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Slope instability along the northeastern Iberian and Balearic continental margins

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ABSTRACT

This paper gathers the available information on submarine landslides identified in the northeastern Iberian continental margin and presents new data on both already known landslides and new, previously unknown ones. The 2,000 km^2, 26 km^3 resulting deposit of the BIG'95 debris flow in the Ebro margin; the 4 up to 16 km^2, 0.4 km^3 Eivissa slides in the Eivissa Channel; the 2 up to 65.6 km^2, 1.46 km^3 Barcelona slides in the shallow southern Catalan margin; and the western Gulf of Lions debris flow in the deep north Catalan margin are presented. This compilation is completed with several other previously undescribed small-scale mass-wasting deposits together with those observed in the Balearic Promontory. The amount and widespreading of submarine landslide deposits in the northern Iberian margins demonstrate that these margins are not an exception to the common occurence of these kind of structures worldwide, and give an idea on these phenomena recurrence even in margins considered moderately quiet, in terms of seismicity.

KEYWORDS Submarine landslides. Seismic stratigraphy. Swath bathymetry. Ebro margin. Catalan margin. Western Mediterranean Sea.

INTRODUCTION

Some decades ago it was thought that submarine landslides were a relatively scarce phenomenon that mostly occurred in seismically active regions, delta fronts and steep slopes (e.g., Moore, 1961). During the last years, the improvement of geophysical techniques devoted to obtain high-resolution bathymetric and sub-seafloor seismic data, and the growth of both the academic and the industrial interest in these processes, have allowed to undoubtedly identify hundreds of submarine landslides, involving variable amounts of sediment, in active and passive, glacial and river-dominated, sedimentary and volcanic margins (Hampton et al., 1996; Stoker et al., 1998; Canals et al., 2004). Now it is widely accepted that submarine landsliding is one of the most important processes in margin destruction and sediment redistribution from the shelf and upper slope to the base-of-slope and abyssal plains.

Under the water, landslides can be triggered by different mechanisms, just like it happens on land; and both onshore and offshore landslides share many characteristics, yet numerous differences can also be found, namely, those dealing with the nature of sediment and the physical characteristics of the environment. Submarine landslides usually travel larger distances and involve much bigger volumes: the largest subaerial landslide, the Mount Shasta landslide, involved 26 km^3 of material (Dingle, 1977), while the submarine Agulhas landslide amounted up to 20,000 km^3 of remobilized sediment (Crandell et al., 1984). Submarine landslides also pose a significant geologic risk since their almost punctual occurrence and the high velocities they can attain involve the release of large quantities of energy that could affect both directly or indirectly man made structures by both direct impact and generation of tsunami waves (Bea and Audibert, 1980; Carlson et al., 1980; Campbell, 1999). Large-scale mass wasting processes in submarine continental slopes have been the target of a large number of papers (i.e., Locat and Mienert, 2003; Mienert and Weaver, 2003) supported by numerous international projects (i.e., Mienert, 2004) aiming at better understanding of the physical mechanisms involved in the triggering, transport and accumulation of the remobilized material, with the final objective of developing an actual predictive ability in a variety of settings.

The Mediterranean Sea is not an exception to the widespread presence of submarine landslides. Some of them have even occurred in historical times and have been observed to happen, i.e. in Nice in 1979 (Gennesseaux et al., 1980) and in El-Asnam in 1980 (El-Robrini et al., 1985). Most of the resultant deposits of recent and sub-recent landslides in the Mediterranean have been identified in its northern margins, which are obviously the most studied ones (i.e., Canals, 1985; Rothwell et al., 1998; Droz et al., 2001; Lykousis et al., 2002; Acosta et al., 2002).

The first study reporting mass wasting processes in the northeastern Iberian margins identified “a very limited slumped slope segment” in the Ebro continental slope (Martínez del Olmo, 1984). Field and Gardner (1990) later reported “a large and thick sediment-slide zone” lying on the surface of the continental slope east of the Columbretes Islets. Alonso et al. (1990) reported mass transport deposits as “both sediment aprons and unconfined debris-flow deposits on the slope and base-of-slope” of the Ebro continental slope. Although these studies were based on a limited number of intermediate resolution and penetration seismic reflection profiles, which did not allow completely mapping the mass transport deposits described, they were the first to deal with the importance of submarine landsliding in the study area.

This paper is devoted to gather the information on submarine landslides identified in the northeastern Iberian and Balearic continental margins, to present new data on both already known landslides and new, previously unknown ones, to provide an overview of the potential failure mechanisms and also to examine their significance as downslope sedimentation mechanism in this Mediterranean region.

GEOLOGICAL SETTING

The Western Mediterranean Sea comprises several basins defined by a structural framework related to the Alpine orogeny, the nature and age of the crust and their recent sedimentological development (Biju-Duval and Montadert, 1976). One of these basins, the Valencia Trough, is bounded by the northeastern Iberian and the northern Balearic margins to the northwest and southeast, respectively. It is a NE-SW tectonic depression that opened simultaneously with the Provençal Basin during the Late Oligocene-Early Miocene (Biju-Duval and Montadert, 1976; Dañobeitia et al., 1990) as a result of the interplay between extensional and compressive processes. Extension concentrated in the Catalan-Valencian domain to the northwest, while compression located mostly in the Betic-Balearic domain to the southeast (Roca, 1992). Several seamounts and buried volcanic edifices have been recognized in the study area (e.g. Lastras et al., 2002).

Two main margin segments can be identified along the northeastern Iberian margin: the Catalan margin, to the north, and the Ebro margin to the south, following the names of the drainage basins that feed the margins, which amount 16,500 and 85,000 km^2 respectively. Sediments in the Catalan margin come mainly from smaller Catalan rivers such as the Llobregat, Tordera and Ter, while the Ebro margin is fed by sediment coming from the Ebro river. The Catalan margin displays a 6-30 km wide continental shelf with several tectonically-controlled V-shaped canyons deeply incised almost to the coastline (IGME, 1986, 1987, 1994). These canyons have steep, abrupt and gullied walls, indicative of the dominance of erosive processes (Fig. 1). The Ebro margin displays an up to 70 km wide continental shelf and a continental slope and rise cut by several, <15 km long submarine canyons and gullies that occasionally inciese the continental shelf (IGME, 1986; Canals et al., 2000). The base-of-slope is occupied by channel-levee complexes and inter-channel areas covered by debris flow and apron deposits, which form the Ebro Turbidite Systems (Alonso and Maldonado, 1990; Alonso et al., 1990; Nelson and Maldonado, 1990). Overall, constructive sedimentary processes seem to prevail in the Ebro margin (Fig. 1). The outbuilding of both margin segments during the Late Quaternary was mainly controlled by glacioeustatic sea-level oscillations, subsidence and changes in sediment supply (Farran and Maldonado, 1990; Ercilla and Alonso, 1996; Chiocci et al., 1997). A southwestwards regional circulation influences the distribution of fines and an underlying structural control predetermines the overall margin physiography.

The Balearic margin shows continental shelves less than 20 km wide and a steep continental slope (Acosta et al., 2002). No submarine canyons exist in the margin north of the Balearic Islands. The Valencia Channel, a mid-ocean channel type submarine valley (Canals et al., 2000), runs northeastwards in between the Iberian and the Balearic margins, collecting sediment from the bounding margins and driving it to the Provençal Basin. The morphological differences between these margins relate to the sediment supply, which is higher in the Ebro margin than in the Catalan margin, with the lowest values corresponding to the carbonate-dominated Balearic margin (Canals and Ballesteros, 1996).

DATA SET

This study is based on a compilation of both new and already published swath bathymetry data and high (HR) and very high resolution (VHR) seismic reflection profiles. Swath bathymetry data were acquired mainly onboard BIO Hespérides research vessel during BIG'95 (1995), MATER-2 (1999) and MARINADA (2002) surveys using Simrad's EM-12 on the slope and rise areas and EM-1002 on the continental shelf. Data were logged using Simrad's Mermaid system and processed using the Swathed software. Total area covered by these surveys

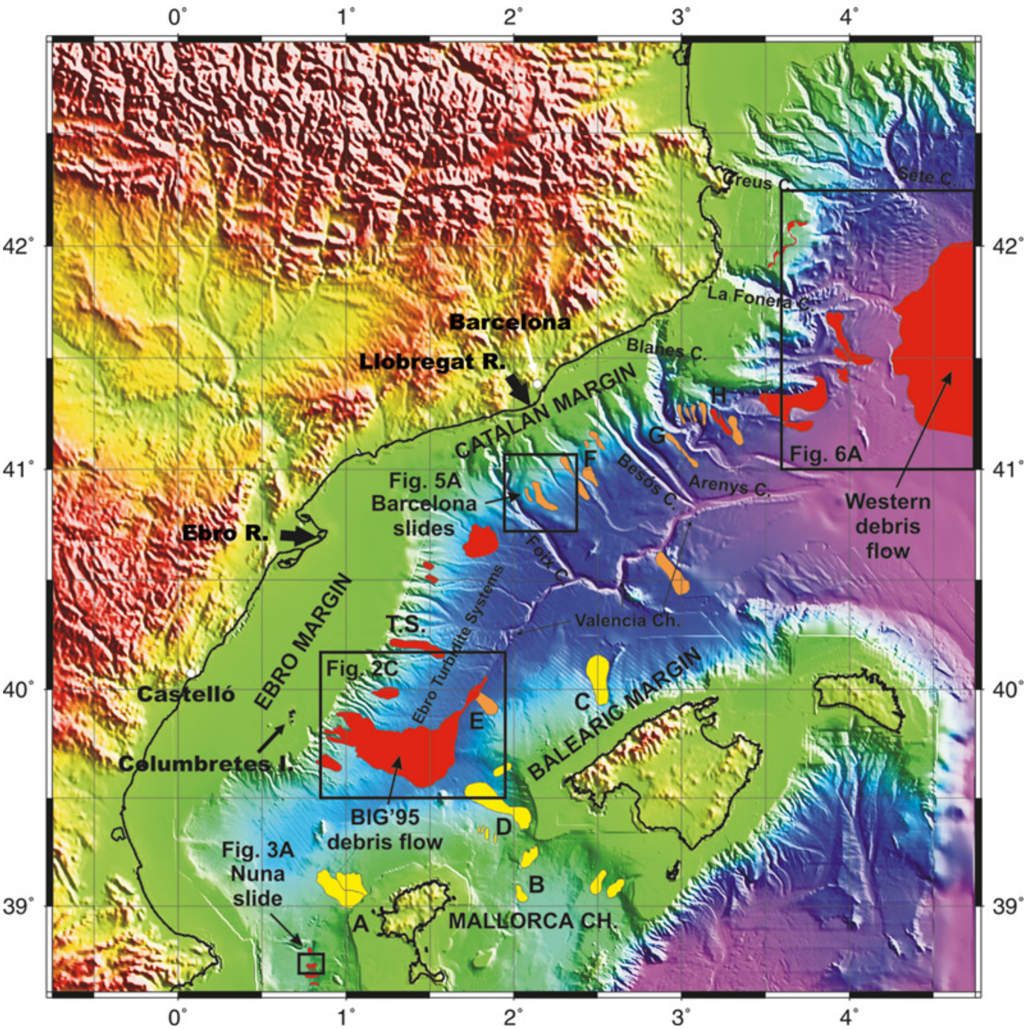

FIGURE 1 | **Digital terrain model of the northeastern Iberian margins and nearby areas, comprising emerged and submarine lands, obtained from the merging of several swath bathymetric data sets with the GEBCO digital database. Submarine landslide limits are shown in red (those atop of the sedimentary sequence) and in orange (buried landslides); those described by Acosta et al. (2001, 2002, 2004) are shown in yellow, whose precise stratigraphic position is unknown. Location of main canyons draining the shelf, and other figures in this paper are also provided. Legend: R.: river; I.: islets; Ch.: channel; C.: canyon; T.S.: Torreblanca slide.**

amounts over 57,500 km^2. This data set is complemented with lower resolution multibeam-derived data sets both on the deep Gulf of Lions and on the Balearic Promontory provided by IFREMER (Institut français de recherche pour l'exploitation de la mer) and IEO (Instituto Español de Oceonagrafía) respectively. The final digital terrain model (Fig. 1), comprising emerged and submarine lands, results from the merging of these bathymetric data sets with the GEBCO digital database (IOC et al., 2003). VHR seismic reflection profiles were acquired simultaneously to the swath bathymetry data using the hull-mounted Simrad TOPAS PS-018, which is based on the parametric interference principle. It yields a resolution higher than 1 m and a typical penetration between 50 and 200 m in deep-sea unconsolidated mud. HR sleeve-airguns profiles were also obtained during the MATER-2 survey simultaneously to the swath bathymetry.

In addition, seven piston cores were obtained in the BIG'95 debris flow area during CALMAR survey (1997) onboard l'Atalante, and two gravity cores during the TTR-11 survey (2001) onboard Professor Logachev. AMS ^{14}C dating of foraminifer shells of five samples taken from the piston cores was made in order to constrain the age of the BIG'95 debris flow (Lastras et al., 2002).

LANDSLIDING

Swath bathymetry, HR and VHR seismic profiles have allowed to identify most of the submarine landslides in the northeastern Iberian margins and westernmost Gulf of Lions, and to better constrain their shapes, dimensions and sea-floor expressions (Fig. 1). These data have shown that seismically transparent units attributed to debris-flow deposits and to non-channeled unsorted deposits are widespread in both the Ebro and the Catalan margins. The BIG'95 debris flow (Lastras et al., 2002) and the Western Gulf of Lions debris flow (Droz, 1983) are the largest known to date in the two margins, respectively. Taking into account that to describe each landslide in the northeastern Iberian margins would be beyond the scope of this paper, we present in the following sections a brief compilation of the landslides of each sub-margin with the most complete dataset: the BIG'95 debris flow in the Ebro margin, the Eivissa slides in the Balearic margins, the Barcelona slides in the southern Catalan margin and the Western debris flow in the northern deep Catalan margin, together with brief comments on other landslide deposits observed on each sub-margin.

The BIG'95 debris flow in the Ebro margin

First identified by Martínez del Olmo (1984) and Field and Gardner (1990), data acquired in and after 1995 showed that the BIG'95 debris flow deposit (formerly known as "Columbretes Slide"; Lastras et al., 2004a) was actually more than seven times the size first proposed (Lastras et al., 2002; Lastras, 2004). It is the most prominent mass-wasting deposit in the Ebro margin, mostly made of transparent seismic facies covering 2,000 km^2 of the southern Ebro continental slope and base-of-slope at depths ranging from 600 to almost 2,000 m (Fig. 2). It is located atop of the Quaternary

TABLE 1 | **Location, area, volume, length and depth of most of the landslides in the northern Iberian margins commented in the text.**

Name	Approx. location		Area affected (km^2)	Deposit volume (km^3)	Length (km)	Min - max depth (m)
	°N	°E				
BIG'95 debris flow	39°30' 40°10'	0° 55' 1° 55'	2,200	26	110	600 >1,800
Ana slide	38°38'30"	0°49'	6	0.14		635 810
Joan slide	38°41'	0°48'	16	0.4		600 ~870
Nuna slide	38°43'30"	0°47'30"	6.3	0.31		675 855
Jersi slide	38°47'30"	0°47'	7.9	0.19		755 905
"E" landslide	39°50' 40°00'	1°40' 1°50'	80	~3	~15	1,400 1,700
Northern Barcelona slide	40°49' 40°57'	2°05'30" 2°15'00"	66	1.46	19	1,100 1,580
Southern Barcelona slide	40°51'30" 40°55'00"	2°04'00" 2°06'30"	14	0.26	7.5	1,200 1,425

sequence, offshore the city of Castelló and off the Columbretes Islets (Fig. 1, Table 1), amounting up to 2,200 km^2 of affected seafloor including the scars. Its mean thickness is 13 m, and its volume has been estimated to be at least 26 km^3, involving approximately 40x10^9 tons of sediment (Lastras et al., 2004b). As a result of this event, pre-existing slope canyons and gullies were truncated, and a channel-levee complex was wiped out (Fig. 2). Four main areas have been distinguished within this debris flow: the scar area (SA), the proximal depositional area (PDA), the intermediate blocky depositional area (IDA) and the distal depositional area (DDA) (Fig. 2C; Lastras et al., 2002).

Seismic characteristics

The scar area (SA) is located between two prominent canyon-channel turbidite systems in a segment of the Ebro continental slope mostly regular and with small gullies, apparently rejuvenated compared to the rest of the margin, with a rougher topography and deep canyons and gullies. The sinuous, irregular BIG'95 headwall scar lies between ~600 m and 1,230 m water depth and opens to the southeast. It is 20 km long and up to 200 m high (Figs. 2A and 2C). It displays a staircase geometry in its easternmost section, a single smooth and regular slope in its central, steepest section, and a single step along its westernmost segment, where the headwall height decreases significantly (Lastras et al., 2003). Locally, the main headwall is partially buried by material released from secondary scars, further upslope. These are generally less than 10 m high and with limited lateral continuity, although two of them are up to 100 m high. Upslope from the main headwall, the debris flow deposit is generally less than 18 m thick. Sediment released from the headwall area flowed south-eastwards to the proximal depositional area, which constitutes the depocentre of the BIG'95 debris flow deposit, with accumulations over 90 m and up to 150 m (Fig. 2A). An up to 40 m high crescent-shaped secondary scar is also located in this area at water depths ranging from 1,350 m to 1,400 m. Although it represents only the 15% of the total affected area, sediment accumulated in this area is more than 40% of the total volume of the debris flow.

The intermediate depositional area (IDA), which displays a pattern of topographically elevated blocks separated by linear depressions, comprises about 50% of the total surface occupied by the debris flow deposit, extending at water depths ranging from 1,400 m to 1,550 m (Lastras et al., 2002). Mean slope gradients in this area are less than 1.2° and never exceed 4°. Up to two hundred irregular blocks, mostly between 1 and 5 km^2 and less than 10 m high, can be counted (Figs. 2B and C). However, there are also some blocks up to 25 km^2 and 35 m high. Altogether the blocks represent a volume of ~5.5 km^3. Depressions separating the blocks are generally less than 1 km wide, but some of them are up to 3 km wide, and are flat-bottomed. Backscattering imagery shows that blocks and depressions display a contrasting backscatter compared to the overall echo-character of the BIG'95 debris flow deposit (Lastras et al., 2002). Within the intermediate depositional area the deposit mostly displays transparent facies although strong internal reflectors are identified on

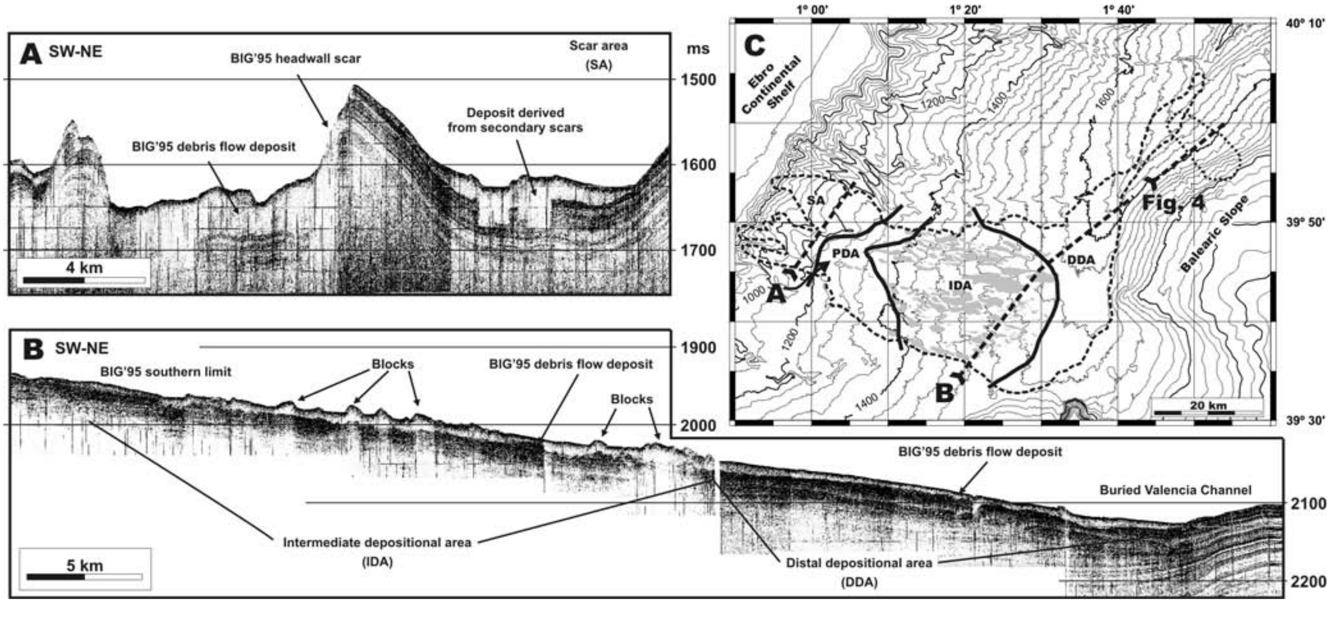

FIGURE 2 **The BIG'95 debris flow. A) Very high resolution seismic reflection profile across the scar area. B) Very high resolution seismic reflection profile across the intermediate and distal depositional areas. C) Swath bathymetry map of the BIG'95 debris flow. In the latter, SA is source area, PDA is proximal depositional area, IDA is intermediate depositional area and DDA is distal depositional area. Location of profile in Fig. 4, and the limits of the landslide deposits are also shown.**

some profiles (Fig. 2B). Blocks and elongate depressions in this area are evidenced by abrupt changes in topography, but no changes occur in seismic facies underneath (Fig. 2B). The base of the debris flow deposit is irregular and does not correspond to any specific reflector.

Flow in the smoother block-less distal depositional area (DDA), at water depths in excess of 1,550 m, was forced to turn NE because of the presence of the northern Balearic slope, before burying the uppermost course of the Valencia Channel. In the distal depositional area the debris flow deposit appears on VHR seismic profiles as a homogeneous, thin layer (<20 m) of transparent acoustic facies with no internal structure (Fig. 2B).

Sedimentological characteristics

Lastras et al. (2002) suggested that the BIG'95 debris flow deposit consists of two main sediment types, with contrasting characteristics and different source areas: a fine, cohesive material that partially kept its internal coherence, forming the observed blocks, and a relatively coarse, more mobile material, that was mostly remoulded during flow, which represents the rest of the debris flow deposit. Post-failure evolution of these two sediment types has been modeled and proved physically possible (Lastras et al., 2005).

Different signatures for in situ, debris flow and post-debris-flow deposits in piston cores were distinguished by direct observation and core logs (Urgeles et al., 2003). Micro-palaeontological analyses from samples taken from the debris flow have "colder" dinoflagelates and more steppic spores when compared to samples from the hemipelagic layer (Lastras et al., 2004b). This is an indication that sediments that later were involved in the debris flow were accumulated in a colder and more arid environment. A thin, 10 to 50 cm thick layer of post-landslide hemipelagic sediment caps the cores. Accelerator mass spectrometer ^{14}C dating of the base of this layer, 119 cm below the seafloor, yields a consistent minimum age of ca. 11,500 cal. yr. B.P. for the debris flow deposit (Lastras et al., 2002).

Other landslides in the Ebro margin

Other older sedimentary deposits that seem to have their origin in other landsliding events are distributed regularly within the Plio-Quaternary sequence of the Ebro continental margin (Lastras, 2004), the most prominent of them being located just overlying reflector G, which separates the Pliocene from the Quaternary sequence (Field and Gardner, 1990; Lastras et al., 2004b, figs. 10, 11 and 12). Other large-scale slides and debris flow deposits, among them the Torreblanca slide, have been observed in the unchannelled areas north and south of the BIG'95 debris flow, although none of them attaining its size and volume (Fig. 1; Casas et al., 2003).

The Eivissa slides in the Balearic margins

Four small slides are located in the Balearic margin of the Eivissa Channel, roughly aligned along the 0º48'E meridian (Table 1), at water depths ranging between 600 and 900 m. From south to north these are named Ana, Joan, Nuna (Fig. 3) and Jersi slides (Fig. 1; Lastras et al. 2004c). Their areas range from 6.0 to 16.0 km^2 and their volumes from 0.14 to 0.40 km^3. Their headwall scars are as high as 50 m and display irregular, horseshoe-shaped morphologies (Fig. 3). They occur in segments of the continental slope where the slope gradient varies from 1.6 to 3º. Their distal, depositional parts are characterized by areas of positive and rougher relief with respect to the surrounding seafloor (Fig. 3), although this relief is much less than the thickness of the disturbed sediment, thus demonstrating that sediment was not fully evacuated from the source area (Lastras et al. 2004c).

Seismic facies observed in VHR seismic reflection profiles vary from broken stratified facies locally at the foot of the headwall scars, to transparent in the slide deposit and discontinuously stratified at the toe, as related to the degree of disintegration of the original stratification. Both extensional and compression ridges have been identified in the Eivissa slides by means of deep-towed high resolution side scan sonar in 2004. Extensional ridges locate in the uppermost part of the slides and formed during retrogression of the headwall scars, while compression ridges appear in the depositional lobes as related to plastic deformation of the sediment during transport and deposition. These features have also been described in other submarine landslides around the world, such as the gigantic Storegga Slide off Norway (Canals et al., 2004; Haflidason et al., 2004).

The slip planes of the four Eivissa slides exploit the same characteristic high-amplitude reflector within the seismically well-stratified slope deposits outside the slides (Lastras et al., 2004c). This reflector is easily identifiable on most of the seismic profiles and must represent a mechanically weak layer over large areas of the Eivissa Channel.

Other landslides in the Balearic margins

Apart from the Eivissa Channel, submarine landslides are quite common around the Balearic Promontory and in the channels between the islands (A to D in Fig. 1). Acosta et al. (2001) identified numerous scars in the Mallorca Channel axis (B in Fig. 1), but the most comprehensive study is the one by Acosta et al. (2002), where two large slides northwest of Eivissa (A in Fig. 1) were identified, with sidewalls up to 50 m high. Furthermore, the same authors described the largest landslide in the Balearic Margins (D in Fig. 1; see fig. 7 in Acosta et al., 2002;

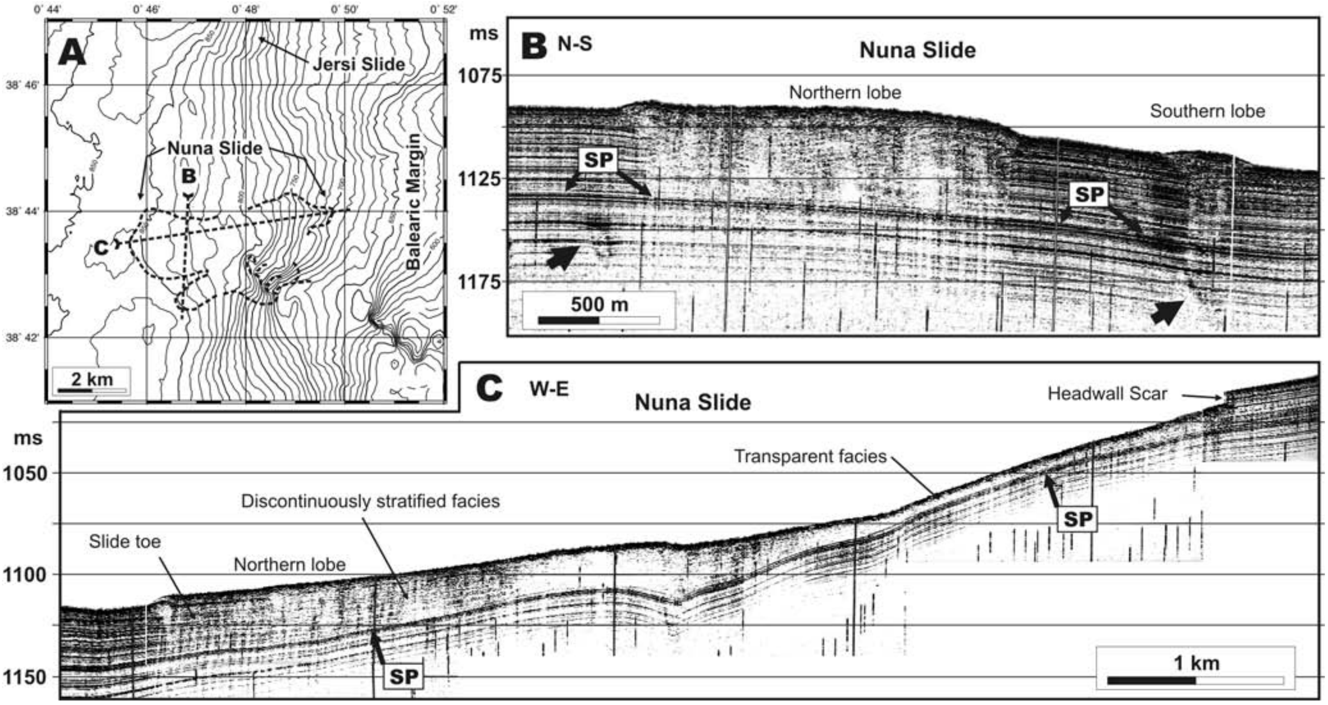

FIGURE 3 **The Nuna slide in the Eivissa Channel. A) Swath bathymetry map. B) Very high resolution seismic reflection profile across the distal lobes. C) Very high resolution seismic reflection profile along the Nuna slide. SP: Slip plane reflector. Bold arrows in B point to bright spots, usually indicative of fluids in the sediment. Profiles across the other Eivissa Channel slides have been provided in Lastras et al. (2004c).**

Acosta et al., 2004), affecting approximately 400 km^2 of the northern Mallorca Channel, and another landslide off the northwestern coast of Mallorca (C in Fig. 1). Although the authors give no data on the stratigraphic position of these submarine landslides, the ones north of Eivissa and in the northern Mallorca Channel (A and C in Fig. 1) look quite fresh in swath bathymetry images and are probably atop of the Plio-Quaternary sedimentary sequence.

Whereas the landslides described by Acosta et al. (2001, 2002, 2004) originated at shallow water depths (<1,000 m) in the Balearic continental slopes, another landslide deposit lying in the continental rise, at ~1,400 m water depth, has been identified recently (E in Fig. 1; Fig. 4). This deposit shows transparent seismic facies, is 40 m thick and is buried under some 25 m of the common continuously stratified seismic facies of the northern Balearic continental slope. Although it is a buried landslide, swath bathymetry data still shows some relief related to this structure, which is approximately 80 km^2 in area (Table 1).

Last but not least, the Balearic megaturbidite described by Rothwell et al. (1998) covers 77,000 km^2 of the Balearic abyssal plain, east of the Balearic Islands, with a 600 km^3 seismically transparent deposit of up to 10 m thick (Rothwell et al., 2000). Although major efforts have recently been made in its study, especially dealing with the location of the source area, its origin is still unknown, though it could be related with one of the major landslides events in the northeastern Iberian margin, the Gulf of Lions or in the other margins surrounding the Balearic abyssal plain.

The Barcelona slides in the southern Catalan margin

The Barcelona slides are two submarine landslides (the southern Barcelona and the northern Barcelona slides) in the southern Catalan margin, offshore south of the city of Barcelona and northeast of the Foix Canyon (Fig. 1). Although both landslides are buried by more than 50 m of sediment, the subdued image of their scar and resulting deposit can be observed in swath bathymetry maps (Fig. 5).

The southern Barcelona Slide (Table 1) is located at water depths ranging from 1,200 m to 1,425 m, in a sector

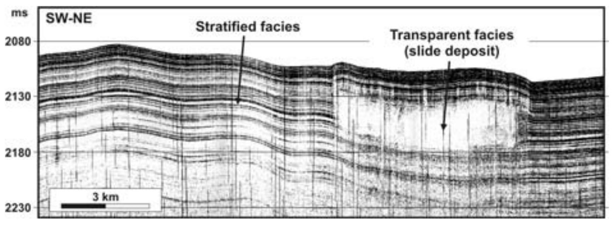

FIGURE 4 **Very high resolution seismic reflection profile across a slide deposit in the very base of the northern Balearic slope. Location of this profile and extent of the slide are shown in Fig. 2C.**

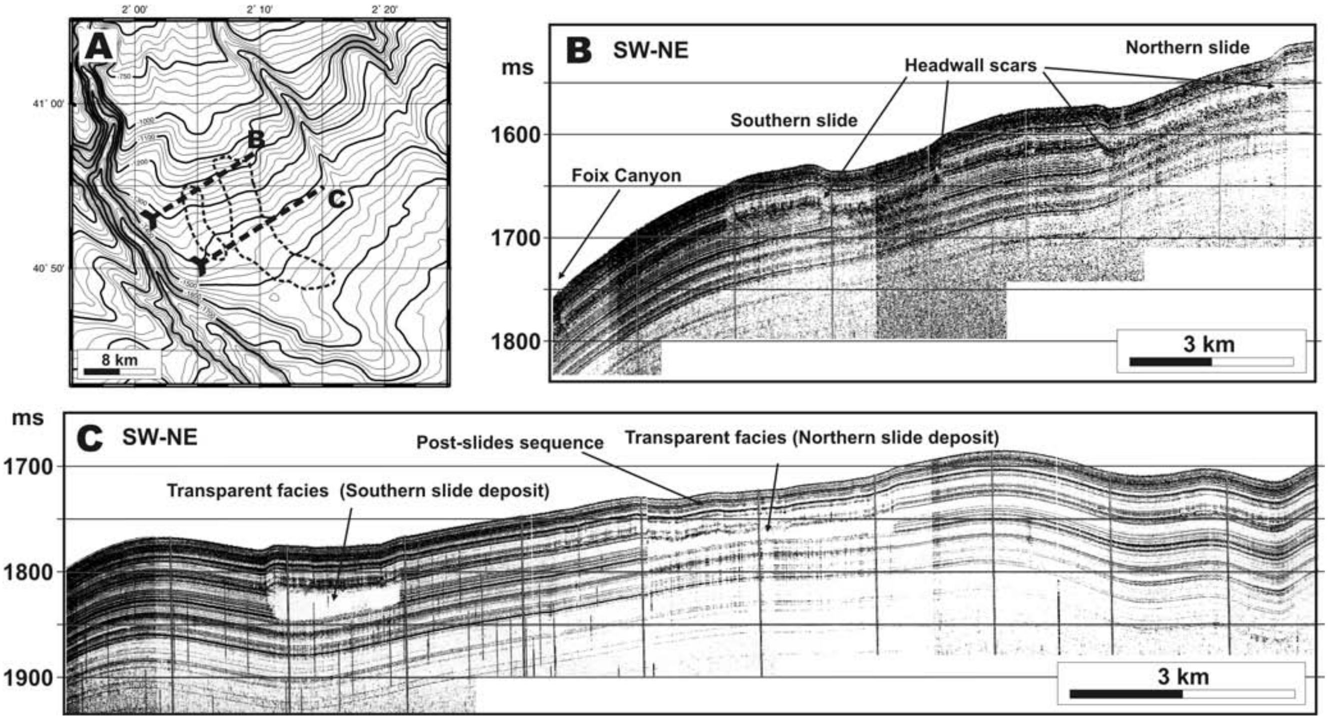

FIGURE 5 | **The Barcelona slides. A) Swath bathymetry map. B) Very high resolution seismic reflection profile across the source areas. C) Very high resolution seismic reflection profile across the depositional areas. The Foix Canyon lies southwest of the slides. Note that these slides are buried under some 40 m of sediment.**

of the margin with a mean slope gradient of 1.5º (Fig. 5A). Its headwall scar is located at water depths between 1,200 and 1,320 m and has a narrow horseshoe shape. Its total length from head to toe is 7.5 km and its mean width is 1.75 km, yielding a total area affected of 14 km^2. Downslope mobilised sediment moved south-eastwards.

The northern Barcelona Slide (Table 1) is located at water depths ranging from 1,100 m to 1,580 m, in a sector of the margin with a mean slope gradient of 1.4º (Fig. 5A). Its headwall scar is located at water depths between 1,120 and 1,310 m and also has a horseshoe shape. It is 19 km long from head to toe and has a mean width of 3.5 km, for a total area of 66 km^2. Downslope mobilised sediment first moved south-eastwards to later turn east south-east-wards.

Two VHR seismic reflection profiles crossing both landslides show that they are embedded in the continuously stratified seismic facies of this part of the margin (Fig. 5). The seismic profile crossing the source areas shows that the headwall scars of the Barcelona southern and northern slides had originally heights of 11 m and 8 m respectively, and that no mobilised sediment can be identified in this source area, thus demonstrating that failed sediment was totally evacuated from this area (Fig. 5B). The seismic profile crossing the resulting deposits shows these as lenses of transparent seismic facies with thicknesses of 35 m and 20 m, respectively (Fig. 5C). The seismic reflectors representing the base and the top of the slide deposits are located at mean depths of ~95 m and ~60 m below the seafloor, respectively, and are the same for both landslides. Taking into account these thicknesses, the volume of sediment involved in the southern landslide has been estimated to be 0.26 km^3, while the northern landslide would be 1.46 km^3.

Other landslides in the southern Catalan margin

Four other seismically transparent deposits (F in Fig. 1) have been identified between the Foix and the Besós canyons, none of them atop of the Plio-Quaternary sedimentary sequence. Another one has been observed between the Arenys and the Blanes canyons (G in Fig. 1). A series of six landslides, one of them atop of the sedimentary sequence, have been observed on the northern wall of the Blanes canyon (H in Fig. 1). All these deposits have approximately the same extension than the Barcelona slides. Smaller landslide deposits have been observed at the foot of an escarpment between La Fonera and Cap de Creus canyons (Fig. 1).

The Western Gulf of Lions debris flow in the northern Catalan margin

Méar (1984), Canals (1985) and Canals and Got (1986) were the first to study the westernmost Gulf of Lions continental slope and rise, and recently the effort

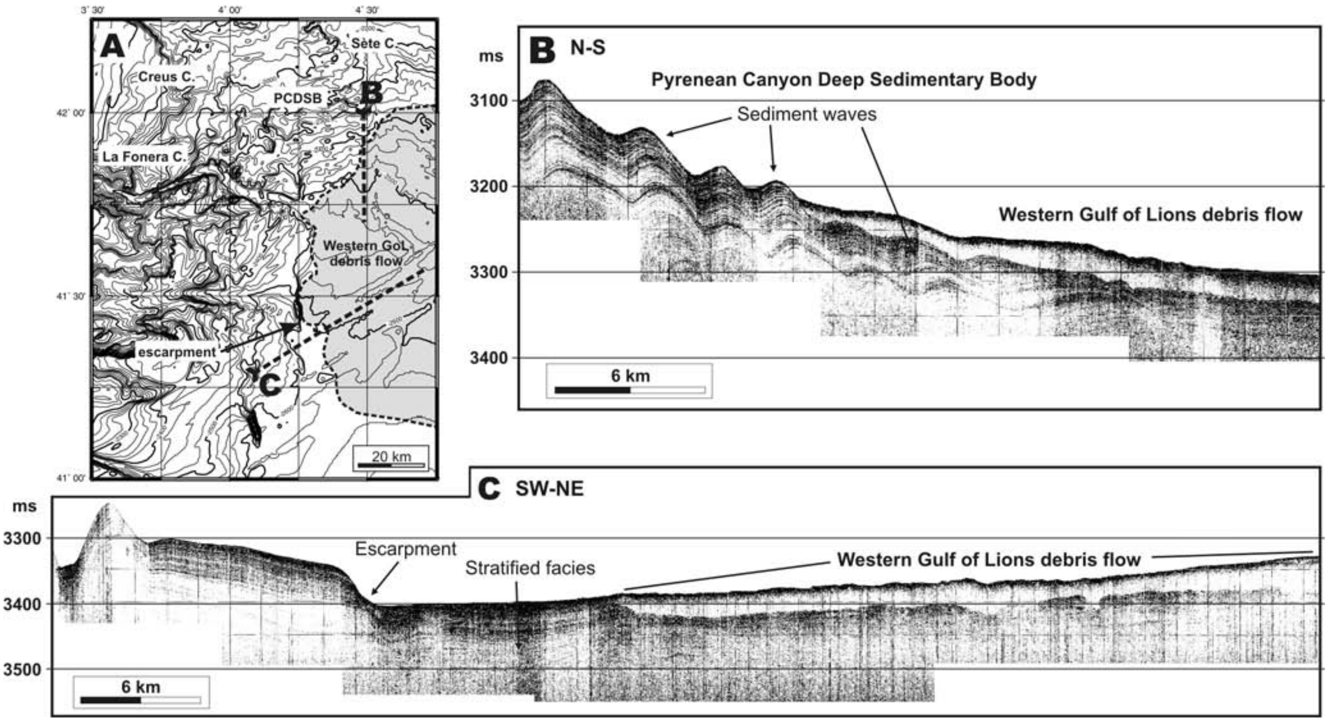

FIGURE 6 | **The Western Gulf of Lions debris flow. A) Swath bathymetry map. B) Very high resolution seismic reflection profile across its northern limit. C) Very high resolution seismic reflection profile across its western limit. The location of the escarpment commented in the text, as well as of the Cap de Creus, La Fonera and Sète canyons, and the Pyrenean canyon deep sedimentary body (PCDSB) are provided.**

has increased with the publications by Gaullier et al. (1998), Berné et al. (1999), Droz et al. (2001) and Bonnel et al. (2005), and the theses by Jallet (2002) and Baztán (2004). The western Gulf of Lions debris flow lies over a remarkable area on the deep Gulf of Lions, between the Pyrenean canyon deep sedimentary body (PCDSB; Canals, 1985; Alonso et al., 1991) and the right levée of the Petit-Rhône Fan (Droz et al., 2001). It is characterised by low backscattering on acoustic images (Berné et al., 1999) and corresponds to a N-S elongated transparent unit, 150 km long, 50 km wide, up to 120 ms thick with a volume of 260 km^3 (Gaullier et al., 1998; Bonnel et al., 2005).

Data available from the 2002 survey shows the westernmost limit of the Western Gulf of Lions debris flow (Fig. 6). VHR seismic reflection profiles allow drawing this limit accurately. This limit partially corresponds to a escarpment located at ~2,600 m water depth (Fig. 6A), although this escarpment only acted as a limit for the spreading of the mobilised material since seismic profiles show that it is not related with the deposit (Fig. 6C). The debris flow deposit, located atop of the sedimentary sequence, is up to 25 m thick and displays transparent seismic facies (Figs. 6B and 6C). In some sectors, it overlies a rough surface showing uncontinuous seismic reflectors (Fig. 6C), while in the northwestern limit it overlies the sediment waves of the PCDSB (Fig. 6B), at the mouth of the Creus, La Fonera and Sète canyons. Since data only cover part of the western Gulf of Lions debris flow, it is not possible to calculate neither the total extension nor the volume of a deposit that resulted from one of the largest mass wasting events, or from a succession of closely spaced events, in the entire area.

DISCUSSION AND CONCLUSIONS

It is clear from these examples, from the literature and in the light of Figure 1, that submarine mass wasting processes are very common in the northwestern Iberian and Balearic continental margins, both on top or embedded in the Plio-Quaternary sequence. But, are these events related to each other? Were they triggered the same way? Which way? Did they occur simultaneously?

Lastras et al. (2004b) concluded that a W-E-oriented volcanic dome located right under the main headwall of the BIG'95 debris flow, which marks an increase in the mean gradient of the Ebro continental slope, played an important role in the triggering of this landslide. Overall, landslide deposits identified in the Plio-Quaternary sequence just below the BIG'95 debris flow deposit show a similar spatial distribution, pointing to the recurrent character of sediment failure at this specific location (Lastras, 2004). The presence of the volcanic dome through time and consequently the oversteepening of the margin, together with overloading due to the sustained input by the Ebro River through time, and small earthquakes, could have lead to sediment destabilization during the past. Baraza et al. (1990) pointed out that seismically induced instability of the Ebro continental slope would need, at least, intensity VI earthquakes, never recorded during the last 70 years, but this value probably would be reduced due to the presence of the volcanic dome. Recently published data suggest that the latest growth pulses of the volcanic Columbretes Islets (Fig. 1) could be as young as the BIG'95 debris flow (Muñoz et al., 2005), and thus much stronger enhanced earthquake activity related to volcanism could have triggered this particular landslide.

Except for the Western Gulf of Lions debris flow, none of the other landslide deposits in the northwestern Iberian margins reach the same volumes of sediment involved, not even those located in the very same Ebro margin, some kilometers north and south of the BIG'95 debris flow (Fig. 1). This suggests that the presence of the dome hugely increased the amount of sediment involved in a single event, if we consider that most of the other landslides were triggered by the same earthquake or by an earthquake of similar magnitude. In other words, the same stress caused by similar earthquakes clearly had different consequences in a region already prone to failure such as that overlying the volcanic dome.

It is obvious by their stratigraphic position that all these landslides did not occur simultaneously following a huge regional triggering. But some of them, such as the northern and southern Barcelona slides, the four Eivissa slides, or some of the landslides described by Acosta et al. (2001) in the Mallorca Channel, occurred, each group, most probably at the same time under the same stress following a unique triggering mechanism: the slides in the Eivissa Channel occupy the same stratigraphic position and share the same slip plane, and the Barcelona slides are buried under the same 50 m thick sedimentary sequence and also share a common slip plane. In addition, the latter are located in a sector of the Catalan margin under the likely influence of old Llobregat river mouths (Fig. 1) and thus probably with high sedimentation rates, which could lead to underconsolidation increasing the instability of the sediment.

On the contrary, the Eivissa slides are located far away from any river mouth, in a margin with low sedimentation rates. In this case, the weakness of the slip plane could have been enhanced because of the escape of fluids from the sediment, as indicated by the observation of numerous pockmarks (Acosta et al., 2001; Lastras et al., 2004c) and other fluid-related features such as "bright spots" seen on the seismic reflection profiles (Fig. 3), indicative of the presence of gas in the sediment. The contribution of fluid venting to sediment instability is also of great importance in the Mallorca Channel, where seafloor is disrupted by the widespread presence of pockmarks of different sizes and depths, which often form pockmark alignments, creating linear discontinuities in the sediment that could lead to failure following a final triggering mechanism such as a small earthquake.

The origin of the Balearic megaturbidite is still unknown, and major efforts are being done to locate its source area, which would provide more evidences to understand the triggering mechanism of such an instabilisation. Its emplacement has been dated to occur during the last low-stand (Rothwell et al., 1998, 2000), thus not coincidently with the other large landslides in the northeastern Iberian margins.

The origin of the Western Gulf of Lions debris flow is discussed. Some authors point out that it can be multiple deposits, following a period of instability involving 370 km^3 of sediment also in a large debris flow in the left levée of the Rhône Fan, after the drop in turbiditic sedimentation in the upper levées, ca. 21 ka B.P. (Méar, 1984). Recent studies interpret it as a single slump or debris-flow deposit with sources from the continental slope between the Sète canyon and the right levee of the Rhône deep-sea fan (Gaullier et al., 1998).

According to the comments above, it is obvious that all these instability processes were not triggered the same way nor occurred simultaneously, except for those forming groups of slumps such as the two Barcelona slides or the four Eivissa slides. Nevertheless, landsliding represents an important process of sediment dynamics in the northeastern Iberian margins. It is difficult to compare the importance of this kind of processes in this margin with other margins around the world due to the fact that this has become one of the most investigated submarine regions in the last decades. Other regions largely surveyed such as the Norwegian margin clearly show different patterns in sediment instability. In the northeastern Iberian margins only one landslide exceeds 100 km^2 of affected area, and a large number of smaller < 100 km^2 landslides (Table 1; Fig. 1) have been identified, whereas in the Norwegian margin large landslides exceeding thousands of km^2 are surprisingly common (i.e. Laberg and Vorren, 2000). These different patterns could be related to the recent history of both margins, their origin and the nature of their sediment. On the contrary, river-dominated margins such as the western and eastern North American continental slopes show a more similar pattern of smaller landslides with a few large ones, as observed in the compilation by McAdoo et al. (2000).

In summary, several landslide deposits have been identified in the northeastern Iberian margin and nearby areas by means of swath bathymetry imagery and HR and VHR seismic reflection profiles. The BIG'95 debris flow affected 2,200 km^2 of seafloor and mobilised 26 km^3 of sediment in the slope and base-of-slope of the Ebro margin 11,500 cal. yr. B.P. Part of the Eivissa Channel is occupied by a series of four small landslides, the largest of which affected some 16 km^2 of its Balearic margin. Several other landslides have been identified in other sectors of the Balearic Promontory such as the Mallorca Channel, and at the very base of the northern Balearic slope, close to the Valencia Channel. Landsliding is also frequent in the intercanyon areas of the Catalan margin. Two of these landslides, the Barcelona slides, amount up to 70 km^2 of disturbed area. Furthermore, a new, more accurate limit has been drawn for the westernmost limit of the western Gulf of Lions debris flow. All these mass-wasting deposits demonstrate the relatively widespread occurrence of instability events in the study area. The analysis of their morphological characteristics is essential to answer further questions on the temporal frequency of these phenomena and the risk that further occurrences may pose to the highly populated coasts of the northwestern Mediterranean Sea.

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