# Seafloor imagery from the BIG′95 debris flow, western Mediterranean

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## ABSTRACT

**Seafloor backscatter data are used to image the product of one of the youngest major mass-wasting events in the northwestern Mediterranean Sea: a 26 km$^3$ debris-flow deposit that covers 2000 km$^2$ of the Ebro continental slope and base of slope, offshore Spain. Backscatter images provide unprecedented insights on debris-flow dynamics in the deep sea. A pattern of low-backscatter patches represents large sediment blocks that moved while keeping their internal coherence. High-backscatter alignments restricted to topographic lows that represent coarse sediment pathways separate the blocks. The results presented prove the occurrence of large catastrophic sediment failures near heavily populated coastal areas even in continental margins considered to be geodynamically quiet, such as those of the northwestern Mediterranean.**

**Keywords:** debris flow, continental slope, seafloor imagery, western Mediterranean.

## INTRODUCTION

This paper presents the results of the study of a large young debris flow on the Ebro margin, northwestern Mediterranean. A unique data set provides crucial information on the transport dynamics and sediment-dispersal patterns of submarine debris flows. The data set consists of swath bathymetry (EM-12E, EM-12 Dual, and EM-1002), 3.5 kHz topographic parametric source (TOPAS) profiles, high-resolution airgun seismic reflection profiles, and piston cores. Most of the data were acquired during a 1995 cruise of the R/V *Hespérides*; additional data were collected in 1997 (R/V *L'Atalante*) and 1999 (R/V *Hespérides*). This paper focuses on swath bathymetry data and derivative products (Figs. 1 and 2), processed using the SwathEd software.

## GEOLOGIC SETTING

The Mediterranean Basin is known for its active geodynamics: earthquakes and volcanic activity affect most of its subbasins and the surrounding landmasses. This situation has a strong potential to trigger catastrophic events such as submarine landslides and turbidity currents, resulting in deposits that have been identified in such settings (i.e., Gallignani, 1982; El-Robrini et al., 1985; Huson and Fortuin, 1985).

The northwestern Mediterranean region, although seismically quieter than other subbasins, has also undergone catastrophic slope failures. Some of them have occurred in modern times and have affected coastal infrastructures, e.g., the failure event off Nice in 1979 (Gennesseaux et al., 1980). Other geologically recent major landslide deposits have been identified in the Valencia Trough (Field and Gardner, 1990), the western Gulf of Lions (Canals, 1985; Berné et al., 1999), and on the Rhone deep-sea fan (Droz, 1983). The largest mass-wasting deposit in the western Mediterranean Sea is the 60 000 km$^2$, 500 km$^3$ turbidite in the Balearic abyssal plain (Rothwell et al., 1998).

The Ebro margin is located on the western side of the Valencia Trough, an early Miocene–Pleistocene extensional basin between the Balearic Islands and the Iberian Peninsula (Fig. 1A). The Ebro margin consists of a Pliocene-Pleistocene progradational sequence overlying the Messinian unconformity (Soler et al., 1983). Its modern base of slope and rise is formed by a series of migratory channel-levee complexes and by nonchanneled aprons. Several canyons slightly incised into the Ebro continental shelf edge feed these channel-levee complexes (Nelson and Maldonado, 1988).

## BIG'95 DEBRIS FLOW

A large sediment body with transparent seismic facies covering part of the southern Ebro slope and base of slope, partially described by Field and Gardner (1990) and termed ''the Columbretes Slide,'' was completely imaged in 1995 in topographic parametric source records and attributed to a debris-flow deposit following Mulder and Cochonat's (1996) criteria and the study of cores recovered in 1997 from the area. This sediment body (named BIG'95) at the top of the Plio-cene-Quaternary sequence is located offshore the city of Castellón and off the Columbretes Islets, from 39°30′N to 40°10′N, and from 0°55′E to 1°55′E. It extends over an area of ~2000 km$^2$, at water depths from 600 m to 2000 m (Fig. 1B), and has an overall golf-club shape. As a reference, this area is four times the area of the neighboring Ibiza Island in the Balearic Archipelago (Fig. 1A).

Although seismically transparent units attributed to debris-flow deposits and to nonchanneled unsorted deposits are widespread in the Ebro margin (Nelson and Maldonado, 1988; Field and Gardner, 1990), the BIG'95 is the largest known to date. Its volume has been estimated as $>$26 km$^3$.

### Source Area

Swath bathymetry allows the main headwall (labeled A in Fig. 1, C and D) and several secondary scars to be identified as the BIG'95 source area. All of these scars are located west of 1°10′E, between two canyon-channel systems. The headwall displays a sinuous shape and develops from west to east between 600 m and 1230 m of water depth. Its total length is ~20 km, and its height is as much as 200 m (Fig. 1D); it extends down into the sedimentary sequence as a southeastward-dipping normal fault (Fig. 3A) related to a dome-like, west-trending structure with chaotic seismic facies on seismic reflection profiles (see structure labeled as ''diapir A'' in Fig. 6 of Field and Gardner, 1990). This structure is interpreted as a volcanic dome associated with the dead Columbretes volcanic field (Maillard and Mauffret, 1993).

Three second-order scars (labeled B, C, and D in Fig. 1, C and D) are identified upslope of the headwall. Scar B, which is at ~1050 m, is 50 m high and trends north. The irregularly shaped scar C's upper rim is at a water depth of 800 m and is 100 m high. Sediment released from this scar partly buries the headwall, thus representing a younger event. Scar D is west trending, and its rim is at a water

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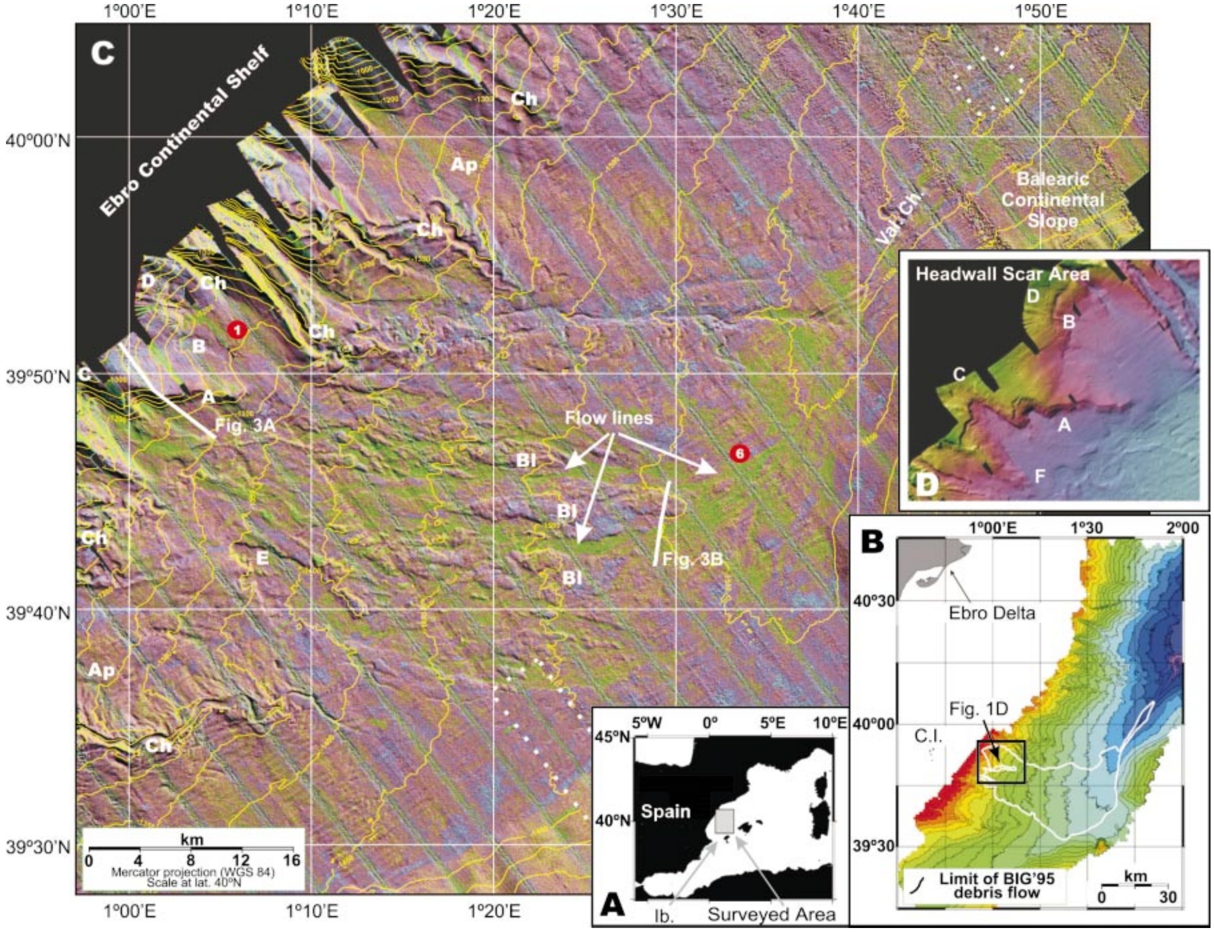

**Figure 1. A: Location map of surveyed area in western Mediterranean; Ib—Ibiza Island. B: Bathymetric map of surveyed area (contours every 50 m). White line bounds BIG'95 debris-flow deposit. Black box shows location of D; C.I.—Columbretes Islets. C: Combined backscatter (color key: green—highest backscatter, purple and blue—lowest backscatter) and shaded relief map of debris-flow area (contours every 50 m). Features: A—headwall; B–E—secondary scars; Bl—block clusters; Ap—apron; Ch—canyon-channel system; Val. Ch.—Valencia Channel; flow lines are also labeled. Labels in red circles show location and number of dated cores (Table 1). Northwest-trending striping is acquisition artifact, and white dotted boxes limit interpolated data. Note relationship between (1) blocks and depressed areas between blocks and (2) backscatter. D: Shaded-relief map of source and proximal area of debris flow; F—ghost of prelandslide channel.**

depth of 600 m. In addition, a fourth second-order, partially buried scar (labeled E in Fig. 1C), to 40 m high, is identified downslope of the headwall at a water depth of 1350 m. The presence of these scars indicates a multistage debris flow. As a result of the BIG'95 event, preexisting slope canyons and gullies were truncated (Fig. 2), and the entire seafloor relief was rejuvenated, both in and around the headwall and farther upslope. Similar effects have been described in other submarine failures, e.g., the Albemarle-Currituck slide in the U.S. mid-Atlantic continental slope (Driscoll et al., 2000).

## Depositional Area

Merging of bathymetric, shaded relief, and backscatter maps (Fig. 1) proves to be particularly efficient in showing the features of the depositional area, and allows the identification of three subareas.

1. The proximal depositional area immediately below the main headwall is relatively flat and constitutes the principal depocenter of the BIG'95 deposit. Transparent seismic facies in topographic parametric source profiles (Fig. 3) indicate a sediment accumulation of between 63 and 135 m (assuming a sound speed of 1800 m·s$^{-1}$ into the sediment) in this subarea. Downslope of the headwall, it has been observed that the debris-flow deposit locally overlies truncated reflectors, as if the underlying sediments had been dragged by the passage of the flow (Fig. 3B). In contrast, upslope of the headwall, debris derived from second-order scar C overlies continuous reflectors (Fig. 3A). These observations suggest a different basal behavior of the flow in the two zones. Ghosts of prelandslide channels (Figs. 1D and 2) are identified in the seafloor in this subarea.

2. The blocky intermediate depositional area is characterized by block clusters surrounded and crossed by linear depressions. Some of the individual blocks are as large as 25 km$^2$ in area and to 35 m high. The average thickness of the debris-flow deposit is <15 m, and never exceeds 35 m, in this subarea (Fig. 3). These blocks have a topographically irregular, low-backscatter surface (Fig. 1) and transparent (Fig. 3B) to chaotic acoustic facies, thus proving that they are part of the debris-flow deposit and not in situ remnants of the previous seafloor. They probably correspond to large sediment blocks that moved downslope while partly keeping their original internal coherence. During transport, original blocks broke into smaller fragments, creating the block clusters that can be observed in the imagery (Fig. 2). Recombining individual blocks within clusters (i.e., colored blocks in Fig. 2), as if they were pieces of a puzzle, allows us to reconstitute original parent blocks. Following this, these reconstituted parent blocks can be backstripped and relocated into a specific source area, downslope of the headwall, thus allowing calculation of runout distances (Fig. 2). Measurements following this procedure yield runouts between 15

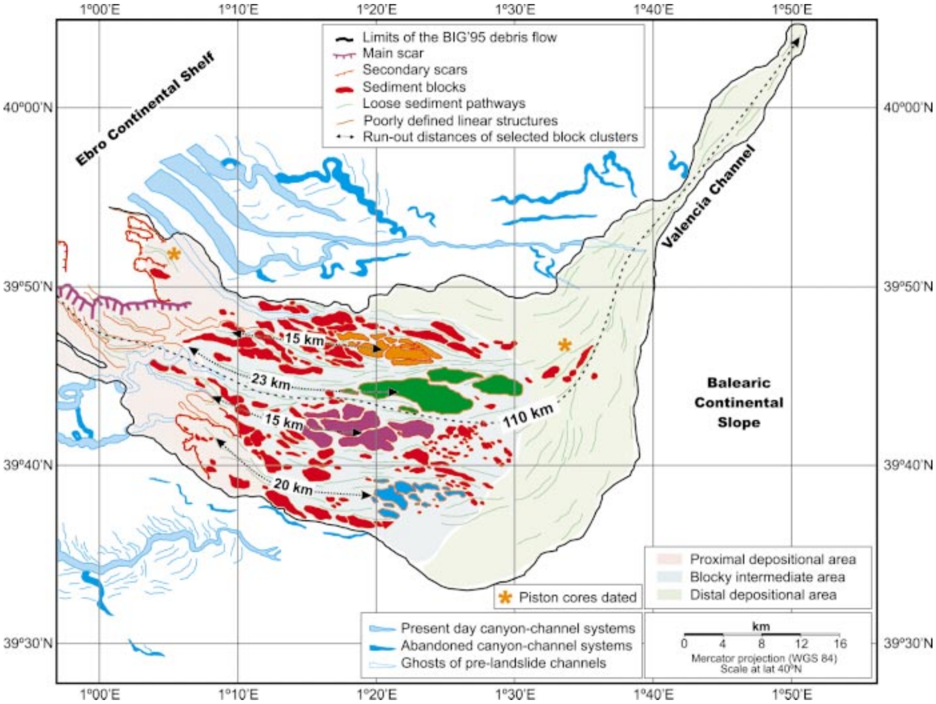

**Figure 2. Interpretation map based on Figure 1. Limits of debris flow (obtained from topographic parametric source), scars, blocks, and looser sediment pathways are shown. Various clusters of blocks are indicated in different colors, and runout distances of these particular clusters and total runout of looser material are shown. Block clusters are defined by relocating individual blocks that previously fit together.**

and 23 km. In the southern edge of this subarea, there is an alignment of blocks that probably detached from the sides of the area and were transported only tens to hundreds of meters. The depressed areas between blocks display a high backscatter, indicating that they consist of a material different from that forming the blocks. Because the overall distribution of the high-backscatter zones delineates the flow lines of the BIG'95 debris-flow deposit, we interpret them as corresponding to loose material, probably sandy and silty mud, the source area of which would be the headwall and upper slope. This material moved separately from and faster than the large blocks, which would have been constituted of more cohesive material from the base of slope (Fig. 2).

3. Only the highly mobile material depicting the flow lines was able to reach the distal depositional area, finally filling the uppermost 20 km of the Valencia Channel, which became flat bottomed (<1° slope). The total distance from the headwall to the distal end of the BIG'95 deposit is 110 km (Fig. 2). The backscatter pattern related to flow lines is less defined in this subarea, as we could expect from a decelerating debris-flow front. Thickness in the Valencia Channel ranges from 10 to 35 m, and is <10 m off channel.

Although the flow was poorly organized in the proximal area, as indicated by a weakly defined flow line pattern, it essentially followed a southeastward direction. Then, in the intermediate area, it turned eastward and finally shifted northeastward in response to the topography of the Balearic slope to the east (Fig. 1C). There is evidence for a climbing behavior of the debris over the lower Balearic slope (see high-backscatter area southeast of core 6 in Fig. 1C). It remains to be investigated whether the BIG'95 led to a turbidity current that would have eventually accumulated downchannel in the Valencia Channel and the Valencia Fan (Maldonado et al., 1985).

A 10–60-cm-thick hemipelagic unit recovered in piston cores drapes the slide deposit. Acclerator mass spectrometer $^{14}$C dating of foraminifer shells from the base of this unit in two cores from the source area downslope scars B and D, and the distal part of the deposit (location of cores in Figs. 1C and 2), provides a consistent minimum age of ca. 11 500 cal. yr B.P. for the BIG'95 debris flow (Table 1).

## CAUSES FOR LANDSLIDING

From the studied data set, at least four factors controlled the triggering of the BIG'95. (1) Differential mechanical behavior between the underlying volcanic rocks and the soft-sediment cover may have resulted in the formation of an upward-propagating normal fault that reached the seafloor forming the headwall (Fig. 3A). (2) Seismicity may have played a part. Although the Ebro margin is a passive margin, significant seismic events that may induce ground motions causing sediment lique-

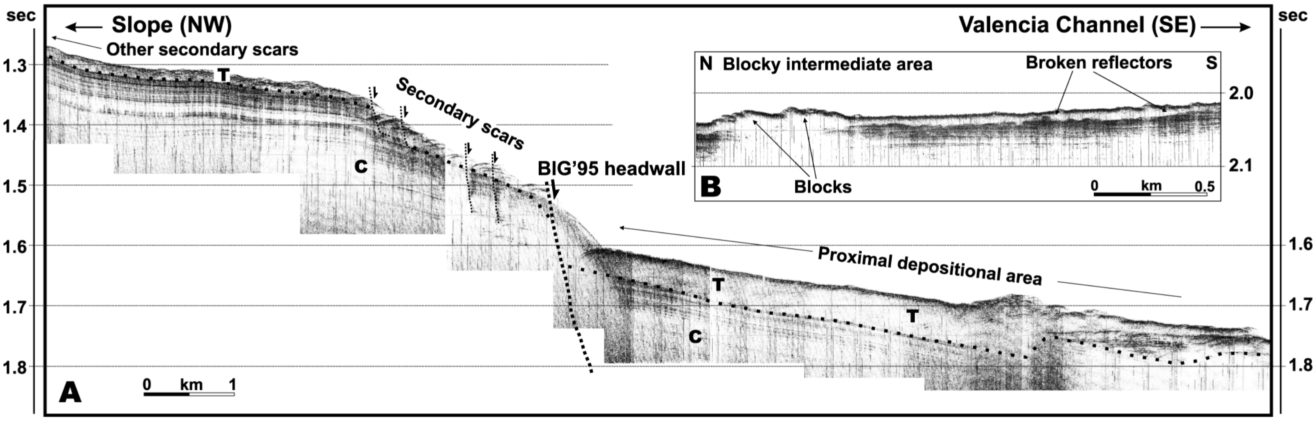

**Figure 3. A: Topographic parametric source (TOPAS) profile across BIG'95 headwall. This profile shows transparent (T) seismic facies that constitute debris-flow deposit overlying continuously stratified (C) facies of upper Quaternary sequence. Locations of headwall and secondary scars are indicated. Vertical exaggeration is ~9. B: TOPAS profile across distal part of blocky intermediate area. Note that debris-flow deposit overlies truncated reflectors. Vertical exaggeration is ~4.5. Time units are in seconds (two-way traveltime). Locations of both profiles are shown in Figure 1C.**

TABLE 1. AMS $^{14}$C AGE DATING

| Location |  | Water depth (m) | Sample | Core depth (cm) | Foraminifers sampled | $^{14}$C age (yr B.P.) | Calendar age (yr B.P.) |
|---|---|---|---|---|---|---|---|
| Lat(°N) | Long(°E) |  |  |  |  |  |  |
| Core 01 |  |  |  |  |  |  |  |
| 39°52.497′ | 1°04.435′ | 1230 | 1 | 39 | *G. ruber* | 3260 ± 50 | 3159–2996 |
|  |  |  | 2 | 99 | *G. ruber* | 8201 ± 60 | 8841–8589 |
|  |  |  | 3 | 119 | *G. bulloides* | 9950 ± 50 | 11124–10979 |
|  |  |  | 4 | 119 | *G. ruber* | 10430 ± 60 | 11647–11129 |
| Core 06 |  |  |  |  |  |  |  |
| 39°46.720′ | 1°33.390′ | 1579 | 5 | 30 | *G. ruber* | 10250 ± 60 | 11593–11531 |

*Note:* The five samples of *Globigerina bulloides* and *Globigerinoides ruber* were obtained from a hemipelagic layer draping the BIG'95 debris-flow deposit. Samples 3–5 are located $<$5 cm above the top of the deposit. $^{14}$C ages have been calibrated to calendar years for $1\sigma$ ranges for the marine environment using Calib3.0. A reservoir age of 402 yr is assumed. Location of cores is shown in Figures 1C and 2.

faction have been reported in historical and recent time (Field and Gardner, 1990). (3) The progradational slope was overloaded and oversteepened by rapid sedimentation, associated with a lowstand sedimentary depocenter of the paleo–Ebro River in the outermost shelf adjacent to the Columbretes Islets (Farran and Maldonado, 1990). (4) Fluid-escape structures, such as pockmarks observed nearby by Acosta et al. (2001), could be associated with local decreases of the sediment shear strength. An increase in near-bottom water temperature during the glacial to Holocene transition could have enhanced fluid release. It might be more than coincidence that reaching the present mean near-bottom water temperature, close to 13 °C in the area, possibly ca. 11 ka (Vergnaud-Grazzini and Pierre, 1991), was preceded by the BIG'95 event.

## CONCLUSIONS

A large sediment failure occurred on the Ebro continental slope close to the beginning of the Holocene. This failure, known as BIG'95, involved $>$26 km$^3$ of sediment and covered an area of $\sim$2000 km$^2$.

Following the formation of the headwall, large slabs of sediment detached mostly from the section now corresponding to the proximal depositional area and moved as far as 25 km downslope, breaking into smaller blocks but maintaining their original internal coherence. The blocks moved surrounded and perhaps supported by a looser, more mobile and coarse matrix released from the headwall, which flowed between and beyond them, reaching areas $>$100 km away from the headwall.

This main event also induced instability of the sediment upslope from the headwall, where second-order scars developed. As a result, additional material was released and incorporated into the matrix. The later release of this material resulted in the partial burying of the headwall. The flowing of the loose matrix created a distinct, horsetail-like pattern recognizable in backscatter images. The flow finally stopped in the Valencia Channel after partially filling a 20-km-long stretch of it.

A set of factors that could favor sediment instability on the Ebro margin has been identified. These include differential mechanical behavior, seismicity, local sediment overload, and fluid escape.

The study of the BIG'95 event provides fundamental insights into the sediment dynamics of submarine debris flows that could be used to design tank experiments for numerical modeling and simulations. Because of current trends and future prospects, oil companies have an urgent need to know more about deep-sea failures. We demonstrate herein that catastrophic sediment failures, such as the BIG'95, can occur in continental margins considered to be geodynamically quiet, such as those in the northwestern Mediterranean Sea. The potential for such events to generate tsunami waves that could damage coastal areas should not be neglected and deserves further research.

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