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Galicia Bank sediment transport activity in response to continuous sedimentary instability dynamics: a geotechnical perspective

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Abstract

The sedimentary instability dynamics occurring over time throughout the isolated Galicia Bank (Atlantic Ocean, NW Iberian Peninsula) have been studied using a sedimentological and geotechnical approach featuring a quantitative assessment of slope stability under different scenarios, including earthquake activity. The erosion of the scarps defining the Galicia Bank includes the continuous development of small instabilities evacuated along gullies and channels or deposited around slopes. These deposits may be subsequently mobilized, evolving into a new instability (e.g., turbidity flow).

The studied sediments consist mostly of poorly to very poorly sorted sands and silts transported by turbidity currents and occasionally by debris flow processes. The sediments in the study area identified as normally

consolidated and located on small slope gradients may become unstable following low-magnitude seismic events. Even under static conditions, they could become unstable if they are located on slopes of $>10^\circ$ without any trigger other than oversteepening. In contrast, overconsolidated sediments on slopes of $>10^\circ$ may remain stable under static conditions and may become unstable when earthquakes occur with the maximum peak ground acceleration (PGA).

The sedimentological and geotechnical models presented herein are complementary approaches that can be utilized to understand the long-term sedimentary instability dynamics observed within the study area. These models are precursors to more sophisticated models yet indicate that low seismic activity can almost exclusively explain the instability of the observed deposits. Such results are critical for better understanding sedimentary models of the dismantling processes of deep seamounts located far away from continental sedimentary inputs.

Keywords: seamount, slope stability, marine sediment strength, geotechnical properties, earthquake, Galicia Bank

1 Introduction

Geotechnical investigations are infrequently yet effectively employed to better understand the evolution of marine sedimentary systems. The basic concepts of soil mechanics may be used to help comprehend, for example, the long-term erosion of isolated oceanic features such as seamounts that remain isolated from the processes that transport sediments from the continent (Wright 1996; Fryer et al. 1997; Wright et al. 2006; Chaytor et al. 2007).

Many contributing factors have been suggested for the initiation of processes that result in sedimentary instability; such processes include short-term triggers, such as earthquakes, and long-term or predisposing factors, such as high sedimentation rates or tectonic activity. Earthquakes contribute to slope failure due to the cyclic loading exerted on sediment by increasing the shear stress on the slope and decreasing the shear strength through the development of excess pore pressure (e.g., Locat and Lee 2002). High sedimentation rates can create a potentially unstable situation due to the generation of an undrained scenario, which can decrease the shear strength under clayey sediments (Sultan et al. 2004). Tectonic activity contributes to slope failure by increasing the shear stress (i.e., tectonic deformation can result in an oversteeping seafloor) and decreasing the shear strength (due to shearing, dilatancy and possible sediment creep). The clear link between sedimentary instability and earthquake/tectonic activity allows us to infer the evolution of the activity of tectonic structures by assessing the distribution and

occurrence of mass transport deposits (MTDs) recorded in different basin infills (Vizcaino et al. 2006; Alonso et al. 2014; Pérez et al. 2016, among others).

The Galicia Bank (Atlantic Ocean, NW Iberian Peninsula) represents an interesting geotectonic setting with which to discuss the occurrence of long-term erosion in deep marine environments. Despite being disconnected from continental sediment sources, erosion and mass transport in the form of channelized and unchannelized gravity flows constitute persistent processes that are widely observed throughout this region, where channel complexes are observed and MTDs and turbidites constantly reshape the slopes (Alonso et al. 2008; Ercilla et al. 2011; Casas et al. 2015). Therefore, the role of sediment transport processes in the ablation of this deep-sea environment is a key issue. Additionally, the controls that create and shape submarine channels without any external influence must respond to their long-term morphodynamic evolution and the continuous processes acting as triggers for the (hemi)pelagites draping this seamount. Furthermore, understanding how mass transport processes can affect channel infill deposits by reactivating channelized flows towards distal domains embodies another key point in the channel architecture (Vendettuoli et al., 2019).

The purpose of this study is to understand the role that mass transport has played in shaping the seafloor of the Galicia Bank seamount area. However, the proposed approach does not consider the role of the sedimentary architecture; rather, the approach is limited to the sediments, although the employed methodology will help to identify the sedimentary behaviour according to the energy available for triggering instabilities or remoulding deposits that may act as sources for subsequent mass wasting processes (Leroueil et al. 1996; Locat 2018). The main aim of this research is to explain the instability dynamics observed by combining interpretations derived from sedimentological, physical and geotechnical data obtained from sediment core samples and by simulating the slope stability under different conditions.

2 Regional setting

The Galicia Bank is located on the western Galicia continental margin (Atlantic Ocean, NW Iberian Peninsula) (Fig. 1a), which can be defined as a starved and non-volcanic passive margin (e.g., Montadert et al. 1974; Laughton et al. 1975; Dupeuble et al. 1976; de Charpal et al. 1978; Groupe Galice 1979; Sibuet and Ryan 1979; Boillot et al. 1979, 1986; Chenet et al. 1982; Olivet et al. 1984; Mauffret and Montadert 1988; Murillas et al. 1990;

Vázquez et al. 2008; Druet et al. 2018). Tectonism has favoured the development of a complex morphostructure along the western Galicia continental margin, wherein the Galicia Bank constitutes one of the most important structural seamounts (Fig. 1a). The Galicia Bank corresponds to a major horst exhibiting a slightly trapezoidal cartographic geometry (Mauffret and Montadert 1988) (Fig. 1.a and b) with two predominant NE-SW and NW-SE orientations (Vázquez et al. 2008; Maestro et al. 2018). Four distinct morphotectonic provinces were defined in the region of the Galicia Bank by Vázquez et al. (2008): the transitional zone, the half-graben domain, the northwestern flank, and the deep Galicia margin (Fig. 1c). These provinces collectively define the Galicia Bank region, a topographic bulge with a mountainous shape that extends from 620 m down to 5000 m water depth (mwd) and is bounded to the north and to the west by the Biscay and Iberian Abyssal Plains, respectively (Fig. 1a through c).

The general catalogue of seismicity along the Galicia continental margin displays earthquakes with a magnitude of < 5.6 mb (e.g., Engdahl and Villaseñor 2002; Custódio et al. 2015). In the Galicia Bank region, seismicity rarely exceeds a magnitude of 4, and the events occur at a depth of approximately 30 km (Veludo et al. 2017). However, considering a wider area (100 km to the NW), a 5.8 mb event was recorded in 2012 (Instituto Geográfico Nacional, 2015). The known epicentres of these earthquakes are usually located over structural features distributed roughly E-W that are associated mainly with the northern flank of the Galicia margin (Engdahl and Villaseñor 2002). In 2002, a dense deployment of 10 ocean bottom seismometers (OBSs) recorded data in the region of the Galicia Bank for 1 month, enabling the locations of three earthquakes of magnitude ≤ 2.5 mb to be ascertained (Ercilla et al. 2006; Díaz et al. 2008).

The results of recent high- and very high-resolution seismic studies define a Valanginian to Quaternary sedimentary register and a wide variety of morphotectonic and morphosedimentary features that reflect the interactions between downslope, alongslope, and vertical settling processes (Fig. 1b; Boillot and Malod 1988; Ercilla et al. 2006, 2011; Medialdea et al. 2008; Llave et al. 2008). The downslope processes mainly comprise mass transport (including turbidites and debrites), which affect large areas of this region (Fig. 1; Alonso et al. 2008). The alongslope processes are linked to the action of several water masses that flow at different depths and velocities and shape the seafloor with contourite features. Their bottom motion erodes, re-distributes and winnows the seafloor sediments of the Galicia Bank plateau, as well as those located around the numerous topographic highs and irregularities dotting the seafloor (Ercilla et al. 2011).

3 Materials and methods

Two sites, defined within channel infill deposits located in the deep Galicia margin and the transitional zone, were sampled (Fig. 1 and Table 1). At each site, two piston cores were recovered: one core was used for sedimentological analysis (K9S and K11S), and the other was employed for geotechnical testing (K9G and K11G). The latter cores were capped, wrapped in cheesecloth and coated with paraffin. A sedimentological and geotechnical model was developed, after which deterministic slope stability analyses were performed using the generalized limit equilibrium (GLE) method.

Numerous analyses, including grain size, sand fraction composition, carbonate content, water content, X-ray and physical property (i.e., bulk density using gamma ray attenuation and magnetic susceptibility) analyses, were carried out to define the main sediment types and sedimentary facies associations. Principal component analysis (PCA) and agglomerative hierarchical clustering (AHC) were performed to classify these sediments. Their geotechnical properties (AENOR, 1999), water content, Atterberg limits and bulk density were analysed in selected sections in conjunction with grain size analyses. The results allowed the classification of samples according to the Unified Soil Classification System (USCS) (ASTM D2487, 2011).

The compressibility of the sediments was determined by consolidation tests using a conventional oedometer. The undrained shear strength (S_u) was evaluated based on the results of the vane shear test, which was performed systematically at the top and bottom of all sections of each core. S_u was also estimated using the empirical relationship between the depth and overconsolidation ratio (OCR). The effective cohesion and effective friction angle were obtained from consolidated undrained (CU) triaxial tests performed using a GDS Triaxial Testing System (GDSTTS) with a 50-mm Bishop and Wesley cell. The triaxial device was manufactured by Global Digital Systems (GDS) Ltd. in the UK.

3.1 Slope stability

Slope stability analyses were carried out using the program Slide 8.0, Rocscience Inc. (2018), which is a 2-D limit equilibrium slope stability software program. The GLE method was employed to analyse the forces (or stresses) acting on an assumed failure surface. Then, the factor of safety (FS), defined as the ratio between the resisting shear strength and the sum of all mobilized shear stresses and calculated using Bishop's simplified method (Bishop 1955), was used to determine whether a slope is unstable ($FS \leq 1$) or stable ($FS > 1$).

Prior to performing the stability analysis, a sensitivity analysis was carried out to select the parameter that most strongly affects the FS (Saltelli et al. 2000, 2004; Hamm et al. 2006). Statistical mean, relative maximum and relative minimum values were assigned to each parameter involved in the analysis.

The slope stability analysis under drained and undrained conditions, including earthquake activity, was designed to assess the instability dynamics of sediment over time. The evaluation of slope stability under earthquake loading is commonly based on pseudostatic analysis (Leynaud et al. 2004). To implement this analysis using the GLE method, models include both horizontal and vertical static loads to simulate the inertias generated by the acceleration of earthquakes (Abramson et al. 2002). This method assumes that the pseudostatic forces generated by an earthquake (F_h : horizontal; F_v : vertical) remain constant over long periods of time (Hampton et al. 1996) and that their magnitudes are defined as follows (Kramer 1996):

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where a_h and a_v are the pseudostatic horizontal and vertical accelerations, respectively; g is gravitational acceleration; W is the load of the unstable mass that is mobilized; and k_h and k_v are the pseudostatic earthquake coefficients. F_h always decreases the value of FS, while F_v increases or decreases the FS depending on its direction since F_v acts on the normal stress and affects the shear strength along the failure surface. However, when studying submarine landslides, the vertical pseudoacceleration can be considered to be null (Urgeles et al. 2006; Sansoucy et al. 2007; Strasser et al. 2007; Zhang and Luan 2013).

4 Results

4.1 Physiography and core setting environments

The deep Galicia margin and transitional zone are mostly characterized by mass movement features (Fig. 1a; Ercilla et al. 2011). The transitional zone is additionally characterized by an irregular sloping seafloor with gradients ranging from < 0.5 to 3° and also presents gullies and channels that are evenly distributed across structural scarps and highs. The channels represent narrow valleys with U- and V-shaped cross-sections that exhibit sinuous to rectilinear pathways in plain view. Their dimensions are variable, as they range from 1.5 km to 90 km in length, several hundreds of metres to a few kilometres in width, and 15 m to < 150 m in relief with gradients ranging from $< 5^\circ$ to 22° . These channels appear as individual elements or form convergent radial drainage systems (Fig. 1b). At the

mouths of these channels, amalgamated bodies (< 10 m thick and up to several hundreds of metres long) that define the irregular seafloor are identified as MTDs (Ercilla et al. 2011).

In contrast, the deep Galicia margin is characterized by a smooth, relatively gentle surface (< 3° to < 1.5°) that dips towards the southwest and is dotted by highs. Two valleys oriented NNW-SSE and NE-SW erode the structural scarp defining the northern boundary of the province, which is approximately 20 km wide and exhibits gradients ranging from < 4° to 17° with relief ranging from 600 to 1800 m. Both the valleys and the entire domain are affected by MTDs, which are mainly associated with slide scars that are recognizable on the seafloor (Fig. 1b; Ercilla et al. 2011).

4.2 Sediment types and sequence features

The channel infill deposits of K9S and K11S yield three main grain size fraction percentages that define a rather homogeneous sedimentary texture ranging from silty sand to silt. The sediments are characterized by poor to very poor sorting, and the silt content ranges from 20 to 90%, although the mean values for K11S and K9S are 45% and 63%, respectively.

Based on the results of PCA, AHC, compositional analyses and qualitative observations (e.g., sedimentary structures), these textural groups can be interpreted as turbidites and debrites. The following seven types of turbidites have been identified: 1. biogenous sandy silts, 2. carbonate-rich sandy silts, 3. terrigenous-rich sandy silts, 4. biogenous silts, 5. carbonate-rich silts, 6. terrigenous-rich silts and 7. carbonate-rich biogenous silty sands (Table 2 and Fig. 2). Carbonate-rich silts (type 5) are predominant in core K9S, whereas carbonate-rich biogenous silty sands (type 7) and carbonate-rich sandy silts (type 2) dominate core K11S (Fig. 2). In all cases, the sand fraction is composed mainly of biogenic components, which comprise well-preserved or fragmented planktonic foraminifera. Only a few samples in both cores represent terrigenous-rich silts (type 6), and biogenous sandy silts (type 1) and terrigenous-rich sandy silts (type 3) are observed only in the coarser sedimentary facies of core K11S (Fig. 2).

The turbidites may represent a single deposit or may be attributed to one of the five main parts of a classic turbidite sequence (Ta to Te; Bouma 1962). The carbonate-rich sandy silts and biogenous silty sands may correspond to the Tb and Te divisions, respectively, of the Bouma turbidite sequence. Consequently, turbiditic deposits with average thicknesses of 10-30 cm in core K9S and < 20-40 cm in core K11S have been defined based on the following observations: 1) vertical sequences of lithofacies; 2) the presence of fining-upward sequences; 3)

changes in bioturbation; 4) coarse sand/silt basal laminae; and 5) vertical changes in physical properties (Figs. 2 and 3).

The debrites display textural and compositional characteristics that are similar to those defining the carbonate-rich biogenous sands/silts. Due to the observed characteristics of their sedimentary structures, such as subtle coarsening-upward sequences or convolute lamination (Fig. 2), they have been interpreted to be linked to plastic flow processes.

4.3 Physical and geotechnical properties

The results of analyses of both continuous and discrete physical properties (Fig. 3 and Table 3) yield a general range of variability for fine-grained deep-sea sediments (e.g., Casas et al., 2006; Alonso et al., 2014).

Atterberg limit testing was conducted for only three silty samples from core K9G and two samples from core K11G due to the non-plastic character of most sampled sediments. The results for K9G indicate an average liquid limit of 56.6 and a plasticity index of 14.6, while the results for K11G indicate a liquid limit of 49.2 and a plasticity index of 15.0. The sediment samples are therefore classified as MH-ML soils (i.e., silts of high-low plasticity).

Magnetic susceptibility (MS) measurements indicate that these sediments are generally low in magnetic minerals with background values ranging from approximately 0.8 (K9S) to $0.6 \cdot 10^{-6}$ (K11S) SI units punctuated by high-amplitude spikes that reach values as high as 23 to $90 \cdot 10^{-6}$ SI units (Fig. 3).

Continuous density measurements yield average values of 1.6 g/cm^3 in both cores. Their downcore density trends are also quite similar and exhibit considerable scatter due to fine-scale lithologic variations (Fig. 3). Despite the fact that the bulk density values obtained from discrete samples (Table 3) are generally slightly lower than those obtained from the multisensor core logger (MSCL), these results are consistent with the fact that sandy silt sediments have the highest densities (Fig. 3).

The effects of low progressive consolidation due to overburdening (i.e., increasing density, the expulsion of interstitial water and decreasing void ratios) can be observed in the downcore trends of the different properties measured here (Fig. 3). In core K9, this tendency seems to be more complex, showing consecutive intervals (i.e., 0 to 2.4 m from the top, 3.6 to 6.80 m, and 6.80 m to the bottom) over which the average density values increase downcore.

4.3.1 Compressibility and consolidation properties

Consolidation tests were used to estimate the following (Tables 3 and 4): the preconsolidation pressure (i.e., the maximum previous effective overburden pressure, σ'_p), the compression index (C_c , a measure of sediment compressibility), the recompression index (C_s , which is equivalent to C_c but during reloading stages), the present overburden pressure (in situ vertical effective stress, σ'_v), the overconsolidation ratio ($OCR = \sigma'_p / \sigma'_v$) and the overconsolidation difference ($OCD = \sigma'_p - \sigma'_v$).

The sediments in both cores exhibit high compressibility, being higher in core K9G ($C_c = 0.352$). Almost all values of the OCR are indicative of overconsolidation conditions (> 1); however, the high OCR values (> 10) obtained in the shallow subsurface samples (< 0.55 mbsf in core K9G; < 1.1 mbsf in core K11G) could be indicative of apparent overconsolidation (Hamilton 1964; Richards and Hamilton 1967; Silva and Jordan 1984; Bryant and Bennet 1988; Wetzel 1990; Sultan et al. 2000; Yenes et al. 2016).

Whereas core K11G is overconsolidated, core K9G is only slightly overconsolidated from 2.13 to 3.92 mbsf and is normally consolidated or slightly underconsolidated from 7 mbsf to the bottom (Table 4). This pattern is consistent with the variations observed in its density and porosity logs (Fig. 3). Additionally, the void ratios in core K9G progressively decrease, and its density progressively increases up to 6.8-7 mbsf; beyond this depth, a quantitative jump is observed that yields higher void ratios and, consequently, lower densities.

Sediment erosion due to the removal of overburden is the most likely cause of the overconsolidation observed in core K9G (from 2.13 to 3.92 mbsf) and core K11G (down to 1.1 mbsf). To evaluate this mechanism, the OCD values were converted into equivalent thicknesses of sediment (Edwards et al. 1987; Yenes et al. 2012). To calculate the excess sediment thickness, it is assumed that the preloading sediment has a submerged unit weight (γ') of approximately 6.1 kN/m^3 in core K9G and 5.2 kN/m^3 in core K11G. Dividing the OCD by this value yields the equivalent thickness of removed sediment; the resulting values range from 1.18 to 4.71 m in core K9G and from 12.40 to 17.87 m in core K11G.

4.3.2 Shear strength

The undrained shear strength values (S_u) determined using vane shear tests follow similar trends in both cores with undrained shear strength gradients (S_u) of 13.6 kPa/m for K11G and of 5 kPa/m for K9G. These values

are considered to be excessively high compared to those obtained using in situ testing methods carried out on this type of sediment (e.g., Locat and Lee 2002; Ai et al. 2014). Thus, the values of S_u were alternatively balanced using the empirical relationship between the depth and OCR (Ladd and Eggers 1972):

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Gradients of 3.14 kPa/m and 0.7 kPa/m resulted for cores K11G and K9G, respectively, using the mean values of the K_n and α constants (which are 0.3 and 0.8, respectively), as well as the mean OCR values (Table 4). These are common values for overconsolidated and normally consolidated or slightly underconsolidated sediments, respectively.

Strength parameters were obtained using triaxial tests in both cores following a strategy defined by their sedimentological and physical properties. For all test paths from K9G (Fig. 4), the samples exhibit contractional behaviour before failure, with their stress paths bending to the left. In this core, using Mohr circles to determine the effective cohesion (c') and effective friction angle (ϕ'), values of $c' = 0$ and $\phi' = 31^\circ$ were obtained in the upper intervals. The ϕ' value is reduced to 28.1° for deeper samples. In core K11G, the sedimentological composition and physical properties are more uniform, and therefore, its strength properties remain constant: $\phi' = 31^\circ$ and $c' = 0$.

5 Discussion: processes and slope stability

Together with terrigenous particles from the tectonic, chemical and physical weathering of structural scarps, planktonic foraminifera from hemipelagites and contourites represent the main sediment sources to be considered in this area (Ercilla et al. 2006; Alonso et al. 2008; Hernández-Molina et al. 2008; Mitchell and Lofi 2008). These sediments are later reworked and transported by channelized and unchannelized mass movement processes evidenced by the occurrence of shallow-seated failures across the entire area (Fig. 1; Ercilla et al. 2011) and the vertical stacking of turbidites and debrites described in this study. The exhumation and erosion of these scarps have favoured the development of gullies that evolve into channels that are linked down-dip to MTDs (Fig. 1). This suggests that the sediments located along (or atop) these steep scarps are continuously eroded by small slope failures and are efficiently evacuated along these channels. Beyond the turbidite record described in this work, similar deposits have also been previously defined in other domains. The frequency and prevalence of the emplacement of turbidites in the half-graben domain (Fig. 1) were established by Alonso et al. (2008), who defined frequencies ranging from approximately 1.2 ka to 3.1 ka in sediments dated between 31.3 ka and 9.1 ka.

The sediments defined in this work are characterized by poorly to very poorly sorted sandy silts to silty sands that are deposited as turbidites and debrites along channels or transported as erosive/channelized turbidity or debris flows to be deposited on distal domains. These sediments are also characterized by a range of properties associated with deep-sea sediments, such as high compressibility and contractional behaviour. Thin deposits (a few centimetres thick) and their relative textural and compositional homogeneity establish a type of uniformity in their physical and sedimentary properties. This homogeneity disappears when the stress history of the sediment changes, as in the case of site K9, where different intervals can be defined based on changes in its strength and consolidation state. This can be explained because turbidites are deposited along the channel or eroded and transported as erosive flows towards distal domains (Vendettuoli et al., 2019), as suggested by the overconsolidation associated with erosion caused by the removal of overburden recorded in both cores.

This homogeneity in the sedimentary processes and deposits, as well as the fact that they share the same source area, suggest that the sedimentary and geotechnical models for the K9 and K11 sites represent complementary approaches and serve as the first step towards understanding the evolution of instability dynamics in the Galicia Bank. Thus, a quantitative assessment of the slope stability was performed for different scenarios, including earthquake activity, following the models defined previously.

5.1 Slope stability analysis

Before carrying out the sensitivity analysis, it was necessary to determine the critical failure surface using deterministic analysis because the sensitivity analysis is performed on this critical surface. The results obtained showed that the critical failure surface under the drained condition model was the result of a very deep circular failure, whereas that under the undrained condition model was approximately parallel to the seafloor and was more similar to an infinite failure, such as the shallow-seated failures observed in this area (Ercilla et al. 2011; Fig. 1), than to a circular one.

5.1.1 Sensitivity analysis

The influences of different geotechnical parameters on the FS were calculated under undrained conditions (i.e., the unit weight, undrained shear strength at the top, undrained shear strength gradient and horizontal seismic coefficient) and for drained conditions (i.e., the unit weight, effective cohesion, effective friction angle and

horizontal seismic coefficient). The sensitivity analysis was performed using values that encompassed the entire range of variations observed in the two analysed zones (Table 5). To extrapolate these effects to different sedimentary domains, a 15° slope gradient was used in all cases, as is common throughout the studied areas.

The results of the sensitivity analysis under undrained conditions indicate that modelling yields a FS that is slightly higher than unity; therefore, any variations in these conditions (e.g., the geometry of the slope, physical properties, or geotechnical parameters) approach the equilibrium limit of being able to cause instability. The gradient of the undrained shear strength with depth appears to be the most sensitive to slope stability, followed by the unit weight. If a horizontal seismic coefficient ($k_h = 0.19 \pm 0.15$) is included in the model, the FS generally drops by almost four points. The influence of the seismic acceleration on slope stability is comparable to that of the gradient of the undrained shear strength, although the influence of the latter is still higher.

The results of performing the sensitivity analysis under drained conditions indicate that the effective friction angle is the most influential, followed by the unit weight. In all simulations, the effective cohesion has little to no influence on slope stability. These sensitivity analyses yielded high FS values, indicating that the generation of instabilities is unlikely under these conditions. Instability is still improbable even after introducing the effects of a pseudostatic load, which considerably reduces the FS.

Consequently, most of the instabilities in this area occurred under undrained conditions. This assumption is further supported by the fact that the analysed sediments have a fine fraction generally exceeding 40%, which indicates that their hydraulic conductivity was low enough that slope breakage could occur only under undrained conditions (Sansoucy et al. 2007).

5.1.2 Slope stability analysis under static conditions

Under static conditions, the factor that triggers instabilities is exclusively gravity, which can be linked mainly to changes in the slope geometry caused by erosion or sediment accumulation.

Following the sensitivity analysis, changes in the FS under undrained conditions with changes in the slope geometry (ranging from 5° to 50°) and the vertical undrained shear strength gradient were analysed (Fig. 5a). The area from which core K11G was recovered is characterized by slope gradients ranging from < 5° to 22°; there, overconsolidated sediments with an estimated S_u value of 3.14 kPa/m were sampled. Therefore, the stability analysis indicates that the sediments of core K11G should be stable under static conditions (Fig. 5a). On the other

hand, the area from which core K9G was recovered features slope gradients ranging from $< 4^\circ$ to 17° and is characterized by normally consolidated or even slightly underconsolidated sediments with an estimated S_u value of 0.7 kPa/m. The stability analysis results indicate that the sediments in this setting could be unstable if the slope exceeds 10° (Fig. 5a). Thus, only potential oversteepening ($> 10^\circ$) in normally consolidated or underconsolidated sediments can be considered a threat.

For the improbable case of failure under drained conditions, the slope gradient was modified from 5° to 30° to determine how it affected the FS (Fig. 5b). In core K9G, in which an average effective friction angle (ϕ') of 29.5° was measured, gravitational instabilities could occur for slope angles as high as 28° . For core K11G, in which $\phi'=31^\circ$, this type of instability would require slope gradients greater than 29° (Fig. 5b). Such inclinations were not measured in either of the two sampled areas; thus, failure is unlikely to occur under drained conditions.

On the other hand, the physical properties of the sediments at site K9 vary between 4 and 7 mbsf, indicating a change from slightly overconsolidated sediments to normally consolidated or even slightly underconsolidated sediments. This change also implies that the strength parameters obtained in the triaxial tests are modified with a range from $\phi'=31^\circ$ for superficial sediments to 28.1° for deeper sediments. Reproducing these conditions in the slope stability analysis model (i.e., a heterogeneous slope with a 7-m thick layer of higher strength) allowed us to determine that these conditions are always more unstable than homogeneous ones (Fig. 6). In both cases, the slope will become unstable ($FS < 1$) at inclinations higher than 27.5° . The maximum reduction in the FS occurs for slopes of $< 10^\circ$ (reduction of 13% for 5°) and reaches a constant reduction of 4% for slopes of $> 10^\circ$.

5.1.3 Slope stability analysis under earthquake loading

To perform a stability analysis during an earthquake, only undrained failure conditions were considered since the cyclic load produced by a seismic shock is exerted rapidly enough to prevent the excess interstitial pressure generated in these fine- to medium-grained sediments from dissipating (Strasser et al. 2007).

The FS under undrained earthquake loading conditions was calculated using pseudostatic analysis. This method generates uncertainties because it does not take into account factors such as the degradation of soft clays, the accumulation of plastic strain or the shear-induced excess pore water pressure with increasing numbers of cycles (Biscontin et al. 2004; Sultan et al. 2004). However, this approach can be used as a first approximation to determine which factors are involved in the stability of an area that is subjected to seismic loads, and thus, this technique has

been widely applied (Seed et al. 1985; Hampton et al. 1996; Nixon and Grozic 2006; Urgeles et al. 2006; Sansoucy et al. 2007; Strasser et al. 2007; Zhang and Luan 2013).

The parameters considered in this pseudostatic analysis were the seismic acceleration and the vertical gradient of S_u based on the sensitivity analysis results. The changes in the FS associated with changes in the slope geometry (i.e., gradients ranging from 5° to 50°) were evaluated (Fig. 7) to compare these results with those of the static analysis (Fig. 5a).

A maximum PGA of 0.34g was calculated using regional seismicity data up to the maximum magnitude (5.8 mb) and the empirical seismic attenuation relationship defined by Campbell and Bozorgnia (2008). For pseudostatic stability analysis, the selection of an earthquake coefficient (k_h) is also critical (Melo and Sharma 2004). Based on the methods proposed by Hynes-Griffin and Franklin (1984) and Leynaud et al. (2004), the value of k_h in the study area is 0.17 or one-half of the PGA.

A seismic shock considerably decreases the FS; nevertheless, the FS does not experience a linear reduction, as the outcome depends on the slope geometry. As a result (Fig. 7), when the PGA reaches a maximum value (0.34g), instabilities affecting the overconsolidated sediments of the transitional zone (core K11G), which yield a S_u value of 3.14 kPa/m, would be produced for slopes of > 10°. In the case of the normally consolidated sediments of the deep Galicia margin (core K9G), which yield a S_u value of 0.7 kPa/m, instabilities would be produced for slopes of < 5°.

5.2 Sedimentary instability dynamics and their implications

The analysis of diverse sedimentary records indicates that the large volumes of turbidites in the distal areas of continental margins exhibit stochastic temporal distributions linked to sedimentary instabilities and their evolution (e.g., Clare et al. 2014; Talling et al. 2014). Other cases suggest that sea level is a dominant control influencing slope stability and can affect, for example, the frequency of canyon-filling turbidity currents (Vail et al. 1977; Shanmugam and Moiola 1982; Owen et al. 2007; Lee 2009; Casas et al. 2013). In the context of the Galicia Bank region, characterized by low sedimentation rates and no continental inputs (Rey et al. 2008), different landslide triggers or sequential combinations of processes that are not influenced by glacio-eustatic sea level variability must be established. The slope stability analysis presented above demonstrates that oversteepening and earthquakes represent the best trigger candidates for the long-term sedimentary instability dynamics that facilitated

the development of widely distributed open slope turbidites (e.g., apron-shaped bodies; Alonso et al. 2008) and channel networks in which eroded incisions are constantly being reshaped and evolving as cut-and-fill features. The susceptibility to large-scale landsliding of the Galicia Bank slope deposits is low because the instabilities in this area may occur under undrained conditions following a model of surficial/shallow-seated failures rather than a model of deep-seated failures.

The pseudostatic analysis performed here is associated with uncertainties (e.g., how earthquake accelerations evolve throughout the area), but the results indicate that the normally consolidated sediments located throughout the area on slopes as high as 5° are highly susceptible to developing instabilities when < 5 mb earthquakes occur. However, the maximum seismic intensity ($\text{PGA} = 0.34g$) used in these calculations is not required to trigger instabilities. A seismic shock decreases the FS, yielding a maximum reduction (85%) for gradients of $< 5^\circ$ (comparing Figs. 5a and 7); thus, modelling the response of a slope with a moderate gradient (5°) affected by increasing seismic accelerations allowed us to verify that low-magnitude seismic events may act as triggers in this area (Fig. 8). Normally consolidated sediments with a S_u of < 1 kPa/m can fail with a pseudostatic earthquake coefficient of 0.06 ($\text{PGA} = 0.12g$). In the case of overconsolidated sediments, which have a S_u of > 3 kPa/m, instability can occur with a horizontal acceleration coefficient of 0.15 ($\text{PGA} = 0.3g$). On slopes with gradients greater than 5° , it will not be necessary to reach these magnitudes to trigger instabilities.

Consequently, the results presented in this study indicate that the long-term sedimentary instability dynamics along the Galicia Bank could be explained by low-magnitude earthquakes (< 5 mb). To explain all the observations made in all provinces requires the use of more sophisticated geotechnical models and more representative samples; however, increasing the availability of fine-scale data such as those in this work enables sedimentary models to be applied in these deep sedimentary environments.

6 Conclusions

Merging geomorphological, sedimentological and geotechnical data allowed us to discuss the role that mass transport processes played in the recent sedimentary evolution of the Galicia Bank. Although this seamount is located far away from continental sedimentary inputs, an extensive channel network is draining the structural highs, particularly from the transitional zone and the deep Galicia margin. Channel infills and slope deposits are related to in situ or remoulded particles from the weathering of structural elements and (hemi)pelagites, which may act simultaneously as sources for subsequent mass-wasting processes. The sediments defined in this work are mostly poorly to very poorly sorted sandy silts and silty sands transported by turbidity currents and occasionally by debris flows. These sediments are characterized by a range of properties associated with deep-sea sediments. They are deposited as turbidites along these channels or are transported as erosive/channelized turbidity flows towards distal domains.

The long-term sedimentary instability dynamics in this area have been studied by quantitatively assessing the slope stability under different scenarios, including earthquake activity. The slope stability analysis performed under static conditions indicates that oversteepening (i.e., gravity) is a trigger for slope gradients of $> 10^\circ$. In these cases, gravity can be considered a threat in scenarios when normal consolidated sediments are involved. Under undrained earthquake loading conditions, the results show that normally consolidated sediments would be unstable on slopes as low as 5° after a 5 mb earthquake, while overconsolidated sediments would fail on slopes of $> 10^\circ$. Modelling the effects of earthquakes throughout the area indicates that low-magnitude seismic events ($PGA = 0.12g$) may act as triggers for normally consolidated sediments deposited on low-gradient slopes in the area (5°). Therefore, the long-term sedimentary instability dynamics observed along this margin can be explained almost exclusively by low-magnitude earthquakes (< 5 mb) and oversteepening.

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References

- Abramson LW, Lee TS, Sharma S, Boyce GM (2002) Slope Stability and Stabilization Methods, second ed. Wiley, New York.
- AENOR (1999) Standard Test Methods for Geotechnical Tests (Soils). Spanish Association of Standardization and Certification (*In Spanish*)
- Ai F, Kuhlmann J, Huhn K, Strasser M, Kopf A (2014) Submarine slope stability assessment of the central mediterranean continental margin: the gela basin. In: Krastel S, Behrmann J-H, Völker D, Stipp M, Berndt C, Urgeles R, Chaytor J, Huhn K, Strasser M, Harbitz CB (Eds.) Submarine Mass Movements and Their Consequences. Springer International Publishing, Heidelberg, pp 225–236
- Alonso B, Ercilla G, Casas D, Estrada F, Farrán M, García M, Rey D, Rubio B (2008) Late pleistocene and holocene sedimentary facies on the SW Galicia Bank (Atlantic NW Iberian Peninsula). Mar. Geol. 249: 46–63
- Alonso B, Ercilla G, Garcia M, Vázquez JT, Juan C, Casas D, Estrada F, D'Acremont E, Gorini C, El Moumni B, Farran M (2014) Quaternary mass-transport deposits on the north-eastern Alboran Seamounts (SW Mediterranean Sea). In: Krastel S, Behrmann J-H, Völker D, Stipp M, Berndt C, Urgeles R, Chaytor J, Huhn K, Strasser M, Harbitz CB (Eds.) Submarine Mass Movements and Their Consequences. Springer International Publishing, Heidelberg, pp 561–570
- ASTM D2487 (2011) Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International, West Conshohocken, PA
- Biscontin G, Pestana JM, Nadim F (2004) Seismic triggering of submarine slides in soft cohesive soil deposits. Mar. Geol. 203: 341–354
- Bishop AW (1955) The use of the slip circle in the stability analysis of slopes. Géotechnique 5: 7–17
- Boillot G, Auxietre J, Durand J, Dupeuble P, Mauffret A (1979) The northwestern Iberian Margin: a Cretaceous passive margin deformed during Eocene. In: Talwani M, Hay W, Ryan WBF (Eds.) Deep Drilling Results in the Atlantic Ocean: Continental Margin and Paleoenvironment. Maurice Ewing Series. American Geophysical Union, Washington, DC, pp 138–153
- Boillot G, Comas M, Girardeau J, Kornprobst J, Loreau J-P, Malod J, Mougénot D, Moullade M (1986) Fonds sous-marins basaltiques et ultramafiques au pied d'une marge stable. Résultats préliminaires de la campagne Galinaute (plongées du submersible Nautila à l'Ouest de l'Espagne). C. R. Acad. Sci. Gen. 303: 1719–1724

467 Boillot G, Winterer AL, Meyer AW (1987) Drilling on the Galicia margin: retrospect and prospect. *Proc. Ocean*
468 *Drill. Program Scientific Result* 103: 809–828

469 Boillot G, Malod J (1988) The North and North-West Spanish Continental Margin: a review. *Rev. Soc. Geol. Esp.*,
470 1: 295–316

471 Bouma AH (1962) *Sedimentology of Some Flysch Deposits: A Graphic Approach to Facies Interpretation*. Elsevier
472 Pub. Co., Amsterdam, NL

473 Bryant WR, Bennet RH (1988) Origin, physical, and mineralogical nature of red clays: the Pacific Ocean Basin as a
474 model. *Geo-Mar. Lett.* 8: 189–249

475 Campbell KW, Bozorgnia Y (2008) NGA ground motion model for the geometric mean horizontal component of
476 PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s.
477 *Earthq. Spectra* 24: 139–171

478 Casas D, Casalbore D, Yenes M, Urgeles R (2015) Submarine mass movements around the Iberian Peninsula. The
479 building of continental margins through hazardous processes. *Bol. Geol. Min.* 126: 257–278

480 Casas D, Ercilla G, Baraza J, Coakley B (2006) Physical properties and their relationship to texture and
481 consolidation effects in Pliocene-Quaternary sediments from Madeira abyssal plain. *Mar. Georesources*
482 *Geotechnol.* 24: 265–286

483 Casas D, Ercilla G, García M, Yenes M, Estrada F (2013) Post-rift sedimentary evolution of the Gêbra Debris
484 Valley. A submarine slope failure system in the Central Bransfield Basin (Antarctica). *Mar. Geol.* 340: 16–
485 29

486 Chaytor JD, Keller RA, Duncan RA, Dziak RP (2007) Seamount morphology in the Bowie and Cobb hot spot trails,
487 Gulf of Alaska. *Geochemistry, Geophysics, Geosystems* 8 (9): Q09016

488 Chenet P, Montadert L, Gairaud H, Roberts DG (1982) Extension ratio measurements on the Galicia, Portugal, and
489 Northern Biscay continental margins: implications for evolutionary models of passive continental margins.
490 In: Watkins JS, Drake CL (Eds.) *Studies in Continental Margin Geology*. AAPG, Tulsa, Oklahoma, pp. 703–
491 715

492 Clare MA, Talling PJ, Challenor P, Malgesini G, Hunt J (2014) Distal turbidites reveal a common distribution for
493 large (>0.1 km³) submarine landslide recurrence. *Geology* 42: 263–266

494 Comas M, Maldonado A (1988) Late Cenozoic sedimentary facies and processes in the Iberian Abyssal Plain, Site
495 637, ODP Leg 103. In: Boillot G, Winterer E et al. (Eds.) Proceedings of the Ocean Drilling Program,
496 Scientific Results. Ocean Drilling Program, College Station, TX, pp. 635–655

497 Custódio S, Dias NA, Carrilho F, Góngora E, Rio I, Marreiros C, Morais I, Alves P, Matias L (2015) Earthquakes in
498 western Iberia: improving the understanding of lithospheric deformation in a slowly deforming region.
499 Geophys. J. Int. 203: 127–145

500 de Charpal O, Guennoc P, Montadert L, Roberts DG (1978) Rifting, crustal attenuation and subsidence in the Bay of
501 Biscay. Nature 275: 706–711

502 Díaz J, Gallart J, Gaspà O, Ruiz M, Córdoba D (2008) Seismicity analysis at the prestige oil-tanker wreck area
503 (Galicia Margin, NW of Iberia). Mar. Geol. 249: 150–165

504 Druet M, Muñoz Martín A, Granja Bruña JL, Carbó Gorosabel A, Acosta J, Llanes P, Ercilla G (2018) Crustal
505 structure and continent ocean boundary along the Galicia continental margin (NW Iberia): insights from
506 combined gravity and seismic interpretation. Tectonics, Vol. 37 (5): 1576-1604

507 Dupeuble PA, Rehault JP, Auxietre JL, Dunand JP, Pastouret L (1976) Resultats de dragages et essai de
508 stratigraphie des bancs de Galice, et des montagnes de Porto et de Vigo (marge occidentale Iberique). Mar.
509 Geol. 22: 37–49

510 Edwards BD, Lee HJ, Karl HA, Reimnitz E, Timothy LA (1987) Geology and physical properties of Ross Sea,
511 Antarctica, continental shelf sediment. In: Cooper AK, Davey FJ (Eds.) The Antarctic Continental Margin:
512 Geology and Geophysics of the Western Ross Sea. Circum-Pacific Council for Energy and Mineral
513 Resources, Houston, TX, pp 191–216

514 Engdahl ER, Villaseñor A (2002) Global seismicity: 1900–1999. In: Lee WHK, Jennings P, Kisslinger C, Kanamori
515 H (Eds.) International Handbook of Earthquake & Engineering Seismology, Part A. Elsevier Science,
516 Amsterdam, NL, pp 665–690

517 Ercilla G, Casas D, Vázquez JT, Iglesias J, Somoza L, Juan C, Medialdea T, León R, Estrada F, García-Gil S, Farran
518 ML, Bohoyo F, García M, Maestro A (2011) Imaging the recent sediment dynamics of the Galicia Bank
519 region (Atlantic, NW Iberian Peninsula). Mar. Geophys. Res. 32: 99–126

520 Ercilla G, Córdoba D, Gallart J, Gràcia E, Muñoz JA, Somoza L, Vázquez JT, Vilas F (2006) Geological
521 characterization of the Prestige sinking area. Mar. Pollut. Bull. 53: 208–219

522 Ercilla G, García-Gil S, Estrada F, Gràcia E, Vizcaino A, Vázquez JT, Díaz S, Vilas F, Casas D, Alonso B,
 523 Dañobeitia J, Farran M (2008) High-resolution seismic stratigraphy of the Galicia Bank Region and
 524 neighbouring abyssal plains (NW Iberian continental margin) *Mar. Geol.* 249: 108–127
 525 Fryer P, Gill JB, Jackson MC (1997) Volcanologic and tectonic evolution of the Kasuga seamounts, northern
 526 Mariana Trough: Alvin submersible investigations. *J. Volcanol. Geotherm. Res.* 79: 277–311.
 527 Groupe Galice (1979) The continental margin off Galicia and Portugal: acoustical stratigraphy and structural
 528 evolution. In: Sibuet J-C, Ryan WBF (Eds.) Initial Reports of the Deep Sea Drilling Project. U.S.
 529 Government Printing Office, Washington, DC, pp 633–662
 530 Hamilton EL (1964) Consolidation characteristics and related properties of sediments from experimental mohole
 531 (Guadalupe site). *J. Geophys. Res.* 69: 4257–4269
 532 Hamm NAS, Hall JW, Anderson MG (2006) Variance-based sensitivity analysis of the probability of hydrologically
 533 induced slope instability. *Comput. Geosci.* 32: 803–817
 534 Hampton MA, Lee HJ, Locat J (1996) Submarine landslides. *Rev. Geophys.* 34: 33–59
 535 Hernández-Molina FJ, Llave E, Ercilla G, Maestro A, Medialdea T, Ferrin A, Somoza L, Gràcia E, Masson DG,
 536 García M, Vizcaino A, León R (2008) Recent sedimentary processes in the Prestige site area (Galicia Bank,
 537 NW Iberian Margin) evidenced by high-resolution marine geophysical methods. *Mar. Geol.* 249: 21–45
 538 Hynes-Griffin ME, Franklin AG (1984) Rationalizing the Seismic Coefficient Method, Miscellaneous Paper GL-84-
 539 13. US Army Corps of Engineers Waterways Experiment Station, Vicksburg, Mississippi.
 540 Instituto Geográfico Nacional, Spain (2018) Catálogo de terremotos. (accessed 20 February 2018)
 541 Kramer SL (1996) Geotechnical Earthquake Engineering. Prentice Hall, New Jersey, NJ
 542 Ladd CC, Edgers L (1972) Consolidated-Undrained Direct-Simple Shear Tests on Saturated Clays. Research Report
 543 R72-82, n° 284. Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, MA
 544 Laughton AS, Roberts DG, Graves R (1975) Bathymetry of the northeast Atlantic: Mid-Atlantic ridge to southwest
 545 Europe. *Deep Sea Res. Oceanogr. Abstr.* 22: 791–810
 546 Lee HJ (2009) Timing of occurrence of large submarine landslides on the Atlantic Ocean margin. *Mar. Geol.* 264:
 547 53–64
 548 Leroueil S, Locat J, Vaunat J, Picarelli L, Lee H, Faure R (1996) Geotechnical charaterisation of landslides. In:
 549 Senneset, K (ed.) 7th International Symposium on Landslides, Balerna, Rotterdam, 1: 53–74

550 Leynaud D, Mienert J, Nadim F (2004) Slope stability assessment of the Helland Hansen area offshore the mid-
 551 Norwegian margin. *Mar. Geol.* 213: 457–480

552 Llave E, García M, Pérez C, Farran M, Ercilla G, Somoza L, León R, Maestro A, Medialdea T, Hernández-Molina
 553 FJ, Álvarez R, Durán R, Mohamed K (2008) Morphological feature analyses of the Prestige half-graben on
 554 the SW Galicia Bank. *Marine Geology* 249(1-2): 7-20

555 Locat J, Lee HJ (2002) Submarine landslides: advances and challenges. *Can. Geotech. J.* 39: 193–212

556 Locat J (2018) Failure and post-failure analysis of submarine mass movements using geomorphology and
 557 geomechanical concepts. Geological Society, London, Special Publications, 477, 30 April 2018

558 Maestro A, Jané G, Llave E, López-Martínez J, Bohoyo F, Druet M (2018) The role of tectonic inheritance in the
 559 morphostructural evolution of the Galicia continental margin and adjacent abyssal plains from digital
 560 bathymetric model (DBM) analysis (NW Spain). *International Journal of Earth Sciences*, Vol. 107, Issue 4,
 561 pp 1267–1286

562 Mauffret A, Montadert L (1988) Seismic stratigraphy off Galicia (Spain). *Proc. Init. G Boillot, E.L Winterer, A.W*
 563 *Meyer, et al. (Eds.) Proc. Ocean Drill. Program Sci. Results*, 103 (1988), pp 13–30.

564 Medialdea T, Somoza L, León R, Farrán M, Ercilla G, Maestro A, Casas D, Llave E, Hernández-Molina FJ,
 565 Fernández-Puga MC, Alonso B (2008) Multibeam backscatter as a tool for sea-floor characterization and
 566 identification of oil spills in the Galicia Bank. *Mar. Geol.* 249: 93–107

567 Melo C, Sharma S (2004) Seismic coefficients for pseudostatic slope analysis. In: 13th World Conference on
 568 Earthquake Engineering, Vancouver, CA, August 1-6, 2004. Paper n° 369.

569 Mitchell NC, Lofi J (2008) Submarine and subaerial erosion of volcanic landscapes: comparing Pacific Ocean
 570 seamounts with Valencia Seamount, exposed during the Messinian Salinity Crisis. *Basin Res.* 20: 489–502

571 Montadert L, Winnock E, Delteil JR, Grau G (1974) Portugal and Bay of Biscay. In: Burk CA, Drake CL (Eds.) *The*
 572 *Geology of Continental Margins*. Springer Verlag, Berlin, Heidelberg, pp 323–342

573 Murillas J, Mougénot D, Boillot G, Comas M, Banda E, Mauffret A (1990) Structure and evolution of the Galicia
 574 interior basin (Atlantic western Iberian continental margin). *Tectonophysics*, 184: 297–319

575 Nixon MF, Grozic JL (2006) A simple model for submarine slope stability analysis with gas hydrates. *Nor. J. Geol.*
 576 86: 309–316

577 Olivet J, Bonnin J, Beuzart P, Auzende J (1984) Cinématique de l'atlantique nord et central. Rapp. Scientifique
578 Tech. 56: 108–112

579 Owen M, Day S, Maslin M (2007) Late Pleistocene submarine mass movements: occurrence and causes. Quat. Sci.
580 Rev. 26: 958–978

581 Pérez LF, Bohoyo F, Hernández-Molina FJ, Casas D, Galindo-Zaldívar J, Ruano P, Maldonado A (2016) Tectonic
582 activity evolution of the Scotia-Antarctic Plate boundary from mass transport deposit analysis. J. Geophys.
583 Res. 121: 2216–2234

584 Rey D, Rubio B, Mohamed K, Vilas F, Alonso B, Ercilla G, Rivas T (2008) Detrital and early diagenetic processes
585 in Late Pleistocene and Holocene sediments from the SW Galicia Bank inferred from high-resolution
586 enviromagnetic and geochemical records. Mar. Geol. 249: 64–92

587 Richards AF, Hamilton EL (1967) Investigations of deep-sea sediment cores, III. Consolidation, in: Richards, A.
588 (Ed.), Marine Geotechnique. University of Illinois, Urbana, IL, pp 93–102

589 Rocscience (2018) SLIDE 8.0-2D Slope Stability Analysis for Soil and Rock Slopes. Rocscience Inc Toronto,
590 Canada, CA

591 Saltelli A, Chan K, Scott EM (2000) Sensitivity Analysis. Wiley, Chichester

592 Saltelli A, Tarantola S, Campolongo F, Ratto M (2004) Sensitivity Analysis in Practice: A Guide to Assessing
593 Scientific Models. Wiley, Chichester

594 Sansoucy M, Locat J, Lee HJ (2007) Geotechnical considerations of submarine canyon formation: the case of cap de
595 creus canyon. In: Lykousis V, Sakellariou D, Locat J (Eds.) Submarine Mass Movements and Their
596 Consequences. Springer, Netherlands, NL, pp 221–230

597 Seed HB, Tokimatsu K, Harder LF, Chung RM (1985) Influence of SPT procedures in soil liquefaction resistance
598 evaluations. J. Geotechn. Eng. 111: 1425–1445

599 Shanmugam G, Moiola RJ (1982) Eustatic control of turbidites and winnowed turbidites. Geology 10: 231–235

600 Sibuet JC, Ryan WBF (1979) Initial Reports of the Deep Sea Drilling Project. U.S. Govt. Printing Office,
601 Washington, DC

602 Silva AJ, Jordan SA (1984) Consolidation properties and stress history of some deep sea sediment. In: Seabed
603 mechanics. Denness B (Ed) International Union of Theoretical and Applied Mechanics, pp 25–39

604 Strasser M, Stegmann S, Bussmann F, Anselmetti FS, Rick B, Kopf A (2007) Quantifying subaqueous slope
 605 stability during seismic shaking: lake Lucerne as model for ocean margins. *Mar. Geol.* 240: 77–97
 606 Sultan N, Cochonat P, Canals M, Cattaneo A, Dennielou B, Haflidason H, Laberg JS, Long D, Mienert J, Trincardi
 607 F, Urgeles R, Vorren TO, Wilson C (2004) Triggering mechanisms of slope instability processes and
 608 sediment failures on continental margins: a geotechnical approach. *Mar. Geol.* 213: 291–321
 609 Sultan N, Cochonat P, Dennielou B, Bourillet J-F, Savoye B, Colliat J-L (2000) Surconsolidation apparente et
 610 pression osmotique dans un sédiment marin. *C. R. Acad. Sci. Gen.* 331: 379–386
 611 Talling P, Clare M, Urlaub M, Pope E, Hunt J, Watt S (2014) Large submarine landslides on continental slopes:
 612 geohazards, methane release, and climate change. *Oceanography* 27: 32–45
 613 Urgeles R, Leynaud D, Lastras G, Canals M, Mienert J (2006) Back-analysis and failure mechanisms of a large
 614 submarine slide on the ebro slope, NW Mediterranean. *Mar. Geol.* 226: 185–206
 615 Vail PR, Mitchum RM, Thompson S (1977) Seismic stratigraphy and global changes of sea level, part 4, global
 616 cycles of relative changes of sea level. In: Payton CE (Ed.) *Seismic Stratigraphy - Applications to*
 617 *Hydrocarbon Exploration*. American Association of Petroleum Geologists Memoir 26: 83–97
 618 Vanney J, Auxière J, Dunand J (1979) Geomorphic provinces and the evolution of the northwestern Iberian
 619 continental-margin. *Annales del Institut Oceanographique* 55: 5–20
 620 Vázquez JT, Medialdea T, Ercilla G, Somoza L, Estrada F, Puga MCF, Gallart J, Gràcia E, Maestro A, Sayago M
 621 (2008) Cenozoic deformational structures on the Galicia Bank Region (NW Iberian continental margin).
 622 *Mar. Geol.* 249: 128–149
 623 Veludo I, Dias NA, Fonseca PE, Matias L, Carrilho F, Haberland C, Villaseñor A (2017) Crustal seismic structure
 624 beneath Portugal and southern Galicia (Western Iberia) and the role of Variscan inheritance. *Tectonophysics*,
 625 717: 645–664
 626 Vendettuoli D, Clare MA, Hughes Clarke JE, Vellinga A, Hizzet J, Hage S, Cartigny MJB, Talling PJ, Waltham D,
 627 Hubbard SM, Stacey C, Lintern DG (2019) Daily bathymetric surveys document how stratigraphy is built
 628 and its extreme incompleteness in submarine channels. *Earth and Planetary Science Letters* 515: 231–247
 629

- Vizcaino A, Gràcia E, Pallàs R, Casas D, Willmott V, Diez S, Asioli A, Dañobeitia J (2006) Sedimentology, physical properties and age of mass transport deposits associated with the Marques de Pombal Fault, Southwest Portuguese Margin. *Nor. J. Geol.* 86: 177–186
- Wetzel A (1990) Interrelationships between porosity and other geotechnical properties of slowly deposited, fine-grained marine surface sediments. *Mar. Geol.* 92: 105–113
- Wright IC (1996) Volcaniclastic processes on modern submarine arc stratovolcanoes: sidescan and photographic evidence from the Rumble IV and V volcanoes, southern Kermadec Arc (SW Pacific). *Mar. Geol.* 136: 21–39
- Wright IC, Worthington TJ, Gamble JA (2006) New multibeam mapping and geochemistry of the 30–35 S sector, and overview, of southern Kermadec arc volcanism. *J. Volcanol. Geotherm. Res.* 149: 263–296
- Yenes M, Casas D, Monterrubio S, Ercilla G, Nespereira J (2012) Geotechnical characteristics of sediments in Galicia Bank region. First results, in VIII Congreso Geológico de España. Oviedo. *Geo-Temas* 13: 529
- Yenes M, Monterrubio S, Nespereira J, Casas D (2016) Apparent over-consolidation in marine sediments, in IX Congreso Geológico de España. Huelva. *Geo-Temas* 16: 307–310
- Zhang L, Luan X (2013) Stability of submarine slopes in the northern South China Sea: a numerical approach. *Chin. J. Oceanol. Limnol.* 31: 146–158

Fig. 1 (a) Location and shaded relief map of the Galicia Bank region within the western Galicia continental margin (Atlantic Ocean, NW Iberian Peninsula) bounded to the north and to the west by the Biscay and Iberian Abyssal Plains, respectively. The locations of sites K9 and K11 are also displayed. The multibeam bathymetry dataset was mostly obtained with a Simrad EM12 Dual in the ERGAP project and complemented with multibeam data from the Spanish Exclusive Economic Zone (EEZ) provided by the Spanish Oceanographic Institute. These data are gridded to a resolution of 25 m. (b) Morphological features and deposits (modified from Ercilla et al. 2011). The locations of sites K9 and K11 are also displayed. (c) Morphostructural provinces of the Galicia Bank region (after Vázquez et al. 2008). (d) Locations of the sites in the topographic profiles

Fig. 2 Sediment core characterization; the lithology, sedimentary log and sediment types (i.e., turbidites and debrites) are indicated for cores K9S and K11S

Fig. 3 Physical and geotechnical properties of cores K9 (a) and K11 (b). Continuous lines: physical properties obtained using a multisensor core logger (MSCL) in sedimentological cores (K9S and K11S). Squares: discrete samples from geotechnical cores (K9G and K11G)

Fig. 4 $s'-t'$ path for all triaxial tests performed using samples from K9G

Fig. 5 (a) Failure under undrained conditions showing the effects of the undrained shear strength gradient and slope angle on the factor of safety. (b) Failure under drained conditions showing the effects of the internal friction angle and slope angle on the factor of safety

Fig. 6 Failure under drained conditions showing the changes in the factor of safety with the inclination on homogeneous and heterogeneous slopes

Fig. 7 Effects of the undrained shear strength gradient and slope angle on the factor of safety showing failure under undrained conditions with a maximum peak ground acceleration (PGA) of 0.34g

Fig. 8 Model of the response of a slope with a moderate gradient (5°) affected by an increasing seismic acceleration showing failure under undrained conditions with different values of the undrained shear strength gradient (S_u)

Table 1 Characteristics of the piston cores used in this study located in two physiographic provinces: the deep Galicia margin (DGM) (2000 to 5300 mwd) and the transitional zone (TZ) (1600 to 2500 mwd)

Table 2 Summary of the main sedimentological and compositional characteristics (in %) for each of the defined turbidity types: 1. biogenous sandy silts; 2. carbonate-rich sandy silts; 3. terrigenous-rich sandy silts; 4. biogenous silts; 5. carbonate-rich silts; 6. terrigenous silts; and 7. carbonate-rich biogenous sands

Table 3 Geotechnical properties. γ : unit weight; w : moisture content; e_o : void ratio; C_c : compression index; C_s : recompression index; S_u : undrained shear strength; c' : effective cohesion; ϕ' : effective friction angle

Table 4 Consolidation test results: preconsolidation pressure (σ'_p); compression index (C_c); recompression index (C_s); present overburden pressure (σ'_v); overconsolidation ratio ($OCR = \sigma'_p / \sigma'_v$); overconsolidation difference ($OCD = \sigma'_p - \sigma'_v$); thickness of removed sediment (OCD / γ')

Table 5 Statistical values for sensitivity analysis (i.e., mean value and relative maximum and minimum values): γ : unit weight; S_{ut} : undrained shear strength at top; S_{ug} : undrained shear strength gradient; c' : effective cohesion; ϕ' : effective friction angle; k_h : horizontal seismic coefficient

Figure 2

Figure 3

[Click here to access/download;Figure;Fig. 3.tif](#)

Figure 4

Figure 6

Figure 7

Figure 8

Table 1

CORE	LATITUDE (N)	LONGITUDE (W)	DEPTH (mwd)	CORE LENGTH (cm)	PHYSIOGRAPHIC PROVINCE	SLOPE GRADIENT (°)
K9S	42° 40.909′	12° 21.265′	4064	946	DGM	1.1
K9G	42° 40.917′	12° 21.265′	4092	850	DGM	1.1
K11S	42° 53.085′	12° 33.628′	2119	718	TZ	2
K11G	42° 53.036′	12° 33.592′	2118	761	TZ	2

Table 2

Lithofacies	Sandy muds			Sandy silts			Silty sands
Turbidite type	1	2	3	4	5	6	7
Sand	46	41	51	16	18	11	67
Silt	46	50	46	75	70	80	30
Carbonate	62	81	56	45	76	27	81
Biogenous	99	99	82	97	99	63	99
Terrigenous	1	1	18	3	1	37	1
Planktonic f.	10	17	10	23	23	10	15
Bioclastic	20	2	11	1	1	1	2

Table 3

PROPERTY	K9G							
	Physical properties			Compressibility		Shear Strength	Triaxial tests	
	γ (kN/m ³)	w (%)	e _o	C _c	C _s	S _u (kPa)	c' (kPa)	ϕ' (°)
Maximun	17.10	113.0	2.876	0.688	0.057	37.50	-	-
Average	15.90	82.0	2.120	0.352	0.034	21.27	0	29.5
Minimun	14.50	61.0	1.519	0.179	0.019	7.00	-	-
Nº of data	41	41	41	14	14	15	22	22

PROPERTY	K11G							
	Physical properties			Compressibility		Shear Strength	Triaxial tests	
	γ (kN/m ³)	w (%)	e _o	C _c	C _s	S _u (kPa)	c' (kPa)	ϕ' (°)
Maximun	16.2	91.4	1.470	0.245	0.017	64.00	-	-
Average	15.0	76.6	1.236	0.168	0.013	37.29	0	31
Minimun	14.3	62.8	0.865	0.103	0.009	13.00	-	-
Nº of data	13	20	13	7	7	7	7	7

Table 4

DEPTH (m)	σ'_p (kPa)	C_c	C_s	σ'_v (kPa)	OCR	OCD	OCD/ γ'
K9G							
0.22	29	0.292	0.025	1.34	21.61	27.66	4.53
0.52	69	0.453	0.031	3.17	21.75	65.83	10.79
0.55	45	0.309	0.030	3.36	13.41	41.65	6.83
2.13	37	0.339	0.025	12.99	2.85	24.01	3.94
2.77	24	0.563	0.057	16.90	1.42	7.10	1.16
3.25	34	0.392	0.034	19.83	1.72	14.18	2.32
3.56	42	0.310	0.030	21.72	1.93	20.28	3.33
3.65	51	0.688	0.057	22.27	2.29	28.74	4.71
3.92	42	0.339	0.039	23.91	1.76	18.09	2.97
7.10	32	0.381	0.046	43.31	0.74	-11.31	-1.85
7.96	36	0.179	0.019	48.56	0.74	-12.56	-2.06
8.07	52	0.185	0.021	49.23	1.06	2.77	0.45
8.23	38	0.290	0.032	50.20	0.76	-12.20	-2.00
8.26	40	0.202	0.025	50.39	0.79	-10.39	-1.70
K11G							
1.05	100	0.122	0.010	5.46	18.32	94.54	18.18
1.10	100	0.157	0.011	5.72	17.48	94.28	18.13
2.78	80	0.168	0.014	14.46	5.53	65.54	12.60
3.95	85	0.103	0.009	20.54	4.14	64.46	12.40
4.80	100	0.134	0.017	24.96	4.01	75.04	14.43
7.13	130	0.245	0.014	37.08	3.51	92.92	17.87
7.18	110	0.245	0.017	37.34	2.95	72.66	13.97

Table 5

	Mean	Rel. Max. / Min.
γ (kN/m ³)	15.5	± 1.6 (17.1/13.9)
S_u (kPa)	5	± 4 (9/1)
S_u (kPa m ⁻¹)	8	± 8 (16/0)
c' (kPa)	50	± 50 (100/0)
ϕ' (°)	33	± 10 (33/23)
k_h	0.19	± 0.15 (0.34/0.04)