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► **To cite this version:**

Massinissa Benabdellouahed, Agnes Baltzer, Marina Rabineau, Daniel Aslanian, Mohamed Sahabi, et al.. Slope morphologies offshore Dakhla (SW-Moroccan margin). Bulletin de la Société Géologique de France, 2016, 187 (1), pp.27-39. 10.2113/gssgfbull.187.1.27 . hal-04200706

**HAL Id: hal-04200706**

**<https://hal.science/hal-04200706>**

Submitted on 5 Jan 2024

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## Slope morphologies offshore Dakhla (SW-Moroccan margin) Morphologies de la pente continentale au large de Dakhla (marge SW marocaine)

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### Abstract :

This study explores a portion of the West African margin at the junction between two well-known segments offshore Dakhla and offshore Mauritania with destructional architecture characterized by giant slides. In between these two segments, the Dakhla segment has historically been described as a constructional section. During an oceanographic Dakhla cruise (2002), high resolution seismic data, swath bathymetry and imagery were acquired around latitude 23° N, offshore Dakhla. This new data set reveals the existence of varied and complex morphologies on the continental slope, interpreted as a "shallow-shaped" canyon, seafloor depressions or pockmarks, ridges and scarps. These morphologies are interpreted as clues of sedimentary transfers and rupture processes. A scenario is proposed for the development of these different sedimentary morphologies.

**Keywords :** African margin, Bathymetry, Seismic interpretation, Pockmarks, Ridges, Scarps

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**Résumé :**

Cette étude s'intéresse à une portion de la marge Ouest Africaine, à la jonction entre deux segments largement étudiés situés au large de Dakhla et de la Mauritanie, caractérisés par une morphologie globale de type destructif avec de larges glissements. Entre ces deux segments, celui de Dakhla est généralement décrit comme une portion de marge de type constructif. Durant la mission océanographique Dakhla (Décembre 2002), au large de Dakhla, de nouvelles données de sismique haute résolution, de bathymétrie et d'imagerie ont été acquises autour de la latitude 23°N. Ce nouveau jeu de données révèle l'existence de différentes morphostructures du fond telles qu'un canyon, des dépressions plus ou moins circulaires (pockmarks), différents types de rides et des escarpements, structures interprétées comme autant de témoignages de processus de transferts sédimentaires et de rupture de pente.

**Mots-clés :** Marge africaine, Bathymétrie, Interprétation sismique, Pockmarks, Rides, Escarpements

**1. Introduction**

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The study of slope stability along passive continental margin is important to understand 48 sediment transfer from the shelf to the oceanic basin and to approach potential geo-hazards. 49 Among them, submarine landslides affect all types of continental margins and landslides are 50 relatively larger on passive margins than along active margins [Masson *et al.*, 2009]

52 Compared to all passive margins, the North-western African continental margin is  
53 characterized by large submarine landslides (>400 - 600 km<sup>3</sup>) such as the Sahara Slide, the  
54 Cape Blanc Slide, the Mauritania Slide, and the Complex Dakar Slide, which are intensively  
55 studied since the 1970's [e.g. Antobreh and Krastel, 2006; Embley, 1982; Gee *et al.*, 2001;  
56 1999; Georgiopoulou *et al.*, 2010; 2009; Hühnerbach *et al.*, 2004; 2004; Jacobi and Hayes,  
57 1992; Krastel *et al.*, 2012; Wynn *et al.*, 2000]

58 In the northern part of the west African coast, south of the Canary Islands and offshore  
59 Dakhla, around 25°N, the margin shows a destructional margin architecture [Ranke *et al.*,  
60 1982] with a steep irregular profile and numerous slumps and slides cutting the slope surface  
61 such as the Sahara slide [Georgiopoulou *et al.*, 2010; Wynn *et al.*, 2000]. In the southern  
62 zone, south of 21°N and offshore Mauritania, two slides have been described by Krastel *et al.*,  
63 [2006] and Antobreh and Krastel [2006], the Cap Blanc slide and the Mauritania slide.

64 Between these two zones, where instabilities are related to relatively high accumulation rates  
65 but rare triggers, [Ranke *et al.*, 1982] described a constructional section of the margin with  
66 smooth convex/concave shape and evidences of shelf and slope progradation.

67 During the Dakhla cruise [2002] devoted to deep investigation of the margin on the R/V  
68 Suroit, high resolution seismic data together with swath bathymetry were additionally  
69 acquired on a relatively unknown portion of the margin, at 23°N offshore Cap Blanc and  
70 Dakhla (Fig. 1). This new data set reveals new morphologies linked to different types of  
71 sedimentary transfer processes, that are described in this paper. A scenario is proposed to link  
72 these different morphologies, with relative ages.

73

## 74 **GENERAL SETTINGS**

75 The West African margin is one of the oldest passive margins in the world: the rifting phase  
76 of this margin occurred between the late Triassic and the Early Jurassic and was followed by

77 oceanic spreading initiated around 195 Ma [Labails, 2007; Labails *et al.*, 2010; Sahabi *et al.*,  
78 2004]. Earthquakes are rare and have been recorded in the old weakness zones created during  
79 the opening of the Atlantic Ocean [Hayes and Rabinowitz, 1975]. From Jurassic to Early  
80 Cretaceous, carbonate platforms have been constructed, followed by marine clastic infill  
81 between Cretaceous and Tertiary. Since the late Cretaceous, erosive cycles have shaped the  
82 margin [Labails, 2007; Labails *et al.*, 2010] and a major eocene erosional surface [Labails,  
83 2007], observed on the opposite American margin by Mountain and Tucholke, [1985], is  
84 associated to a succession of gullies and canyons perpendicular to the margin.

85 On the Dakhla coast (Fig. 1), the shelf-break is located at 100-200 m of water depth. Beyond,  
86 the continental slope has a width of 50-250 km [Wynn *et al.*, 2000], and displays slope angles  
87 of 1-6°. In some areas, e.g. adjacent to the Sahara Canyon System, slope angles may reach  
88 14°. The slope evolves to the continental rise at water depths of 1500-4000 m, with gradients  
89 decreasing from about 1° on the lower slope/upper rise, to 0.1° on the lower rise [Masson *et*  
90 *al.*, 1997]. The rise is generally 100- 1500 km wide and terminates at water depth of 4500-  
91 5400 m, the deep abyssal plains.

92 Offshore the Dakhla margin, quaternary deposits are constituted of pelagic and hemipelagic  
93 sediments [Georgiopoulou *et al.*, 2010; Wynn *et al.*, 2000]. This fine-grained clastic slope  
94 apron, with pelagic/hemipelagic ‘background’ sedimentation is overprinted by downslope  
95 gravity flows, shaped by along slope bottom currents [Wynn *et al.*, 2000]. Zühlsdorff *et al.*,  
96 [2008] showing successions of turbiditic and hemipelagic deposits in the Cap Timiris Canyon  
97 system that were correlated to the alternation of arid and humid climatic conditions. They  
98 explained that both atmospheric systems: the northerly Trade winds and the southerly African  
99 monsoon, interact with each other and with seasonal shifts: northwards during times of boreal  
100 summer (or climatically forced on larger time scales) due to Trade winds weakening and  
101 southwards when the Trade winds strengthen. The effect for western Africa is humidification

102 when monsoonal pattern prevails and aridification when Trade winds become stronger  
103 [Zühlsdorff *et al.*, 2008].

104 Offshore Mauritania, high accumulation areas of biogenic detritus have also been observed at  
105 water depths of 1000-1500m in relation with intense upwelling activity in the area [Fischer *et*  
106 *al.*, 2009; Henrich *et al.*, 2008]. Oceanic upwelling is seasonally and spatially variable on the  
107 northwest margin [Mittelstaedt, 1991; Van Camp *et al.*, 1991] with a major upwelling zone as  
108 seen on figure 1. The region off Cap Blanc is dominated by a persistent upwelling and strong  
109 activity of small-scale eddies, filament and jets [Karakas *et al.*, 2006]. The area between 26°N  
110 and 21°N shows that a permanent upwelling has been recorded since 2002 and reported by the  
111 Bulletin of Upwelling, [2015]. High sediment accumulations areas of biogenic detritus are  
112 also observed at 1000-1500 m water depths (mwd) in relation with intense upwelling activity  
113 in the area [Fischer *et al.*, 2009].

114 Thus, the large open-slope landslides (>400-600 km<sup>3</sup>) occurring on this continental slope  
115 (Fig. 1), like the Mauritania, Cap Blanc and Sahara Slides [Embley, 1982; Gee *et al.*, 1999;  
116 Georgiopoulou *et al.*, 2009; Georgiopoulou *et al.*, 2007; Henrich *et al.*, 2008; Krastel *et al.*,  
117 2006] largely consist in remobilized hemipelagic sediments [Gee *et al.*, 1999; Krastel *et al.*,  
118 2006].

119 The Canary Islands contribute to the sedimentation by an input of volcanoclastic material by  
120 both large-scale landsliding [Wynn *et al.*, 2002] and slow fallout through the water column  
121 into the hemipelagic sediments.

122 Together with the presence of these islands and seamounts, the existence of deep-water  
123 bottom currents locally influence the sedimentation pattern of this margin.

124 The general water mass structure of the northwest African margin includes at about 600-700  
125 mwd the southward-flowing North Atlantic Central Water (NACW), at 2000-3800 mwd, the  
126 North Atlantic Deep Water (NADW) flowing in a southerly direction, and below 3800m, the

127 Antarctic Bottom Water (AABW) flowing in a northeasterly direction. These bottom currents  
128 have velocities ranging from 1 to 6 cm/s [Lonsdale, 1982; Sarnthein *et al.*, 1982].  
129 Oceanic upwelling is seasonally and spatially variable on the northwest margin [Mittelstaedt,  
130 1991; Van Camp *et al.*, 1991] (blue dashed line on Fig. 1). A major and persistent upwelling  
131 center in the region off Cap Blanc is characterized by strong activity of small-scale eddies,  
132 filament and jets [Karakas *et al.*, 2006] and between 26°N and 21°N a permanent upwelling  
133 has been recorded since 2002 and reported by the Bulletin of Upwelling [2015].

134

## 135 **DATA AND METHODS**

### 136 ***EM300***

137 The EM300 is a multi beam swath sonar mapping system which gives a high-resolution  
138 bathymetry and an acoustic backscatter imagery. This system uses a single 30 kHz Mills  
139 Cross array and is able of swath mapping at depth ranges between 10 and 5000 m. When  
140 operated down to approximately 5000 m depth swath widths are about 5000 m. It runs with  
141 up to +/- 75° angular swath with 135 beams per ping, and features dynamically variable beam  
142 with configuration range from 1° to 4°, to achieve both high spatial resolution in deep and  
143 shallow waters. The Bathymetry of Dakhla Cruise is processed with Caraïbes software  
144 (developed by Ifremer) and have a spatial resolution better than 50 m (in water depths  
145 <2000 m).

### 146 **Chirp**

147 The Chirp is a hull-mounted sediment echosounder. The signal is characterized by a long  
148 impulse (50 ms), lineari modulated in time and frequencies. Thus, its frequency spectrum  
149 ranges 2-5.2 kHz with an average at 3.2 kHz. This frequency bandwidth allows a very high  
150 resolution (dm) in surficial layers (high frequency) and a deep penetration with the lower  
151 frequency that may reach about 100 m. 39 profiles (Fig. 1) have been recorded equivalent to

152 229 hours of data. For display purposes the envelope of the signal is computed and low-pass  
153 frequency filtered (2000 Hz). No automatic gain control is applied to the data, to avoid  
154 blanking features close to the seafloor reflection.

155

## 156 **Multichannel seismic data**

157 A total of 1500 km of multichannel seismic profiles (**Fig. 1**) were shot during the Dakhla  
158 cruise on board the N/O Suroit in 2002 [Klingelhoefer *et al.*, 2009; Labails 2007; Labails *et*  
159 *al.*, 2010]. The system was composed of a 4.5 km long streamer of 360 channels, with a 12.5  
160 m group interval, which was towed at 15 m immersion. The data were sampled at 4 ms.

161 Two different marine seismic sources were used during the cruise. For the deep crustal targets  
162 a large (8100 in<sup>3</sup>) airgun array was used in the single bubble mode consisting of 12 airguns  
163 between 250 in<sup>3</sup> and 976 in<sup>3</sup> (16 l). The airgun array was shot at a constant interval of 150 m.

164 Processing of the multichannel seismic data was performed using the Sispeed package. It  
165 included spherical divergence correction, FK-filtering, band-pass filtering (3-5-50-60 Hz),  
166 internal mute and dynamic corrections. The last processing steps included applying an  
167 automatic gain control and a Kirchoff migration using water or stacking velocities.

168

## 169 **RESULTS**

### 170 **Morpho-sedimentary structures**

171 The study area is characterized by a broad continental shelf, with a width ranging from 50 to  
172 80 km and a shelf break at a water depth of 100-120 m. The swath bathymetry map of the  
173 continental slope, with a 100 m grid cell size resolution, reveals a complex seafloor  
174 morphology from the shelf break at 120 m to 3000 m (**Fig. 2**).



175 The bathymetric map (Fig. 2) shows an undulating morphology that can be described as a  
176 bulge-like structure with a large radius of curvature of around 40 km shown on the profile (ef)  
177 (Fig. 2). This undulating morphology is oriented NW-SE, perpendicular to the shoreline.  
178 Based on the slope map and the bathymetric profiles, we divide this portion of the continental  
179 slope in three sections (Fig. 2 – profile (ab):  
180 - the first section, between 120 and 500 m water depth, is characterized by a slope angle of 5°  
181 and corresponds to the lower slope.  
182 - the second section, between 500 and 2100 mwd, is characterized by a slope angle ranging  
183 from 2° to 4° , with a convex longitudinal shape from 1000 to 2000 (profiles ab and cd,  
184 Fig. 2) and a complex bulged shape seen on transversal profiles (ef) and (gh) (Fig. 2).  
185 - the third section, between 2200 and 3000 mwd, is characterized by a gentle slope, less than  
186 2°, with well-marked scarps (S1 and S2, Fig. 2). The southern part of the study area, between  
187 2600 and 3000 mwd, is characterized by the presence of a meandering channel.  
188 From upslope to downslope, four sea floor features are identified, on the morphobathymetric  
189 map (Fig. 3), 1) the "shallot-shaped" canyon, 2) the sea floor depressions, 3) different ridges  
190 types and 4) scarps which will be described in the following paragraphs.

191

## 192 **Scarps**

193 The morphobathymetric map shows the presence of two scarps (i.e. S1 and S2, Fig. 3) that cut  
194 the downslope part respectively between 2400 and 2600 mwd and between 2100 and 2600  
195 mwd (Fig. 3). They both show a general N-S trend, with a complex broken shape almost  
196 imbricated.

197

198

199

200 **Dakhla "shallow-shaped" canyon:**

201 This canyon deeply incises the northern portion of the studied area, between 800 and  
202 2200 mwd (Fig. 4). This canyon, named the "shallow-shaped" canyon because of its specific  
203 shape, is globally oriented E-W and can be spitted in three sub-parts: a proximal part, a  
204 median part and a distal part.

205 The proximal part of the canyon runs from 800 m down to 1000 m axial depth (Fig. 4) and  
206 displays a V-shaped with a steep flank to the South ( $4^\circ$ ; 100 m-deep axial incision) and a  
207 terrace to the North (Fig. 4 profile ab).

208 The median part, from 1000 m to 1400 mwd (Fig. 4), corresponds to the enlargement of the  
209 incising feature reaching up to ten kilometers with smoother slope (axial incision  $<2^\circ$ ) and  
210 edges. Profiles (cd) and (ef) show a 40 m-deep axial incision.

211 On the distal part, from 1400 to 2200 mwd (Fig. 4), the incision narrows down to a single  
212 channel seen on profile (gh).

213

214 **Ridges morphologies:**

215 Two groups of ridges may be observed on the figure 5.

216 The first one, from 1000 to 1300 m, is only visible on the bathymetric map (nor on the chirp  
217 profiles because of the rough weather and neither on the slope map), in the eastern part of the  
218 central bulge (5A). These small scale ridges reveal a regular morphology of 3 to 5 m high for  
219 a wavelength of 50 m, with a N30 orientation, thus oblique to the main slope (Fig. 5A).

220 A second group of ridges, larger and irregular, occur between 1500 and 1800 mwd. These  
221 ridges are larger, with 1-12m high with kilometeric lengths (2-20 km) and spaced by 1 to 5 km.  
222 They show a perpendicular orientation to the main slope (Fig. 5A, western part).

223

224

225 **Seafloor depressions:**

226 Asymmetric seafloor depressions have been observed in the central part of the area around  
227 1500 mwd (Fig. 5B). Three types of seafloor depressions have been mapped and detailed on  
228 figure 5B: 1) circular (Fig. 5 – profiles 3 and 4) with a diameter varying from 0.5 to 1 km, 2)  
229 troughs 0.5–1.5 km wide, 6–9 km long and up to 45 m deep; oblique to the slope, oriented  
230 SW/NE and 3) troughs parallel to the slope.

231

232 **Echo Types classification**

233 The studied area can be divided into several zones based on the dominant echo types. Five  
234 echo types (Fig. 6 - for location see Fig. 3) have been identified and grouped within the four  
235 main classes following the classification of Damuth [1980] and Damuth and Hayes [1977]:  
236 distinct (I), hyperbolic (II), transparent (III), indistinct (IV). Each acoustic facies is described  
237 using amplitude, lateral continuity, frequency and geometry of the sub-bottom echoes (Fig. 6).

238

239 *Distinct echoes (I)*

240 Those echo types are characterized by a distinct sharp continuous bottom echo with parallel  
241 sub-bottom reflectors. It has been further subdivided into two sub-types (Fig. 6).

242 Facies I-1 is a laminated facies constituted by alternation of parallel continuous thin high and  
243 low amplitude reflections up to 60 ms thick.

244 This facies covers a large part of the study area, from the base of the continental slope to the  
245 western most part of the area. The reflections have slightly higher amplitude than in deeper  
246 water depths, between 800 to 2200 and 2200 to 3000 mwd. This facies covers the wavy  
247 morphologies (ridges area), seafloor depressions and scarps.

248 Facies I-2 is similar to facies I-1 with alternation of parallel continuous thin high- and low  
249 amplitude reflectors, but is topped by a transparent upper layer (0.0025 ms), with a thick and  
250 diffuse seafloor reflector. This facies is mapped between 1600 and 2200 mwd.

### 251 *Hyperbolic echoes (II)*

252 This echo is characterized by irregular overlapping hyperbolae with chaotic sub-bottom  
253 reflections of relatively high amplitude. The signal shows slight even none sea-floor  
254 penetration (Fig. 6). It is restricted to the area of the shallot-shaped canyon.

### 255 *Hard echoes (III)*

256 It has been subdivided into two sub-types (Fig. 6)

257 Facies III-1 is characterized by high-amplitude reflectors with no sub-bottom echoes and/or  
258 diffuses returns on seismic profiles and a rough seafloor. It occurs on the upper continental  
259 slope and shelf break.

260 Facies III-2 displays hard echoes with subbottom reflectors, this echo type shows  
261 discontinuous and inclined subsurface reflectors, appearing as discontinuous patches. Facies  
262 III-2 is mainly represented on the continental shelf of our study area.

263

## 264 **INTERPRETATION**

### 265 **Sedimentary structures**

266 High-resolution multibeam and bathymetry data show a highly-complex superficial  
267 morphology described above. In order to understand the origin of those sedimentary  
268 structures, we use deep penetrating multichannel seismic profiles (Figs. 7 and 8). The seismic  
269 profile AB (Fig. 7) can be divided in two parts: the lower part, below the cretaceous reflector  
270 [Labails, 2007], displays long amplitude undulations that are related to the presence of a  
271 tectonic bulge described by several authors [e.g. Jolivet *et al.*, 1984; Patriat and Labails,  
272 2006]. On the other hand, the upper part of the profile AB (Fig. 7) shows undulations of the

273 sedimentary layers with wavelengths of about 40 km, probably related to a geological heritage  
274 with the presence of numerous canyons and interfluves (Fig. 7). This large-scale undulating  
275 morphology is locally complemented by peculiar features described in previous paragraphs:  
276 two scarps, the "shallow-shaped" canyon, the ridges and the seafloor depressions. The aim of  
277 the discussion will be to try to understand each of the sedimentary process triggering these  
278 deposit features.

279

### 280 **The scarps morphologies**

281 The two scarps (S1 and S2) correspond to 30- 40 m steps which are observed on the seismic  
282 profile CD (Fig. 8). The seabed and shallow reflectors are separated by shallow faults or  
283 hydro-fracturing due to fluid pressure that connect to surface discontinuities (sliding surfaces;  
284 Figs. 7 and 8). The scarps morphologies have affected the continuous echoes i.e. seismic  
285 facies I-1 and I-2 (Fig. 8). According to the literature, Facies I-1 and I-2 generally correspond  
286 either to an alternations of pelagic/hemipelagic (muddy/silty) sediments or to turbidites  
287 deposits [e.g. Damuth, 1980]. The reflectors (pelagic/hemipelagic facies) that drape S1 are cut  
288 by S2 can be observed on the seismic profile (Fig. 9). This observation proves that Scarp S1 is  
289 older than S2.

290

### 291 **Shallow-shaped canyon**

292 The "shallow shaped" canyon (Fig. 4) corresponds in its proximal part, to a group of V- shaped  
293 incisions similar to the gullies described on other continental slope by [Twichell and Roberts,  
294 1982]. They are issued from the shelf edge and further join together into a single canyon  
295 going downslope and finally reach the abyssal plain in its distal part. The sharp incision of the  
296 canyon (ab) does not show any sedimentary pelagic drape on the chirp profiles, The median  
297 part of the shallow-shaped canyon is characterized by an hyperbolic echo (type II, Fig. 6)

298 interpreted by several authors [Damuth, 1980; Jacobi, 1976] as a rough seafloor covered with  
299 coarse elements such as blocks or mass-transport deposits so-called debrites [Lee *et al.* 1999].  
300 The chaotic nature of the echo in the shallot-shaped canyon suggests a high degree of  
301 sediment remobilization and thus deposition from turbidity currents or debris flows. Collapse  
302 of the canyon flanks (see Fig. 3 for location) may contribute to the widening of the channel  
303 and to the irregular deposit morphology. Following Lonergan *et al.*, [2013], we propose that  
304 the gullies channelize turbidity currents originating from the shelf, supplying sediments  
305 downslope in relation with intermittent activity. The coarser elements are deposited in the  
306 median part (Fig. 4), while the rest flowing down evolves into turbidity currents by  
307 incorporating water and transforming its matrix into a fluid, which goes through the canyon  
308 (profile gh – Fig. 4), in the distal part of the system like the scenario described by Mulder and  
309 Alexander [2001].

310 No clear scar, headwall or departure zone has been identified on bathymetric data to explain  
311 mass wasting processes on the upper slope, therefore the simplest way to explain the presence  
312 of debris flow deposits would be the connection with a continental supply system with  
313 sporadic but intense and extreme events.

314 Turbidity current pathways were inferred in this area but not connected to permanent present  
315 day drainage system on land because of the saharian desertic climate [Wynn *et al.*, 2000].  
316 Thus, the origin of many submarine canyons, on this continental margin of north-west Africa  
317 between 15°N and 26°N, like Cap Timiris Canyon, are assumed to be related to a major sub  
318 aerial river system that was active in the past in relation with "green sahara" periods since  
319 Plio-Pleistocene times [Antobreh and Krastel, 2006; Larrasoaña *et al.* 2013; Vörösmarty *et*  
320 *al.*, 2000]. Recent studies [McGee *et al.*, 2013; Skonieczny *et al.*, 2013] revealed that eolian  
321 dust fluxes varied a lot during the last 20 ka, with maximum values during Heinrich Stadial 1

322 and the Younger Dryas, and minimum fluxes during the end of the African Humid Period  
323 between 8 and 6 ka.

324

### 325 **The seafloor depressions**

326 Sea-floor depressions observed around the 1500 m isobath reveal two types of shape (Fig. 5).

327 The circular shaped depressions may be assimilated to pockmarks features. Pockmarks are

328 circular to elongated seafloor depressions which are often associated with fluid gas escape

329 flow from the subsurface [Judd and Hovland, 2007]. The bright amplitudes seen on the figure

330 9 may correspond to hard lithology like seep carbonates which would likely be associated

331 with gas venting [Cathles *et al.*, 2010; Çifçi *et al.*, 2003; Çifçi *et al.*, 2003; Gay *et al.*, 2006;

332 Hovland *et al.*, 2010; Hovland *et al.*, 2002; Judd and Hovland, 2007]. An unconformity is

333 observable on the seismic chirp profile (Fig.9) around 1.95 twt (s) (1500 mwd).

334 To explain the formation of the second type of depressions, the elongated ones (Fig. 5), we

335 examine three hypotheses. The concentration of circular pockmarks can cause the formation

336 of the elongated pockmarks observed at 1500 m. The Fig. 5B shows an outstanding example

337 of the evolution of pockmarks from circular to elongated shape. The addition of two

338 pockmarks may be observed before complete coalescence on the profile 2 (Fig. 5C) and a

339 detailed observation show that the large pockmark (Fig. 5B) is composed of a coalescence of

340 ten to twenty smaller depressions. This first hypothesis corresponds to groups or long chains

341 of pockmarks described by [Hovland and Judd, 1988].

342 Another hypothesis is that these linear depressions reflect the surface expression of a deeper

343 structure such as a meandering channel or a subjacent fault draped by sediment, as suggested

344 by the third cartoon on the top of the figure 8. Meandering paleo-channels are clearly seen on

345 the figures 3 and 5A and may explain the occurrence of some of the elongated seafloor

346 depressions.

347 The dissymmetry or "*en échelon*" or "*festooned*" appearance of this succession of holes and  
348 troughs depressions have already been observed on a portion of this margin, between Cap  
349 Timiris and Nouakchott by Yang and Davies [2013]. They described troughs, either parallel  
350 or oblique to the slope dip, with elongate *en-echelon* plan-forms. These troughs have variable  
351 length, ranging from 0.5 to 10 km and are related to 2 types of gravity-driven faults: tear  
352 faults and normal faults. Based on 3D seismic data, these authors analysed a set of times  
353 slices with amplitude maps and suggest that the "*en echelon* and linear" troughs were formed  
354 as a result of multiple episode of down slope creep and have propagated through 60-140 m of  
355 sediments. These observations area in close agreement with our data, suggesting that the  
356 seafloor depressions may be assimilated to a potential rupture line and represent the surface  
357 expression of tear and/or linear faults affecting the upper sedimentary column. The location of  
358 "*en echelon* and linear" troughs at the slope inflexion (around 1500m) may suggest the  
359 departure zone of a sliding event.

360

#### 361 **Ridges areas :**

362 The two ridges areas are observed on both sides of the sea-floor depressions area (Figs. 5).  
363 Upper slope ridges, smaller in size and presenting an oblique orientation to the slope are  
364 assimilated to sediment-wave morphology, which would be in agreement with the existence  
365 of numerous sediment-wave fields mapped in the northern part of the margin by [Wynn *et al.*,  
366 2000]. These morphologies are commonly reported on the continental slopes of passive  
367 margins [Faugères *et al.*, 2002; Faugères *et al.*, 200; Viana and Rebesco, 2007] and active  
368 margins [Lee and Chough, 2001]. The bad weather prevent any further investigation of these  
369 small ridges features on the chirp data and thus, our observations are only based on the  
370 bathymetry map.



371 The second group of ridges, larger in size are located from 1500 to 1800 mwd. These  
372 undulations are parallel to the bathymetry and occur just below the seafloor depressions area  
373 (Fig. 5), traducing a deformation of the superficial sedimentary cover. We suggest they may  
374 be interpreted as compressional ridges.

375

## 376 **DISCUSSION**

377 All those sea-floor features, pockmarks, compressive ridges and scarps, canyons, reveal the  
378 existence of sediment transfer and instability processes from upslope to downslope. Here we  
379 suggest a potential link between these specific morphologies.

380 According to the literature, non-random pockmarks show spatial arrangement related either to  
381 complex underlying geology or to local disturbance of the seabed, whereas random  
382 distribution of pockmarks is commonly displayed on the lower slope where sediments are  
383 generally fine-grained and tectonic structures are rare [Pilcher and Argent, 2007].

384 In our study area, pockmarks are arranged along a "festooned line" on a N-S direction  
385 parallel to the bathymetry. However the seismic SMT profiles (Figs. 7 and 8) do not show  
386 deep faults or tectonic structures with complex underlying geology. The only visible fault is  
387 the one displayed in the scarp S2 (Fig. 8 - cartoon 2) and it appears to shift the first three  
388 reflectors). This fault is therefore considered as superficial and might be rooted in a layer  
389 which constitutes a sliding surface (basal detachment) seen on the figure 8.

390 Pilcher and Argent [2007] described linear pockmark trains which are associated with listric  
391 slump faults in different cases of continental slope instability. We suggest that scarps S1 and  
392 S2 are former zones of pockmarks alignments (Fig. 10).

393 The "festooned line" or "en-échelon" line of coalescent pockmarks could witness a weakness  
394 zone on the slope which could evolve into a future detachment area and form a new scarp S3.

395 This phenomenon of high concentration of pockmarks (causing their fusion) is widely  
396 observed e.g. in the Congo Basin [Gay *et al.*, 2006; Gay *et al.*, 2003], Nigeria margin [Sultan  
397 *et al.*, 2014; Wei *et al.*, 2015] in the Northwestern Atlantic [Fader, 1991], the Ionian Sea,  
398 Greece [Hasiotis *et al.*, 2002], the North Sea [Hovland, 1984; Hovland *et al.*, 1987; Hovland  
399 and Sommerville, 1985] and the Mediterranean [Dimitrov and Woodside, 2003].

400 The occurrence of compressive ridges below the pockmarks area also evidence initiation of  
401 gravitary movement.

402 The main triggering mechanism for slope instability and thus gravity mass movements  
403 processes, across the NW-African continental margin, is believed to be the overload of  
404 sediment [Georgiopoulou *et al.*, 2010; Masson *et al.*, 2010]. Whereas, other triggers such as  
405 earthquakes, free gas, gas hydrates or diapirism are believed to be of minor importance  
406 [Georgiopoulou *et al.*, 2010; Krastel *et al.*, 2006].

407 During the late Pleistocene, the repeated slope instabilities appear as a common characteristic  
408 of NW African margin [Antobreh and Krastel, 2006; Georgiopoulou *et al.*, 2010; 2007]. This  
409 margin has also been strongly affected by Quaternary sea-level cycles [Church and White,  
410 2006; Wien *et al.*, 2006]. According to Georgiopoulou *et al.* [2010], sea level changes appear  
411 to be important and giant slides appear to coincide with periods of deglaciation. During the  
412 latter periods, the sedimentation occurred in the vicinity of the present shore line  
413 [Georgiopoulou *et al.*, 2010]. Thus, major sedimentary events on the northwest African  
414 margin appear coincident with glacial - to - interglacial transitions [Church and White, 2006;  
415 Georgiopoulou *et al.*, 2010]. According to Riboulot *et al.* [2014; 2013; 2012], the upper-  
416 Pleistocene 100 ka cyclicity sea-level changes are the predominant driving factor of pockmark  
417 formation in the Gulf of Lions and Nigeria. On the basis of these observations, we suggest  
418 that Pleistocene sea level and sediment load associated with fluids escapes are the main  
419 process for soft-sediment deformation off Dakhla.

420 No core or drilling wells are available in the study area, however we propose correlations  
421 based on sea-level curves. The main goal of this correlation is to propose an age for the scarps  
422 morphologies and pockmarks formation (Fig. 10).

423 Riboulot *et al.*, [2013] have estimated the formation of a pockmark to last ~100 ka. Based on  
424 that assumption, we correlate morphologies with the sea-level curve from Waelbroeck *et al.*  
425 [2002] and propose the following chronology (Fig. 10):

426 - A) During the Marine Isotopic Stage MIS8 to MIS7: formation of the first generation of  
427 pockmarks caused by sedimentary load at 2600 mwd, that induced the formation of a sliding  
428 plane of the scarp 1. This scarp is draped by hemipelagic deposits;

429 - B) During the MIS 6 to MIS 5: formation of the second generation of pockmarks at 2200  
430 mwd, that induced the formation of a sliding plane of the scarp 2. And folding of the  
431 hemipelagic layer.

432 - C) During the MIS 4-2 to MIS 1 : formation and the alignment pockmarks at 1500 mwd and  
433 future scarp S3 (?). This area of pockmarks is contemporary to Sahara Slide, El Golfo /  
434 Canary Debris Flow and the Mauritania Slide [Siddall *et al.*, 2003].

435 During low sea level phases, cannibalization of the shelf combined with "green sahara"  
436 periods since Plio-Pleistocene times (Larrasoaña *et al.* 2013) induced an overload of sediment  
437 on the slope that may have favored sediment failures. The slope destabilization might also be  
438 linked to the liberation of hydrate dissociation by variation of temperature and pressure,  
439 linked to glacial/interglacial phases.

440

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444

445 **CONCLUSION**

446 The analysis of multibeam bathymetry, high-resolution sub-bottom and seismic data on the  
447 continental slope of the off Dakhla allowed us to identify several morphologies such as  
448 shallot-shaped canyon, pockmarks, wavy morphologies and two scarps (S1 and S2). A  
449 detailed observation of these morphologies on chirp sub-bottom profiles and seismic data  
450 shows evidences rupture processes and transfer of sediments. Compressive ridges is primary  
451 linked to deformation mechanisms and creeping movements. This deformation is probably  
452 enhanced by the presence of fluids or gas associated with internal discontinuities acting as  
453 basal shear planes for creeping events. The scarps S1 and S2 indicate at least two generations  
454 of slides on this margin. We suggest that slide development was caused by rapid sea level rise  
455 after glaciation periods when sedimentation rate was maximum on the slope. This  
456 sedimentary load induced fluid or gas migrations along unconformities and superficial faults  
457 in the sediment. Fluid migration has lead to the formation and concentration of aligned  
458 pockmarks in weakness zones. These slides are believed to be 100-ka cycle events controlled  
459 by sea level variations during the second half of the quaternary period.

460 However, more regional studies using high resolution but deeper seismic penetration are  
461 needed in the area as well as coring and geotechnical studies to fully assess the timing of the  
462 events, the existence of gas hydrates and to determine whether creeping is still active today.

463

464 **Acknowledgement**

465 Special thanks are due to the captains of the N/O Suroit and Nadir and their crews together  
466 with the Genavir technical staff during the Dakhla cruise. This work was partly funded by  
467 Total in the frame work of the IFREMER/TOTAL Dakhla project. Authors would like to  
468 thank Bruno Marsset for his help on seismic processing and Frauke Klingelhofer, Jean Nizou  
469 for their comments on an earlier version of the manuscript. The two reviewers A. Gay and P.

470 Imbert and the editor O. Lacombe are thanks for their fruitful comments that helped us to  
471 improve this paper.

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769 **FIGURE CAPTIONS:**

770 **Figure 1:** Bathymetry and global relief map from [Smith and Sandwell, 1997] (Mercator  
771 projection, WGS84). of the NW Africa margin showing the study area (Dakhla zone) and the  
772 main morphologic features, described in literature like slides and debris flows (with a color  
773 code depending on authors), canyon and channel systems and the upwelling location of NW  
774 Africa. A green line underlines the isobath 1500 m. Insert box shows the profiles (seismic and  
775 bathymetry) position retrieved during the Dakhla cruise.

776

777 **Figure 2:** Bathymetric map of the offshore Dakhla from SIMRAD EM300 acquired during  
778 the Dakhla cruise and Slope-gradient (in degrees) map calculated from the bathymetry data. A  
779 synthetic bathymetric profiles shows the global morphology of the continental slope from  
780 upperslope (- 80 m) downslope (- 3000m).

781

782 **Figure 3:** Morphobathymetric interpretation on shaded relief map showing the main  
783 morphological features and echo-character mapping showing the distribution of the different  
784 echo types (see Figure 6) in the study area. Dakhla canyon is shown (in yellow) , ridges areas,  
785 the depressions shown (in dark blue) on the mid-slope, scarps S1 and S2 (in red) on the  
786 lower slope and a meandering canyon is still visible on the south western part.

787

788 **Figure 4:** Detailed bathymetric map of the Dakhla shallot-shaped canyon. The Dakhla canyon  
789 is divided into 3 parts: the "proximal part" upslope which groups several incisions, the  
790 "median part" which shows the enlarged part of the structure and the "distal part" which  
791 channelises turbidites issued from the median part. The bathymetric profile (ab) across the  
792 proximal part shows the sharp incision. Bathymetric profiles (cd) and (ef) across the median

793 part show the large morphology of incision. Bathymetric profile (gh) across distal part shows  
794 the main enlarged canyon downslope.

795

796 **Figure 5:** Focus on the mid-slope area with the wavy morphologies (ridges) and depressions.  
797 (B) Shaded relief map showing the examples of the evolution of depression (pockmarks) from  
798 a circular to an elongated giant shape. Synthetic bathymetric profiles (1, 2, 3 and 4) show the  
799 different bathymetric sections on 1) the wavy morphologies (ridges) 2) the combining two  
800 depressions (pockmarks) ; 3) a circular depression (isolated pockmark), 4) elongated  
801 depressions (giant pockmarks).

802

803 **Figure 6:** List of the main chirp "echo types" described in the investigated area: distinct  
804 echoes (I) with facies I-1 and I-2, hyperbolic echoes (II) and Hard echoes (III) with facies III-  
805 1 and facies III-2. The description of the echo and the area where it occurs are detailed in the  
806 main text.

807

808 **Figure 7:** Dakhla seismic profile (AB profile) and interpretation showing the global  
809 morphology of the continental slope and the main sedimentary layers (main surfaces; top  
810 Jurassic, Cretaceous surfaces and Eocene surface [Labails, 2007]). The seismic profile shows  
811 significant seismic undulations of the sedimentary layers parallel to the seabed (location of  
812 the seismic profile AB on figure 1).

813

814 **Figure 8:** Dakhla seismic profile (CD profile) and interpretation showing the global  
815 morphology of the continental slope and the main surface sedimentary layers (main surfaces;  
816 top Jurassic, Cretaceous surfaces and Eocene surface in [Labails, 2007]). seismic profile across  
817 scarp S1, scarp S2 and depressions. Insert box shows (Chirp subbottom seismic) profiles

818 across the scarp S1, scarp S2 and depressions. The seismic profile shows significant bulge of  
819 the basement (location of the seismic profile CD on figure 1).

820

821 **Figure 9** : The chirp profiles P02 and interpretation (location on figure 5A) shows the  
822 seafloor depression and bright spots in this depression and overpressure ridges. The  
823 unconformity surface truncates the subjacent reflectors and is recovered by parallel  
824 reflectors.

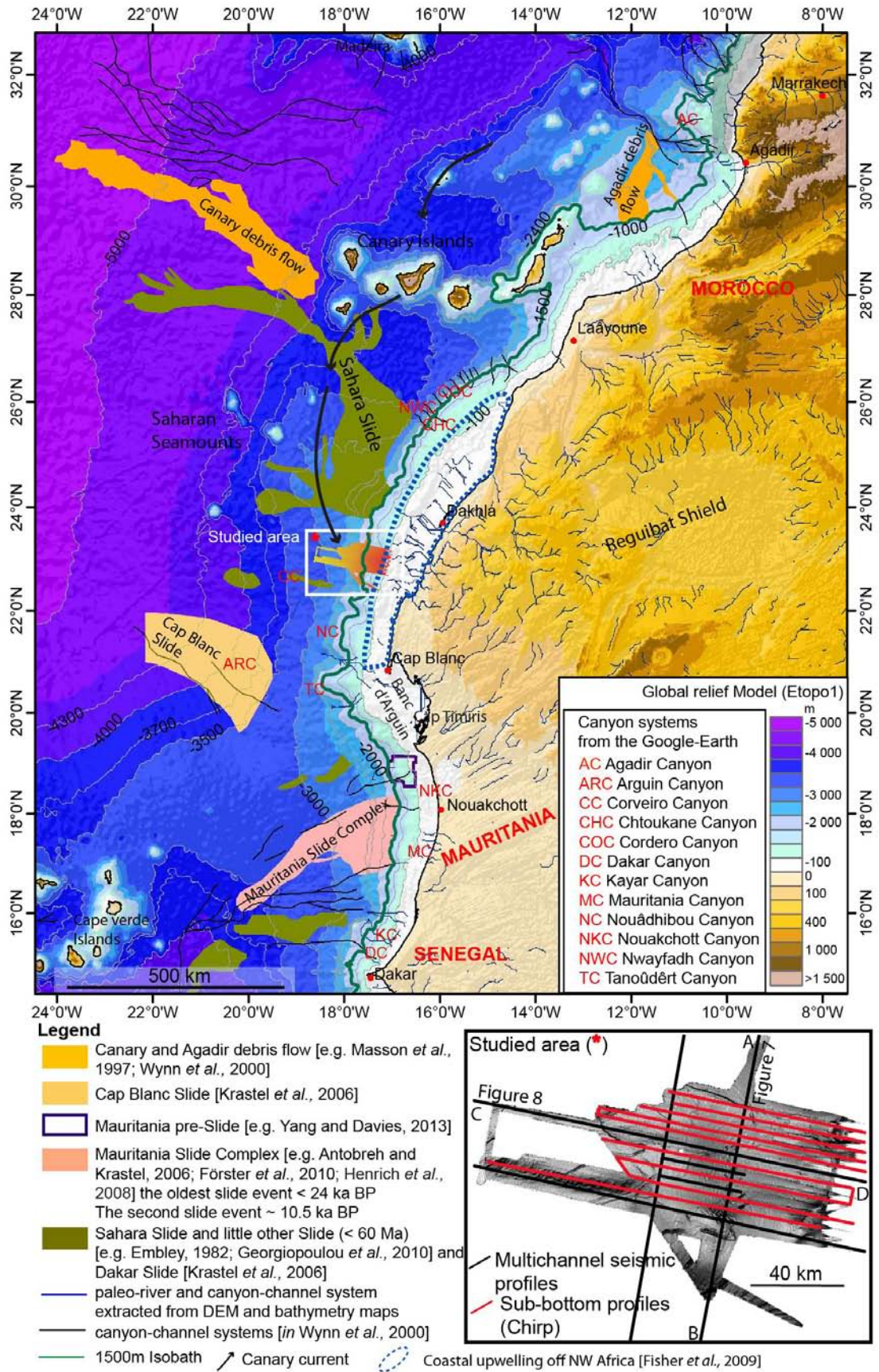
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826 **Figure 10**: Schematic illustration of the influence of pockmarks on seafloor stability and  
827 relationship with sea-level [Sea-level curve from Waelbroeck *et al.*, 2002]. The model is  
828 based on seismic profiles and bathymetry interpretation, A): formation and the alignment  
829 pockmarks at 2600 mwd during stage MIS 8 then sliding (scarp 1) event during stage MIS 7.  
830 B): formation and the alignment pockmarks, at 2200 mwd during stage MIS 6 then sliding  
831 during stage MIS 5 (scarp 2 ); C) (MIS 2 to 0) : formation and the alignment pockmarks at  
832 1500 mwd during stage MIS 2 and probable future sliding (S3).

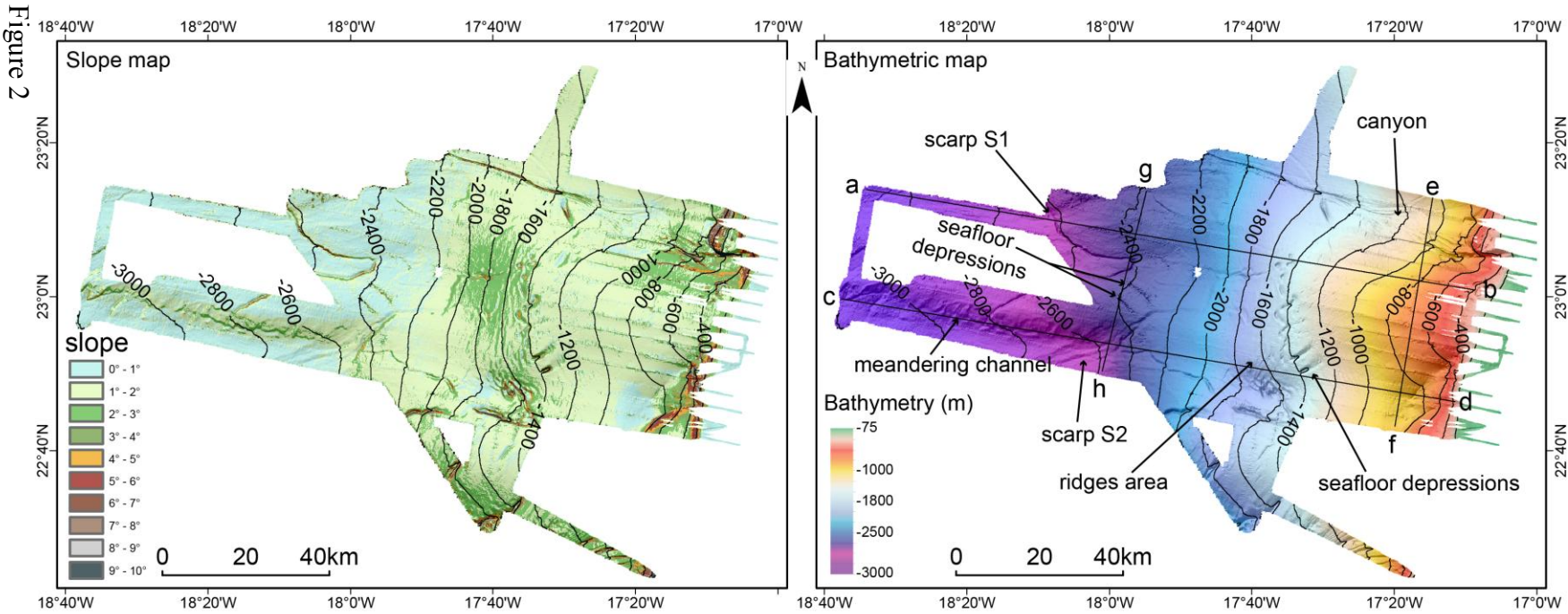
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**Bathymetric profiles**

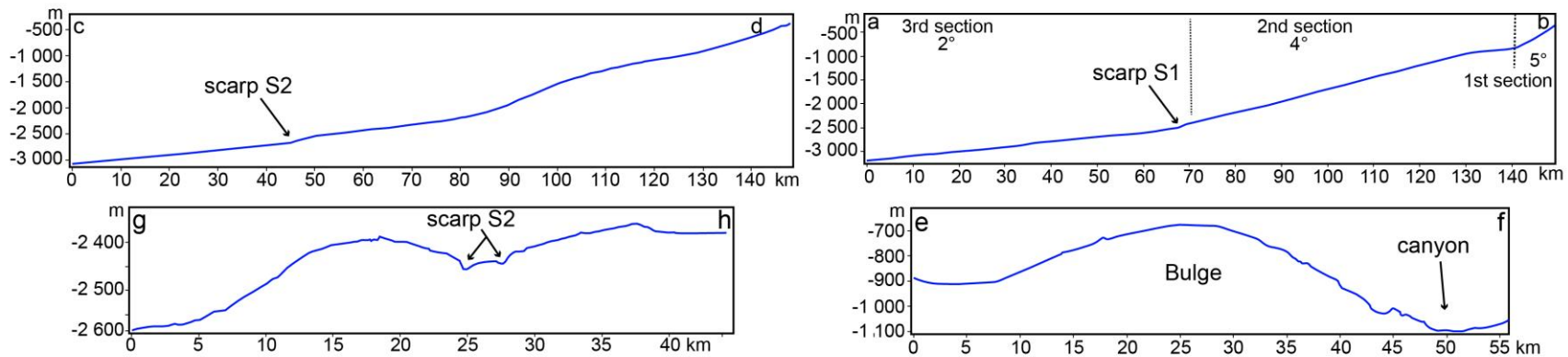
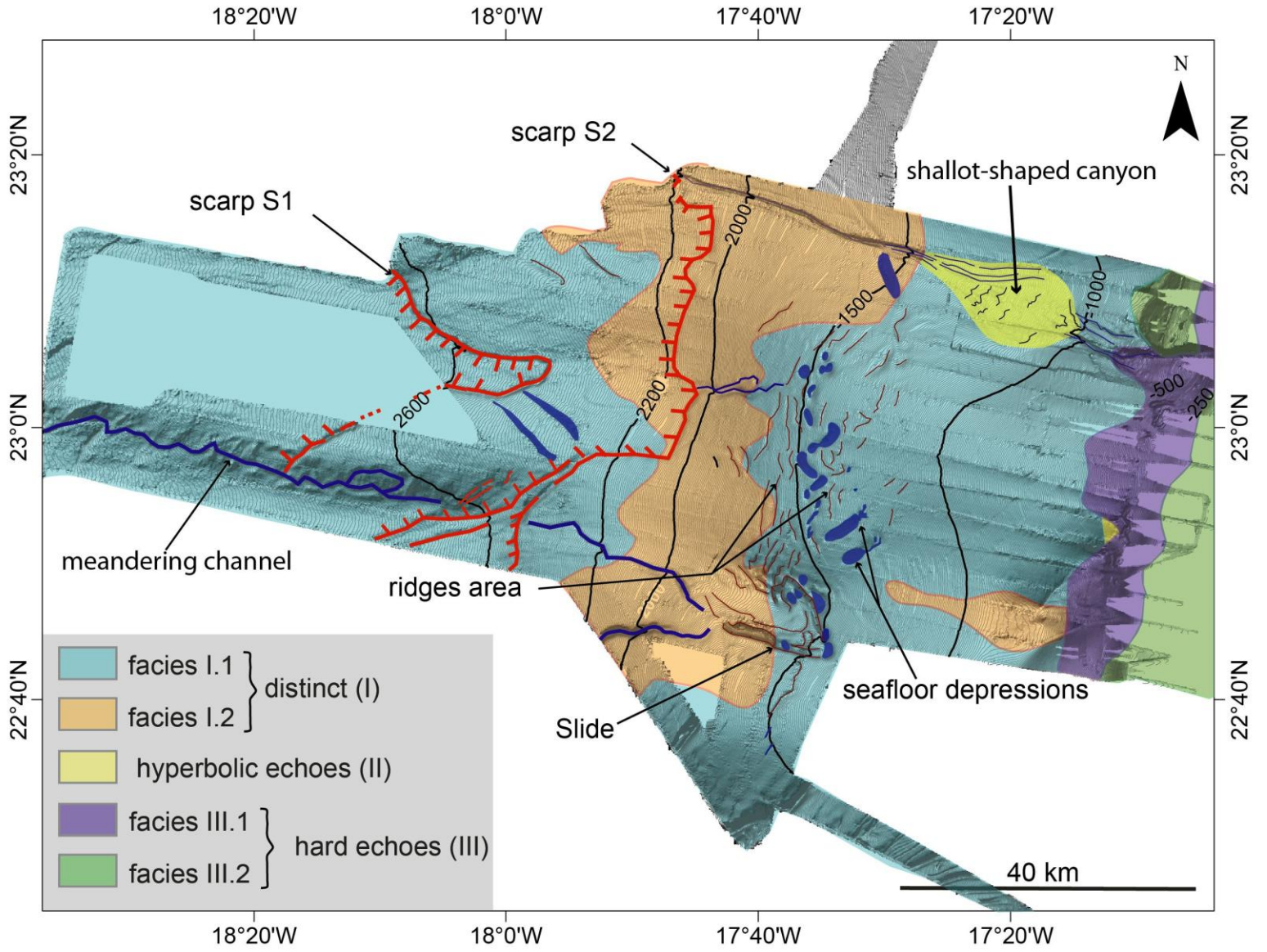
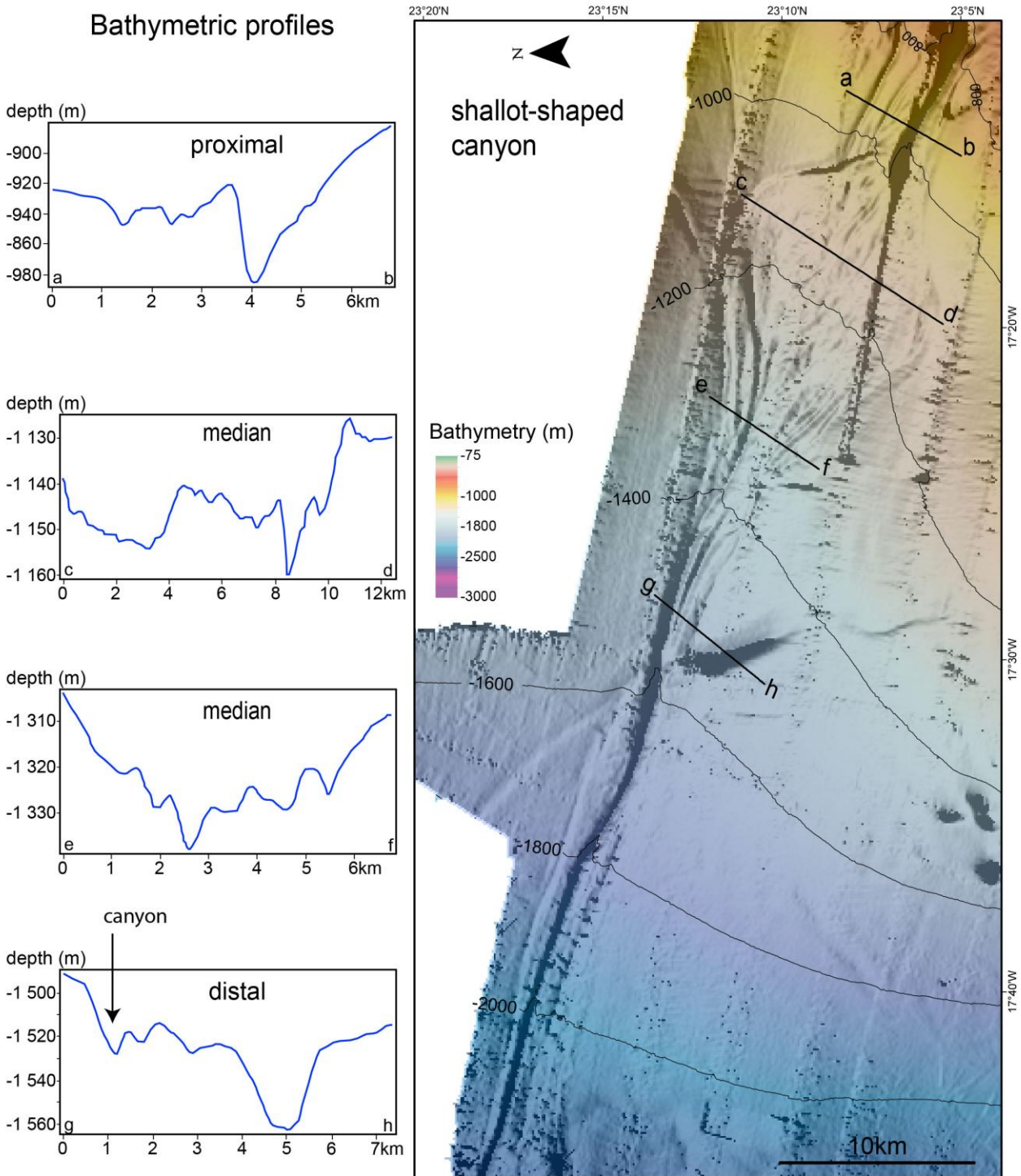


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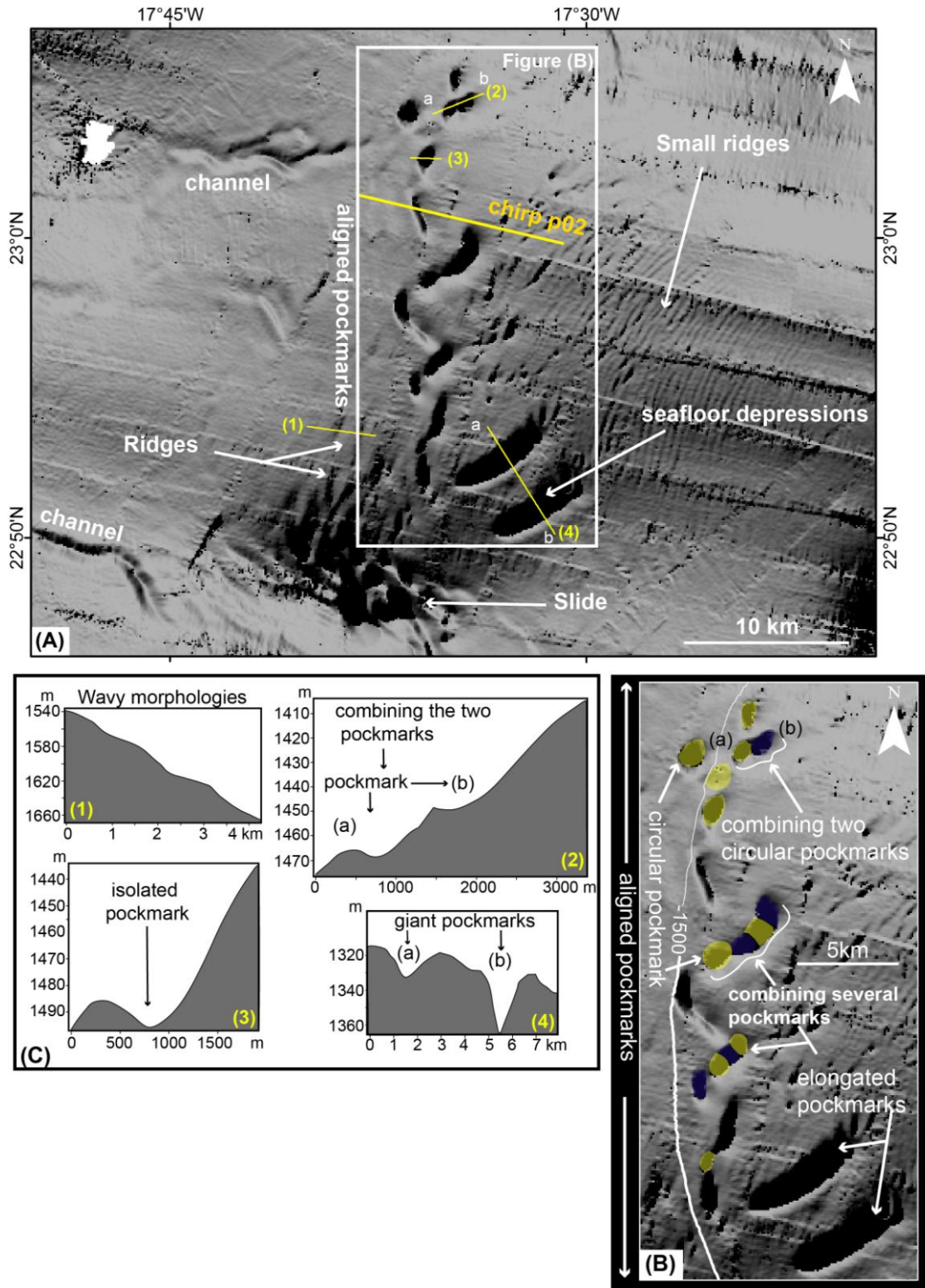
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Figure 3






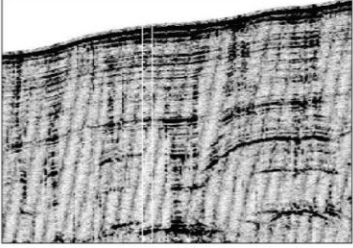

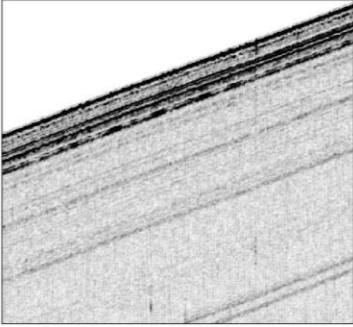

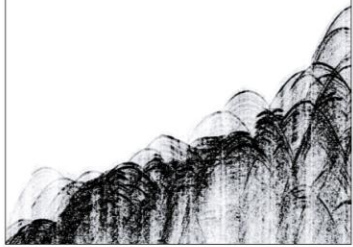

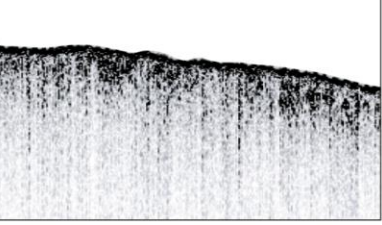

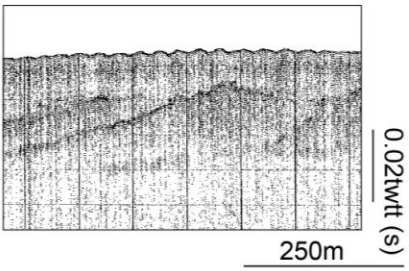
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Figure 4



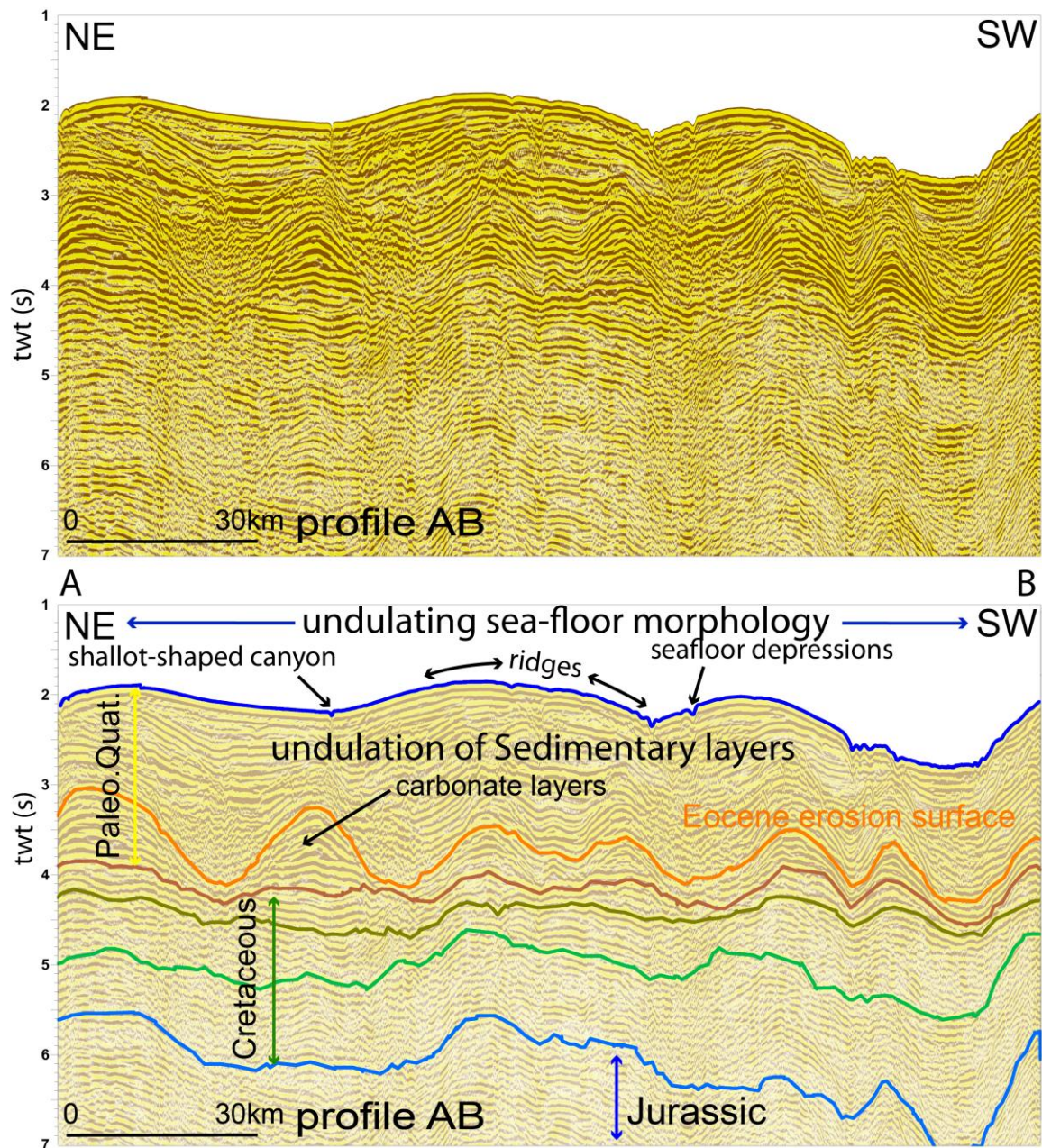
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Figure 5

Type		Type - Example	Zone	Description
distinct echoes (I)	facies I.1 		base continental slope and large part of the studied area	continuous and parallel reflectors of high amplitude and medium frequency
	facies I.2 		continental slope between 1600 and 2200	continuous and parallel reflectors with a transparent thin upper layer
hyperbolic echoes (II) 			mass transport deposits «troughs and holes»	is characterised by dense irregular overlapping hyperbolae
Hard echoes (III)	facies III.1 		upper continental slope	Hard facies is characterised by a dark surface reflector, with few or no sub-bottom reflectors
	facies III.2 		continental shelf	Hard subsurface with oblique reflectors (bed rock)

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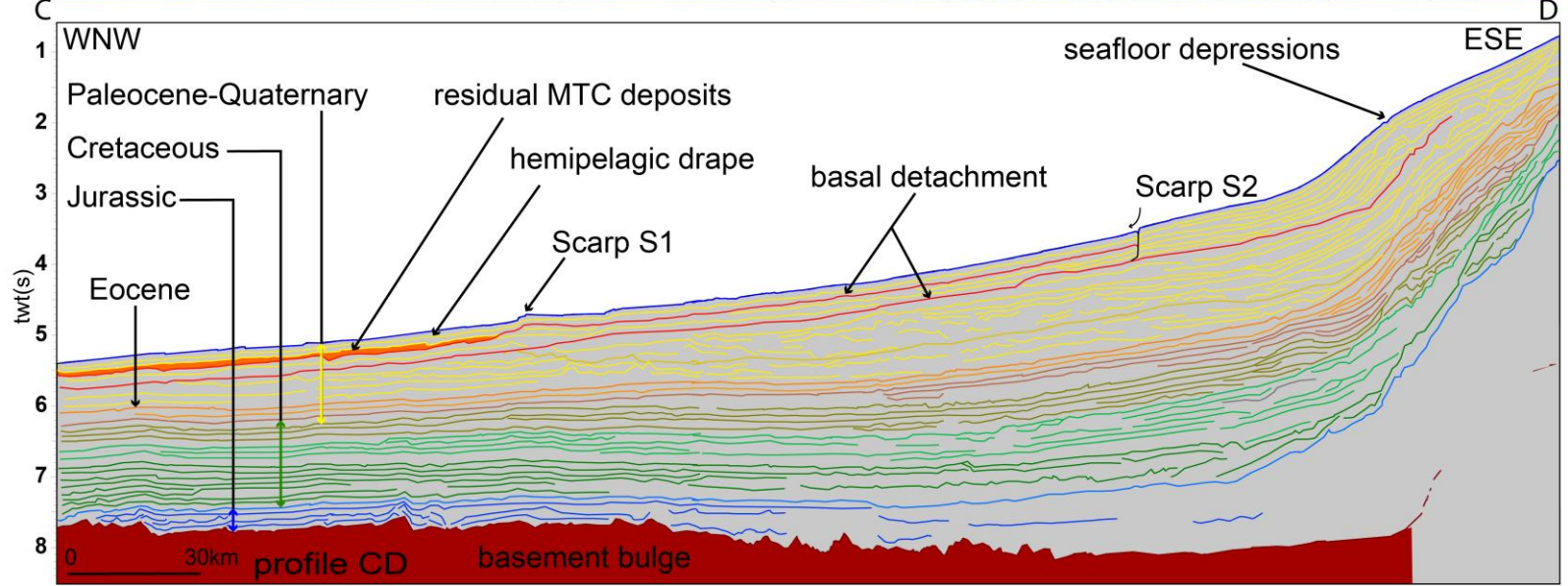
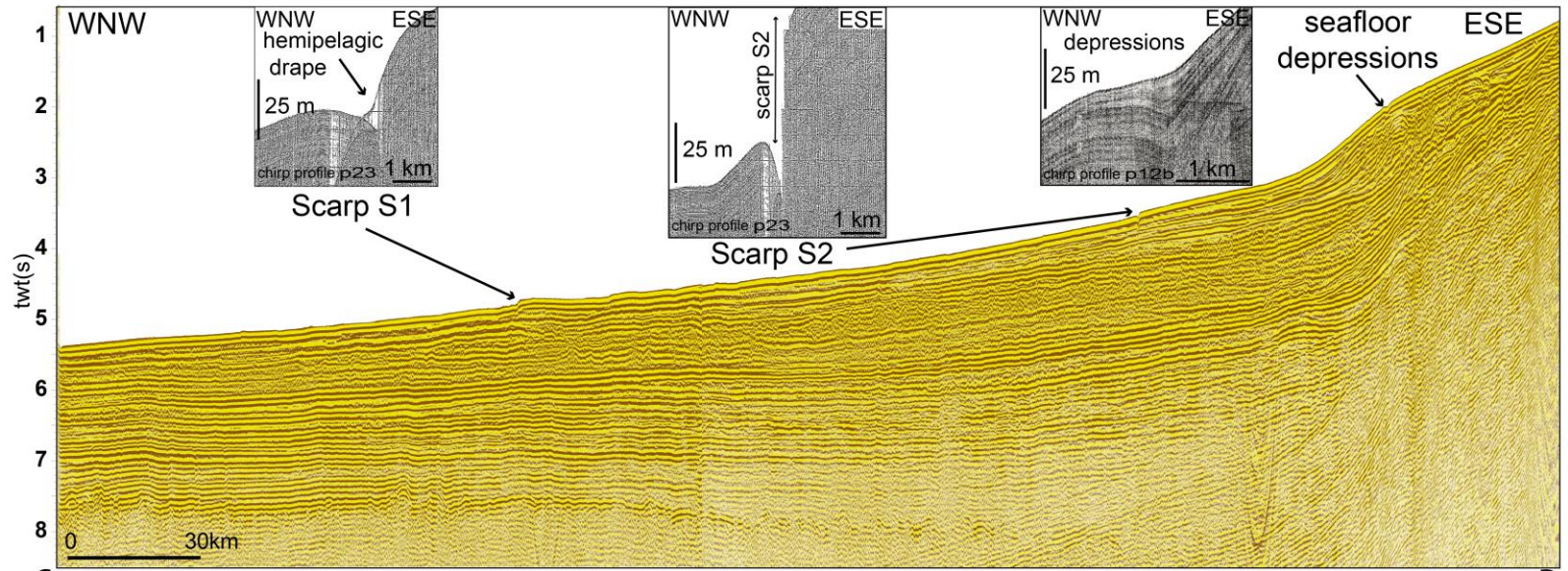
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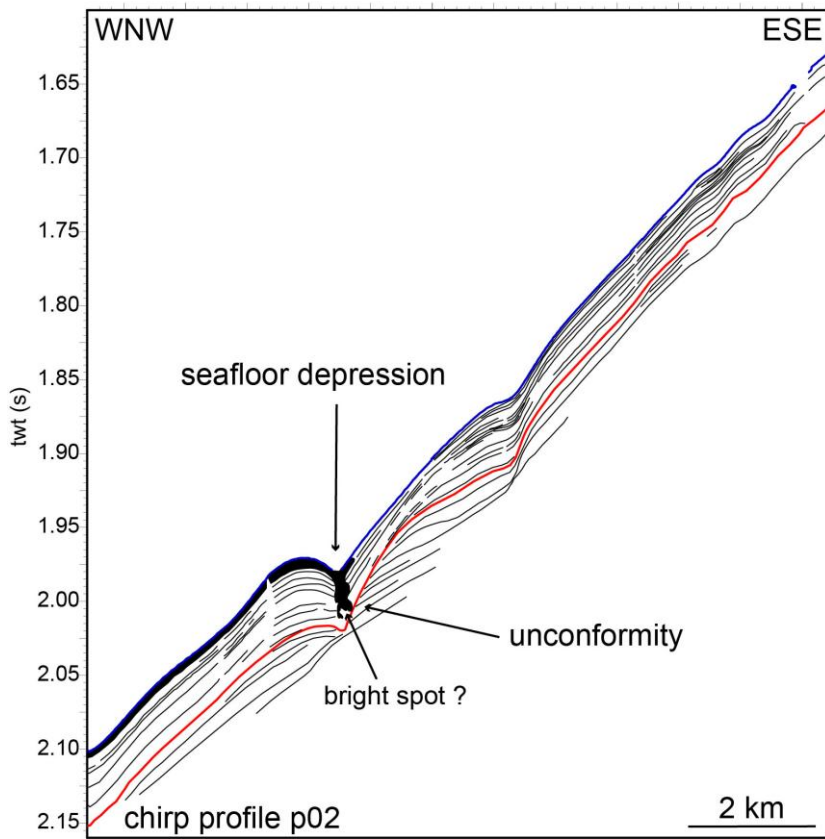
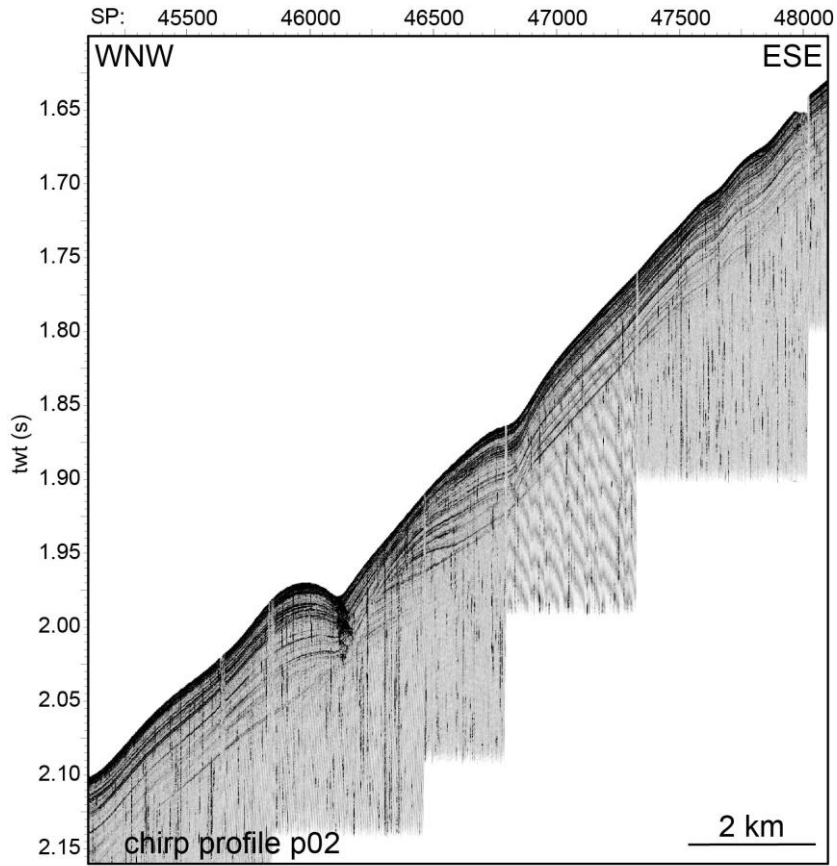


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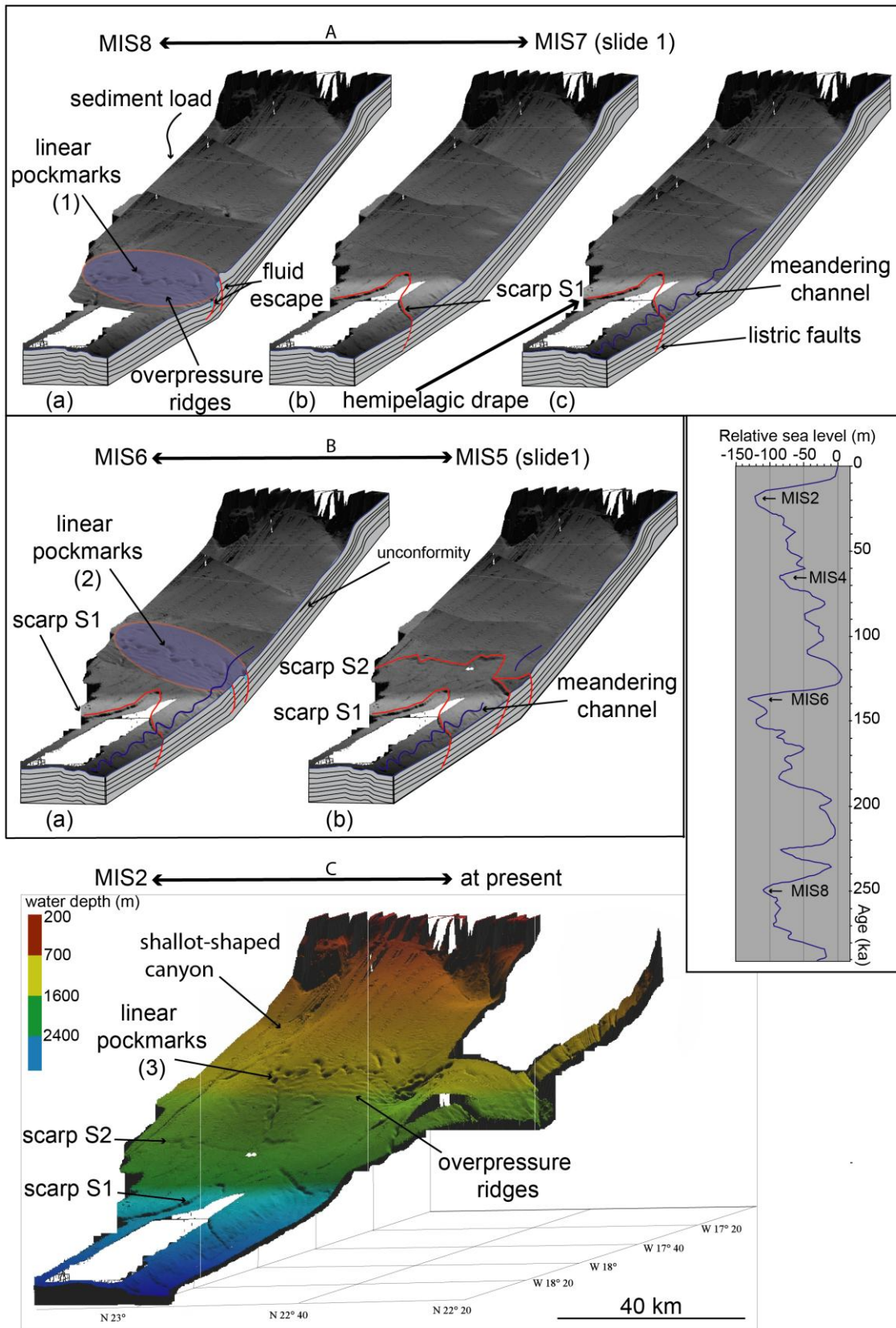
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Figure 8





868  
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Figure 10