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# Morphology, distribution and origin of recent submarine landslides of the Ligurian Margin (North-western Mediterranean): some insights into geohazard assessment

Sébastien Migeon<sup>1,\*</sup>, Antonio Cattaneo<sup>2</sup>, Virginie Hassoun<sup>1</sup>, Christophe Larroque<sup>3</sup>, Nicola Corradi<sup>4</sup>,  
Francesco Fanucci<sup>5</sup>, Alexandre Dano<sup>1</sup>, Bernard Mercier de Lepinay<sup>3</sup>, Françoise Sage<sup>1</sup>  
and Christian Gorini<sup>6</sup>

<sup>1</sup> UMR GéoAzur, Université de Nice-Sophia Antipolis, CNRS, OCA, Port de la darse, 06235 Villefrance/Mer, France

<sup>2</sup> IFREMER, GM-LES, 29280 Plouzané, France

<sup>3</sup> UMR GéoAzur, Université de Nice-Sophia Antipolis, CNRS, OCA, 250 Rue A. Einstein, 06560 Valbonne, France

<sup>4</sup> University of Genova, Dip.Te.Ris, Corso Europa, 26 16100 Genova, Italy

<sup>5</sup> University of Trieste, DiGe, Italy

<sup>6</sup> UMR ISTeP, Université Pierre et Marie Curie, 4 Place Jussieu, 75252, Paris cedex05, France

\*: Corresponding author : Sébastien Migeon, email address : [migeon@geoazur.obs-vlfr.fr](mailto:migeon@geoazur.obs-vlfr.fr)

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## Abstract :

Based on new multibeam bathymetric data, seismic-reflection profiles and side-scan sonar images, a great number of submarine failures of various types and sizes was identified along the northern margin of the Ligurian Basin and characterized with 3 distinct end-members concerning their location on the margin, sedimentary processes and possible triggering mechanisms. They include superficial landslides mainly located in the vicinity of the main mountain-supplied rivers and on the inner walls of canyons (typically smaller than  $10^8$  m<sup>3</sup> in volume: Type 1), deep scars 100–500 m high along the base of the continental slope (Type 2), and large-scale scars and Mass Transport Deposits (MTDs) affecting the upper part of the slope (Type 3 failures). The MTDs are located in different environmental contexts of the margin, including the deep Var Sedimentary Ridge (VSR) and the upper part of the continental slope in the Gulf of Genova (Finale Slide and Portofino Slide), with volumes of missing sediment reaching up to  $1.5 \times 10^9$  m<sup>3</sup>. High sedimentation rates related to hyperpycnal flows, faults and earthquake activity, together with sea-level fluctuations are the main factors invoked to explain the distribution and sizes of these different failure types.

**Keywords :** Ligurian Sea ; Submarine landslides ; Seafloor morphology ; Seismic-reflection profiles ; Side-scan sonar

## 33 **1. Introduction**

34 Submarine failures have been described with increasing details, especially during the last two  
35 decades, in a wide range of climatic and tectonic settings, from glacial to subequatorial areas  
36 [*Huhnerbach and Masson, 2004; Imbo et al., 2003; Laberg et al., 2000; McAdoo et al., 2000;*  
37 *Piper et al., 1997*] and along both passive and active margins [*Collot et al., 2001; Goldfinger et*  
38 *al., 2000; Moore et al., 1989; Urgeles et al., 1997*]. Triggering factors are, consequently, as  
39 diverse as sea-level fluctuations, earthquakes, high-sediment supply leading to the overload of  
40 under-consolidated deposits, fluid charging and more [*Sultan et al., 2004b*]. Depending on their  
41 size and location on a margin, submarine failures could be responsible for various hazards  
42 including tsunami and destruction of infrastructures such as submarine cables [*Fine et al., 2005;*  
43 *Kvalstad, 2007; McAdoo and Watts, 2004; Piper et al., 1999*].

44 The interpretation of seafloor morphology in terms of mass wasting processes and the  
45 identification of the potential factors controlling sediment failure are of major importance for the  
46 geohazard assessment in a given area. The Mediterranean margins, which are tectonically active,  
47 have a steep morphology and are fed by small mountain-supplied rivers, are highly affected by  
48 severe landsliding processes. The Ligurian Basin experienced recently such phenomena: in 1979,  
49 a submarine failure ( $8 \times 10^6 \text{ m}^3$ ) occurred in shallow-water depth during infilling operations  
50 seaward of the Nice airport [*Gennesseaux et al., 1980*] and generated three successive waves, 2-  
51 3 m high, that broke along the coastline between the cities of Nice and Antibes. Three historical  
52 tsunamis are also well-known in the area (1564, 1818, 1887 AD) and are closely related to  
53 historical earthquake events. Earthquakes could have been responsible for tsunamogenic failures  
54 in the Ligurian Sea, as previously described in other margin settings [*Fryer et al., 2004; Lòpez-*  
55 *Venegas et al., 2008*].

56 The present study focuses on the northern margin of the Ligurian Sea where more than 500  
57 submarine failures of various sizes have been identified on the continental slope between the  
58 cities of Nice (France) and Genova (Italy). To analyse their morphologies and distribution on the  
59 slope, and to identify their triggering mechanisms, a large dataset including Simrad EM300  
60 multibeam bathymetry, seismic-reflection profiles, echo-sounder profiles and deep-tow side-scan  
61 sonar was acquired in the frame of the MALISAR cruises (2006, 2007, 2008). Our goal is to  
62 present the characters of the continental slope to outline the main features of the submarine  
63 failures and factors controlling their distribution. These results will help improving our ability to

64 predict such geohazards along the Ligurian Margin and every margins with a similar  
65 environmental context.

66

## 67 **2. Geological Setting**

### 68 2.1. Morphology of the margin and sediment supply

69 Along the northern margin of the Ligurian Sea, the continental-shelf width ranges from a  
70 maximum of 2 km to less than 200 m at specific location like along the “Baie des Anges”, in  
71 front of the city of Nice. The shelf break is thus located close to the coastline, at 50-100 m of  
72 water depth as an average but could be much shallower, i.e. less than 20 m of water depth, like in  
73 front of the Nice airport [Dan *et al.*, 2007]. The continental slope is steep and extends over 20 km  
74 to a water depth of 2000 m with an average angle of 11° [Cochonat *et al.*, 1993]. The base of the  
75 slope is characterised by a sharp decrease of the slope angle, to less than 3°. In the deep part of  
76 the basin (2600 m of water depth), the slope angle decreases to 1° or less.

77 The main sedimentary accumulation of the Ligurian Margin is the Var turbidite system,  
78 extending from the coastline offshore Nice to the Corsica island [Migeon *et al.*, 2006; Savoye *et*  
79 *al.*, 1993]. Particles are delivered to the Var system through two canyons, the Var and Paillon  
80 canyons, directly connected to rivers on land. Sediments are then distributed on the slope via  
81 gravity-flow processes or via the decantation of surface plumes [Klaucke *et al.*, 2000]. The Var  
82 and Paillon canyons coalesce at 1600 m of water depth and merge into a single submarine valley  
83 about 170-km long [Migeon *et al.*, 2006]. In its middle part, the Var Valley exhibits an East-West  
84 trend, and it is bordered to the south by a thick sediment accumulation, the Var Sedimentary  
85 Ridge.

86 Although the present-day morphology of the margin mainly results from Plio-Quaternary  
87 sedimentary processes, it has also been shaped by a sea-level lowering of about 1500 m during  
88 the Messinian Salinity Crisis (~5.96-5.32 Ma). The Messinian deposits marks a relevant step in  
89 the geological history of the Mediterranean. Their depocenter is partially controlled by inherited  
90 morphology, as demonstrated in cases where the pre-Messinian deposits are imaged in seismic  
91 profiles [Bertoni and Carthwright, 2006; Strzeczynski *et al.*, 2010]. On the Mediterranean  
92 margins, the Messinian sea-level lowering was responsible for the incision of canyons on the  
93 slope and the deposition of conglomerates at the base of the slope [Lofi *et al.*, 2005; Sage *et al.*,  
94 2005]. In the deep basin, it resulted in the deposition of thick evaporite layers [Hsu *et al.*, 1973].

95 The northern Ligurian margin is fed by numerous small mountain-supplied rivers, like the Var,  
96 Paillon, Roya, Taggia, Argentina, Arroscia, and Lavagna rivers. The largest one, the Var river,  
97 forms in the southwestern Alps, at 2352 m of altitude and 120 km inland, and drains a 2822 km<sup>2</sup>  
98 catchment basin [Mulder *et al.*, 1996]. These rivers experience abrupt flash floods during fall and  
99 spring seasons. The average water discharge of the Var river, about 50 m<sup>3</sup>/s, can increase tenfold  
100 during floods, and suspended sediment concentration can reach tens of kg/m<sup>3</sup>. From the rating  
101 curve of the Var river, [Mulder *et al.*, 1998] estimated that hyperpycnal currents could be  
102 generated during river floods, with a return period of about 2 to 5 years. Such turbulent flows are  
103 generated at river mouth when the density of fresh water transporting suspended particles exceeds  
104 the density of the ambient sea water. Thick fine-grained beds resulting from surface-plume  
105 deposition [Klaucke *et al.*, 2000], and coarser but thinner inversely graded beds resulting from  
106 hyperpycnal flows [Mulder *et al.*, 2001a] have been described on the slope offshore of Nice, as  
107 well as at greater water depth in the basin [Migeon *et al.*, 2001]. Sedimentation rates related to  
108 the activity of hyperpycnal flows can be as high as 1-2 m/100 years [Mulder *et al.*, 2001b]

109

## 110 2.2. Seismotectonic setting

111 The Ligurian basin is thought to originate from backarc extension related to the convergence  
112 between the European and African plates [Jolivet and Faccenna, 2000]. The Oligo-Miocene  
113 Ligurian rifting phase was followed by oceanic accretion between 20.5 and 18-15 Ma,  
114 responsible for the 30° counterclockwise rotation of the Corsica-Sardinia block [Réhault *et al.*,  
115 1984; Rollet *et al.*, 2002]. On land, some ancient and active faults exhibit a NW-SE trend  
116 corresponding to the direction of transfer faults that guided the rifting [Larroque *et al.*, 2001]. At  
117 sea, the continuity of the faults has not already been observed but the steep margin is incised by  
118 numerous canyons that could follow their direction [Chaumillon *et al.*, 1994].

119 Historical and instrumental seismicity is mainly located in the western part of the Ligurian  
120 margin (from the Cap Ferrat to Imperia), from the coastline to the base of the continental slope  
121 [Courboulex *et al.*, 1998; Eva *et al.*, 2001; Larroque *et al.*, this issue]. Some earthquake  
122 epicentres correlate with the location of faults and probably originated between 5 and 15 km  
123 below the seafloor [Courboulex *et al.*, 1998]. The southwestern Alps and the continental margin  
124 from Nice to Imperia experiences a recurrent seismic activity mainly characterised by several  
125 moderate and some strong historical earthquake events (1564 AD, Intensity MKS I=IX-X; 1644

126 AD, I=VIII; 1818 AD, I=VIII; 1887 AD, I=X) and recent events (1963 AD, Magnitude M=6.0;  
127 1981 AD, M=4.5; 1985 AD, M=4.1; 1989 AD, M=4.5; 1995 AD, M=4.7; 2001 AD, M=4.6;  
128 [Bakun and Scotti, 2006; Chaumillon et al., 1994; Larroque et al., 2009]). For the 1887 Ligurian  
129 earthquake, the macroseismic equivalent of magnitude has been estimated between 6.2 and 6.7  
130 [Bakun and Scotti, 2006; Ferrari, 1991]. Among the most recent earthquakes, some of them like  
131 the 1963, 1989, 1995 and 2001 events attest for reverse and strike-slip faulting [Courboulex et  
132 al., 1998]. This suggests a tectonic inversion of the margin implying reactivation of inherited  
133 transverse structures and development of new faults [Béthoux et al., 2008; Béthoux et al., 1992;  
134 Larroque et al., 2009]. This tectonic reactivation is responsible for an uplift of the margin that is  
135 mainly pronounced offshore the city of Imperia (Italy) [Bigot-Cormier et al., 2004].

136

### 137 **3. Methods and Data**

138 The dataset presented here was collected in the frame of the MALISAR Project. Three cruises  
139 were conducted in 2006, 2007 and 2008 along the whole Ligurian margin, from the city of Nice  
140 (France) to the Gulf of Genova (Italy) onboard R/V Le Suroît.

141 Multibeam bathymetry was collected using a Simrad EM300 and GPS-based navigation. Raw  
142 bathymetric data were processed and merged using the Caraibes software (Ifremer, France) to  
143 build a DTM with a spatial resolution of 25 m (Fig. 1). Bathymetric surveys covered the whole  
144 margin between 100 and 2500 m water depth. The general bathymetric map allowed a detailed  
145 study of seafloor morphology and the identification of mass-wasting related features. As  
146 headwall scars of submarine landslides are well defined on bathymetric data, it was possible to  
147 calculate the volume of sediment missing in some scars by reconstructing the pre-slide seafloor  
148 topography and subtracting the pre- and post-slided surfaces with the Caraibes and GMT  
149 software.

150 Side-scan sonar images and 3.5 kHz echo-sounder profiles were collected using the deep-towed  
151 SAR (Système Acoustique Remorqué) system developed by Ifremer for very high-resolution  
152 investigations of seafloor texture and micromorphology for water depths ranging from 200 to  
153 6000 m. The SAR is a side-scan sonar towed about 80-100 m above the seafloor, at an average  
154 speed of  $1 \text{ ms}^{-1}$  (2 knots). The system provides a 1500-m wide swath of the seafloor with a  
155 spatial resolution of 25 cm, and 3.5 kHz profiles with a vertical resolution of about 80 cm.

156 The internal architecture of slope deposits, failure scars and mass-transport deposits have

157 been studied using (1) Chirp profiles collected using a hull-mounted system (3 to 5 kHz) during  
158 the bathymetric surveys, and (2) seismic-reflection profiles of various resolution collected  
159 using a 300-m long 24-channels streamer and two mini-GI air gun (one 75/75 ci and one  
160 40/40 ci), and a 450-m long 72-channels streamer and six mini-GI air gun (three 25/25 ci and  
161 three 15/15 ci). Additional seismic-reflection profiles were collected during geophysical  
162 training cruises conducted by the Villefranche-sur-Mer marine station. The data were recorded  
163 using a 250 m-long 6-channel streamer and the seismic source was a mini-GI air-gun.

164

## 165 **4. Results**

### 166 4.1. General morphology of the Ligurian margin

167 Based on morphological characteristics, the Ligurian margin was divided in a western and an  
168 eastern segment separated by a SW-NE trending ridge called the Imperia Promontory (Fig. 1;  
169 Larroque et al., this issue). The study area comprises several morphologic domains that are  
170 briefly described below:

171 - Seventeen canyons erode the continental slope from the city of Nice to the Gulf of Genova.  
172 From west to east, they are the Var, Paillon, Roya, Nervia, Taggia, Verde, Mercula, Laigueglia,  
173 Cuenta, Varatella, Pora, Finale, Noli, Vado, Polcevera, Bisagno and Levante Canyons.  
174 Canyons initiate either at shallow water depth, directly at the mouth of some of the rivers  
175 feeding the Ligurian continental slope and basin, or at greater depth, along the outer  
176 continental shelf or on the upper continental slope. Along the western segment (Fig. 1),  
177 canyons are mainly straight and perpendicular to the direction of the margin. Along the eastern  
178 segment (Fig. 1), the Mercula and Laigueglia Canyons exhibit an unusual parallel direction to  
179 the margin that is clearly constrained by the presence of the Imperia Promontory. All the  
180 canyons identified along the eastern segment merge at about 2000 m water depth into a larger  
181 submarine valley called the Genova Submarine Valley.

182 - The Var Sedimentary Ridge (VSR) is a thick W-E elongate sediment accumulation  
183 corresponding to the right-hand levee of the Var Valley (Figs 1 and 2) [Migeon et al., 2006]. It  
184 lies at the base of the continental slope between 2100 and 2500 m water depth. The slope angle  
185 varies from 10° on the inner flank (facing the Var Valley) to 2-3° on the outer flank. On seismic-  
186 reflection profiles, the internal architecture of the Ridge show well-layered, low to moderate-  
187 amplitude reflections corresponding to the rhythmic alternation of turbidites and hemipelagites

188 [Migeon *et al.*, 2006; Savoye *et al.*, 1993]. Several lenticular bodies, with high-amplitude  
189 discontinuous to chaotic reflections and interpreted as paleochannels, are interbedded within the  
190 well-layered seismic facies at several depths below the seafloor [Migeon *et al.*, 2006; Savoye *et*  
191 *al.*, 1993]. The VSR built on top of the thick evaporite layer deposited during the Messinian  
192 Salinity Crisis [Savoye *et al.*, 1993].

193 - Numerous remarkable large-scale failure scars affect the base of the continental slope along the  
194 western segment (Fig. 1). Similar scars are absent from the eastern segment. The different types  
195 of slope instabilities, their distribution and potential triggering factors are described and  
196 discussed below.

197 - Several fault scarps tens of meters high, with a SW-NE trend, are located at the base of the  
198 continental slope or at greater depth in the basin, south of the Imperia Promontory (Fig. 1). The  
199 relationship between these faults and the deformation and seismicity of the Ligurian margin is  
200 discussed by Larroque *et al.* (this issue).

201 The main geohazards identified by means of multibeam bathymetry and geophysical data are  
202 failure scars and faults. The integration of observations coming from bathymetric data side-  
203 scan sonar images and seismic-reflection profiles allows us to distinguish three main Types of  
204 slope failures along the northern Ligurian margin, based on the morphology, size and specific  
205 location of scars on the continental slope.

206

#### 207 4.2. Type 1 failure scars

208 Type-1 failure scars are mainly superficial and affect the uppermost 30 to 90 m of deposits  
209 below the seafloor, representing volumes less than  $10^8 \text{ m}^3$  on average (Table 1). The largest  
210 number of Type-1 scars (about 200) was found on the upper slope in the vicinity of the main  
211 feeding rivers, i.e. the Var and Paillon rivers (Fig. 2). This is the case of the so-called “Nice  
212 1979” submarine landslide that was triggered at the transition between the outer continental shelf  
213 and the upper continental slope (Fig. 3A) [Dan *et al.*, 2007]. There, the continental slope exhibits  
214 a concave-up topographic profile (Fig. 1) and slope angle is 10 to 15°. Some Type-1 failure scars  
215 are also located: (1) on the inner walls of most of the canyons eroding the continental slope,  
216 where the slope angle exceeds 20°, and (2) on open slope environments, far from direct sediment  
217 supply and canyons but close to earthquake-epicentral areas like the one of the 1887 earthquake,  
218 where the slope angle is about 5°.



219 Whatever their location on the continental slope, Type-1 scars mainly exhibit an ellipsoidal or  
220 amphitheatre-like morphology (Fig. 3). In some cases, scars are more complex, and consist of  
221 several nested amphitheatre-like morphologies (Fig. 3B). Each scar is continuing on the slope by  
222 a chute that evidences the erosive power of the failed mass remobilized in the scar (Fig. 3). The  
223 chutes are essentially straight in the direction of the main slope angle in their downslope part,  
224 whereas they exhibit a low-sinuosity pattern in their upstream part (Fig. 3A). They are few  
225 hundred meters to 5-km long. The chutes show a width comparable with that of the scars in the  
226 upper reach, then enlarge and deepen downslope. In most cases, on both bathymetric data and  
227 Chirp profiles, Mass-Transport Deposits (MTD) are not found downstream from the scars, in the  
228 chutes. A similar observation was made by [Klaucke and Cochonat, 1999] from the detailed  
229 study of the Nice slope using SAR data. This suggests that the remobilized deposits are  
230 completely evacuated to the base of the slope, in a manner similar to „disintegrative“ mass  
231 failures [McAdoo et al., 2000]. Rare small-scale MTD were identified from the presence of  
232 compressive ridges (Fig. 3B) and transparent echofacies. They are mainly located at the  
233 transition between the canyon walls and the canyon floors where the slope angle decreases  
234 rapidly.

235

#### 236 4.3. Type 2 failure scars

237 Type 2 failure scars are large scars affecting the base of the continental slope, between 1700  
238 and 2200 m of water depth (Fig. 2; Table 1). The best known example of such type of failure is  
239 the so-called “Cirque Marcel” [Savoie and Piper, 1991]. Fourteen failures of Type 2 have  
240 been identified along the 50-km long segment of the slope comprised between the cities of  
241 Nice (France) and Imperia (Italy). Here, the continental slope exhibits a convex-up  
242 topographic profile (Fig. 1). The location of scars correlates with the steepest part of the  
243 continental slope, where the slope angle is of about 6°.

244 Type-2 scars are 2 to 4-km wide, 4 to 6-km long as an average. Volumes of remobilized deposits  
245 decrease gradually eastward from  $2\text{-}2.6 \times 10^9 \text{ m}^3$  to less than  $25 \times 10^6 \text{ m}^3$ . In plan view, they  
246 exhibit a complex amphitheatre-like morphology resulting from several semi-circular nested  
247 scars (Fig. 4). In the Cirque Marcel, from the top to the base, four scars are present with heights  
248 ranging from 100 to 300 m. They are separated by flat areas 1 to 2-km wide. These areas exhibit  
249 evidences of erosional processes, revealed by the presence of smaller-scale scars and scours

250 (Figs 4 and 5). The scars also exhibit semi-circular geometry on both bathymetric profiles (Fig.  
251 4) and Chirp and 3.5 kHz (SAR) profiles (Fig. 5). Draping hemipelagic-like deposits are not  
252 observed on 3.5 kHz (SAR) profiles (Fig. 5), suggesting recent phase of triggering or superficial  
253 sediment removal by low-density gravity flows and bottom currents. Accumulations of  
254 destabilized deposits are located at the foot of these structures, at the base of the continental  
255 slope (Figs 4 and 5). They are 20 to up to 80 m in thickness and extend laterally over maximum  
256 distances of 5 km. Rocky blocks, tens of meters in diameter, are scattered on top of these  
257 accumulations (Fig. 5 and 6). For the Cirque Marcel, the volume of the accumulation is about  
258  $1.3 \times 10^8 \text{ m}^3$ , i.e. 20 times lower than the total volume of the missing sediment in the scar.  
259 Seismic-reflection profiles suggest these large failure-related scars affected in most cases the  
260 whole Plio-Quaternary section, 300 to 500-m thick, and the slip plans correlate with the top of  
261 the Messinian conglomerates (Fig. 7). In the “Cirque Marcel”, this interpretation is supported by  
262 direct observation reporting the presence of messinian-conglomerates and pliocene-marl  
263 outcrops within the main scars [Savoye and Piper, 1991].

264 In the area offshore Nice to Imperia, the base of the continental slope is also strongly affected by  
265 faults (Figs 2 and 7). The deepest ones broke and shifted vertically the Messinian conglomerates,  
266 but the penetration of the seismic-reflection profiles did not allow the observation of these faults  
267 at greater depth (Fig. 7). Vertical displacements could be in the order of 300-400 ms (about 200-  
268 300 m). The shallowest faults affect the Plio-Quaternary deposits: some of them are visible on  
269 side-scan sonar images of the seafloor (Fig. 6), suggesting a recent activity. Vertical  
270 displacements along these faults are less than 50 ms (about 40 m).

271  
272 4.4. Type 3 Failure scars  
273 Type-3 failures are more superficial than failures of Type 2 but affect wider areas and rework  
274 larger volumes of pre-existing deposits (Table 1). They are located in different environmental  
275 contexts of the margin, including the deep Var Sedimentary Ridge (VSR) and the upper part of  
276 the continental slope in the Gulf of Genova. In contrast with Type-1 and -2 failures previously  
277 described, Type-3 scars are also associated with the presence of mass-transport deposits.

278  
279 *The VSR Slide* – The VSR slide is located in the western part of the outer flank of the VSR (Fig.  
280 8). It consists of a main scar 6-km wide and 100-m high that gradually smooths to the west. It

281 was generated along the crest of the Ridge, at about 1800 m of water depth, and it extends  
282 downslope to 2100 m of water depth. The inner wall of the main scar is affected by smaller-scale  
283 failures, 0.5- to 1-km wide, separated by elongated ridges (Fig. 8). The ridges probably consist of  
284 poorly disturbed material as coherent and continuous reflections are still observed (Figs 9 and  
285 10). The volume of missing sediment in the whole failure-related area is of  $1.5 \times 10^9 \text{ m}^3$ .

286 A lenticular-shaped chaotic to transparent unit deposited at least 12 km downstream from the scar  
287 (Fig. 11): it is interpreted as a mass-transport deposit (MTD). The MTD is up to 20 m in  
288 thickness and 2-3 km wide. Its basal contact is erosive, as evidenced by the truncation of  
289 reflectors of the well-layered echofacies corresponding to the VSR deposits (Fig. 11). Erosion  
290 affected locally up to 5-10 m of VSR deposits. The MTD is draped by hemipelagic-like deposits  
291 5-m thick (Fig. 11). By assuming a sedimentation rate of 17 cm/1000 yrs in that part of the VSR  
292 [Piper and Savoye, 1993], the age of the MTD could be about 29-30 ka BP.

293 The VSR Slide is located above a network of syn-sedimentary faults exhibiting a flower-like  
294 pattern and affecting the upper 400 ms of sediment below the seafloor (Fig. 9). The lateral limits  
295 of the scar correlate with faults reaching the seafloor (Figs 9 and 10). The apparent vertical  
296 displacement along these faults suggests that the whole failure area subsided within the  
297 surrounding deposits of the VSR. The superficial faults gradually converge at depth and are  
298 located above some larger-scale faults that affect the paleo-channels and are rooted on top of the  
299 Messinian evaporites (Figs 9 and 10). Vertical displacements along these deep faults are about  
300 50 to 200 ms (about 55 to 220 m).

301  
302 *The Finale Slide* – The Finale Slide was identified in the northwestern part of the Gulf of  
303 Genova during the MALISAR1 cruise (Fig. 12). It is located on an interfluvial area where the  
304 Pora and Noli Canyons coalesce (Fig. 13). Here, the slope angle is about  $4^\circ$ . The scar lies at 700  
305 m water depth. It is 10-km wide, 3-km long and 50-m high as an average. The volume of  
306 missing sediment in the scar is of  $1.5 \times 10^9 \text{ m}^3$ . Two superficial semi-circular failures with  
307 volume lower than  $10^5 \text{ m}^3$  affected the scar in its eastern part (Fig. 13). A chaotic to transparent  
308 body deposited in the continuity of the scar and reached the Noli Canyon (Fig. 14). It is  
309 interpreted as a MTD resulting from the transformation of the destabilized deposits. The MTD is  
310 about 20-30 m thick near the base of the scar and it thins to 10-15 m in the Noli Canyon (Fig.  
311 14). Draping hemipelagic-like deposits are not observed on top of the MTD on Chirp profiles,

312 suggesting a recent emplacement.

313  
314 *The Portofino Slide* – The Portofino slide was first identified on Sparker profiles by [Corradi et  
315 al., 2001] and its western part was mapped during the MALISAR2 cruise. It is located in the  
316 northeastern part of the Gulf of Genova (Fig. 12), on the upper continental slope where the mean  
317 slope angle is about 3°. The scar lies at about 250 m water depth. It consists of a sharp  
318 escarpment (slope angle of about 7°) 300-m high followed at its base by a MTD about 200-m  
319 thick. The volume of missing sediment was not evaluated in that case as the scar was  
320 incompletely mapped. The MTD extend about 10 km downstream from the scar (Fig. 12). Its  
321 internal architecture partly exhibits the original organisation of deposits evidenced by the  
322 presence of well-layered moderate-amplitude reflections [Corradi et al., 2001]. The change of  
323 reflection dip along the whole MTD was interpreted by [Corradi et al., 2001] as a slight  
324 rotational movement of the destabilized deposits. The distal part of the MTD is now eroded by  
325 the Levante Canyon (Fig. 12). A field of pockmarks is located west of the Portofino Slide and  
326 lies at a water depth ranging from 300 to 500 m (Fig. 12).

327

## 328 **5. Discussion**

329 The specific location of each Type of failure scars along the Ligurian Margin could give hints  
330 on the controlling factors influencing their triggering, including the structure of the margin, the  
331 presence of large faults, the areas of highest earthquake activity and of highest sedimentation  
332 rate.

333

### 334 5.1. Single vs multiple-failure events

335 In terms of geohazard assessment, it is important to understand the processes leading to the  
336 formation of the scar morphologies identified on the present-day seafloor. Depending on these  
337 processes, estimation of volumes of deposits reworked on the continental slope or intensity of  
338 slope-deposits erosion during a single event could differ totally and change our ability to estimate  
339 the tsunamigenic potential of submarine failures.

340 Looking at the morphology of Type-1 failures, each erosional chute seems to have originated  
341 from a single scar, suggesting that a single failure event triggered on the upper slope and evolved  
342 downslope to an erosive cohesive mass-flow (Fig. 3). Within the chutes, the lack of mass-

343 transport deposits (MTD) suggests that when a failure is triggered, the remobilized deposits are  
344 completely evacuated to the base of the slope. On the Nice slope, this interpretation is supported  
345 by the fact that debris-flow deposits were only identified at the base of the slope, in two areas  
346 close to the Var and Paillon Canyons [*Klaucke and Cochonat, 1999*].

347 For Type-3 failures, the presence of a single thick MTD downslope from the scar also suggests a  
348 single failure event, although it is possible that the MTD characterises only one of the recorded  
349 phases of failure. However, phases of seafloor erosion older than the one identified at the base of  
350 the MTDs were not observed, suggesting that the MTDs are, at least, associated to the main  
351 failure event. In the example of the VSR Slide (Fig. 8) and the Finale Slide (Fig. 13), secondary  
352 small-scale failures are present within the main scar, but their volumes are too small to be  
353 responsible for the emplacement of the large MTD identified downstream of the scars. These  
354 secondary events are post-failure processes probably related to the local oversteepening created  
355 along the scar together with the sediment decompression affecting the surrounding deposits. We  
356 therefore infer that they generated directly on the main scar as it adjusted to a critical inclination  
357 with a mechanism of retrogressive failure.

358 Along the western Ligurian margin, at the base of the continental slope, large-scale imbricated  
359 scars of Type 2 are an evidence of multiple failure events. The presence of several scars showing  
360 a step-like morphology results from several décollements that followed distinct stratigraphical  
361 surfaces likely acting as mechanical discontinuities, like the surface between the consolidated  
362 Pliocene marls and the Messinian conglomerates, and in few cases, the surface between the soft  
363 Quaternary deposits and the Pliocene marls. The differences in physical properties of the  
364 sedimentary units could have controlled the location and action of the shear stress within the  
365 sedimentary column. It is still unclear whether several failure events were triggered in a very  
366 short period of time or if distinct failure events affected successively the Messinian  
367 conglomerates, then the Pliocene marls and the Quaternary deposits. The outstanding difference  
368 between the volume of reworked deposits accumulated at the base of the scars and the volume of  
369 missing deposits within the scars should favour the second hypothesis: large volumes of the  
370 reworked-deposit accumulation could have been evacuated between two successive failure events  
371 by thick and energetic gravity flows flowing into the Var Valley.

372

373 5.2. Factors promoting submarine failures along the Ligurian margin

374 Several factors may promote the distribution and triggering of submarine failures along the  
375 Ligurian margin. Each factor may act differently in time and space but it is the conjunction of  
376 all these parameters that controlled the failure emplacement. Undoubtedly, some factors  
377 interact or are closely connected but, for clarity, we discuss their effect separately.

378  
379 *Effect of slope angle.* The slope angle is known as an important factor controlling the location  
380 and volume of submarine failures [Canals et al., 2004; McAdoo et al., 2000]. However, as  
381 submarine landslides are found associated with a large spectrum of slope angles, the slope  
382 angle is not always considered as a good indicator of susceptibility to landsliding [Huhnerbach  
383 and Masson, 2004]. Along the Ligurian margin, areas with smallest-scale but more abundant  
384 failures (Type-1 failures) correlate with areas of highest slope angle (10-20°) like the upper  
385 continental slope offshore the Var-river mouth and the inner canyon walls (Fig. 2). Areas with  
386 large-scale but rarer failures are located on lower slope angle, of about 5-6° (Type-2 failure  
387 scars) and 2-4° (Type-3 failure scars). Similar inverse correlation between the slope angle and  
388 the size of failures was made along the US continental margins [McAdoo et al., 2000] and the  
389 North Atlantic margins [Huhnerbach and Masson, 2004]. Because high slope angle will  
390 promote regular failure events, it will also prevent thick unstable sediment accumulation to  
391 build through time. In that case, only small volume of continental-slope deposits will be  
392 remobilized during each failure event, as it is observed along similar steep margins of the  
393 Mediterranean, like the Algerian margin [Cattaneo et al., 2010].

394 Slope angle might also play an important role on the post-failure processes and the  
395 transformation of a failed mass into a gravity flow. Mass-transport deposits are never found  
396 immediately downslope of Type-1 and Type-2 scars, or they are found far from these scars  
397 where the slope angle decreases drastically (Fig. 5), while MTDs are always found  
398 downstream of Type-3 scars. This suggests that slope angles greater than 5-6° should promote  
399 a complete disintegration and evacuation of the failed mass while slope angles lower than 4°  
400 should conserve the cohesion of the failed mass. One possible interpretation could come from  
401 a difference in the rheology of the material that could be stiffer and more consolidated on  
402 gentler slopes and softer and less consolidated on steeper slopes, also as a consequence of the  
403 shorter time of residence/accumulation of sediment in very steep settings. High slope angles  
404 could also promote a rapid acceleration of the failed mass just after the failure occurred, what

405 should increase the process of disintegration.

406

407 *Effect of sedimentation rates and hyperpycnal currents.* Sedimentation rates are high in the  
408 surrounding areas of the mouths of the main feeding rivers like the Var, the Paillon, the Roya,  
409 the Taggia. There, sediment deposition mainly results from both direct and rapid supply by  
410 hyperpycnal flows, inducing sedimentation rates as high as 1-2 m/100 yrs [Mulder *et al.*,  
411 2001b], then by slower decantation of surface plumes [Klaucke *et al.*, 2000]. Geotechnical  
412 analyses described these deposits as underconsolidated [Cochonat *et al.*, 1993]. Due to angles of  
413 10-15°, failures of Type 1 are thought to occur regularly, but small volumes of deposits are  
414 involved for each episodes of failure. Hyperpycnal flows could have a direct impact on the  
415 seafloor and the triggering of small-scale failures through mechanisms of friction at the seabed  
416 creating a temporary additional loading. They are also involved in the gradual erosion of the  
417 base of the canyon walls, leading to local oversteepening responsible for the triggering of  
418 failures of Type 1 (e.g. [Baztan *et al.*, 2005]).

419

420 *Effect of uplift, inherited structural features and earthquakes.* The triggering of landslides is  
421 commonly associated to earthquakes on the North Atlantic margin [Piper *et al.*, 1999; St-Onge  
422 *et al.*, 2004; ten Brink *et al.*, 2009], in the Mediterranean [Cattaneo *et al.*, 2010; Hassoun *et al.*,  
423 2009; Lastras *et al.*, 2004] and in the Pacific [Lamarche *et al.*, 2008]. On the eastern Canadian  
424 margin, [Piper *et al.*, 2003] interpret large buried landslides to largely result from earthquakes.  
425 In the western Ligurian margin (Fig. 2), the location of Type-2 failures at the base of the  
426 continental slope is uncommon: on passive margins, large-scale failures are usually triggered on  
427 the upper continental slope where the slope angle and the thickness of deposits are the highest  
428 [Garziglia *et al.*, 2008; Haflidason *et al.*, 2004; McAdoo *et al.*, 2000]. In the western Ligurian  
429 margin, the specific location of failure morphologies correlates with the presence of numerous  
430 faults affecting the base of the slope (Figs 2, 6 and 7). The origin of these faults is still discussed  
431 [Larroque *et al.*, this issue], but they induced through time a total vertical displacement of at least  
432 300 m (Fig. 7). At sea, most of the earthquake epicentres are located on these structures  
433 [Courboulex *et al.*, 1998; Larroque *et al.*, this issue]. As strong vertical displacement along faults  
434 usually correlates with earthquakes, the triggering of large collapses of Type 2 could result from  
435 earthquakes and the combined effect of ground rupture along faults and cyclic loading affecting

436 the sediment cover. In addition, that part of the margin also experience a present-day  
437 deformation/uplifting stage starting during the Pliocene [*Bigot-Cormier et al.*, 2004]. The uplift is  
438 responsible for the gradual oversteepening of the margin, resulting in a progressively more  
439 marked convex-up morphologic profile (Fig. 1). As the margin exhibits seaward dipping strata  
440 (Fig. 7), it may require less energy under these conditions to generate a failure during  
441 earthquakes.

442 The strongest earthquake events are also probably responsible for the direct and rapid  
443 triggering of landslides through processes of shacking and loading, as for failures of Type 1  
444 identified in the open-continental-slope epicentral area of the 1887 event [*Hassoun et al.*,  
445 2009], or for the large Finale Slide that triggered on low slope angle. It is possible that the  
446 presence of layers or surfaces of contrasting lithology, like the coarser layers that are prone to  
447 liquefaction during earthquakes, provide preferential weak planes where failure may originate.

448  
449 *Effect of the presence of a mobile evaporite layer.* The large failure event identified in the  
450 western part of the VSR locates in an area where the low slope angle and the low sedimentation  
451 rates should not have favoured its development. It is also located above a fault network that roots  
452 into the Messinian evaporites (Figs 9 and 10). All over the Mediterranean Sea, the Messinian  
453 evaporites are considered as a mobile layer that affect the overlying Plio-Quaternary succession  
454 in numerous ways [*Masclé et al.*, 2006]. The main processes evoked include the thin-skinned  
455 gravitational tectonics linked to salt withdrawal (downdip migration or dissolution) of the  
456 evaporites as evidenced on recent high-resolution 2D data offshore Algeria [*Strzeczynski et al.*,  
457 2010] and 3D data offshore Israel (e.g., [*Bertoni and Cartwright*, 2006]). As a thick sediment  
458 accumulation, the VSR exerted a strong lithostatic pressure on the evaporites that gradually  
459 glided to the south following the regional slope gradient. This is evidenced by the thickening of  
460 the salt layer and the presence of salt diapirs along the southern border of the VSR, where the  
461 sediment accumulation thins out [*Savoie et al.*, 1993]. The slow downslope movement of the  
462 evaporite layer resulted in a decompression at depth and the formation of normal syn-sedimentary  
463 faults that gradually propagated upward (Figs 9 and 10). Both decompression and faults affected  
464 the Plio-Quaternary deposits that subsided rapidly, triggering the destabilisation of the seafloor.

465  
466 *Effect of sea-level fluctuation.* On passive margins, the triggering of large-scale failures is



467 quite often closely connected to phases of sea-level rising or lowering [*Garziglia et al.*, 2008;  
468 *Maslin et al.*, 2005]. Sea-level changes can act on slope instability through several processes  
469 like seaward migration of the main sediment depocenters leading to an increasing  
470 sedimentation rate on the continental slope together with a rapid sediment loading, change of  
471 the physical properties of deposits experiencing an increase or decrease of their excess pore  
472 pressure, and dissociation of gas hydrates. In the absence of direct dating, it can be only  
473 speculated that large failures triggered at shallow water depth, like the Portofino Slide  
474 affecting segment about 5-km long of the upper slope, could have been triggered by the latest  
475 phases of sea-level lowering or rising of about 110 m, during the Last Glacial Maximum or the  
476 early Holocene respectively [*Lambeck and Purcell*, 2005]. The Portofino Slide being located  
477 far from direct sources of sediment supply, seaward migration of depocenters and sediment  
478 overloading on the upper continental slope during the latest phase of lowered sea level should  
479 not be responsible for the triggering of that large failure. Decomposition of gas hydrates is  
480 known to trigger large-scale landslides during phases of sea-level lowering, mainly if they  
481 occur on the upper continental slope [*Maslin et al.*, 2004; *Sultan et al.*, 2004a]. In the present  
482 case, evidence of bottom simulating reflector (BSR) as an indicator of gas hydrates in the  
483 deposits was not yet observed on seismic-reflection profiles from the Ligurian margin but the  
484 field of pockmarks located at a similar water depth than the Portofino Slide (Fig. 12) could be  
485 an evidence of the potential dissociation of gas hydrates.

486

### 487 5.3. Impact on geohazard assessment

488 Along the Ligurian margin, factors promoting submarine landslides act at specific locations.  
489 Correlation between the types of factors and the types of submarine failures could help to  
490 discriminate between areas that are prone to low-to-high geohazards.

491 Type-1 failure scars correlate with areas of both high slope angle and direct high particle-  
492 supply by hyperpycnal flows. These two factors promote high-frequency failures, with  
493 volumes classically lower than  $10^8 \text{ m}^3$ . As these two factors are closely connected with river  
494 discharges and seafloor erosion, these failures are restricted in small areas localized in the  
495 vicinity of river mouths and on the inner flanks of canyons. As a consequence, they do not  
496 strongly impact the morphology and the erosion of the whole margin. However, from the  
497 example of the 1979 Nice-airport landslide, such failures are able to generate tsunami despite

498 their small volume because they occur at shallow water depth [Ioualalen *et al.*, 2010]. In the  
499 case of the 1979 event, three waves less than 3-m high broke along the coastline between the  
500 cities of Antibes and Nice less than 8 minutes after the failure occurred. Similar Type-1  
501 failures triggering at shallow water depth are thus thought to generate low-elevation tsunami  
502 affecting the coastline within a radius of 5-10 km around the point of sediment rupture and  
503 within a very short-time period. Such failures are also able to rapidly transform into gravity  
504 flows that can expand drastically through processes of seafloor erosion [Mulder *et al.*, 1997;  
505 Piper and Savoye, 1993]. Their increasing volume and density allow these flows to transport  
506 large volume of particles to the deep part of the margin and to break submarine cables more  
507 than 100 km away from their source as it happened for the 1979 flow. Type-1 failures could  
508 thus have a low-to-high hazard potential, not necessarily linked to regional seismicity as in the  
509 case of the 1979 Nice event [Dan *et al.*, 2007].

510 Type-2 failure scars correlate with the uplifting area of the margin and with the presence of  
511 main fault planes where earthquakes are also mainly concentrated. We infer that these three  
512 factors are responsible for the triggering of low-to-mid frequency failures with large volumes,  
513 ranging from 1 to 3 km<sup>3</sup>. These failures affect the base of the continental slope along the whole  
514 western Ligurian margin (between E7°20" and E8°10" in longitude) and thus have a strong  
515 impact on its evolution in time and space. Despite their location at water depth ranging from  
516 1700 to 2000 m, such failures could potentially generate tsunami several metres high when  
517 assuming the worst possible conditions in the tsunami-simulation scenario, i.e. remobilisation  
518 of large volume ( $> 10^9$  m<sup>3</sup>) during a single failure event [Ioualalen *et al.*, 2010]. As these  
519 failures occurred about 20 km offshore from the coastline, the tsunami would be able to  
520 propagate within the whole western Ligurian basin and to affect the coastline in an area 20-50  
521 km long around the location of the failure [Ioualalen *et al.*, 2010]. Type-2 failures could thus  
522 have a high hazard potential, especially in the scenario of single event, which is still difficult  
523 to prove in the absence, in most cases, of clearly identifiable proximal MTDs or distal turbidite  
524 deposits associated to the failure scars.

525 Type-3 failure scars are always associated to the presence of clearly identified MTDs and seem  
526 to represent single main failure-events in which large volumes ( $> 10^9$  m<sup>3</sup>) of deposits could  
527 have been remobilized. The VSR slide is very deep ( $> 2000$  m water depth), possibly  
528 associated with the presence of deep faults, and, owing to its depth, unlikely to have generated

529 significant tsunami waves. The two large submarine landslides identified in the eastern  
530 Ligurian margin (Finale and Portofino Slides) represent probably large events. Because they  
531 triggered at 250-700 m water depth, these failures could have been responsible for significant  
532 tsunami waves but more detailed investigations are still needed to assess their potential  
533 geohazard.

534

### 535 **Conclusions**

536 Recent cruises conducted in the frame of the MALISAR project provided a huge dataset  
537 including multibeam bathymetry, Chirp echo-sounder profiles, 24- and 72-channels seismic-  
538 reflection profiles, and deep-tow side-scan sonar along the whole northern margin of the  
539 Ligurian Basin, from the cities of Nice (France) to Genova (Italy). The dataset revealed that the  
540 margin is affected by a remarkable number of slope instabilities of different morphologies and  
541 sizes and allowed us to obtain a first order screening of the potential geohazards present in the  
542 area.

543 The superficial failures of Type 1 are mainly located in the areas surrounding the mouth of the  
544 mountain-supplied rivers like the Var and the Paillon rivers, and along the walls of canyons  
545 eroding the continental slope. High sedimentation rates related to hyperpycnal flows and  
546 gradual basal erosion of canyon walls are thought to be the main trigger mechanism of such  
547 failures. By comparison with the effects of the 1979 Nice-airport landslides, Type-1 failures  
548 with volume lower than  $10^8 \text{ m}^3$  and occurring at shallow water depth could have a low-to-high  
549 hazard potential.

550 Large scars corresponding to failures of Type 2 are located at the base of the continental slope,  
551 between 1700 and 2200 m of water depth. Their location correlates with the presence of faults  
552 that are also the areas of highest earthquake activity. They could result from multi-phase mass-  
553 wasting events; however, the reconstruction of the timing of such events is still matter of an  
554 open debate. Because large volumes (greater than  $10^9 \text{ m}^3$ ) are potentially remobilized during  
555 single failure events, Type-2 failures could have a high hazard potential.

556 Large-scale scars, affecting segment of the margins several kilometres long, and MTDs from  
557 failures of Type 3 are located at different places along the Ligurian margin: on the upper part of  
558 the continental slope or on the Var Ridge in the deep part of the Ligurian basin. Depending on  
559 their locations, triggering factors for such landslides could be strong earthquakes, sea-level

560 fluctuations, and slow downslope movement of the mobile evaporite layer deposited in the deep  
561 basin during the Messinian Salinity Crisis: a case-by-case approach with additional data is  
562 probably necessary to assess the related geohazards for this last type of failures.

563

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570

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780 Figure caption

781 Figure 1: General shaded bathymetric map of the northern Ligurian margin collected during the  
782 MALISAR project between the cities of Nice (France) to Genova (Italy). (A) and (B) are  
783 bathymetric profiles. FS are fault scarps observed south of the Imperia Promontory. Location of  
784 Figures 2 and 12 is also shown.

785 Figure 2: Shaded bathymetric map illustrating the morphology of the western Ligurian margin  
786 and the location and distribution of the three types of failures identified. The dark dashed lines  
787 at the base of the continental slope illustrate the location of faults identified on the seismic-  
788 reflection profiles. Map location shown in Figure 1.

789 Figure 3: A) Shaded bathymetric map illustrating the morphology of failures of Type 1 located  
790 on the upper part of the continental slope offshore the Var and Paillon rivers. B) Shaded  
791 bathymetric map illustrating the morphology of failures of Type 1 in and nearby the epicentral  
792 area of the 1887 earthquake. The inset shows a scar and a MTD. The white dotted lines  
793 underline the contour of the scars. Location in Figure 2.

794 Figure 4: Shaded bathymetric map illustrating the morphology of failures of Type 2 located at  
795 the base of the continental slope in the western part of the Ligurian margin. The white dotted  
796 lines reveal the contour of the accumulation of debris identified at the foot of the failures. (1) is  
797 a bathymetric profile crossing longitudinally the Cirque Marcel. The white dashed line is the  
798 location of the bathymetric profile. Location of Figures 5 and 6A is also shown.

799 Figure 5: Side-scan sonar data collected in a failure of Type 2. Profile location shown in Figure  
800 4. A) Seafloor image revealing the presence of small-scale scours affecting some of the scars  
801 within the failure area and of bloks (B) several tens of meters in diameter at the foot of the  
802 failure. B) 3.5 kHz profile illustrating the step-like morphology of the scars and the presence of  
803 an accumulation of debris at the foot of the failure.

804 Figure 6: A) Side scan sonar image collected at the base of the continental slope and revealing  
805 the presence of a fault escarpment on the seafloor. Image location shown in Figure 4. B) Side  
806 scan sonar image showing a fault escarpment at the base of the continental slope and the  
807 presence of bloks (B) several tens of meters in diameter located at the foot of some scar  
808 failures. Image location shown in Figure 2.

809 Figure 7: Seismic-reflection profile crossing a Type-2 failure at the base of the continental slope  
810 in the western Ligurian margin. Note the faults affecting the base of the continental slope. Profile  
811 location shown in Figure 2.

812 Figure 8: General shaded bathymetric map of the western part of the VSR. The white continuous  
813 line follows the contour of the main scar. The white dotted line outlines the presence of small-  
814 scale scars separated by elongated ridges on the inner wall of the main scar. Location of Figures  
815 9, 10 and 11 is also shown.

816 Figure 9: Strike seismic-reflection profile collected across the failure area identified in the  
817 western part of the VSR. It locates on top of faults with a flower-like structure. Undisturbed  
818 deposits of the VSR are characterized by a well-layered acoustic facies. Two paleochannels and  
819 the top of the Messinian evaporites are identified at depth and are affected by faults taking root in  
820 the evaporites. Profile location shown in Figure 8.

821 Figure 10: Dip seismic-reflection profile collected across the crest of the VSR and the failure  
822 area. Surficial deposits of the VSR are affected that syn-sedimentary faults that prolonged at  
823 depth by larger normal faults affecting some paleochannels and the Messinian evaporites. Profile  
824 location shown in Figure 8.

825 Figure 11: Hull-mounted Chirp profiles collected in the western part of the VSR and showing  
826 the presence of a lenticular transparent unit in the continuity of the Type-3 failure identified in  
827 Figures 8, 9 and 10. The transparent unit is interpreted as an MTD. Profile location shown in  
828 Figure 8.

829 Figure 12: Shaded bathymetric map illustrating the morphology of the upper continental slope  
830 in the Gulf of Genova. The white dotted line follows the edge of the Portofino Slide. Figure  
831 location shown in Figure 2.

832 Figure 13: Shaded bathymetric map showing the morphology of the Finale Slide, located in the  
833 interfluvium between the Pora and Noli canyons. The white dotted line follows the top of the main  
834 scar. The white lines are the location of Chirp profiles from Figure 14. Figure location shown in  
835 Figure 12.

836 Figure 14: Chirp profiles showing the presence of a chaotic to transparent unit downstream  
837 from the scar of the Finale Slide. The unit is interpreted as a MTD related to the failure. Profile  
838 location shown in Figure 13.

839

**Fig. 1**

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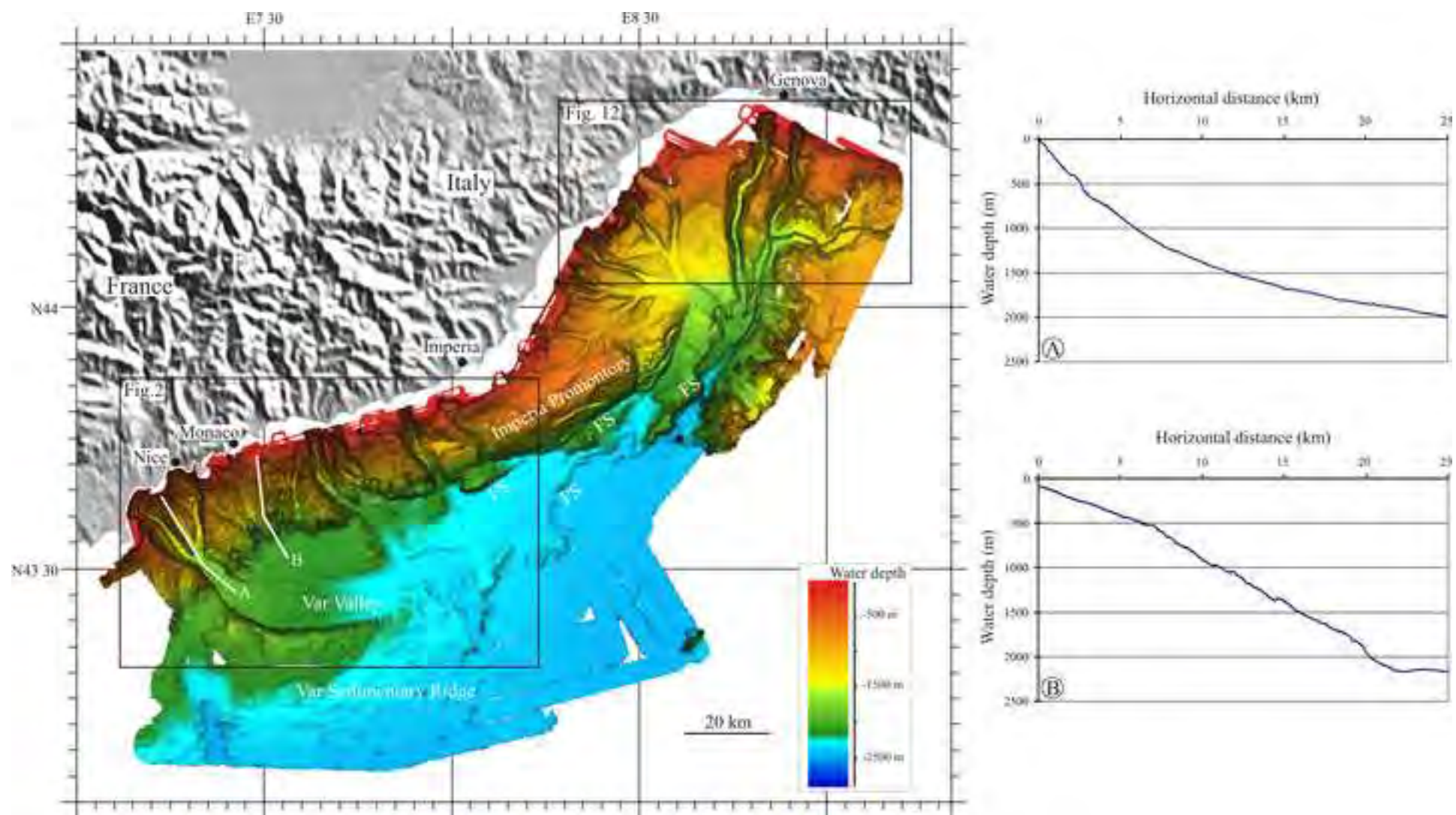
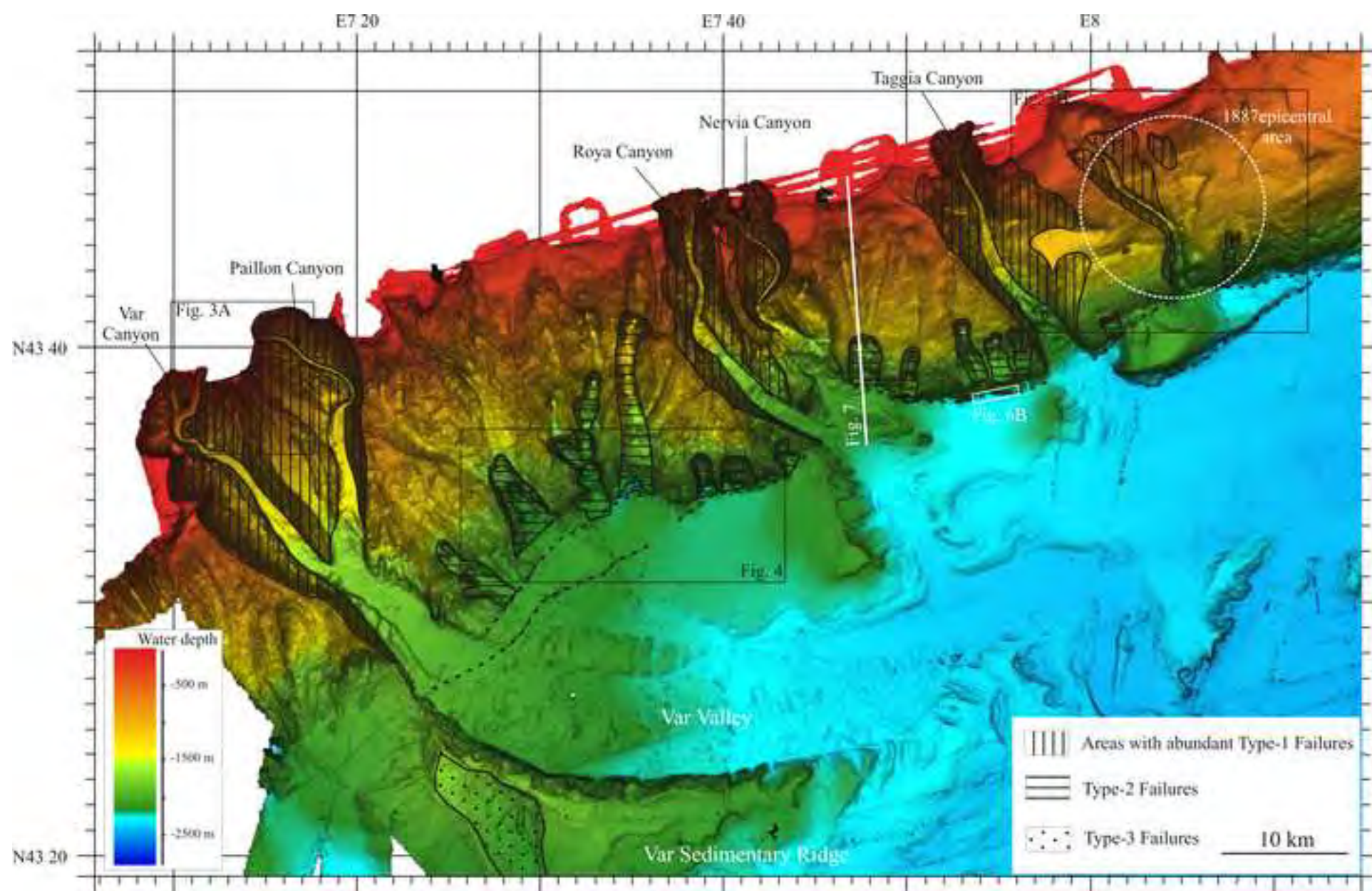


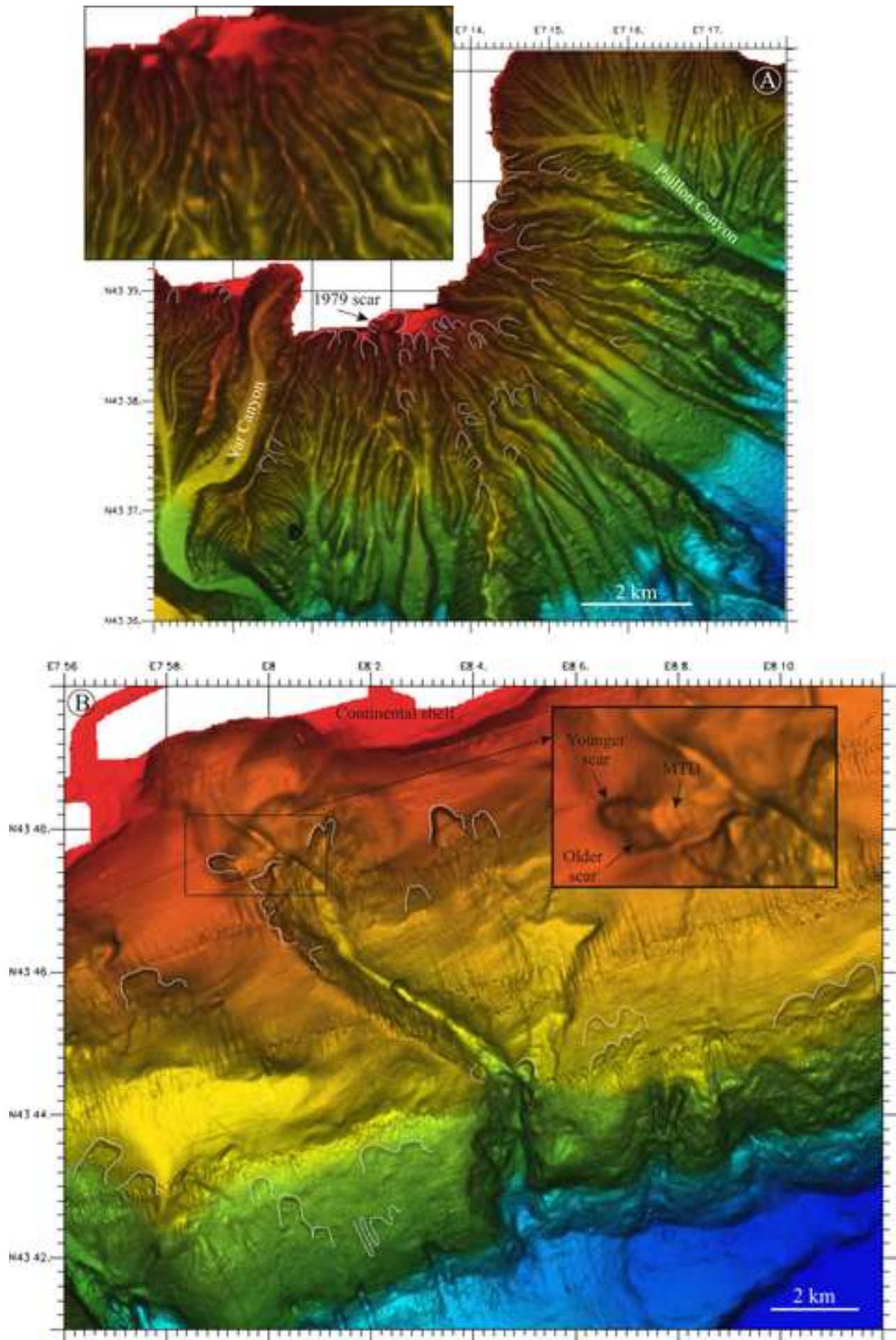
Fig. 2

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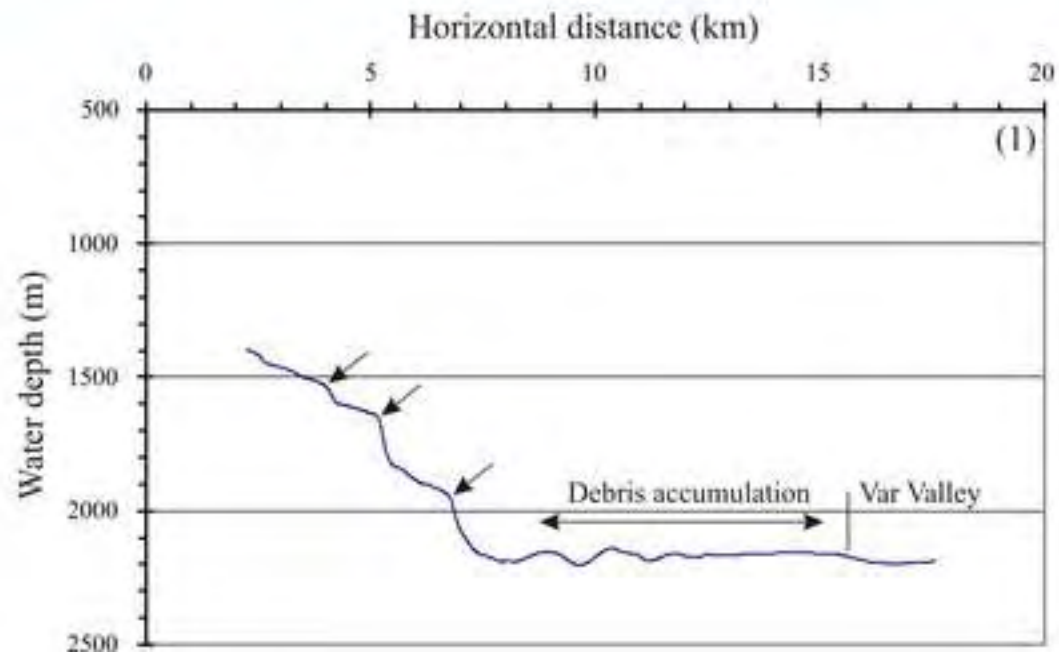
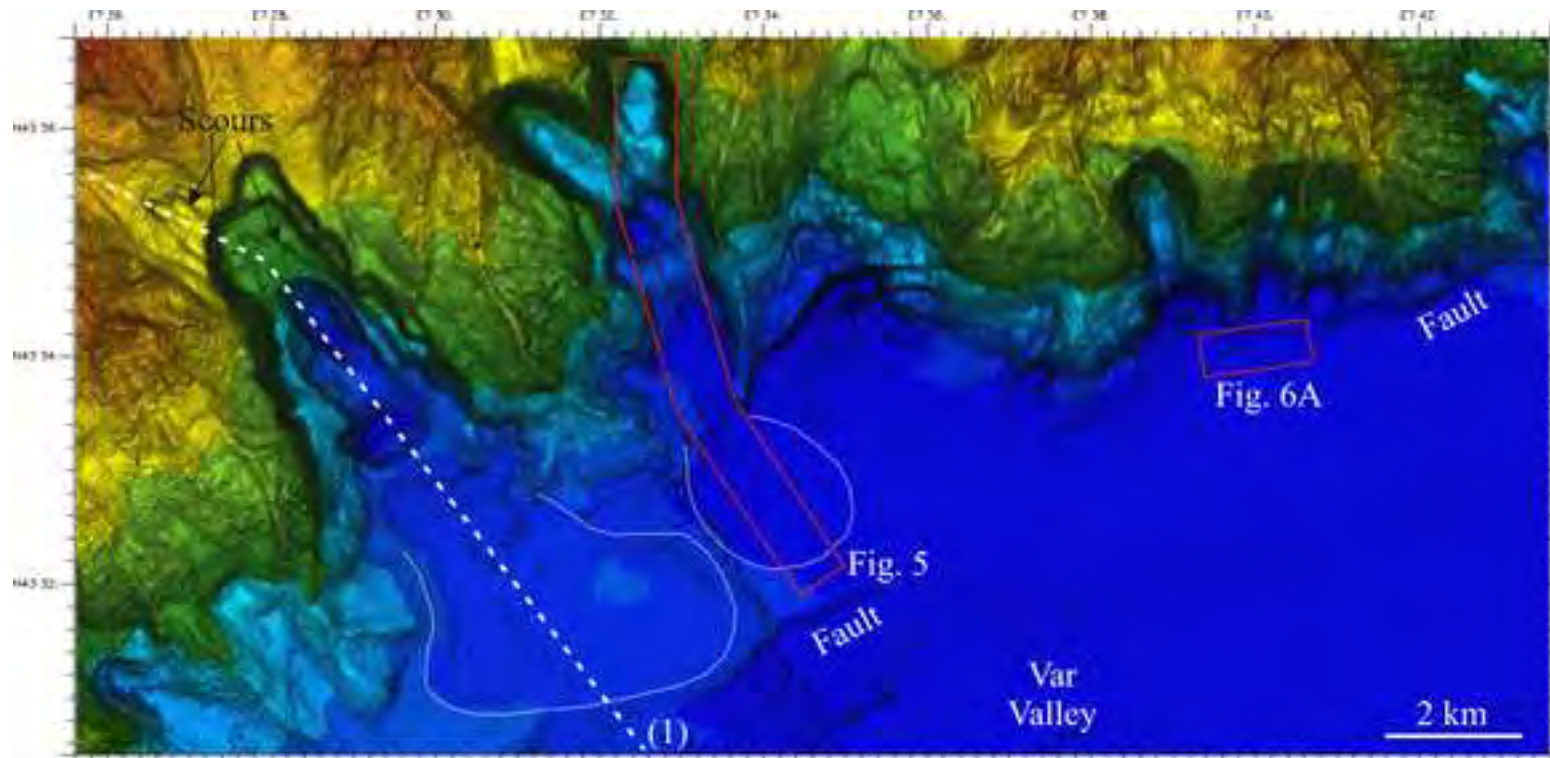
**Fig. 3**

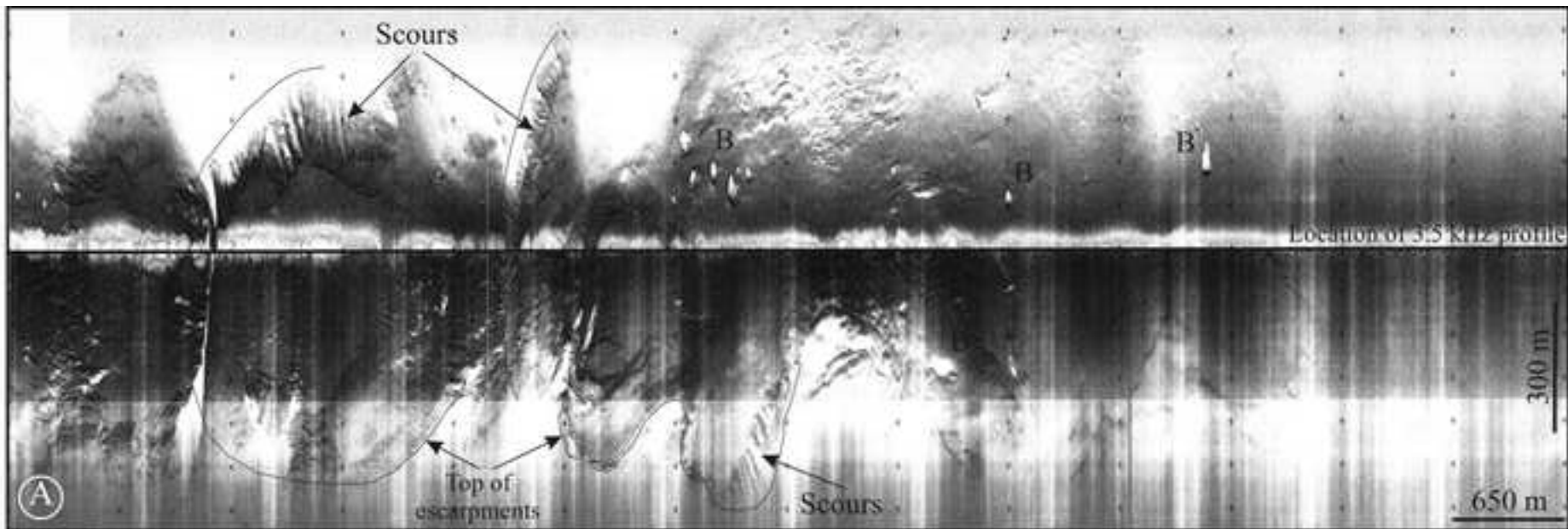
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**Fig. 4**

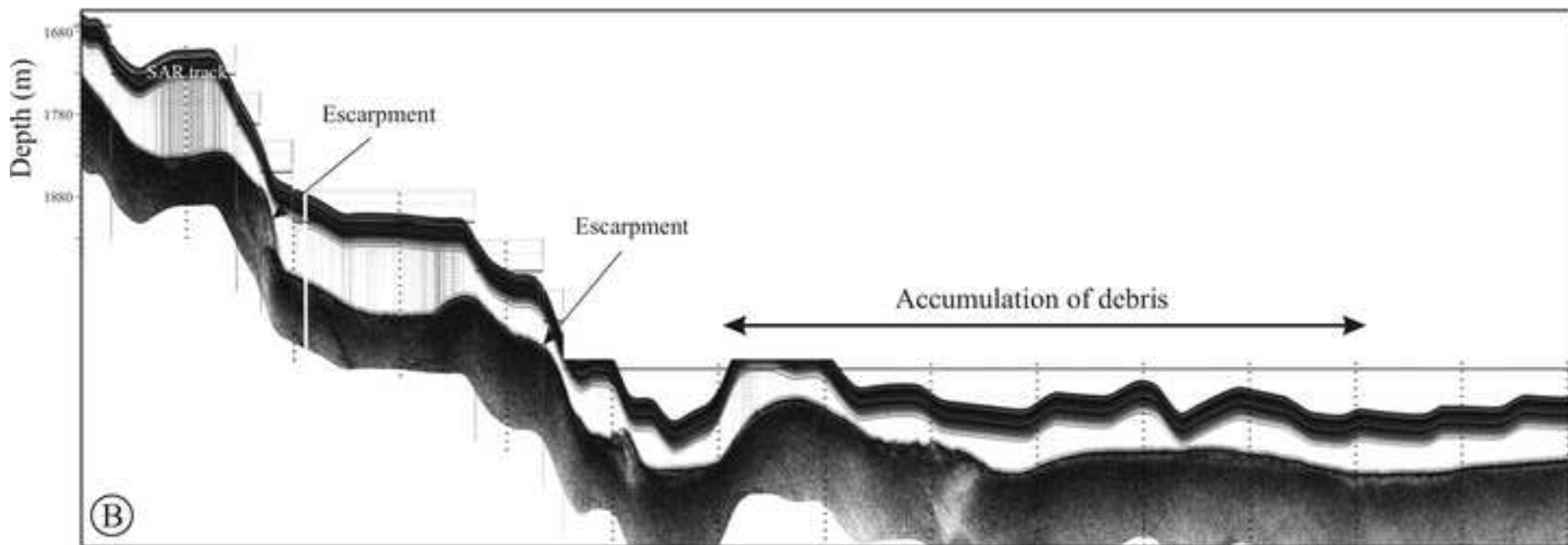
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North

South



(B)

Fig. 5 [Click here to download high resolution image](#)

**Fig. 6**

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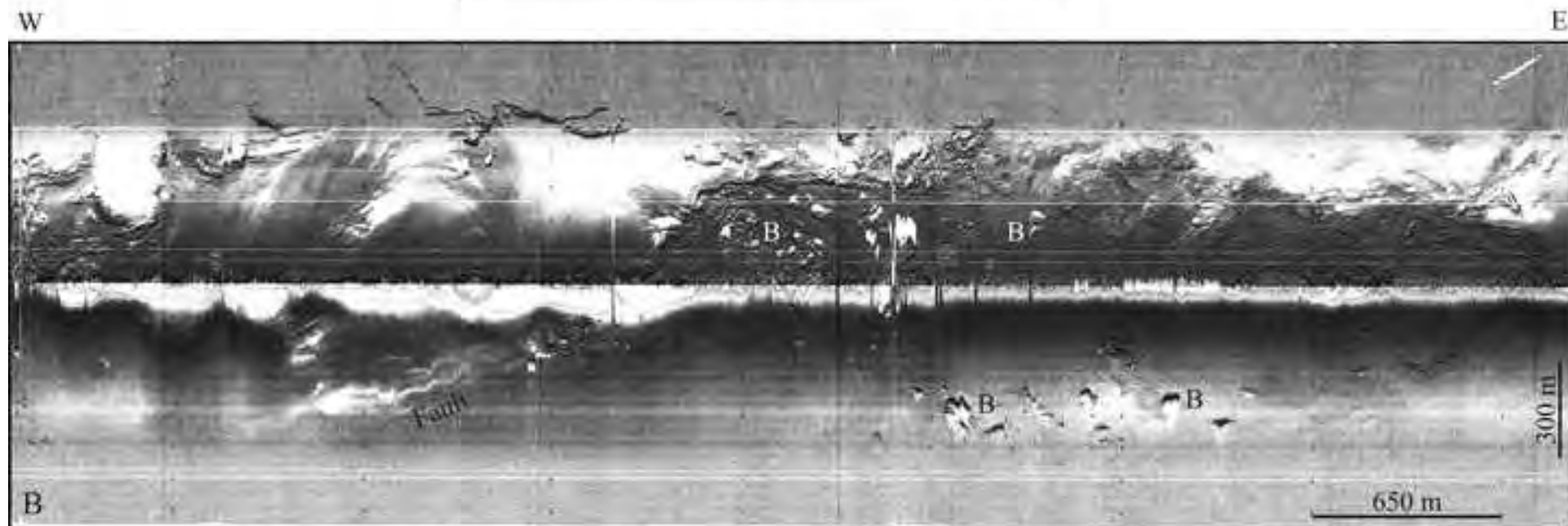
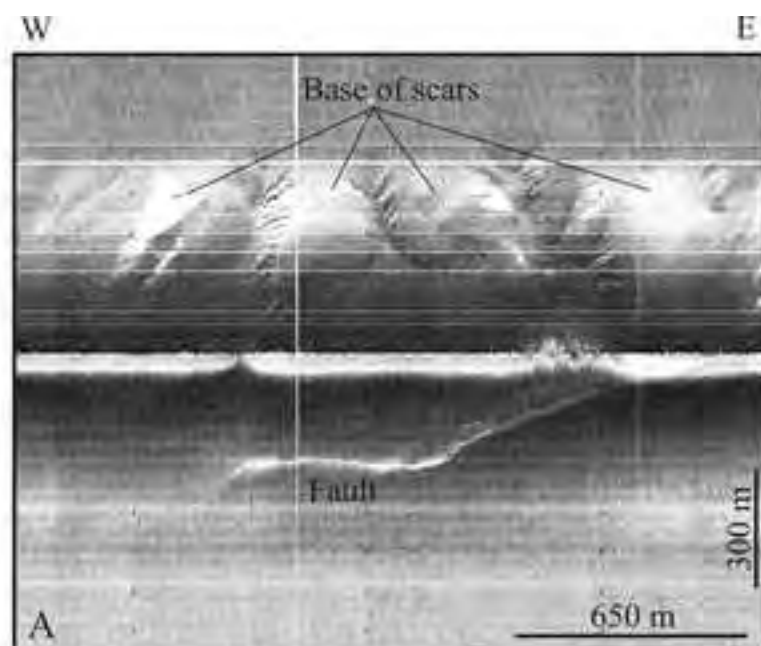
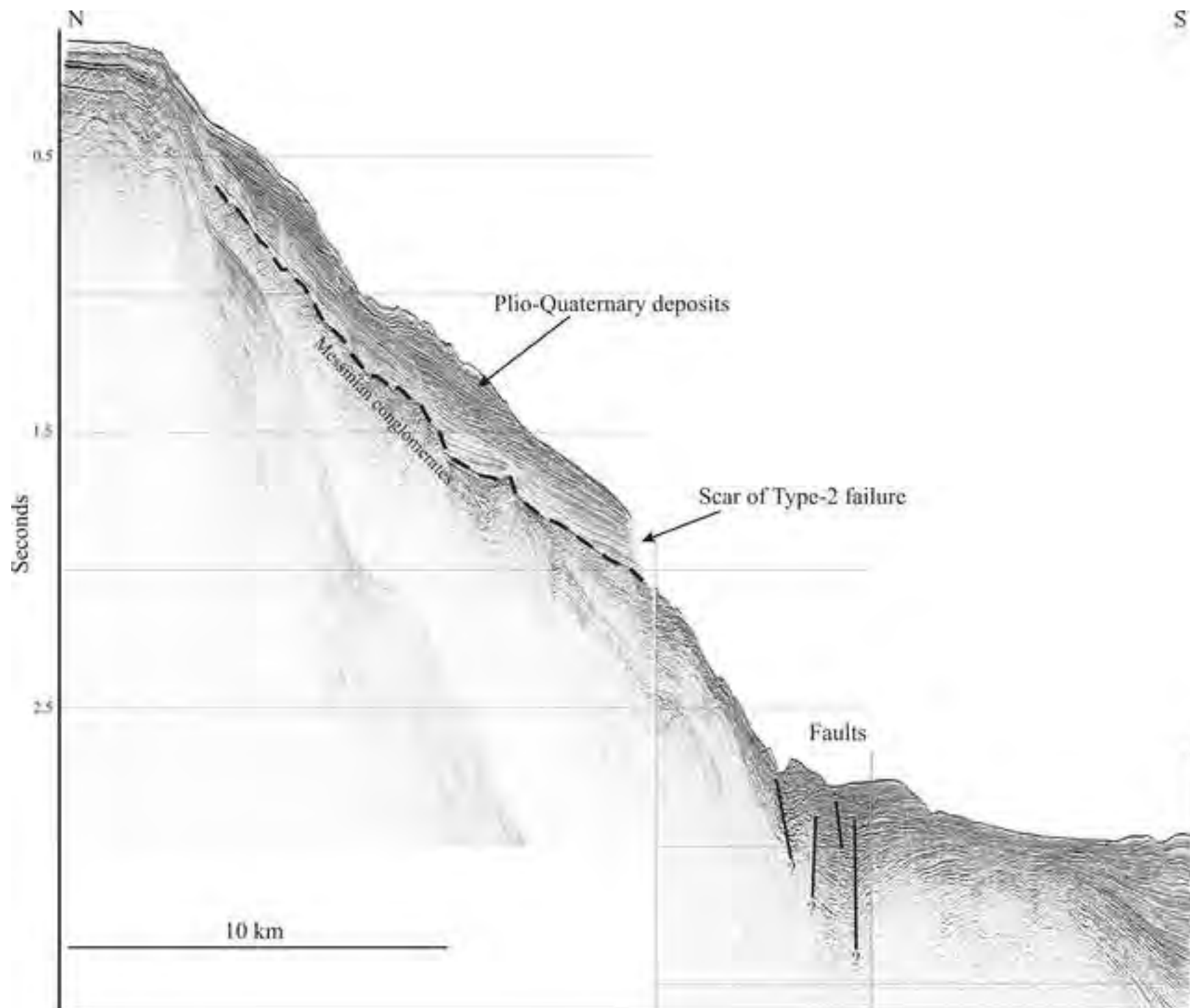




Fig. 7

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**Fig. 8**  
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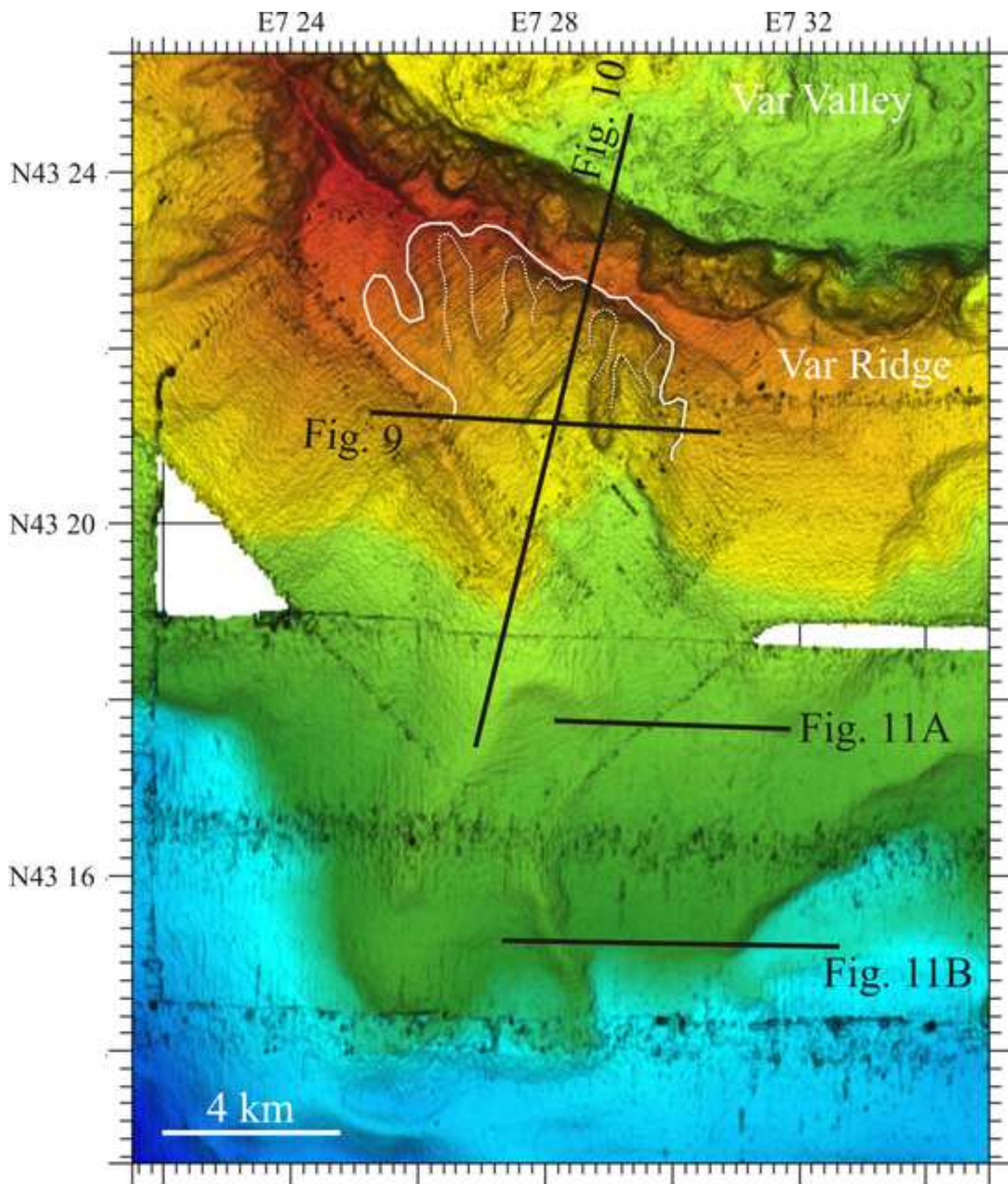
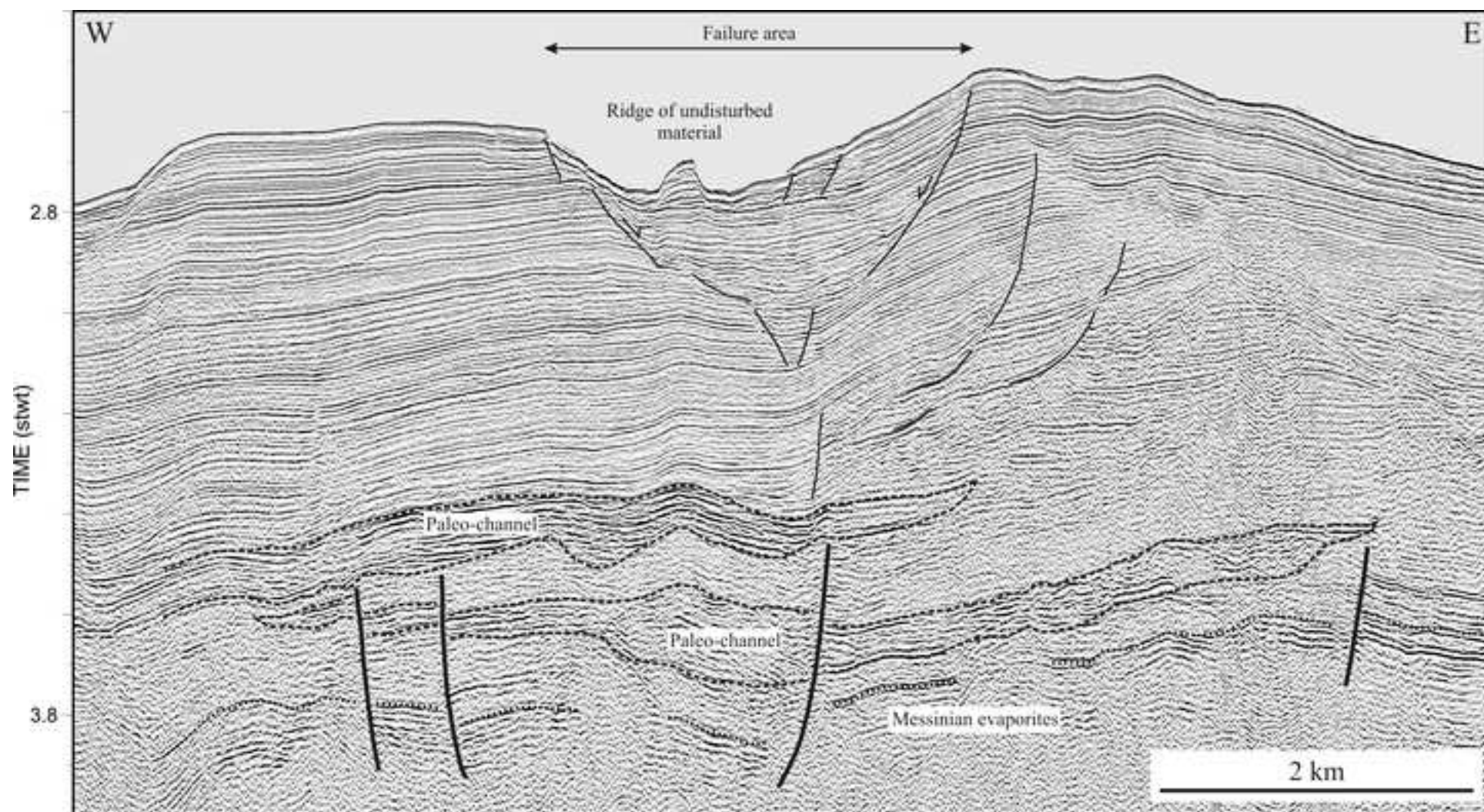
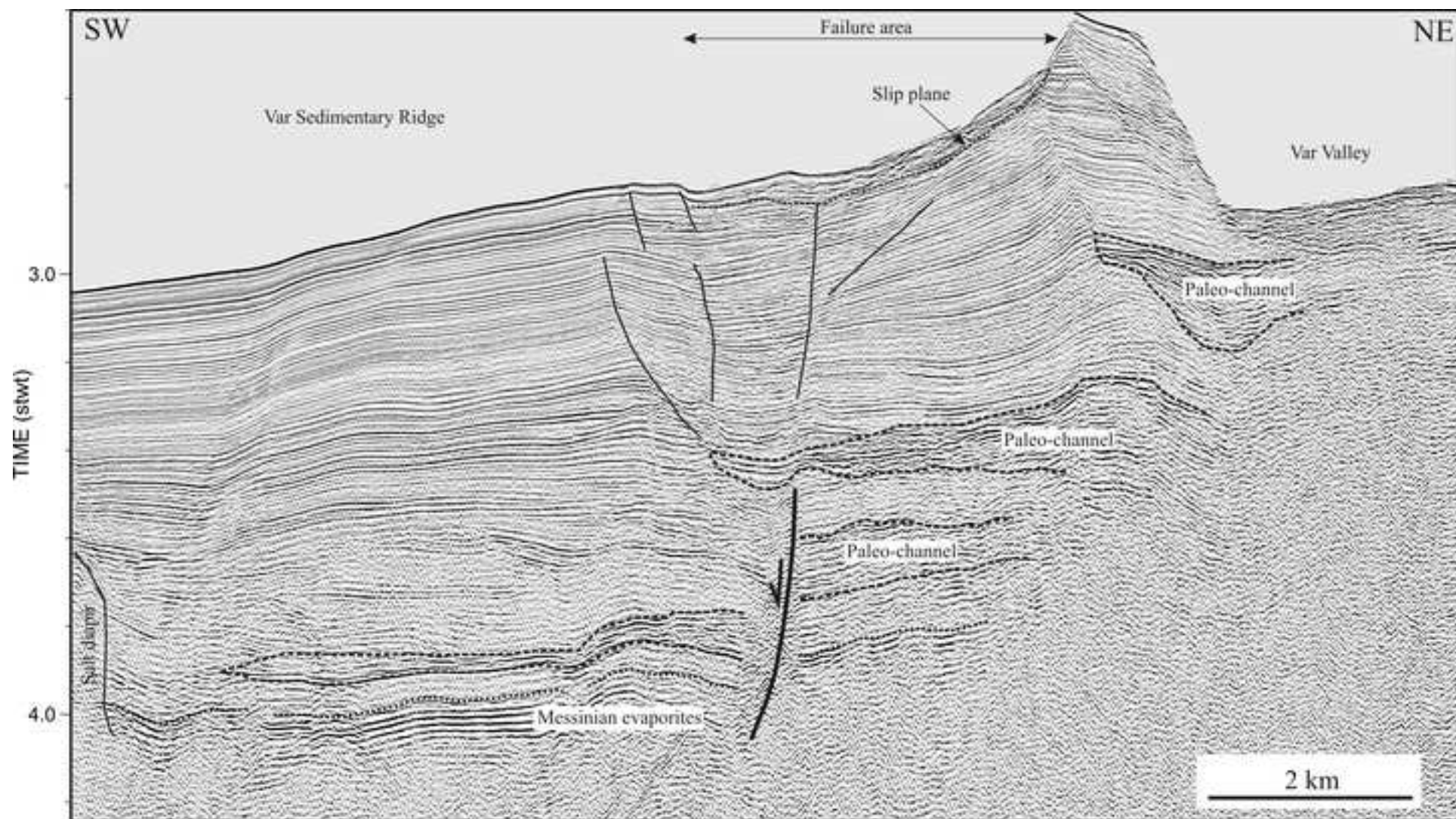


Fig. 9

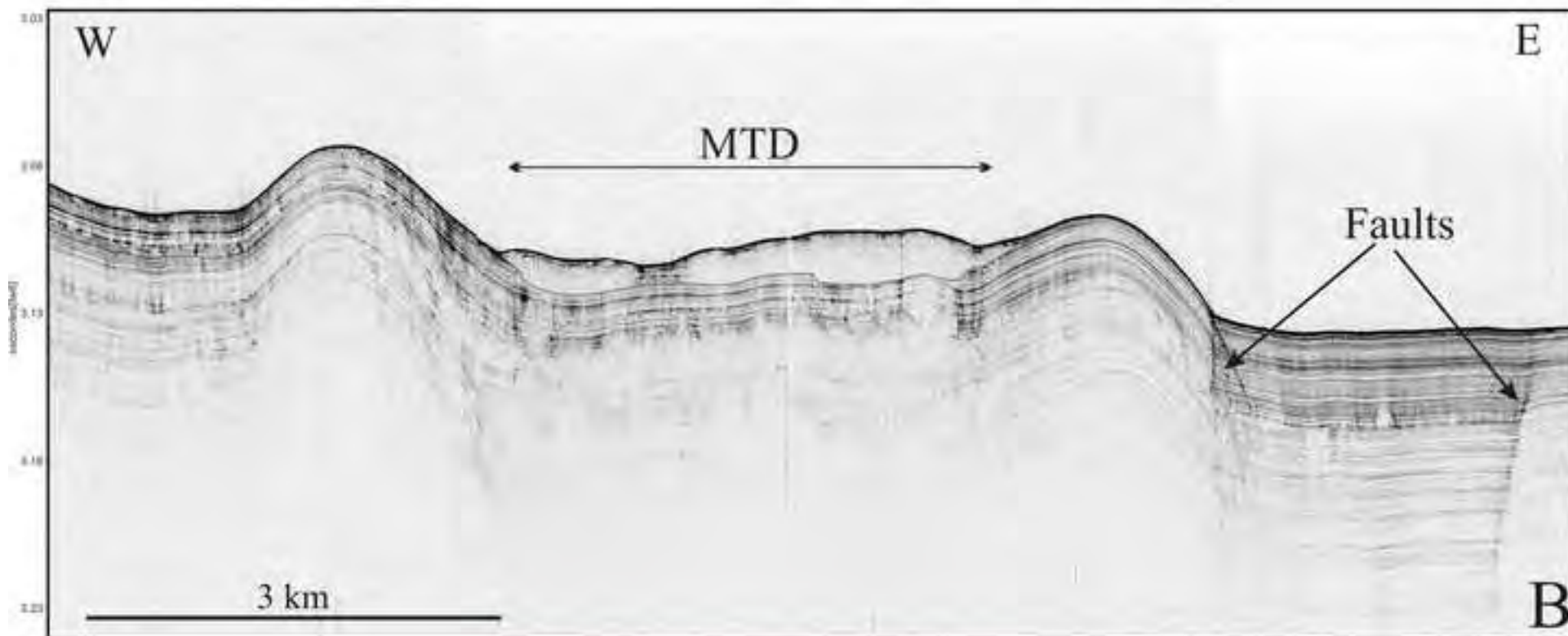
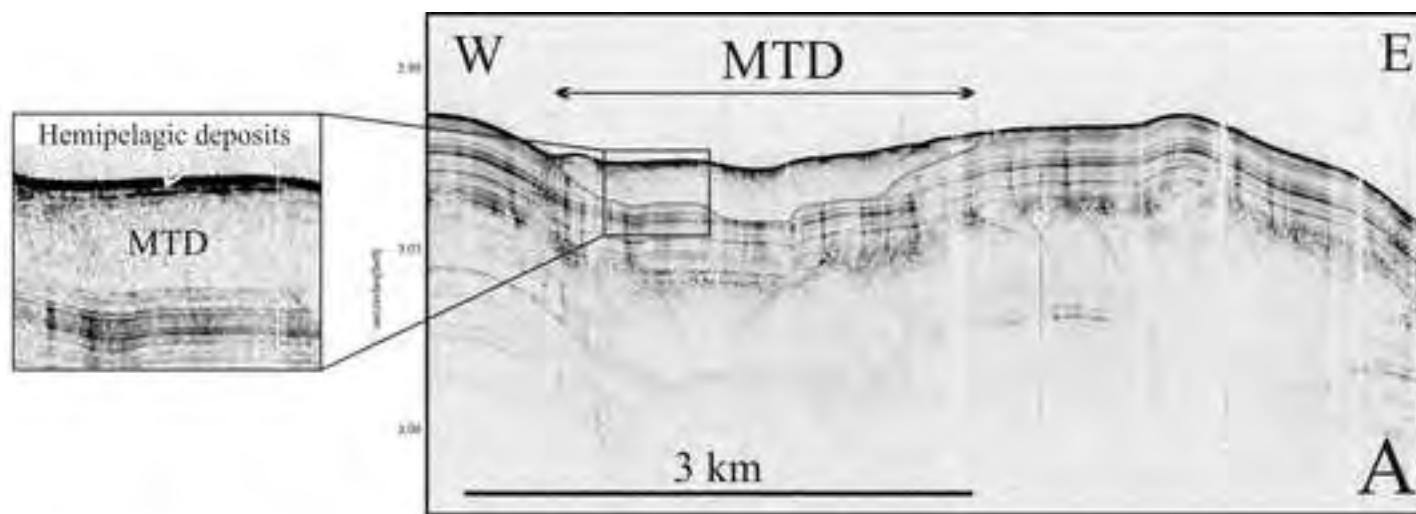
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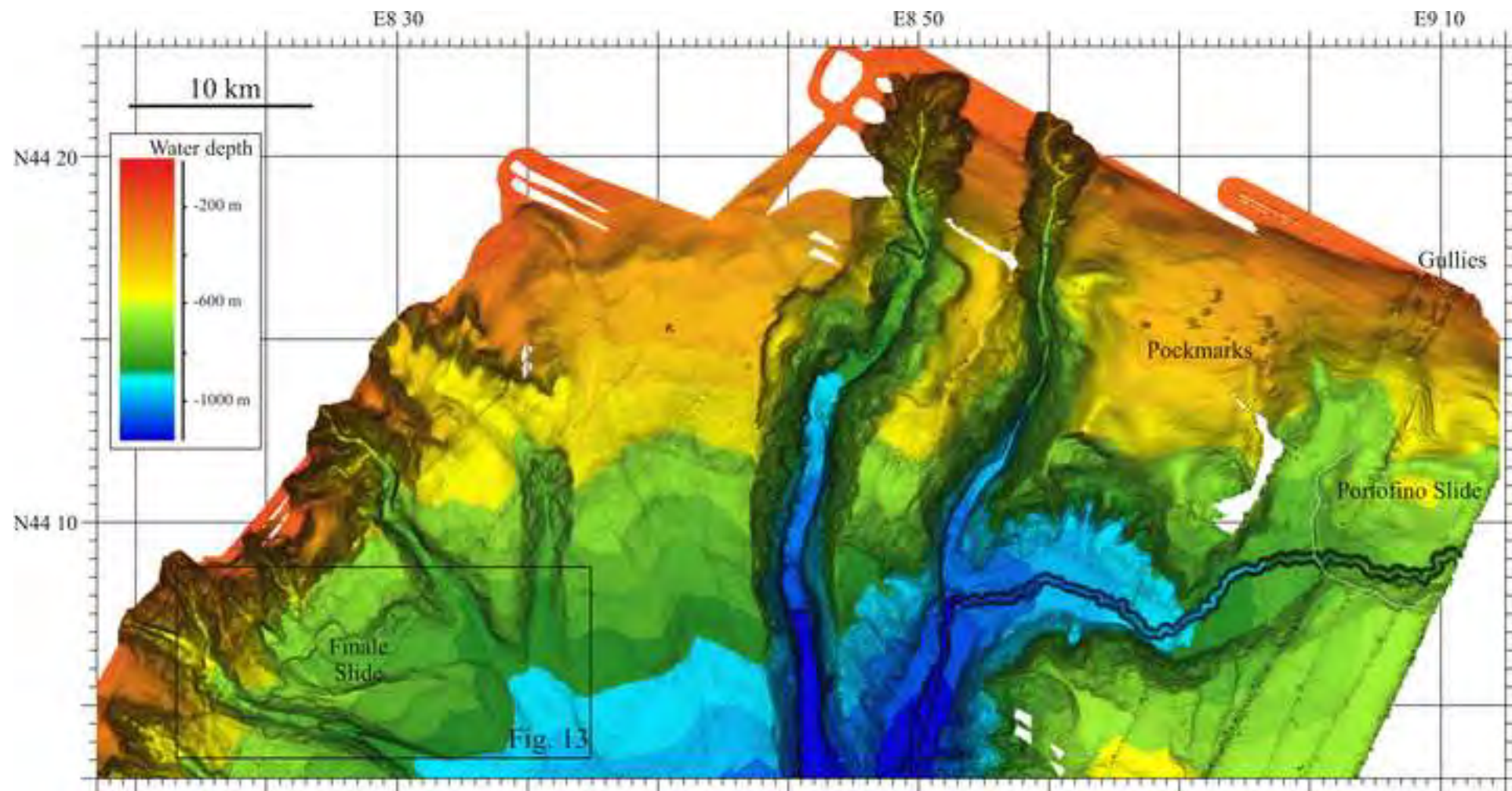
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**Fig. 11**  
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**Fig. 12**  
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**Fig. 13**  
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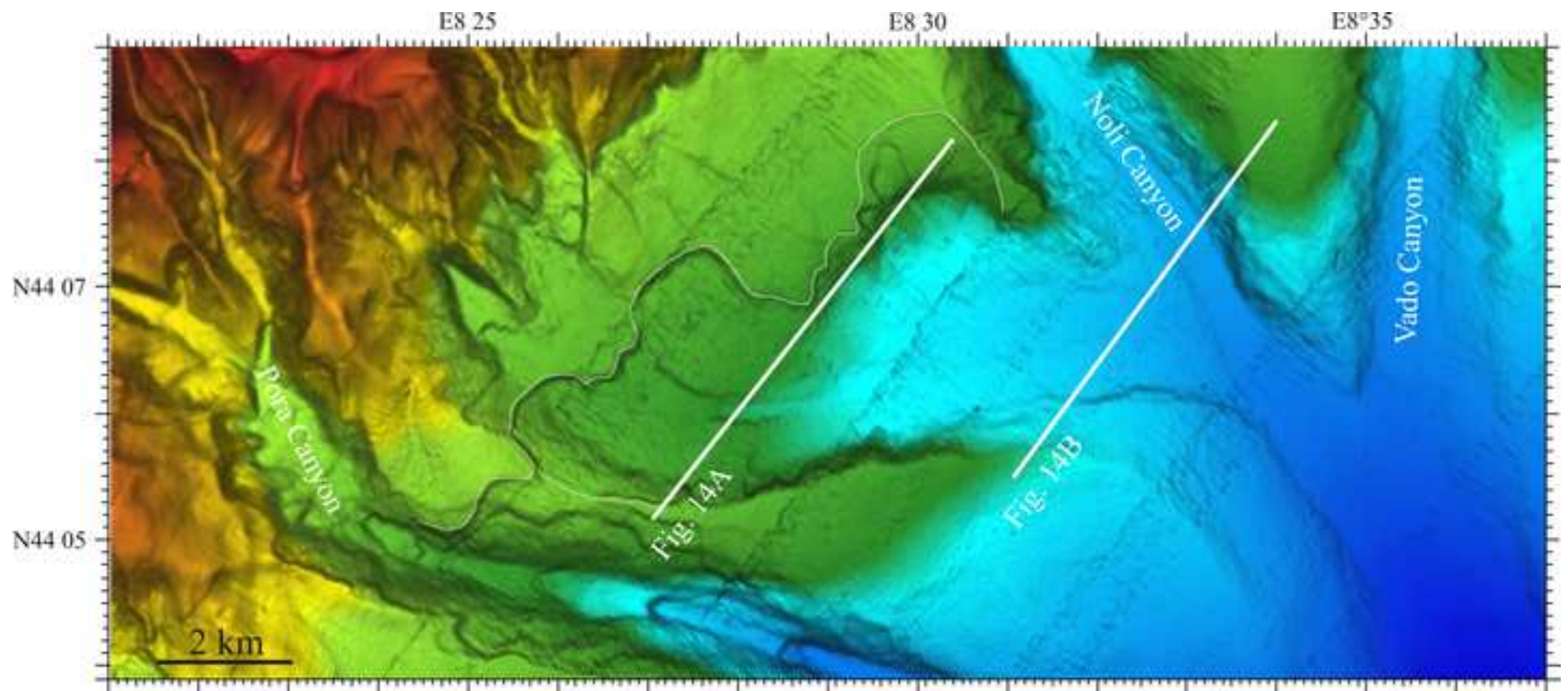
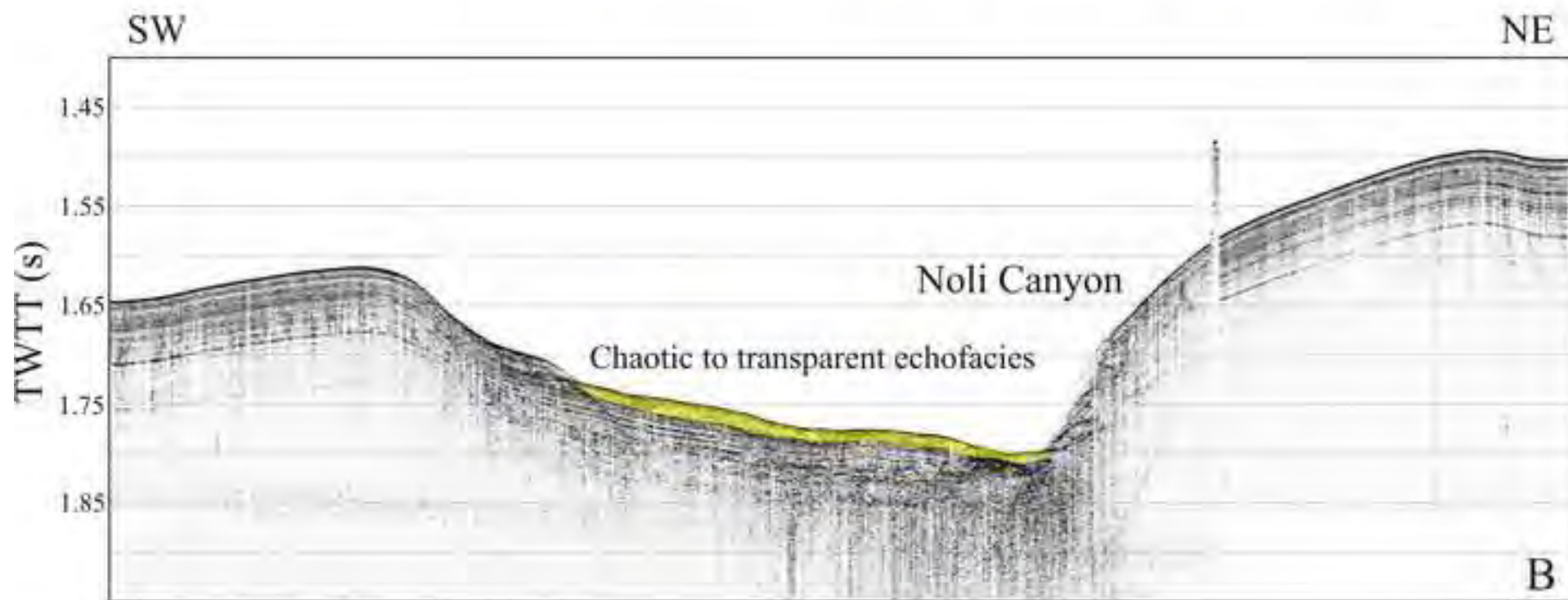
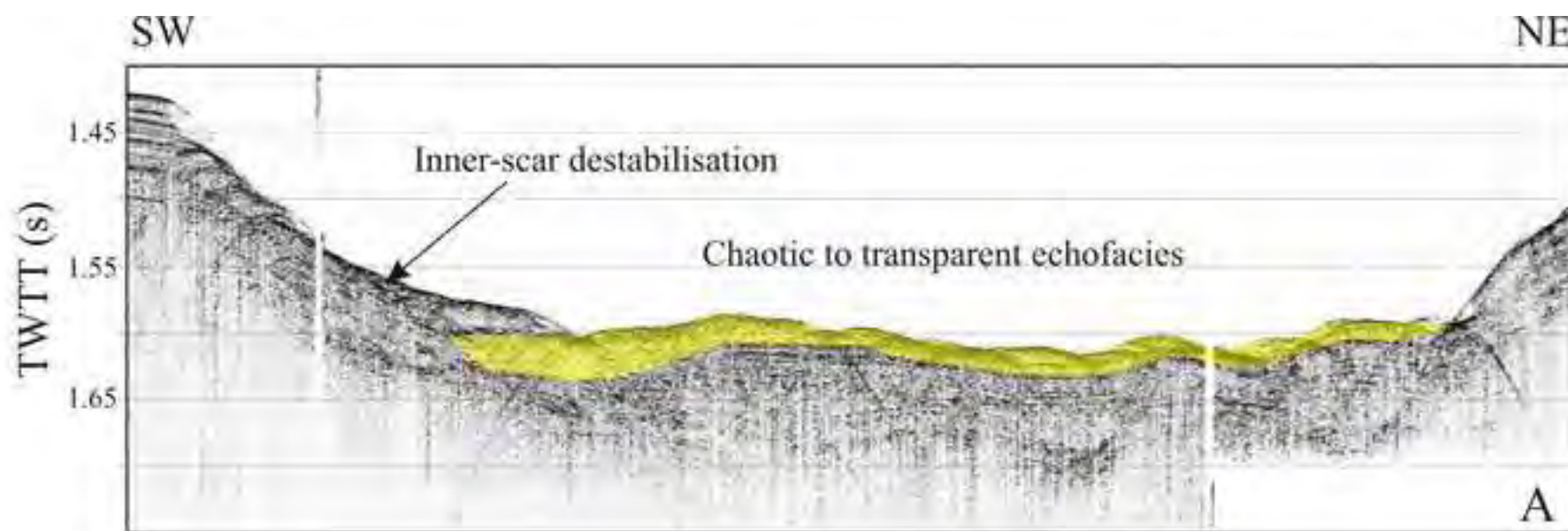


Fig. 14  
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**table 1**[Click here to download table: Table1.doc](#)

	<b>Type-1 scars</b>	<b>Type-2 scars</b>	<b>Type-3 scars</b>
Number of studied scars	> 400	14	3
Examples	1979 Nice-airport landslide	‘Cirque Marcel’	VSR Slide Finale Slide Portofino Slide
Water-depth range (m)	0-2000	1700-2200	250-2100
Preferential location	Shelf edge, upper continental slope, canyon walls	Base of continental slope	Continental slope, deep basin
Size (H-W-L)	Small	Medium/large	Medium/large
Length	Few hundreds of meters	4-6 km	3-5 km
Width	100-400 m	2-4 km	6-10 km
Height	30-90 m	100-500 m	50-300 m
Volume	< 0,1 km <sup>3</sup>	1 to 3 km <sup>3</sup>	1 to 3 km <sup>3</sup>
Regional slope	10-20°	6°	< 4°
Associated with	River mouths, erosional chutes	Faults, accumulations of debris	MTD
Main process	Mass wasting, disintegration process	Mass wasting, disintegration process	mass wasting
Potential geohazard associated	Low to high : tsunami, cable brakes	High : tsunami	Low : submarine landslide High : tsunami

Table 1: Summary of the main characteristics of each type of failure scars identified on the Ligurian margin.