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Geological characterization of the *Prestige* sinking area

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Abstract

The tanker Prestige sank off NW Iberia on the 19th November 2002. The stern and bow of the Prestige wreck are located on the southwestern edge of the Galicia Bank, at 3565 m and 3830 m water depths, respectively. This bank is a structural high controlled by major faults with predominant N–S, NNE–SSW, and NNW–SEE trends. It is characterized by moderate to low seismic activity. The faults have controlled the local depositional architecture, deforming, fracturing, relocating and distributing sediments since the Valangian (early Cretaceous). The Prestige sinking area corresponds to an asymmetric half-graben structure with a N–S trend, which conditions the present-day morphology. The faulted flank outcrops and its activity and erosion have favoured the occurrence of mass-movements (slumps, slump debris, mass-flows and turbidity currents), building valleys and depositional lobes. Nearsurface sediments comprise mostly terrigenous and biogenous turbiditic muds and sands with a minor presence of hemipelagic muds, except on the fault scarp where pelagites predominate. Potential geological hazards resulting from tectonic and sedimentary processes affect almost the entire Prestige sinking area.

Keywords: Prestige; Galicia Bank; Morphology; Sedimentology; Tectonics; Mass-movements; Geological hazards

1. Introduction

On Wednesday 13th November 2002, in stormy weather conditions, a serious accident occurred involving the oil tanker "Prestige", which was sailing off the west coast of Galicia. It was reported that the ship was carrying 77,000 tonnes of heavy fuel on board. After several days on the high seas with rough weather, a large crack on the starboard side of the hull made the vessel sink rapidly on 19th November 2002. A detailed geological study has been carried out in the area where the Prestige sank in order to determine the geological factors that can be considered as potential hazards. In the past few decades, studies evaluating potential geological hazards have become necessary to

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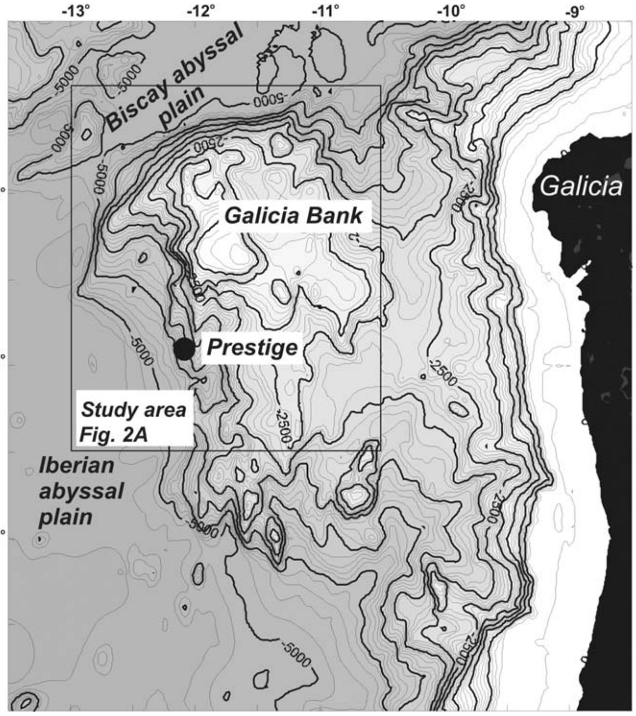

Fig. 1. Bathymetric map of the western Galicia continental margin (Atlantic NW Iberian continental margin) showing the location of the Prestige wreck on the Galicia Bank.

assess engineering and environmental projects related to economic development or the exploitation of resources in offshore areas. In the Prestige project, this type of study was considered necessary for the engineering activities that were planned in order to control the oil spilling into the sea. A comprehensive geological study was therefore conducted. The previous knowledge of this sector of the Spanish continental margin and deep sea area made it necessary to consider a variety of topics in order to determine the morphologic, stratigraphic, sedimentological and tectonic features that define a varied and complex set of environmental conditions.

The Prestige sinking area is located in the southwestern part of the Galicia Bank, in the NW Iberian continental margin, 130 miles off the shore of Galicia in the NE Atlantic Ocean (Fig. 1). Before sinking, the vessel broke into two. The stern is located at a depth of 3565 m and the bow at a depth of 3830 m.

2. Geological setting

The Galicia Bank is a structural high in the western Galicia continental margin (Fig. 1). The literature indicates that offshore studies in this margin began 35 years ago. Most of them have focussed on the analysis of its structure and tectonic evolution, showing its great complexity (e.g., Montadert et al., 1974; Laughton et al., 1975; Dupeuble et al., 1976; De Charpal et al., 1978; Boillot et al., 1979; Groupe Galice, 1979; Sibuet et al., 1979; Chenet et al., 1982; Olivet et al., 1984; Boillot et al., 1986). The Galicia continental margin can be defined as a starved, non-volcanic passive margin and its complex structure has resulted from Mesozoic rifting phases and Eocene compression (Pyrenean orogeny). In fact, the Galicia Bank is a Mesozoic tilted block that was reactivated and uplifted during early Pyrenean tectonics. Tectonic movements observed in the Galicia Bank can be correlated with the kinematics of the north Atlantic, and these movements can be divided into three different stages: pre-rift, syn-rift, and post-rift (Mauffret and Montadert, 1988; Murillas et al., 1990). The region of the Galicia Bank is defined by four morphological provinces (Boillot et al., 1975), which are from east to west: the Galicia Interior Basin, the Transitional Zone, the Galicia Bank and the Deep Galicia Margin. They are bounded to the north and west by the Biscay and Iberian abyssal plains, respectively (Fig. 1).

The sedimentary cover of the Galicia continental margin is thin (0–4 km) (Boillot and Malod, 1988). This cover comprises sediments from the Oxfordian to the Quaternary, and their distribution is very irregular. Seven seismic units (7–1 from oldest to youngest) are identified and they can be divided into three categories according to their relationship with the structural evolution of the margin: pre-rift units comprise seismic units 7 and 6 (Oxfordian to Berriasian); syn-rift units comprise seismic units 5 and 4 (Valangian to Aptian); and post-rift units comprise seismic units 3, 2 and 1 (Albian to Quaternary).

3. Methodology

3.1. Definition and design of the study area

The Prestige sinking area was surveyed from two perspectives: a regional study and a detailed local study. A grid was designed in each case taking into account the regional water depths and the general orientation of the morphological and structural features (Fig. 2). The regional study covered the Galicia Bank (about 34,000 km^2) and involved 11 profiles (bathymetry and single- and multi-channel seismics) of different orientation according to the structural configuration (Fig. 2A) and seismicity data (land stations and ocean bottom seismometers (OBSs)). The local study covered a sector of about 200 km^2 that included the stern and bow of the Prestige wreck. The data acquired (bathymetry and single-channel seismics) consisted of 35 W–E profiles with track spacing of about 250 m, and 16 N–S profiles with track spacing of about 650 m. In this area 10 sampling stations were also placed around the stern and bow of the wreck (Fig. 2B). Acoustic surveys were made at a ship speed of 5 kn.

3.2. Data acquisition

Multi-beam bathymetry, seismic profiles and sediment cores were acquired on board the Hesperides vessel. The high-resolution bathymetric map was obtained with the Simrad EM-12 S120 multi-beam echosounder. This system

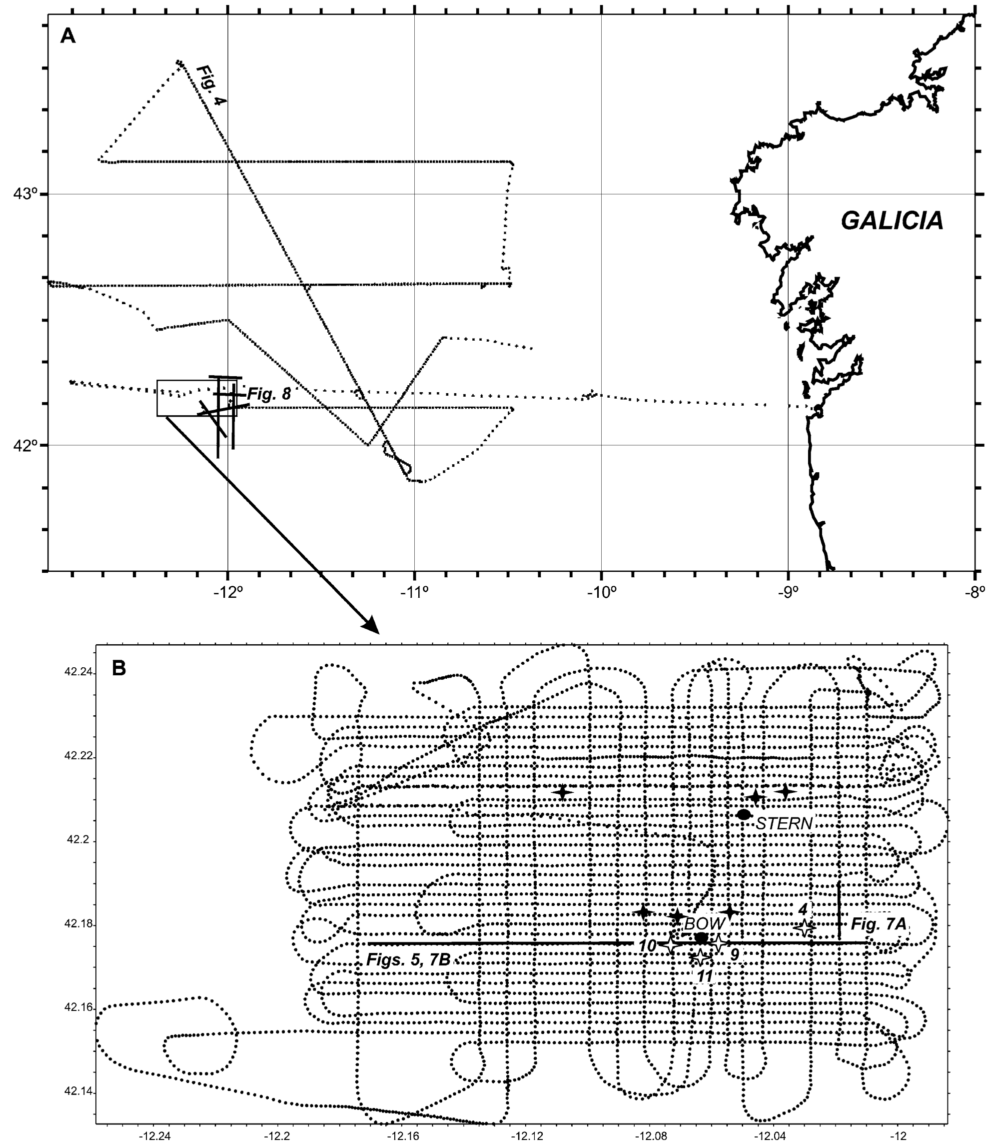

Fig. 2. (A) Map showing the location of bathymetric and seismic lines surveyed on the Galicia Bank. The long dotted lines refer to single-channel seismic lines (slevee-guns) and the short continuous lines to multi-channel seismic lines (bolt airguns). (B) Map showing the location of bathymetric, single-channel seismic lines (sleeve-guns and TOPAS) surveyed in the Prestige sinking area. Also location of gravity cores (stars) recovered around the stern and bow of the Prestige wreck are also displayed. White stars with numbers refer to location of cores in Figs. 10 and 11.

covers a sector of the seafloor covering approximately three times the water depth at which it is working, uses a frequency of 12 kHz, has an aperture angle of 120°, and provides 81 values of bathymetry across the ship track, corrected for the geometric propagation of sound in the stratified water column. The seismic records comprise multi-channel profiles and high and ultra-high resolution single-channel profiles. The multi-channel profiles were collected using a 2500 in.^{3} bolt gun array using a 48-channel, 3 km long streamer. The penetration of the signal was >2 s. The high and ultra-high resolution single-channel records were obtained, respectively with airguns and the Topographic Parametric Sonar (TOPAS) system. The airgun records were collected using a sleeve-gun array (140 in.^{3}). The penetration of the acoustic signal was <2 s two-way travel time. The TOPAS system is a hull-mounted seabed and sub-bottom echosounder based on the parametric acoustic array, which operates using non-linear acoustic properties of the water (Dybedal and Boe, 1994). The system transmits a modulated frequency sweep of between 1.5 and 4 kHz. The penetration of the acoustic signal achieved with the TOPAS system varies between 0 and 200 ms at full oceanic depths.

For acquisition of sampling data for ground-truthing, the 10 cores were recovered using a gravity corer up to 3 m long. A large variety of sedimentological analyses were carried out on the sediment samples in order to define types of sediments. These analyses include grain size, sand fraction composition, carbonate content, X-ray and geochemical analysis. Grain size analysis of selected sub-samples was conducted using a hand sieve and settling tube for the fraction greater than 50 μm and by the Sedigraph procedure (Micromeritics model 5100) for the fraction smaller than 50 μm. The composition of the sand fraction was determined with the aid of a binocular microscope. The carbonate content was obtained using a Bernard's calcimeter (Vatan, 1967). X-radiographs were made in order to recognise detailed sedimentary structure and disturbance features. Further to these, a systematic high-resolution geochemical and petromagnetic study was carried out to establish the composition, magnetic properties and age of the sediment types. The methodological strategy comprised an initial approach in which two high resolution (1 cm) records were obtained from U-channels based on: (a) XRF semiquantitative determination of K, Ca, Ti, Mn, Fe, Cu and Sr using a core-scanner and (b) magnetic property determination (k, dec, inc, ARM, IRM700) obtained using a 2G cryogenic magnetometer. A number of representative discrete samples were then obtained from the most significant horizons and analyzed in more detail. These comprised XRF quantitative elemental analysis, C, N, H and S determination on a LECO, XRD mineralogical diagnosis, and SEM-based textural studies of undisturbed sediment samples.

Seismicity studies included acquisition of seismic events using land and marine stations as well as compilation of events using global and regional catalogues (International Seismological Centre, Instituto Geográfico Nacional of Spain). The instrumental data comprised 12 seismometer land stations that were deployed between March and October 2003, and 10 OBSs that were recording for 25 days from August to September 2003.

4. Morphology

The morphological provinces of the Galicia Bank (i.e., Galicia Interior Basin, Transitional Zone, Galicia Bank and Deep Galicia Margin) define an irregular sub-rounded high whose top is located at <700 m water depth (Fig. 3). The new multi-beam bathymetry shows the summit to be a dome-shaped feature exhibiting concentric bathymetric contours. The flanks are irregular. The northwestern wall is defined by an abrupt scarp >3000 m in height. The other flanks have relatively smoother gradients and irregular cross-section profiles showing small platforms and striking highs. The limits between the morphological provinces are defined by changes in the regional slope gradients, scarps or structural highs (Figs. 3 and 4).

The morphological provinces are affected by submarine valleys, instability deposits, contourite deposits and outcropping structural highs (Figs. 3–5). The valleys display V- and U-shape cross-sections, and have metric and kilometric widths with reliefs of tens to thousands of meters (Figs. 4 and 5). The valley pathways are slightly sinuous

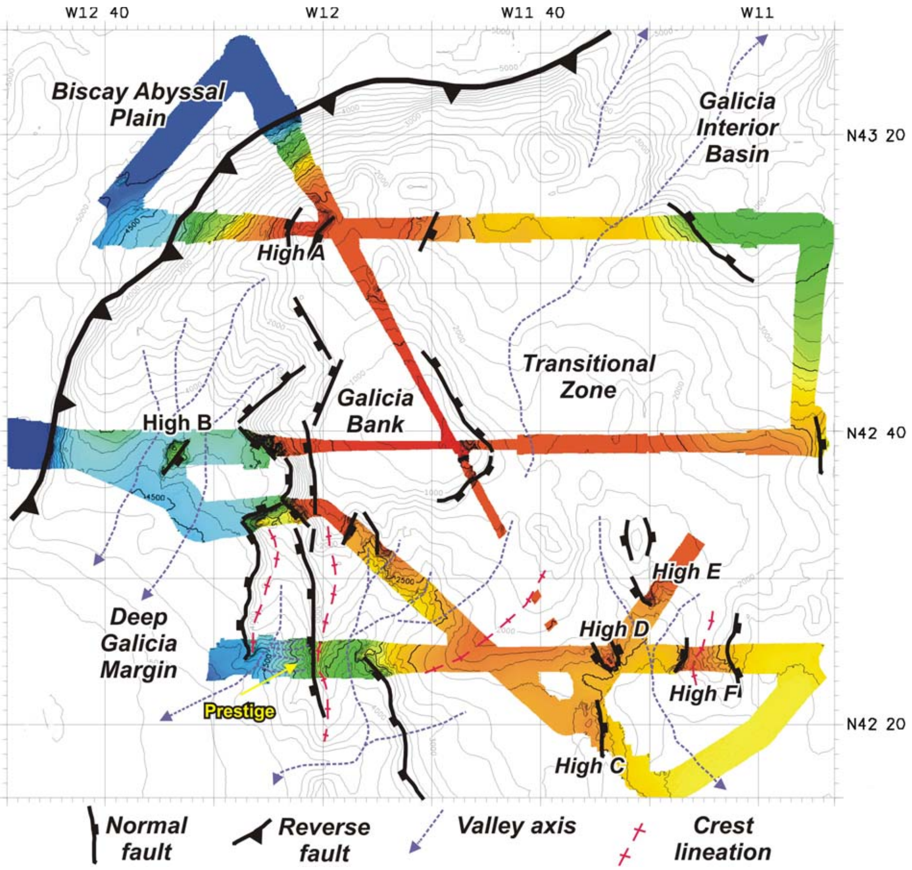

Fig. 3. Morphostructural map displaying the main features identified in the different provinces that make up the Galicia Bank. The colours display the multi-beam bathymetry obtained in this study.

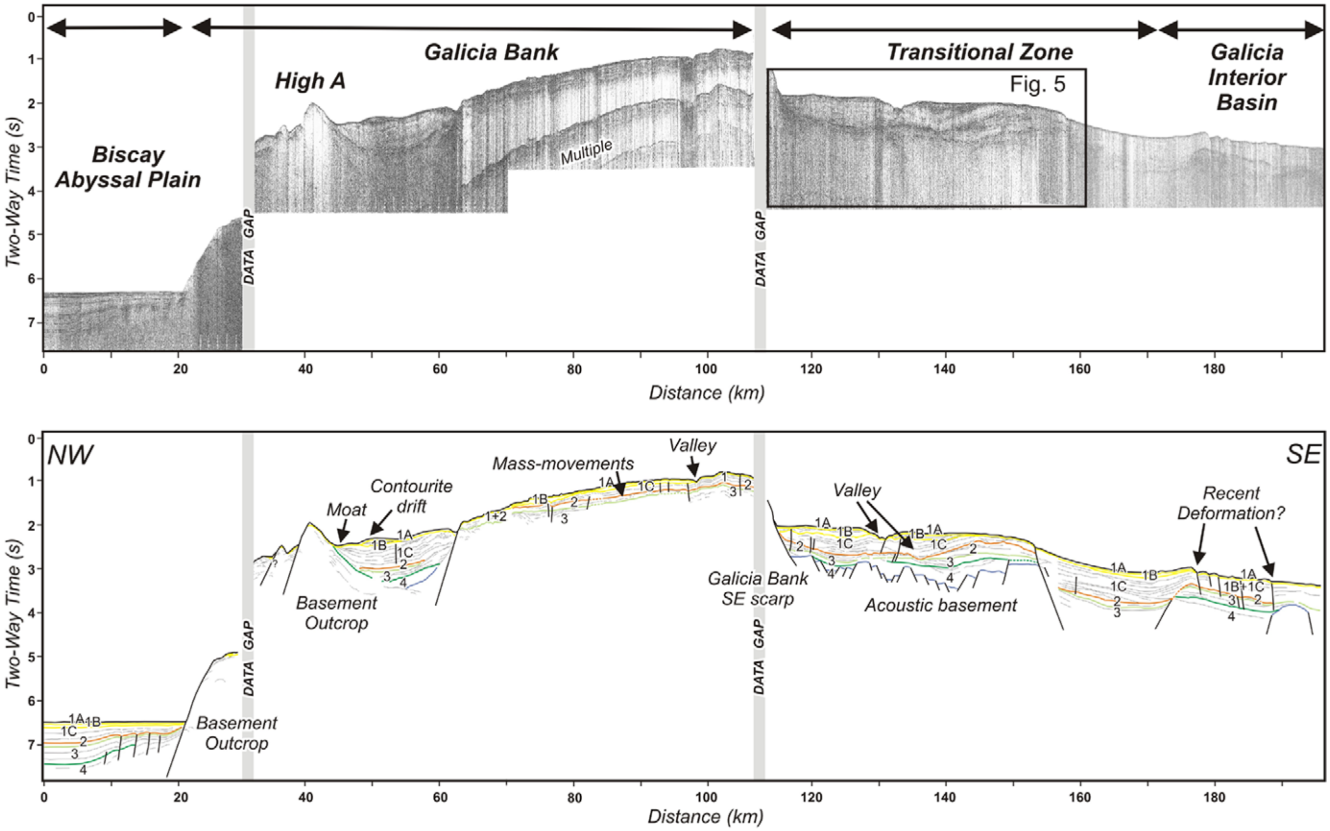

Fig. 4. Single-channel seismic profile and line drawing showing the seismic stratigraphy defined in the different morphological provinces of the Galicia Bank. Location of profile in Fig. 2A.

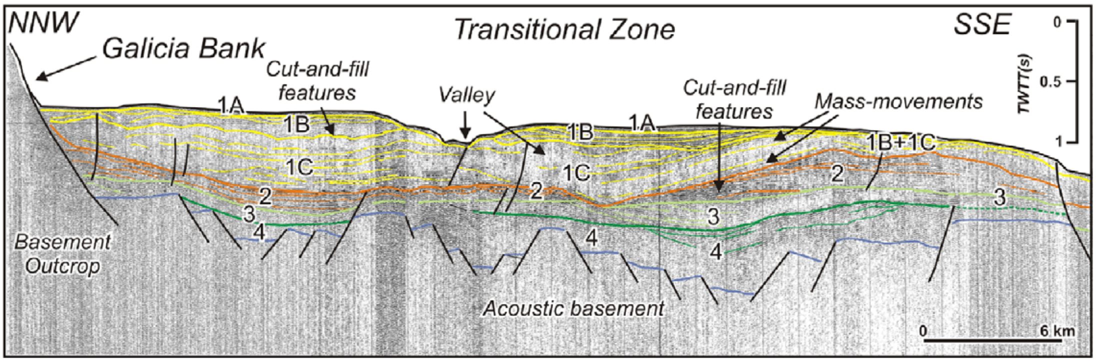

Fig. 5. Single-channel seismic profile showing the detail on the seismic stratigraphy defined in the Galicia Bank. Location of seismic profile segment in Fig. 4.

and all together form a radial system that drains the flanks of the Galicia Bank (Fig. 3). The instability deposits develop mostly at the foot and on the walls of the structural highs, and they deform/fracture the surficial sediments forming an irregular seafloor (Fig. 4). The contourite deposits comprise a mound associated with a moat located adjacent to the foot of some structural highs. The mound appears as a prominent feature that forms a contourite drift, and the moat defines a depression with a U-shape cross-section of a few kilometre width (Fig. 4). Six structural highs have been identified and are named from A to F. They have heights of hundreds of metres and display sub-rounded to rounded shapes in plain view (Figs. 3 and 4).

The Prestige sinking area is located on the southwestern flank of the region of the Galicia Bank, specifically in the Deep Galicia Margin province, where slope gradients are very variable, ranging from <1 to 26°. Morphologically, the area is defined by the presence of a N–S trending scarp that extends from 2790 to 3600 m water depth (Fig. 6). At the foot of this scarp several elongate–lobate positive reliefs

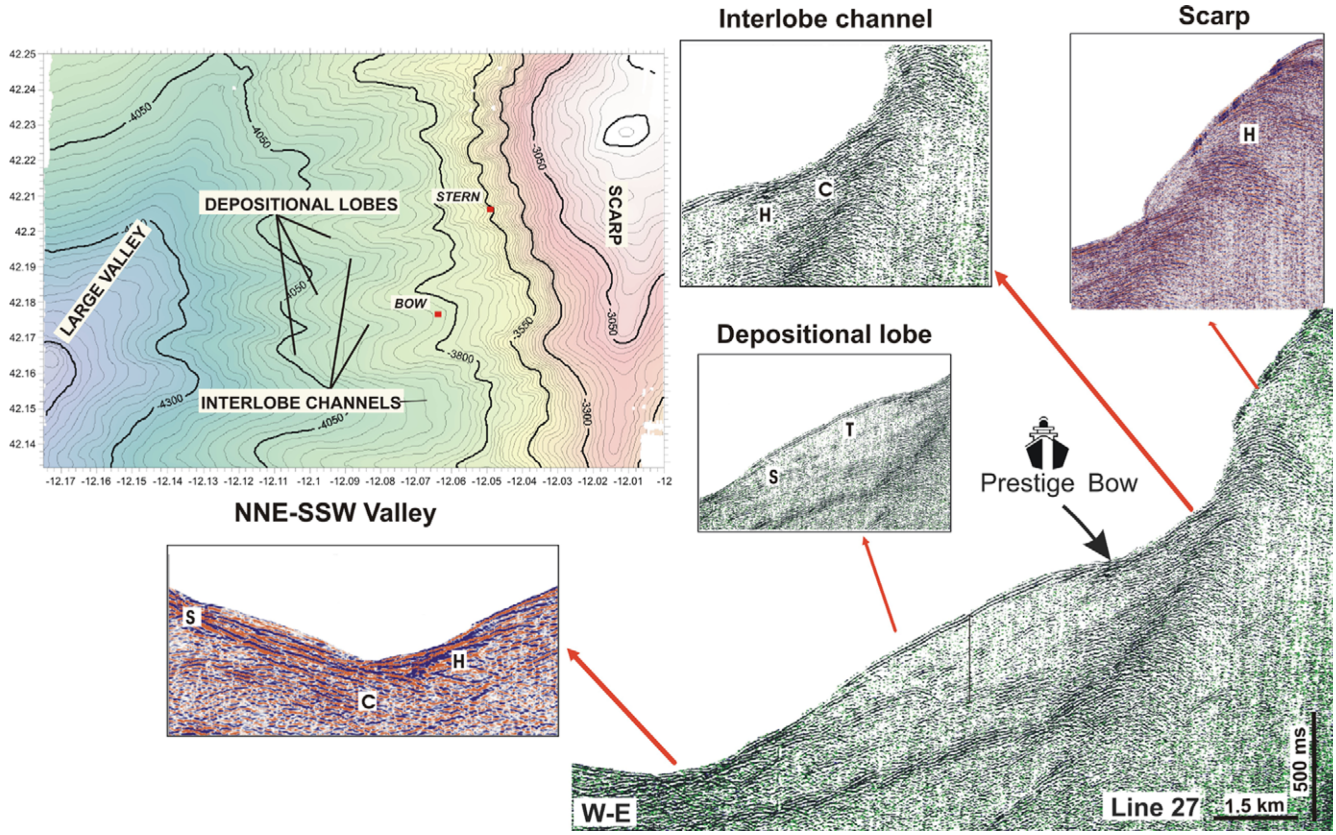

Fig. 6. Multi-beam bathymetry of the Prestige sinking area displaying the main morphological features. The figure also shows the most representative acoustic facies that characterize the nearsurface sediments in the different sedimentary environments (scarp, depositional lobe, interlobe channel, and large valley). Explanation in the text. Legend: H, hyperbolic facies; C; chaotic facies; T, semitransparent facies; and S, stratified facies. Location of profile in Fig. 2B.

(i.e., depositional lobes) have developed with variable lengths (maximum 9.5 km) and widths (hundreds of meters), separated by linear to slightly sinuous negative reliefs resembling channels (i.e., interlobe channels); these features have an E–W direction and connect with a large (2 to >3 km wide) submarine valley that crosses the sinking area from NNE to SSW (Fig. 6).

5. Seismic stratigraphy

The seismic stratigraphy of the Galicia Bank is made up of five seismic units (1–5 from youngest to oldest) resting on an irregular acoustic basement (Fig. 4). The seismic division was based on the correlation between single-channel seismic stratigraphy obtained in this study and multichannel seismic profiles from the literature (Groupe Galice, 1979; Boillot et al., 1987; Mauffret and Montadert, 1989; Murillas et al., 1990). Based on this correlation, seismic unit 1 can be assigned as Middle Eocene to Quaternary, seismic unit 2 as Campanian to Middle Eocene, seismic unit 3 as Albian to Campanian, seismic unit 4 as Hauterivian to Upper Aptian, and seismic unit 5 as Valangian. The distribution of these units is variable; seismic units 5 and 4 have a local presence and fill the paleotopographic depressions defined by the acoustic basement; seismic units 3–1 have a more generalized distribution and cover and obliterate the basement paleotopography (Figs. 4, 5 and 7).

The seismic units are bounded by discontinuity surfaces that can be traced at a regional scale of the bank and surrounding abyssal plains, and their correlative continuity surfaces (Fig. 4). The seismic facies display a vertical change, changing from facies characterized by a predominance of chaotic, hyperbolic and transparent facies (seismic units 5, 4 and partially 3) to stratified facies defined by reflections of high to low acoustic amplitude and long to short lateral continuity, (semi)transparent and locally chaotic facies (seismic units 3–1) (Fig. 5). The configuration of facies is parallel, sub-parallel, divergent and wavy, and their lateral continuity is affected by deformational structures such as highs and faults, gravitational movements of sediments, and erosive surfaces that correspond to (paleo)valleys, cut-and-fill features and contouritic moats (Figs. 4 and 5).

A detailed stratigraphic study was carried out in the Prestige sinking area. The results show that the lateral continuity of the seismic units is interrupted by the presence of the N–S scarp. Due to the low resolution of our sleeve-gun profiles, the above-mentioned stratigraphy is difficult to define in this area, and some seismic units represent the sum of several of them. Thus, on the top of the scarp,

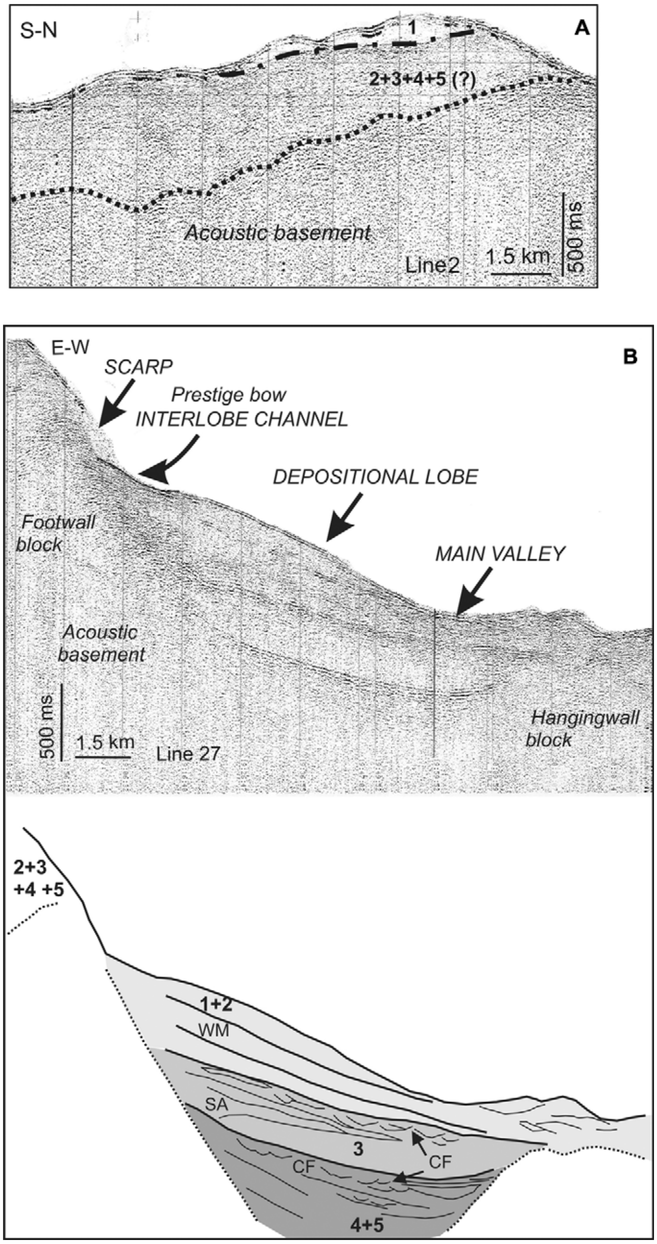

Fig. 7. (A) Single-channel seismic record in the Prestige sinking area illustrating the stratigraphy defined on the top of the N–S morphological scarp. (B) Single-channel seismic profile and line drawing in the Prestige sinking area illustrating the stratigraphy defined at the foot of the morphological scarp. Explanation in the text. Legend: WM, wedge of mass-movement deposits; SA, slope apron; and CF, cut-and-fill features. Location of profiles in Fig. 2B.

two seismic units are identified (Fig. 7A). Following the above-mentioned nomenclature, the upper unit probably corresponds to deposits of seismic unit 1, acoustically characterized mainly by transparent facies, and the lower unit corresponds to deposits of seismic units 2–5, acoustically defined mainly by discontinuous stratified and chaotic facies. At the foot of the scarp, the stratigraphy is defined by three seismic units: 4 + 5, 3, and 1 + 2 (Fig. 7B). The deposits of seismic unit 4 + 5 have an internal divergent configuration, and display cut-and-fill features and slope aprons. The cut-and-fills are defined by erosive U-shaped surfaces filled with chaotic and discontinuous stratified facies. The slope aprons are formed by chaotic facies deposited at the foot of the scarp. The deposits of seismic unit 3 are similar to the previous ones, though they display a sub-parallel configuration and the facies have a lesser acoustic amplitude. The deposits of seismic unit 1 + 2 comprise E–W trend sedimentary wedges whose thicknesses (tens of milliseconds) decrease downslope, have low lateral continuity (hundreds of meters), and the most recent ones display an elongate lobe-shape in plan view (i.e., they correspond to the depositional lobes). Internally, they are characterized by the vertical stacking of discontinuous stratified, transparent and chaotic facies that correspond to mass-movement deposits. These wedges extend from the scarp to the large NNE–SSW valley. In fact, the distal ends of the wedges are cannibalized by this valley, which is defined by chaotic and hyperbolic facies on the floor and stratified facies on the right margin.

6. Structural features and seismicity

Structurally, the Galicia continental margin is controlled by the formation of an extensional fault system, in which the Galicia Interior Basin province corresponds to a tectonic domain governed by grabens, the Transional Zone province to a horst-graben system, the Galicia Bank province to a horst, and the Deep Galicia Margin province to a half-graben system (Mauffret and Montadert, 1981; Murillas et al., 1990) (Fig. 4). Within this structural framework, the region of the Galicia Bank is characterized by the presence of faults with N–S, NNE–SSW, NNW–SEE directions (Fig. 3). These faults bound structural highs and horst-and-grabens of the acoustic basement, affect the seismic units, and some of them reach the seafloor with a surficial expression (Figs. 4 and 5). Thus, they condition the general morphology of the bank and also the stratigraphic architecture (Figs. 3 and 4).

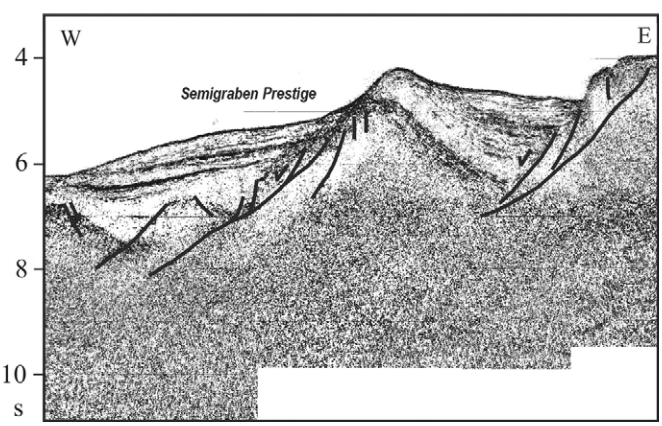

Fig. 8. Multi-channel seismic record displaying the main tectonic features (faults) that define the structural configuration of the Prestige sinking area. Explanation in the text. Location of profile in Fig. 2A.

The detailed study of the Prestige sinking area indicates that it corresponds to an asymmetric half-graben structure with a N–S trend (Fig. 8). The faulted flank (footwall block) of the half-graben is located in the eastern sector and corresponds to the N–S scarp, which is easily identified in the multi-beam bathymetry (Figs. 6 and 7B). It is therefore a fault scarp where the acoustic basement and older, uplifted and titled sediments outcrop. The tilted and sunken (hangingwall block) block is located in the western part, and is also defined by a N–S structural high bounded by antithetic faults (Fig. 8). The tilting of this block is probably due to block rotation as it slides down the listric fault toward the rift axis (Montadert et al., 1979). This block is partially covered by seismic units 3 and 1 + 2, or only 1 + 2 (Fig. 7B).

The seismicity studies in the Galicia continental margin go back about 30 years (Engdahl and Villaseñor, 2002). The general catalogue displays earthquakes with a magnitude <5.5, and known epicenters are usually located over structural features (Fig. 9). They would occur in relation to the E–W Galicia marginal trough, and to the N–S, NNE–SSW to NNW–SSE faults that mostly define the structural configuration of this margin. Our land stations have detected seismicity events with magnitudes varying between 4.5 and 1.8 and their epicentre locations are also indicative of the activity of the North Iberian Trough, Galicia marginal trough, and of those faults that mostly define the structural configuration of this margin. The results from OBSs detected seismic events with magnitudes varying between 2.5 and 3. All the data together allow us to state that although the Galicia continental margin displays a moderate level in the global catalogue of seismicity, it can be considered to have a low to moderate level of local seismicity (5 > Mag > 1.5).

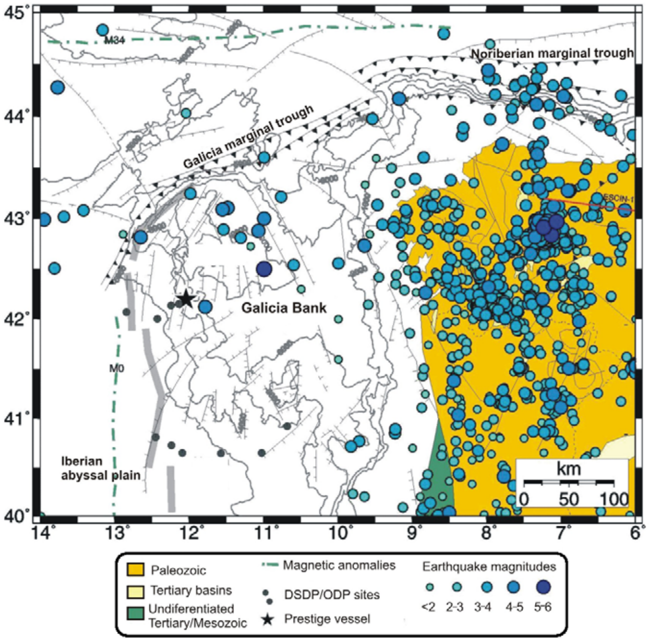

Fig. 9. Simplified sketch map showing the seismicity in the Galicia continental margin (from International Seismological Centre, Instituto Geográfico Nacional of Spain, and Engdahl and Villaseñor, 2002).

7. Modern sedimentary environments

This study only focussed on the Prestige sinking area. Three modern sedimentary environments were defined using multi-beam bathymetry and high and ultra-high resolution seismic records: scarp, depositional lobe and valley environments (Fig. 6).

The *scarp environment*, located between 2790 and 3600 m water depth, has a steep seafloor which is acoustically characterized by surficial prolonged echoes and

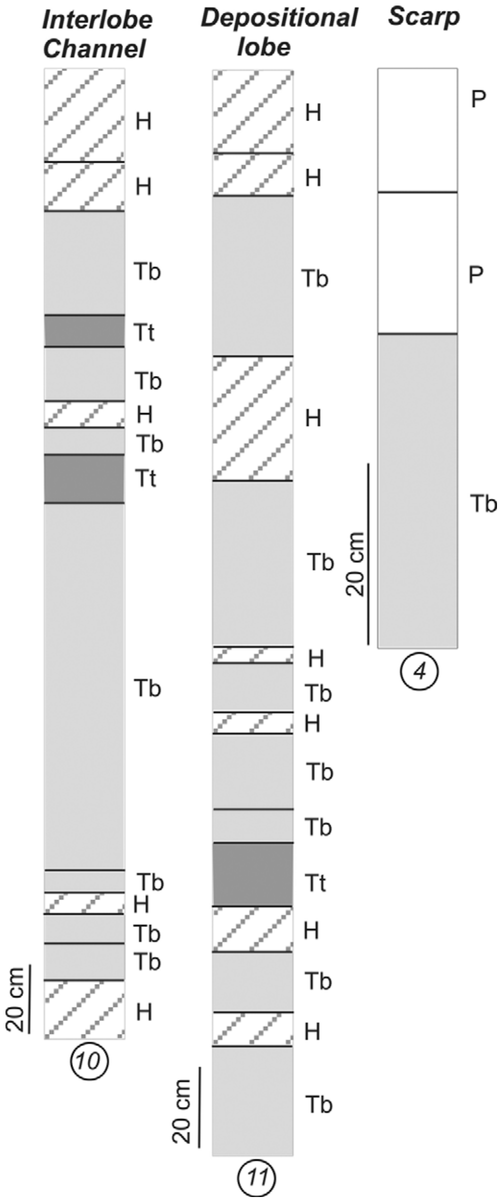

Fig. 10. Stratigraphic logs showing the vertical arrangement of the type of sediments defined in the sedimentary environments of the Prestige sinking area. Legend: H, hemilagites; P, pelagites; Tt, terrigenous turbidites; Tb, biogenous turbidites. Encircled numbers refer to names of cores. Location of cores in Fig. 2B.

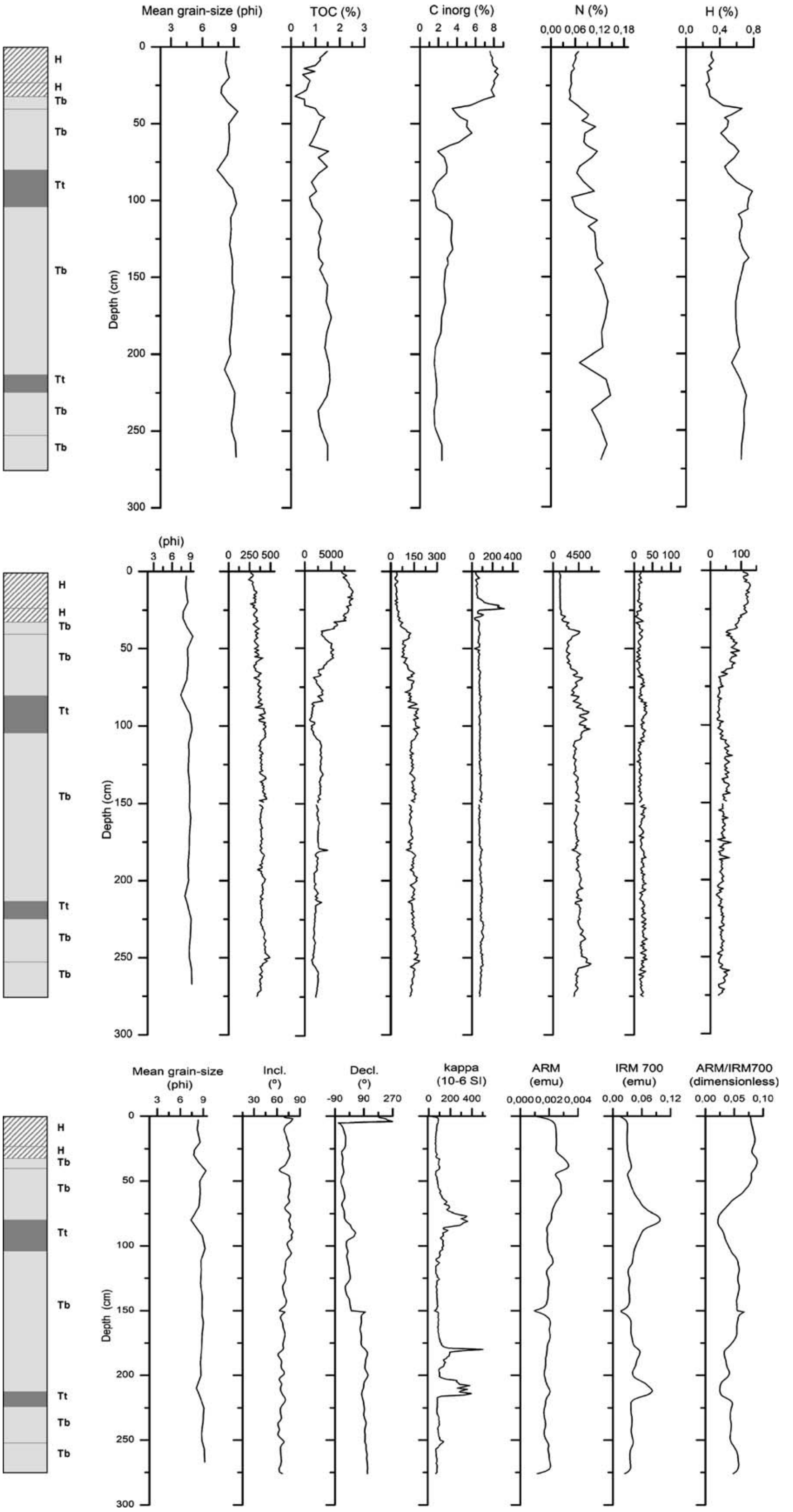

Fig. 11. Vertical distribution of the studied variables from XRF core-scanner elemental analyses and 2G petromagnetic properties for the core 9 nearest to the bow in the interlobe channel environment. Location of core 9 in Fig. 2B.

irregular hyperbolas with diffuse sub-bottom reflections. These facies define an irregular seafloor surface, suggesting the presence of gullies, scarps, slumps and slope aprons. The summit is defined by an erosive surface that truncates stratified and transparent facies.

The *depositional lobe environment* occurs from 3600 to 4400 m water depth, where several sedimentary lobes develop. They are easily observed on the bathymetric map as elongate–lobate positive reliefs. The lobes display an upward convex seafloor surface in cross-section and their near-surface sediments are acoustically defined by prolonged echoes, discontinuous stratified facies of low to medium acoustic amplitude, and semitransparent and chaotic facies. Internally, these deposits are affected by erosive surfaces.

The *valley environment* occurs in the interlobe channels and the large valley. The interlobe channel environment extends from 3600 to >4600 m water depth. The channel and valley floors are characterized by an acoustic signature including prolonged, hyperbolic and chaotic facies. These facies form an irregular, erosive surface with sharp echoes and hyperbolae. Likewise, the large valley has a well-defined right margin that appears as a convex-upward ridge that is internally defined by stratified to transparent facies.

8. Nearsurface sediments

Three sediment types are identified in the Prestige sinking area: turbidite (biogenous and terrigenous), hemipelagite and pelagite (Figs. 10 and 11). Their thickness ranges from a few to tens of centimetres, the turbidites being the most predominant sediment (about 75% of core length). These sediments are divided into two facies associations based on their sedimentological characteristics and sedimentary environment location: (i) fault scarp facies, and (ii) channel-and-depositional lobe facies (Fig. 10). The fault scarp facies comprise mainly the vertical succession of pelagic or biogeneous turbidite muds and sands with carbonate contents of about 70–85%. Minimum sedimentation rates averaged 0.2 cm per thousand years in these areas.

The channel-and-depositional lobe facies show that the top (0 to 20–40 cm) are mainly characterized by carbonate-rich muds of hemipelagites dominated by calcite (95%) and dolomite, low Ti (0.14–0.21%) and Fe (0.04–0.05%) content, and low mean magnetic susceptibility ($60–70 \times 10^{-6}$ SI). In contrast, the lower parts of the recovered cores are dominated by terrigenous turbiditic muds and biogenous turbiditic muds and sands (Figs. 10 and 11). These are volumetrically much more important in the sequence and may have small (2–20 cm) hemipelagic mud horizons interbedded. The turbidites consist of 35–50% of calcium carbonate with about 14% of dolomite. Detrital minerals comprise quartz (10–20%), plagioclase (5–10%), mica (5–10%) and K-feldspar (4–8%). Their Ti (0.36%) and Fe (4.05–4.61%) content and magnetic susceptibility ($90–170 \times 10^{-6}$ SI) are significantly higher than in hemipelagites (Fig. 11). A high intracore (vertical) and intercore (lateral) compositional variability is observed, resulting from significant differences in detrital to biogenic provenances. Radiocarbon age determinations estimate averaged sedimentation ratios of around 3 cm per thousand years in hemipelagites for the channel-and-depositional lobe facies, and suggest that the last turbidite event took place around 9100 years ago.

9. Discussion and conclusions

9.1. Tecto-sedimentary architecture

The depositional architecture of the Galicia Bank is controlled by the main structures that define its tectonic framework, i.e., faults with predominant N–S, NNE–SSW, NNW–SEE trends (Fig. 3). The spatial and temporal distributions of seismic units 5–1 imply that the development and evolution of the region of the Galicia Bank involved a distribution and relocation of sedimentation controlled by fault activities (Figs. 4, 5 and 8). In fact, the new seismicity data indicates that today tectonic activity seems to continue, although it is moderate to low. The fault activity of the area can be divided into three different stages, pre-rift, syn-rift, and post-rift, and these tectonic movements can be correlated with the kinematics of the north Atlantic (Mauffret and Montadert, 1989; Murillas et al., 1990). By correlation with these studies and based on the seismic facies features (acoustic facies, configuration, lateral relationship, geometry) that make up units 5–1, we can establish that the syn-rift units 5–4 are characterized by gravitational deposits filling the basins defined by the horst and graben systems (Fig. 4). The occurrence of these deposits seems to be associated with the fault activity of these systems. Sedimentation of post-rift units 3, 2 and 1 comprises black shales, red lutites, marls rich in nanno-fossils, pelagites, contourites, and instability deposits associated with mass-movements and valleys (Boillot et al., 1987) (Figs. 3 and 4). The spatial distribution of these deposits has been mainly conditioned by the paleostructural configuration of the Galicia Bank, whereas the valleys and bottom currents have played a secondary role.

These regional tectonic stages have also conditioned the depositional architecture of the Prestige sinking area. Within this regional structural context, two active tectonic periods interrupted by a calm period may be differentiated according to the seismic facies features. The first active tectonic period occurred during the formation of unit $4 + 5$ (Hauterivian to Valangian), and corresponds to the half-graben development that is filled with divergent deposits associated with a complex drainage systems of channels, channel-filling deposits and slope aprons (Fig. 7). The second tectonic period occurred during the building of unit $1 + 2$ (Middle Eocene to Quaternary) and corresponds to a re-activation phase of the main fault system (Fig. 7). This reactivation can be related to the later Alpine compression (Boillot and Malod, 1988) and led to a new rotation of tilted blocks, the formation of the large valley and the exhumation and erosion of the N–S fault scarp that favoured the formation of depositional wedge-shape units of mass-movement deposits (i.e., depositional lobes and interlobe channels in plain view) (Figs. 7 and 8).

9.2. Recent sedimentary evolution

The recognition of the ultra-high and high resolution acoustic features of the near-surface sediments in the Galicia Bank shows both erosion and deposition by mass-movements and bottom current activity. The mass-movements represented by gravity flows (e.g., mass-flows and turbidity currents) favoured the development of drainage systems that distribute the sediment on the flanks of Galicia Bank; the location of those systems is mainly governed by the structural trends. Likewise, slumps and mass-flow deposits appear around the structural highs, and were probably triggered by tectonic movements (Fig. 4). Bottom currents favoured the formation of contourite deposits around some of the structural highs. The bottom currents interact with the shape of these edifices and probably modify the general circulation accelerating the bottom currents that erode and rework the seafloor forming moats and separated lateral drift accumulations.

Acoustic reflection features (hyperbolic, chaotic and discontinuous stratified facies, and erosive surfaces) plus the nearsurface sediment types (mostly turbidites) of the Prestige sinking area show that erosion and deposition by mass-movements are the main sedimentary processes (Figs. 6, 10 and 11). As it has been mentioned above, the sediment source of these processes is represented by the scarp environment whose exhumation and erosion have favoured the occurrence of mass-movements. Erosive processes (e.g., slumps, mass-flows and turbidity currents) occur in the scarp, interlobe channels and large valley environments. Deposition from mass-movements governs depositional lobe building from successive slump debris, mass-flows and turbidity currents. Deposition from sediment gravity flows also occurs on the right margin of the large valley, probably from successive mass-flows and turbidity currents running along the valley axis which led to the deposition of stratified and transparent facies. In addition to these processes, deposition from hemipelagic settling also occur in the interlobe channels and depositional lobes, and deposition from pelagic settling takes place on the N–S scarp environment.

9.3. Potential geological hazards for the Prestige vessel

The present study on the geological characterization of the area in which the Prestige sunk suggests the existence of potential natural geological factors (morphological, tectonic and sedimentologic) that might cause hazards to the stern and bow of the Prestige vessel. Taking into account these factors, two main categories of potential hazards can be differentiated according to their distinct origin: (i) hazards related to sedimentary processes, and (ii) hazards related to tectonic processes.

Hazards related to sedimentary processes are suggested by the occurrence of slope instabilities. Sediments accumulating on the seafloor may become unstable due to slope oversteepening, and in the Prestige sinking area this factor seems to be one factor responsible for the occurrence of mass-movements. Morphologically, the stern of the vessel is located on the scarp, where the slope gradient is about 19°, and the bow is situated on the floor of an interlobe channel with gradients of 4–5° (Fig. 6). Slope instabilities are identified in the scarp environment (slumps, turbidites, slope aprons), and in the depositional lobe and valley environments (slump debris, mass-flow deposits and turbidites) (Figs. 6, 10 and 11). These seafloor instability features cover almost the whole area where the stern and bow are located, and sediment instability must therefore be considered as a potential hazard where it shows different degrees of remobilization. Sediment cores studied for ground-truthing indicate that hemipelagic sedimentation has predominated at least during the last 9100 years (Figs. 10 and 11); this would suggest a pause of the mass-movement activity and then it makes the turbidite hazard in the area much lower. Nevertheless, taking into account the tectonic context (a fault scarp as a sediment source) and the seismic and sedimentary stratigraphy, this temporarily cease may be of little significance because the sedimentary evolution is characterized by the predominance of deposition by mass-movements, occasionally interrupted by hemipelagic deposition. This deposition would be related to the lack of instability pulses on the N–S fault scarp.

With respect to the hazards related to tectonic processes, the tectonic framework of the Prestige sinking area is mainly controlled by its relationship with the structures of the Galicia Bank (Figs. 3, 4 and 8). The main potential hazards that are relevant in the area are faults and seismicity. Faults with N–S, NNE–SSW, NNW–SSE trends control the Galicia Bank, and specifically a N–S faulting controls the structural trends of the sinking area. As a general rule, faults that reach the seafloor surface can be considered as recently active or potentially currently active. Some of the faults that affect the Galicia Bank seafloor and the N–S faulting of the Prestige sinking area may be considered hazardous as they are responsible for the existence of the scarps that produce the vertical displacement of the seafloor and interrupt the lateral continuity of the stratigraphic units. Although the state of activity of these faults has not been determined, these morphological and stratigraphic criteria plus the occurrence of mass-movements during seismic unit 1 and near-surface turbidite events may indicate a young age and/or high potential for recent activity (from a geological point of view). Nevertheless, information about sedimentation rates during seismic unit 1 would be necessary in order to precise the potentially of faults, specifically of the N–S faulting of the Prestige sinking area. This is because at low sedimentation rates, even weak topography will persist over long periods, so fault scarps will take a long time to smooth over. In this case, we could not stay that an outcropping scarp must be recently active.

With respect to seismicity, it is usually cited as a common triggering mechanism for many offshore instability processes (Heezen and Ewing, 1952; Seed, 1967). Earthquakes of moderate to low magnitude have characterized the Galicia continental margin, and have been recorded in the surrounding areas of the Galicia Bank (Fig. 9). From a qualitative point of view, these data allow us to consider that the Prestige sinking area is an area of active seismicity, and that relative movements along faults have occurred recently and have potential for movement in the future.

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