LANDSLIDE AND GRAVITY FLOW FEATURES AND PROCESSES OF THE NAZARÉ AND SETÚBAL CANYONS, WEST IBERIAN MARGIN

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Abstract

The Nazaré and Setúbal Canyons of the west Iberian margin are highly complex seafloor environments, displaying a range of sedimentary features and processes that reflect the transition from erosive upper to depositional lower canyon. Upper sections are characterised by a deeply incised, narrow, V-shaped thalweg, and frequent localised intra-canyon slope failures. Lower sections have a U-shaped floor with heterogeneous sediment distribution. Two types of gravity flow are observed: thin-bedded, fine-grained deposits that may be the result of frequent turbidity currents generated by high sediment supply to canyon heads, and thicker, siliciclastic coarse sandy turbidites, probably generated by larger earthquake-triggered slope failures on much longer timescales. Our results highlight the complex interplay of sedimentary processes operating within major canyon systems.

Keywords: Nazaré, Setúbal, submarine canyon, continental margin, mass wasting, turbidity current

1. Introduction and aims

Previous work on submarine canyons has established that they are major pathways for the transport of sediment from land to the deep ocean (Berner, 1982; van Weering *et al.*, 2002; Canals *et al.*, 2006). Sediment accumulates at the canyon head from fluvial and/or shelf sources, producing a temporary sediment reservoir (Mastbergen & van den Berg, 2003). Sediment instability, due to higher supply rates, faster progradation and intense resuspension during storms and floods, is enhanced by the presence of rough topography and steep slopes in the upper canyon (Mulder *et al.*, 2001; Mullenbach *et al.*, 2004; Puig *et al.*, 2004). Failure can also be induced by earthquake-triggered deformation of sediment (Jones & Omoto, 2000). The failed sediment is then transported mainly by low frequency, high-energy gravity flows (Normark & Piper, 1991). Thus, the main sedimentary processes in canyons seem to be failure by mass wasting and subsequent transport by gravity flows. However, the dynamics of these processes in most modern canyons are poorly constrained, as is their overall role in the offshore export of sediment, due to difficulties in direct monitoring of sediment transport in canyons and in sampling in such rugged canyon topography.

Submarine canyons along European continental margins have recently been extensively studied as part of the EC-EUROSTRATAFORM project and the currently ongoing

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HERMES project (Weaver *et al*., 2004). In particular, the two projects have generated a significant amount of new data from Nazaré and Setúbal Canyons, offshore west Iberia, some of which are presented here. The principal aim of this study is to highlight the key gravity flow and mass wasting (i.e. slope failure) processes in the Nazaré and Setúbal Canyons. De Stigter *et al*. (in press) have recently suggested that gravity flows in Nazaré Canyon vary between yearly and centennial timescales, depending on the nature of the material being transported. Although the timing of gravity flow events has also been analysed as part of this study, it will be covered in detail in a future contribution and is only briefly discussed here.

2. Methodology and database

This study is based upon geophysical and sedimentological data collected during EC-EUROSTRATAFORM cruise CD157 (2004) and HERMES cruises D297 and CD179 (2005-2006). The data include multibeam bathymetry surveys, medium-resolution (30 kHz) deep-towed sidescan sonar mapping, and 3.5 kHz shallow seismic profiles. Over 40 shallow piston cores were recovered from accurately targeted sites along the two canyon systems in order to ground-truth the geophysical data. Piston cores were visually inspected, including estimates of grain size, and photographed.

3. Regional setting

The Nazaré and Setúbal Canyons (Fig. 1) are the two largest canyons of the west Iberian margin and are located on the central part of the margin, oriented roughly perpendicular to the coast in an east-west direction. Nazaré Canyon, ~100 km north of Lisbon, cuts across the shelf almost to the beach but is not connected to a major river system. Distally the canyon leads into the Iberian Abyssal Plain, some 210 km from the coast at a water depth (WD) of ~5000 m. About 30 km south of Lisbon, the Lisbon and Setúbal Canyons extend landwards across the shelf towards the mouths of the Tagus and Sado Rivers, respectively. Lisbon Canyon connects to Setúbal Canyon as a tributary at ~1500 m WD, and Setúbal Canyon then continues downslope until it reaches the Tagus Abyssal Plain at ~4840 m WD, some 175 km from the canyon head.

4. Observations of mass wasting and gravity flow features

4.1. NAZARE CANYON

4.1.1. Terraces and gullies in the upper section

The upper Nazaré Canyon (< ~4000 m WD) is characterised by rugged topography and steep slopes (Fig. 2), with abundant gullies incising into semi-circular erosional scarps (Figs. 3A,B). Intra-canyon terraces, which are generally long and narrow and oriented roughly parallel to the canyon axis, are observed only in the steepest locations, where the narrow V-shaped canyon has undergone multiple phases of incision into surrounding bedrock and semi-lithified sediments.

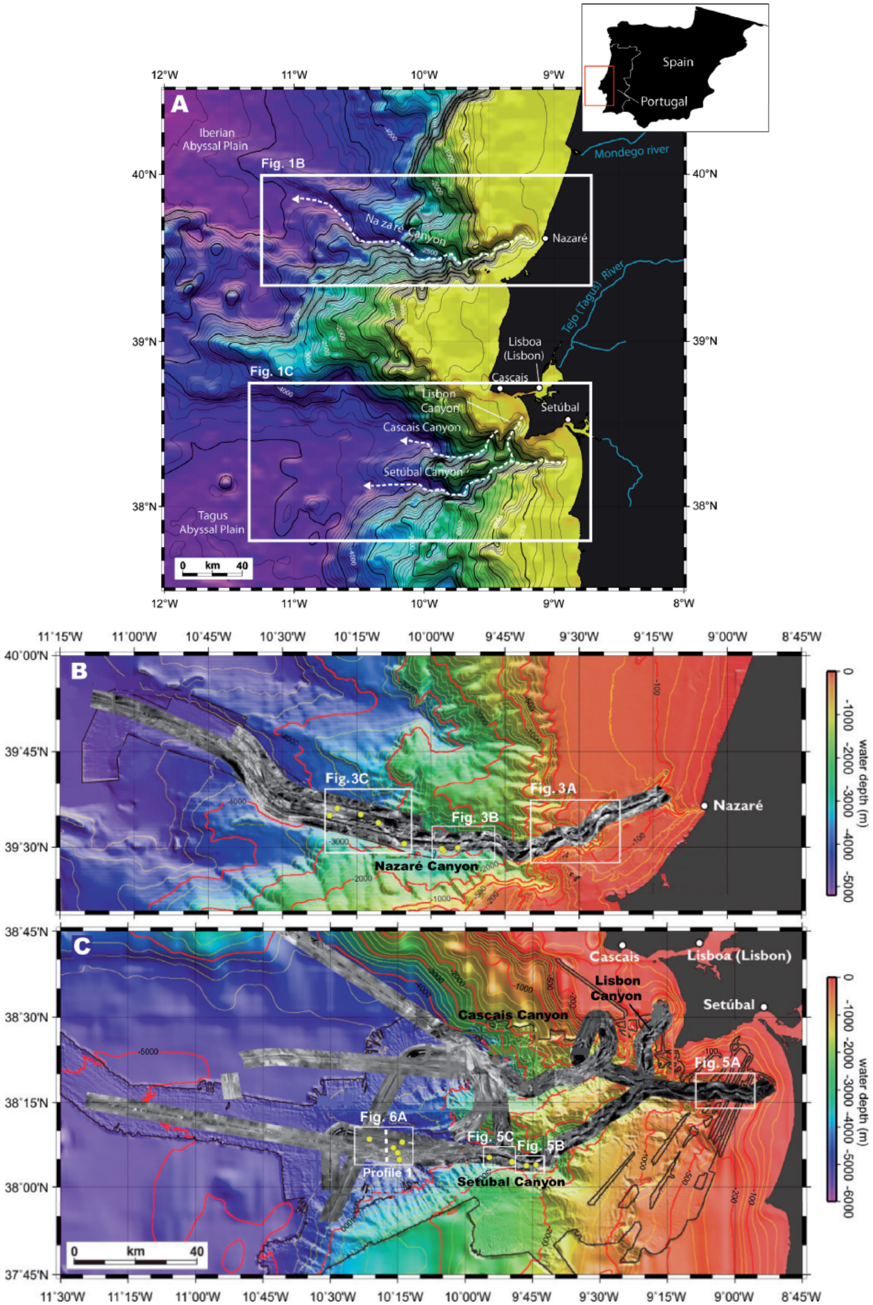

Figure 1. (A) Bathymetry map of the west Iberian margin showing the locations of Nazaré and Setúbal Canyons. (B,C) Coverage of sidescan sonar data for each canyon. Yellow dots represent the positions of piston cores. The dashed white line is shallow seismic profile 1 (Fig. 6B). Contours are every 25 m down to 200 m, then every 100 m.

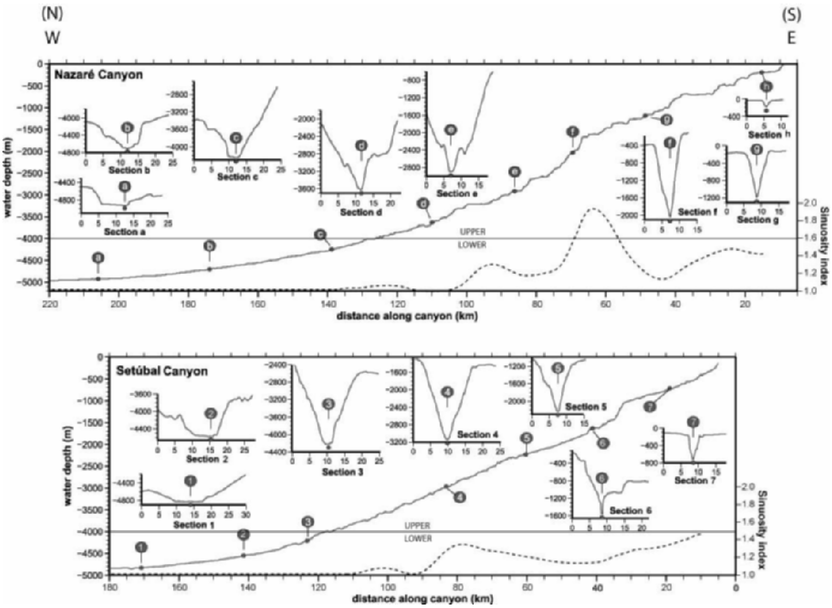

Figure 2. Down- and across-canyon bathymetric profiles of Nazaré and Setúbal Canyons (across-canyon profiles are taken facing up-slope, i.e. north is on left). A clear distinction can be made between the steep, deeply incised upper section, and the much flatter lower section in both canyons, with the boundary at ~4000 m water depth (WD). The sinuosity index is the sinuous distance over the straight distance (dashed lines), and appears to be highest in the upper sections and decreases considerably towards the lower sections.

4.1.2. Heterogeneous turbidite deposition in the lower section

Nazaré Canyon widens out abruptly ~130 km from the shelf edge and at ~4000 m WD, leading into the lower section with a 4-5 km-wide flat floor (Figs. 2, 3C). Cores in this area display two distinct types of turbidite: 1) thin-bedded, fine-grained silt-sand, organic- and mica-rich turbidites, and 2) thick, coarse-grained, clean siliciclastic sandy turbidites (Fig. 4). Backscatter variations on sidescan sonar data indicate heterogeneous distribution of sediment across the canyon floor, with the coarser-grained, siliciclastic sandy turbidites dominating on the thalweg and deeper parts of the canyon floor (e.g. core CD56419), and the finer-grained, thin-bedded turbidites being more abundant on the terraces and canyon margins (e.g. cores CD56420 and D15756).

4.2. SETUBAL CANYON

4.2.1. Terraces, small-scale mass wasting and gravity flows in the upper section

Upper Setúbal Canyon (< 4000 m WD) is V-shaped with steep terraced and gullied walls and a narrow thalweg (Figs. 2, 5A-C). Turbidites are widespread, e.g. core CD56416 (Fig. 5D). At ~4000 m WD, a striking example of a canyon margin failure can be seen (Fig. 5C), with several 100 m-wide blocks scattered across the canyon floor adjacent to an area of 1 km-long erosional lineations. Core CD56826 was recovered from the opposite side of the canyon to this rockfall, on a 140-160 m-high terrace. It displays a spectacular polymict debrite containing a variety of sub-rounded, semi-lithified silt and mud clasts up to 25 cm in diameter (Fig. 5D).

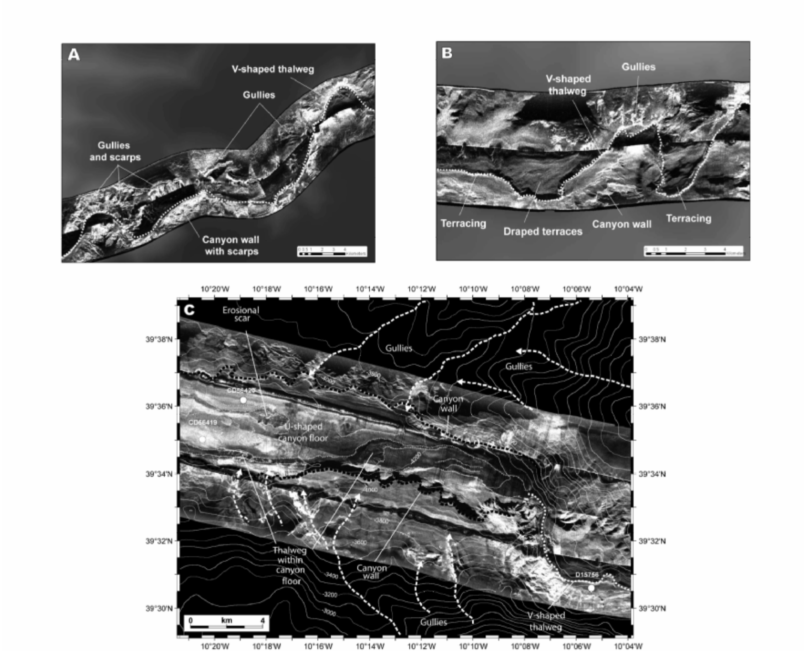

Figure 3. (A-B Sidescan sonar images of upper Nazaré Canyon features down to 3500 m WD. Note the narrow and sinuous V-shaped thalweg (white dotted line), and steep gullied and terraced walls. (C) The abrupt transition to the wider lower canyon occurs at ~4000 m WD. 100 m contours; cores described in Fig. 4.

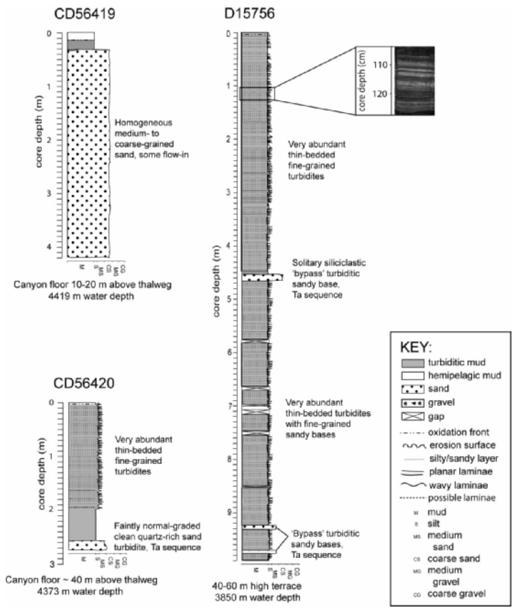

Figure 4. Logs of cores CD56419, CD56420 and D15756, recovered from Fig. 3C, show two types of turbidite: thick siliciclastic sandy and thin-bedded, fine-grained organic- and mica-rich (photographed).

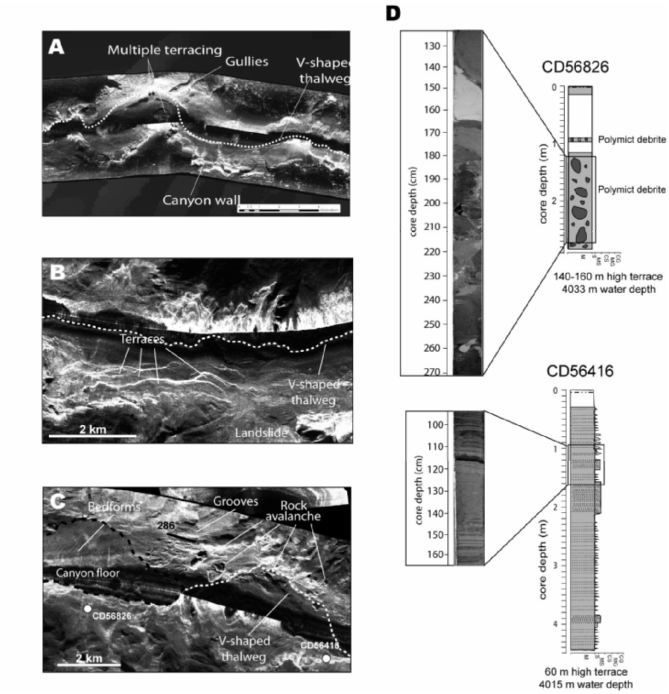

Figure 5. (A-C) Sidescan sonar images of upper Setúbal Canyon (~1000-1500 m, ~3000-3600 m and ~3700-4200 m WD respectively). Landslides and rockfalls are common, as is terracing due to incision of the narrow thalweg into the steep canyon margin, and grooves caused by erosive turbidity currents. (D) Sedimentary logs and photographs of cores, recovered from terraces in C. They show debris flow deposits and thin-bedded, fine-grained turbidites similar to those in upper Nazaré Canyon (c.f. Fig. 4). Refer to Fig. 4 for a key of sedimentary structures and symbols.

4.2.2. A large-scale submarine landslide in the lower section

The lower Setúbal Canyon rapidly widens below 4000 m WD (Figs. 1, 2). The flat canyon floor initially opens out to a width of 2 km and gradually 12 km near the canyon mouth. The canyon floor displays a 'zebra-stripe' backscatter pattern and cores recovered normally-graded, polymict gravel (CD56845, Fig. 6C), indicating that the backscatter pattern represents coarse-grained sediment waves (Wynn and Stow, 2002).

An area of uniform low backscatter can be seen on sidescan sonar data extending from the northern canyon margin and across part of the 'zebra-stripe'-patterned canyon floor (Fig. 6). Cores from this low backscatter area (CD56407, CD56408, CD56414, CD56415), both on the margin terraces and edges of the canyon floor, show thick remobilised sequences of contorted fine-grained hemipelagic and turbiditic sediments, as well as ungraded gravel. The turbidites are similar to those observcd on the upper canyon terraces (Figs. 4, 5D). They suggest that a slope failure on the N margin of lower Setúbal Canyon could have formed a debris flow/slump that remobilised both turbiditic and hemipelagic deposits on the terraces and coarse gravel bedforms on the canyon floor, but bypassing the area around un-remobilised core CD56845, possibly because it is slightly elevated (Fig. 6B).

5. Mass wasting and gravity flow processes in Nazaré and Setúbal Canyons

5.1. MASS WASTING PROCESSES

Several examples of intra-canyon mass wasting events are observed in the upper (< ~4000 m WD) Nazaré and Setúbal Canyons. These events are localised and small-scale (< 10 km^2), and include submarine landslides, debris flows and rockfalls; they are especially numerous in the upper Setúbal Canyon (Fig. 5). Such slope failures can be initiated by two types of factor (e.g. Masson *et al.*, 2006); external factors include short-period (minutes to hours) ground shaking by earthquakes, and longer-lasting (hundreds to thousands of years) effects of sea level change (Weaver and Kuijpers, 1983). Internal factors include sediment overpressure caused by rapid deposition, overloading, oversteepening, etc. (e.g. Terrinha *et al.*, 2003; Puig *et al.*, 2004).

The slope failures in the Portuguese Canyons are most likely caused by under-cutting and oversteepening of upper canyon margins by erosive turbidity currents (evidence is in the large number of terraces and high wall steepness), and/or ground shaking during regional earthquakes (e.g. Mulder *et al.*, 1998). The latter is believed to be particularly important here since the Iberian Peninsula is located just north of the present-day Africa/Eurasia plate boundary. Seismic activity along this fault zone is believed to be associated with historical large earthquakes in the area (such as the 1755 Lisbon earthquake, e.g. Weaver *et al.*, 2000). Only one instance of mass wasting beyond 4000 m WD is observed (Fig. 6). It is unknown what caused this slump/debris flow; however, a possible cause might be seismic-induced failure rather than overloading of sediment by storms or floods, as the latter are more influential in the shallower reaches of the canyons rather than at these depths > 4000 m.

5.2. TURBIDITY CURRENT PROCESSES

There appear to be two main types of turbidity current in the Nazaré and Setúbal Canyons: those that form the stacked, thin-bedded, fine-grained sand turbidites that are rich in mica and organic material, and those that produce the thicker, siliciclastic, coarser-grained sand turbidites. The former deposits have been successfully cored both on upper and lower canyon terraces ~40-60 m above the floor in both canyons (Figs. 4, 5D, 6C). They are also inferred to be present in the upper canyon floor along with the coarse siliciclastic turbidites; however, coring has been unsuccessful in this area due to poor penetration. The thin-bedded, closely-stacked deposits of the fine-grained turbidites indicate that they were regular flows that probably entered the canyon semi-continuously as small pulses of sediment that remained mainly in the upper canyon. Based on the unvarying small size of the deposits throughout the canyons (1-2 cm-thick bases, < 5 cm-thick mud caps; Figs. 4, 5D, 6C), it seems unlikely that the turbidity currents transported much sediment beyond the canyon mouths. These turbidity currents are thus inferred to be small-scale, relatively regular events (possibly on an annual scale, as proposed by de Stigter *et al.*, in press) that are probably the result of failures generated by overloading and over-steepening of sediment during floods and/or storms (e.g. Mulder *et al.*, 1998).

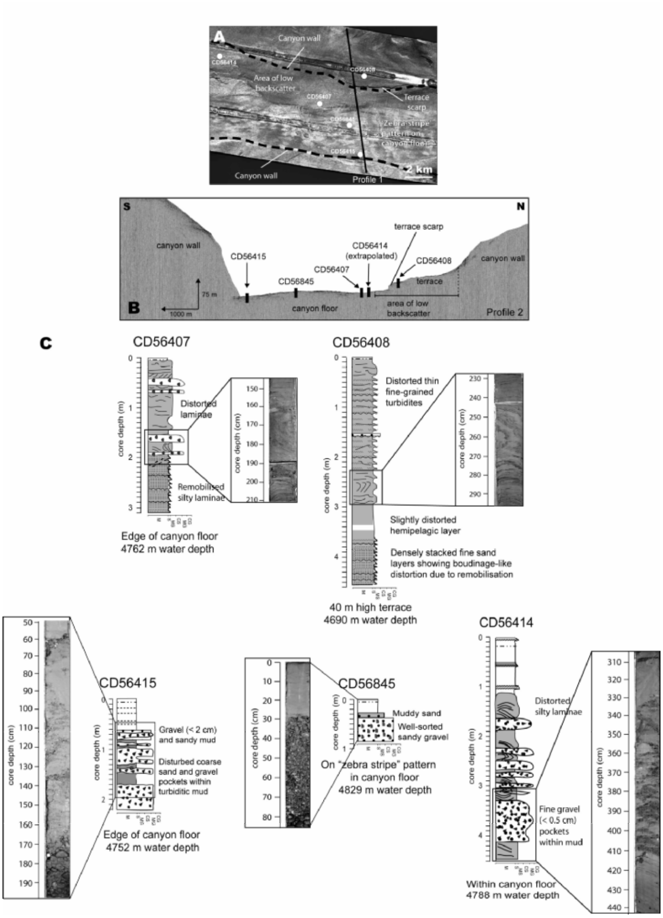

Figure 6. (A) Low backscatter area across lower Setúbal Canyon (canyon floor edges in dashed black lines). A suite of cores was recovered across this area (shown in C). (B) 3.5 kHz profile 1 taken across this area, with labelled location of cores. (C) Sedimentary logs and photographs of the cores shown in A and B. They imply that the low backscatter area is a debris flow/slump deposit that remobilised both terrace turbidites and canyon floor gravel waves, but that its trajectory did not affect core CD56845, possibly because of its slightly raised location (see B). Refer to Fig. 4 for a key of sedimentary structures and symbols.

The other type of turbidite, the clean siliciclastic sand, is generally observed on the terraces and floor of the lower sections, beyond ~4000 m WD (Fig. 4). The reason for this is probably varying settling velocities within different parts of the flow causing them to deposit in separate areas. The occasional occurrence of siliciclastic sandy bases on upper canyon terraces is probably due to centrifugal forces causing basal part of the flows to be deflected towards the outside (apex) of large bends, where they undergo superelevation and spill over the canyon margins (Keevil *et al*., 2006). These flows are inferred to flush through the entire canyons, as their deposits are found in the lower canyon floor, the abyssal plains (Thomson and Weaver, 1994) and are inferred to be present in the upper canyon floor (thalweg) due to repetitive failed coring. They are erosive flows, evidenced by considerable erosion in the lower canyon and mouth floor of both canyons, including large-scale scours and grooves that incise recent sediment deposits (Fig. 3C). They are therefore inferred to have completely eroded any earlier deposits of the stacked, thin-bedded, fine-grained turbidite type in the canyon floor, which is why none have been preserved here. A likely cause for these large and less frequent turbidity currents is therefore a larger-scale, less regular trigger such as earthquakes (e.g. Mulder *et al.*, 1998), and which are also relatively commonplace in the west Iberian margin. A likely centennial or longer timescale is suggested for this type of turbidity current in the Portuguese Canyons (de Stigter *et al.*, in press).

6. Conclusions

This new dataset comprises data at very different scales, from hundreds of km-scale imaging (multibeam bathymetry) to cm-scale detail (sediment cores). The integration of all these data show the high level of complexity that exists throughout all scales in the canyons of the west Iberian margin. The processes of gravity flow and mass wasting can, however, be simplified and the main similarities and differences observed in the Nazaré and Setúbal Canyons are listed below.

1. There are two main types of gravity flow that occur in Nazaré and Setúbal Canyons: 1) small, regular, organic- and mica-rich turbidity currents that deposit mainly on the shallower intra-canyon terraces, and 2) large, less regular, canyon-flushing turbidity currents that deposit mainly in the deeper parts of the canyon and the abyssal plains.
2. Turbidity currents seem to be the dominant mode of sediment transport and erosion taking place in the canyons, evidenced by the dominance of gravity flow deposits and erosive scours throughout both canyons.
3. Mass wasting events tend to be small-scale (< 10 km^2), localised and in the steep upper canyon sections, especially in Setúbal Canyon. Failure events in the lower sections are rare, as these areas are dominantly depositional and have more gentle gradients; however, one large failure deposit has been identified in lower Setúbal Canyon. These results suggest that Setúbal Canyon may have been more recently unstable than Nazaré Canyon, although there is no evidence for any significant difference in the gravity flow activity between the two canyons.

7. Acknowledgements

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