) are the best features for defining the sediment dynamics and their evolution.

On the basis of its well-defined morphology, geometry, internal pattern, and the vertical trend of the seismic facies and surfaces, the sediment dynamics and evolution of the Baraza Slide is defined by three stages: metastable, flowing, and sliding (Fig. 24). The flowing stage began when the metastable equilibrium was broken and occurred when the downslope-oriented shear stress exceeded the shear strength, resulting in the development of an instability plane within the stratified slope deposits. The sliding stage occurred when the Baraza Slide was reactivated with a different instability mechanism: a slide-type movement. This movement affected both the buried mass-flow deposits and the overlying sediments, which moved with a shear-dominated movement along the plane of the scar.

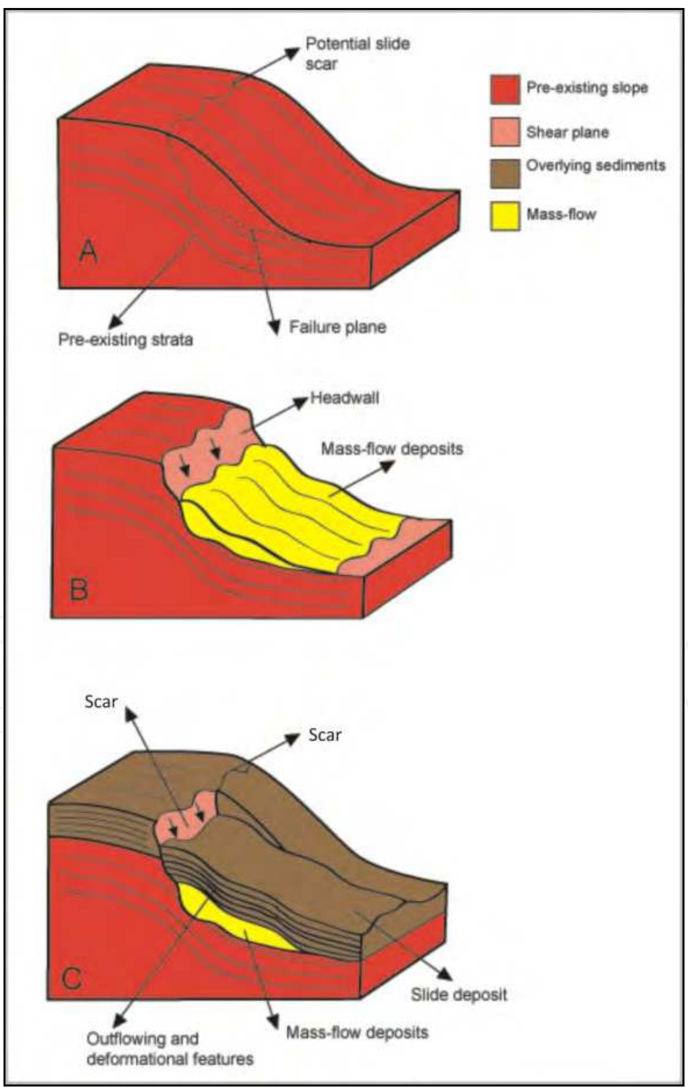

Fig. 24. Evolution of the Baraza Slide. Modified from Casas et al. (2011).

Regarding the dynamics of Torreblanca Slide its geometry and internal pattern allow defining its evolution in four stages: metaestable, triggering, sliding and stopping stages (Fig. 25). During the initial moment the slope was in metastable equilibrium mainly governed by downslope gravitational forces. Under this equilibrium some bedding planes acted as a zone of weakness. This is suggested because the subsequent shear plane is subparallel to older strata and is roughly parallel to the regional slope. The triggering stage occurred when the downslope-oriented shear stress exceeded the shear strength, resulting in the development of an instability bed within the stratified slope deposits. The initial combined rotational and horizontal displacement evolves to the sliding stage with a tensional regime which was responsible of the extensional features observed along the moving sediment package. The stopping stage began when the downslope-oriented forces decreased because the action of friction along the shear plane. The slowing of the motion produced a compressional regime which was responsible of the formation of compressional deformation on the toe of mass movement.

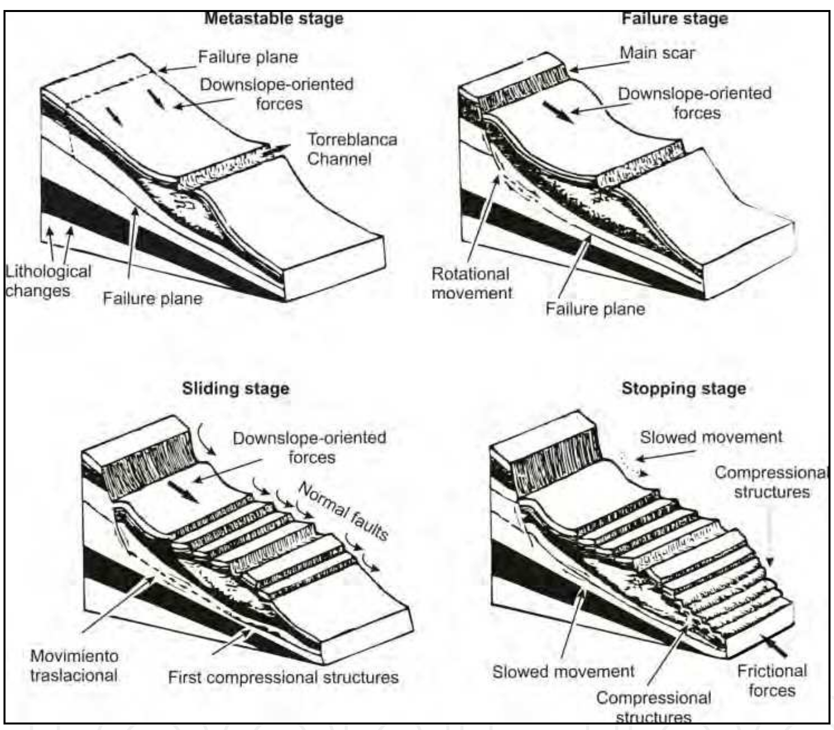

Fig. 25. Evolution of the Torreblanca Slide. Modified from Baraza (1989).

Seismic analysis offers a concise description of the dynamics and evolution of instabilities. Although mass movements present diverse behavior during the failure and post-failure (re-activation) stages even for sediments *a priori* equivalents. This is still a non-well known point. The deep understanding of this behavior must involve the geotechnical analysis. The case study from the Antarctica Peninsula slope highlighted the effort integrating seismic and geotechnical measurements. Another example can be drawn from the Ebro slope if we contrast our observations with a geotechnical model done by Baraza et al. (1990) based on surficial cores (<3 m long) on the central and southern sectors of that slope.

This model defines two different areas on the basis of physical and geotechnical properties: the upper slope (<500m) and the lower slope (>500m). On the upper slope, prodeltaic mud with high silt content is dominant. The average water content is 33% dry weight, slightly below the liquid limit, which is about 34%. The plasticity index is about 15% and the sediment is highly to moderately overconsolidated (OCR as high as 8).On the lower slope predominates hemipelagic. In addition, the water content is higher than in the upper slope (approaching 90%) and is above the liquid limit (ranging from 55 to 75%), the plasticity index is higher and the degree of overconsolidation is lower (OCR 2-3). Normalized strength parameter S (ratio of strength to consolidation stress) for normal consolidation are both lower, whereas the cyclic strength degradation factor (Ar) is higher than that of the upper slope. According to the geotechnical results, the upper slope deposits are slightly more stable under undrained static loading conditions while the lower slope is more stable under drained or very long term static conditions. Maximum slopes in Ebro area appear to be stable under static (gravitational) loading. Following this model nevertheless, localized instability might be produced between 200 and 700 m depth by a combination of oversteepening (5º and 10º) and infrequent, intense seismic loading.

The proposed geotechnical zonation could explain why most of debris flow deposits are concentrated in the lower slope, since there the sediment has a higher plasticity than the sediment in the upper slope (Casas et al., 2003c). Likewise, the geotechnical zonation could help to understand why the large scale slides have their scars on the upper slope; this is because between 200 and 700 m water depth the slope would the more susceptible area to failure triggered by seismic loading. But this model is certainly insufficient to explain the variability of settings, types, scales, and geometries of the mass movement features as well as depositional environments where they occur. This fact suggests that the distribution and variability of mass movement features and their probable triggering mechanisms should be studied individually from a geotechnical point of view in order to know local conditions of stability or failure. This proposed approach may be a good way to know why one region of seafloor remains intact whereas the neighbouring sector fails and why it fails in the way that it does. Likewise, in-situ geotechnical measurements (i.e. shear strength and pore pressures) could represent an important boost to better understand of submarine mass movements.

Contribution 3: The need of knowing the physical parameters: The physical properties are important for slope instability analysis because they offer basic information about sediment type and are necessary in the assessment of the potential stability of a slope area. Our studies suggest that sediment fabric is a key feature for the physical properties, and the mineralogical properties have a more relevant effect in the absolute value of those properties.

The continuous and high-resolution log of physical properties (basically bulk density, P-wave velocity and magnetic susceptibility) of marine sediments are important to understand the different sedimentary environments and the geological events that occur in them. Different studies have focused on the relationship between physical properties and textural parameters of marine sediments, since they depend largely on lithology, grain size and composition. The bulk density for example, is related to porosity and grain density but is also partially controlled by the grain size. P-wave velocity is controlled by the porosity, carbonate content or clay minerals. Magnetic susceptibility relates to the sediment composition and then changes in magnetic susceptibility can be important parameters to obtain information about sediment provenance, palaeoclimate, bottom-water flow conditions and regional stratigraphy. The physical properties are strongly influenced by diagenetic processes, such as the decrease of porosity by compaction, cementation or dissolution of carbonate. These properties also provide useful information related to geotechnical properties which are essential in estimating the stability of a particular area.

The physical properties obtained in our case studies have allowed us to study in detail the stratigraphy, vertical trends in cores and their lateral correlation. It has been useful also for refining the characteristics of the sediments described as well as into the stability assessment.

The knowledge or definition of one type of sediment exclusively from its physical properties is a complex exercise. The problem arises because in practice, the physical properties depend on many variables which in turn are interrelated in complex ways. We are therefore in front of a multi-variable problem, mathematically complex and do not have a single solution. But it is possible to state different statistically acceptable relationship between physical properties and sediment variables. These relationships are not constant, and depend largely on the characteristics of each type of sediment (geological environment). There are patterns in the records of density, magnetic susceptibility and P-wave velocity associated with the "style" of sedimentation. This can be observed on relatively similar records of cores recovered from the slope of the Antarctic Peninsula and the Anaximander mud volcanoes. In both cases the "style" of diamicton (glacial-marine origin) and the mud breccia (volcanic origin) is similar and contrasts with strictly marine sediments (e.g., turbidites). Obviously the diamicton and mud breccia have a completely different genesis, and their composition is not at all comparable. But they have in common to be sediment matrix containing clasts of various sizes and shapes. It thus appears that sediment fabric is of key importance in the physical properties and the mineralogical composition have a significant effect on the absolute value of these properties.

In our case studies where marine processes dominate, physical properties are basically controlled by the consolidation (compaction of the sedimentary column) with differences of minor order that roughly correspond to lithological changes. Besides that in cores with deposits associated to glacio-marine and mud-volcanism processes, the physical properties seem to be controlled by sediment characteristics; the effect of consolidation, if observed, is secondary.

Contribution 4: Forces controlling triggering of mass-movements: Destabilizing forces and processes that can trigger mass-movements depend on both geologic regional factors and specific processes of sedimentary environments. The characterization of revelant, pre-disposition and trigger factors could provide a good approach for defining and mapping the instability hazard.

The destabilizing forces and processes that originate the mass-movement deposits presented in the different case studies depend on both the regional framework and local factors. Both condition particular processes for each sedimentary environments. The characterization of revelant, pre-disposition and trigger factors could provide a good approach for defining and mapping the instability hazard (Leroueil et al., 1996). The revelant factors are evidences, for example, of previous mass movement, creep etc. The pre-disposition factors are those conditioning the stability of a slope. The trigger factors are the processes that effectively cause one mass movement (Table 2).

The spatial distribution, variability, types of mass movement deposits and their evolution in the Ebro and Alboran continental slope are influenced by independent factors. These factors include unequal contribution of sediment, the failure frequency, thickness of the affected sediment, slope gradients, and proximity to the epicenters of earthquakes. Relatively high slopes present in the Ebro (2.5º to 5.8º) and Alboran (3º to 3.5º) continental slopes and the rapid deposition directly onto the upper slope during periods of lowstand stages of sea level were probably the main conditioning factors destabilizing the slope. The high sedimentation rate is responsible of sub-consolidation sediments and their consequent decrease in shear strength. These elements are probably the main predisposing factors, however, failure could have been triggered by seismic shaking (or by tectonic-related activity), and also by bottom currents in the Alboran slope (Ercilla et al., 2011). The potential link between high slope gradients, under consolidation, earthquakes, and instability along continental margins has been discussed by numerous authors (e.g., Hampton et al. 1996).

Factors	Ebro	Alboran	Cádiz	Anaximander	Bransfield
Predisposition	Tectonics Sedimentation rates Slope gradients Lithostatic load	Tectonics Sedimentation rates Slope gradients Lithostatic load	Gas and gas hydrates in sediments Tectonics	Gas and gas hydrates in sediments	Seismic activity
Trigger	Lithostatic load ? Earthquakes Storms Internal waves	Lithostatic load? Earthquakes Storms Internal waves	Gas Tectonic movements		Volcanic activity Earthquakes
Revelant	Previous instabilities	Previous instabilities	Pockmarks Diapirs	Previous instabilities	Previous instabilities

Table 2. Main conditioning factors for slope instability identified in the different case studies presented.

In the continental slope sediments of the Gulf of Cadiz, the area affected by mass movement deposits occurs in a domain with sediments containing free gas and then it is the critical element in sediment stability of an area. This presence of gas has been evidenced by acoustic turbidity and also "bright spots" features in seismic records. The presence of pockmarks and diapirs are revelant factors, whereas the presence of gas hydrate could be a predisposing factor, although its limited presence mainly associated to diapirs, suggests that the dissociation of these hydrates as triggering factor is not relevant. In the area of the Anaximander Mountains, as happens in the Gulf of Cadiz, the distribution of gas hydrate in the sediment appears to be limited, although in this case it occurs within the mud volcanoes and the southern flank of the Volcano Amsterdam. This suggests that although their presence can be considered a pre-disposition factor, its dissociation would not be a relevant triggering.

In the continental slope of the Antarctic Peninsula, contrasting with the continental margin of the Ebro, lithostatic load (sub-consolidation) is not a pre-disposition factor. Based on the geotechnical analysis results, the maximum slope measured in that area (20 º) would be stable according to the concepts of stability under static load (lithostatic) and then instabilities observed, could not be explained by characteristics of the sediment because they are stable themselves. Based on the geological framework: volcanic activity, bottom currents, tidal currents, glacial loading-unloading and/or earthquakes can be considered as triggering factors.

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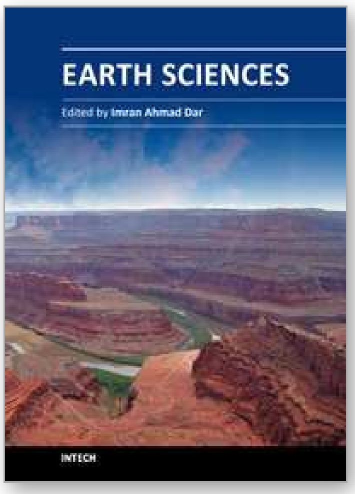

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The studies of Earth's history and of the physical and chemical properties of the substances that make up our planet, are of great significance to our understanding both of its past and its future. The geological and other environmental processes on Earth and the composition of the planet are of vital importance in locating and harnessing its resources. This book is primarily written for research scholars, geologists, civil engineers, mining engineers, and environmentalists. Hopefully the text will be used by students, and it will continue to be of value to them throughout their subsequent professional and research careers. This does not mean to infer that the book was written solely or mainly with the student in mind. Indeed from the point of view of the researcher in Earth and Environmental Science it could be argued that this text contains more detail than he will require in his initial studies or research.

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