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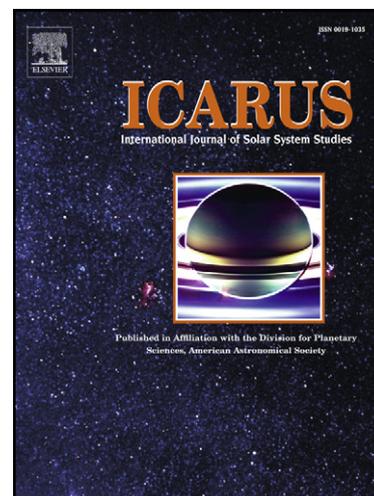
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Large asymmetric polar scarps on Planum Australe, Mars:

Characterization and evolution

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24

25 **Abstract**

26

27 Numerous scarps with similar characteristics have been observed in the polar layered deposits of
28 Planum Australe, Mars. They are referred to as LAPSs (for Large Asymmetric Polar Scarps)
29 because of their typical cross-section featuring a trough between a straight slope on one side with
30 outcrops of layered deposits and a convex slope on the other side without any outcrops. These
31 LAPSs are restricted to the outlying region of Ultimi Lobe. Topographic data, optical images, and
32 subsurface radar observations have been analyzed and compared to produce a complete
33 morphologic and stratigraphic description of these scarps. In all, 167 LAPS-like features have
34 been identified. All have similar dimensions and characteristics and appear to be deep
35 depressions in the ice. The polar deposits have an average thickness of 1 km in this region and the
36 LAPS depressions commonly reach half of that thickness. Subsurface data indicate that the
37 depressions could reach bedrock at certain locations. Many surface features of the polar deposits
38 of Mars are considered to be consequences of depositional and/or erosion processes. We propose
39 a mechanical failure of the ice for the LAPSs origin, given the striking similarities in shape and
40 size they show with rollover anticlines above listric faults commonly observed as a crustal
41 extension mode on Earth. This tectonic scenario would imply a substantial outward sliding of the
42 polar deposits in the region of Ultimi Lobe and a low basal shear stress. No information is
43 available to determine whether such a system could be active at present. Confirmation of the
44 "mechanical failure" hypothesis of these LAPSs on Mars is of major importance as it could be a
45 macro-expression of fundamental differences between ice-sheet behavior under Martian and
46 Terrestrial conditions.

47

48 **Keywords:** Mars, polar geology; Mars, polar caps; Ices; Radar observations; Tectonics

49 **1. Introduction**

50
51 The south and north polar plateaus of Mars - respectively Planum Australe and Planum Boreum -
52 are the only known examples of extraterrestrial ice-sheets comparable to those of the Earth. Many
53 striking similarities with the Earth's ice-sheets exist. For instance, the volumes of both Planum
54 Australe and Planum Boreum (respectively $\sim 1.6 \times 10^6 \text{ km}^3$ and $\sim 1.1 \times 10^6 \text{ km}^3$) are of the same
55 order as that of the Greenland ice sheet ($\sim 2.6 \times 10^6 \text{ km}^3$), with similar average thicknesses of
56 about 1000 to 1500 m (Plaut et al., 2007; Smith et al., 2001; Weidich, 1995). Moreover, water ice
57 is the major ice-sheet component on both Earth and Mars, with an average impurity fraction that
58 is likely less than 10% for Planum Australe (Plaut et al., 2007) and close to 5% for Planum
59 Boreum (Grima et al., 2009). When the mass-balance is positive, the growth process of ice sheets
60 on both planets is driven by the deposition of isochronous layers (known on Mars as polar
61 layered deposits, PLD). Their impurity contents vary with the time of deposition (Cutts and
62 Lewis, 1982; Thomas et al., 1992). Furthermore, the ice of the Earth's ice sheets is crystallized in
63 the hexagonal system (ice-Ih). Although cubic ice (Ice-Ic) could form under Martian conditions
64 by vapor deposition on the surface, it would be metastable (Gooding, 1988). Given the annual
65 rise of surface temperature above the Ic/Ih irreversible transition ($\sim 150 \text{ K}$), the Martian ice sheets
66 are likely exclusively composed of stable ice-Ih as on Earth. And finally, the evolution of the ice
67 sheets on a geological time-scale is mainly driven by Milankovitch orbital cycles (obliquity,
68 eccentricity, and precession variations) leading to planetary climate forcing (Hays et al., 1976;
69 Head et al., 2003), as on Earth.

70 Nevertheless, the polar environment on Mars is different than on Earth. For instance,
71 temperatures in Martian polar regions can be as low as 150 K in both hemispheres (Lewis et al.,
72 1999), while the average surface pressure is 0.008 bars with seasonal variations of $\pm 20\%$
73 (Clifford et al., 2000) and gravity is 0.38 times less than on Earth. Furthermore, the base
74 elevations of the two Martian polar plateaus differ by around 6000 m, far more than on Earth. On
75 Mars, the geothermal heat flow that largely determines the basal temperature of a glacier is
76 estimated to be in the range of 15 to 45 mW m^{-2} (e.g. McGovern et al., 2004; Nimmo and
77 Stevenson, 2000; Reese et al., 1998), lower than the value of $\sim 65 \text{ mW m}^{-2}$ for the Earth's
78 continents (Pollack et al., 1993). Consequently, the surface mass balance of the Earth's ice sheets
79 is mainly determined by melting of snow and ice, whereas condensation and sublimation are the
80 dominant processes on Mars (Rognon et al., 2007). Orbital parameters vary with a comparable
81 timescale on Mars and Earth, but with greater amplitudes on Mars. Over the past 10 Myr, Martian
82 obliquity has exceeded 45° and the eccentricity of the orbit has reached maximums twice that of
83 the Earth's (Laskar et al., 2002; Ward, 1992). Taking all these similarities and dissimilarities into
84 account, Mars can be considered as a full-scale laboratory for the study of the behavior of an
85 Earth-like ice-sheet system over extended conditions. Consequently, the peculiarities observed on
86 the Martian polar plateaus can help us improve our understanding of the Earth's ice-sheet system
87 in general and make the first steps toward meaningful comparative planetology in polar science.
88 With this in mind, this paper provides a geomorphologic description of polar scarps frequently
89 observed in the region of Ultimi Lobe (UL), Planum Australe (see Fig. 1). Despite their km-size
90 and typical asymmetric profile that will be described, equivalent formations have never been
91 reported to date on polar glaciers on Earth. Because of their particular shape, we call these
92 formations LAPSs (for Large Asymmetric Polar Scarps). Until now, only a few studies have

93 reported such LAPSs on Viking images (Howard, 2000; Thomas and Weitz, 1989), attributing
94 them to an eolian origin. Here LAPSs are described by coupling optical images, surface
95 topography, and radar sounding from recent datasets. This multi-instrumental approach makes it
96 possible to establish profiles of the surface and subsurface of the LAPSs. A LAPS inventory was
97 undertaken and 167 corresponding formations were identified across UL, providing
98 geomorphologic elements to identify and discuss different formation processes for LAPSs. Most
99 of the observations appear to be consistent with a mechanical failure of the ice, analogous to a
100 “listric fault/rollover” system. This tectonic process will be discussed along with certain direct
101 implications.

102

103 **2. Regional context**

104

105 Planum Australe overlies heavily cratered highlands that are reported to be Noachian and
106 Hesperian in age (Tanaka and Scott, 1987). The middle-Hesperian Dorsa Argentae Formation
107 (DAF) is thought to be the youngest surrounding terrain of ~~Planum Australe~~. The Planum
108 Australe mound accumulated during the late Amazonian period (Kolb and Tanaka, 2001) and
109 presently has a maximum thickness of 3700 m (Plaut et al., 2007). Cratering records estimate the
110 plateau's surface to be as old as 10 to 100 My (Herkenhoff and Plaut, 2000; Koutnik et al., 2002).
111 Signatures of the former extent of the ice sheet have been observed in the DAF where esker-like
112 ridges could be the consequence of past basal-melting (Head and Pratt, 2001; Kargel and Strom,
113 1992; Milkovich et al., 2002). Present-day conditions on Mars preclude exceeding the melting
114 temperature of water ice, except in cases of substantial geothermal anomalies (Clifford, 1987),
115 not likely to be detected by any in-flight instrument, or in the case of saline water (Renno et al.,

116 2009 and references therein). UL is an outlying region of Planum Australe, opposite DAF and
117 extending over equivalent latitudes. It is the only part of Planum Australe below 80°S, with
118 latitudes as low as 72°S (Fig. 1). It covers 400,000 km² (i.e. one-third of the entire plateau area).
119 Without this region Planum Australe would be almost perfectly symmetric instead of being offset
120 from the pole. UL seems to have been subjected to a slight outward horizontal motion during
121 recent geological times, revealed by two opposing signatures co-existing along its border. The
122 first is a viscous deformation of the ice, suggested by glacial tongue-like mounds flowing
123 outward in a series of craters dotting the edge of UL (Byrne, 2003). Similar behavior was
124 reported by Head (2001) in the nearby region of Promethei Lingula. The other glacial signature
125 involves brittle processes such as slumping, landsliding and faulting that have also been reported
126 all along the northern border of UL (Byrne, 2003; Murray et al., 2001). These fractures were
127 interpreted as evidence of modest basal sliding of the whole region, seen as a brittle plate.

128

129 * Location of Fig. 1 (1.5 column width).

130

131 **3. Data**

132

133 Five different data sources were used for this study:

134 (i) The digital elevation model of the surface acquired by the Mars Orbiter Laser Altimeter
135 (MOLA) (Smith et al., 2001). We used the gridded polar map at 256 pixels/° (~230 m/pixel) with
136 a vertical accuracy of 1 m.

137 (ii) Visible images from the High Resolution Imaging Science Experiment (HiRISE) with a
138 resolution of 25 to 32 cm/pixel (McEwen et al., 2007). Only a few HiRISE images are available
139 over UL.

140 (iii) Visible images from the High-Resolution Stereo Camera (HRSC) experiment with a
141 resolution of 10 to 20 m/pixel (Jaumann et al., 2007). Despite a more limited resolution than
142 HiRISE, HRSC were retained because of its high coverage of the UL region.

143 (iv) Radar subsurface cross-sections (radargrams) of Planum Australe from SHallow RADar
144 (SHARAD) (Seu et al., 2004). The radar signal (20 MHz) penetrates as deep as ~ 1500 m into
145 water ice materials with 10×300 m vertical \times along-track resolution. The radar waves are back-
146 scattered by dielectric gradients along the propagation path that are closely related to impurity
147 ~~rate~~ variations in the ice. Thus, SHARAD is able to detect the layers forming Planum Australe. In
148 UL, the detection signal is faint and can suddenly disappear before reappearing tens of kilometres
149 downtrack. This could be due to a low dielectric contrast between isochronous layers. However,
150 the regional density of SHARAD data is high and it was possible to select some radargrams to
151 support morphologic interpretations. Initially, radargrams have a vertical timescale representing
152 the time delay of the echoes. They have been migrated in depth by using a relative dielectric
153 constant of 3.10 as inferred by Grima et al. (2009) for the nearly pure ice of Planum Boreum.
154 Off-nadir surface reflections (clutter) can generate highly delayed echoes that can be confused
155 with subsurface structures. Adaptation of radar simulation developed by Nouvel et al. (2004)
156 allowed us to identified the biggest clutters.

157 (v) Bedrock elevation as mapped by Plaut et al. (2007) based on the Mars Advanced Radar for
158 Subsurface and Ionosphere Sounding (MARSIS) data (Picardi et al., 2005). Compared to
159 SHARAD, the MARSIS wavelength (1.8 to 5 MHz) provides a lower vertical resolution of ~80
160 m in the ice. However the signal penetrates deep enough into Planum Australe to be clearly back-

161 scattered by the bedrock. The vertical uncertainty on the inferred basal topography is assumed to
162 be 200 m (Plaut et al., 2007). It must be emphasized that this bedrock elevation map were
163 obtained by interpolation of a limited-density dataset: the resolution was sufficient to get the
164 basal regional trend but not to detect local anomalies of the bedrock.

165

166 **4. Morphological description**

167

168 *4.1. Spatial shape and distribution*

169

170 The first recognizable feature of the LAPSs is their spatial shape. They appear to be arch-shaped,
171 tens of kilometers long, and are distributed over the surface of the ice (Fig. 1). Howard (2000)
172 described this particular signature as a scalloped or a “gull-winged” shape. This criterion enabled
173 us to identify 167 LAPSs over Ultimi Lobe (Fig. 2). This count is not accurate for two reasons:
174 (i) sometimes up to three or more LAPSs are aligned and/or connected, often making it difficult
175 to precisely define how many LAPS there actually are; (ii) the arch-shaped LAPSs can be
176 confused with the rims of shallow-buried craters. To avoid this, we do not consider scarps that
177 are obviously linked to a circular structure (an example is shown Fig. 5B). However, since the
178 surface topography is quite disturbed, we cannot rule-out that some less obvious crater-linked
179 formations were counted. The count shows that LAPSs are widespread over Ultimi Lobe. Their
180 “horn-to-horn” width is in the range of 10 to 20 km, while some can reach 50 km. Most of them
181 are gathered in aligned series. As already observed by Howard (2000), their regular size and close
182 spacing cannot be universally explained by a crater rim origin. This strongly supports the
183 assumption that most of the LAPSs considered in this study are not mainly linked to shallow-

184 buried craters. As shown in Fig. 3, the concave sides of the LAPSs never face the South Pole and
185 the dominant orientation is not towards the equator (i.e. azimuth = 0°). Neither is the orientation
186 constant with respect to longitude. For instance, in a given area, adjacent LAPSs can be almost
187 right-angled (e.g. white arrows in Fig. 2). The regional orientation in the polar stereographic view
188 is also a relevant parameter. Let us define 0° and 90° as the angles for which LAPS concavities
189 face the bottom and the right border of the map respectively. Figure 3 shows this regional
190 orientation in a circular histogram. The whole set of LAPSs appears to be essentially directed
191 towards the same quadrant between 0° and 90° .

192

193 * Location of Fig. 2 (no particular restriction on the size).

194 * Location of Fig. 3 (no particular restriction on the size).

195

196 4.2. *Cross-section*

197

198 The second noteworthy feature is the asymmetric shape of LAPS cross-sections (giving them the
199 second letter of their acronym). They exhibit a trough between a straight slope on one side,
200 comparable to a scarp, facing a gentle convex upward slope on the other side that flattens as it
201 rises. Figure 4 and the cross-sections in Fig. 6 illustrate this profile. The LAPS system forms
202 extremely deep troughs in the ice with respect to the local ice thicknesses. The height of the
203 scarps ranges from 200 m to 700 m with an average value of 400 m. The East part of UL (left
204 side on the map) hosts the highest scarps. The resulting troughs regularly penetrate Planum
205 Australe to half its thickness. In some cases, the trough reaches the top value of the basal
206 elevation estimated by MARSIS. This usually occurs when the trough seems flat and parallel to
207 the bedrock slope, as shown in Fig. 6 for cross-sections 1b-1b' and 3b-3b'. This leads to the

208 possibility that the bedrock could in some cases become locally exposed. Some LAPSs exhibit a
209 more complex topography on the side of the convex slope (cross-sections 4a-4a' and 4b-4b').
210 Their curved shape is broken by one or more flat plateaus, more or less horizontal. These LAPSs
211 are essentially located in the heart and in the Eastern part of UL (left side of Fig. 2). Despite these
212 very particular topographies - asymmetric and deep troughs - it is important to emphasize the
213 relative flatness of the system. The slope of the scarps ranges from 2° to 15° , with an average
214 value of 10° . Indeed, the mean horizontal distance between the foot and the top of the straight
215 slope is 3.5 km. Therefore, the horizontal scale of the LAPS system is roughly an order of
216 magnitude larger than the ice thickness. This thinness and flatness are highlighted in Fig. 6 by the
217 inserts that display no vertical exaggeration.

218

219 * Location of Fig. 4 (no particular restriction on the size).

220

221 4.3. *Hillocks*

222

223 Another feature is regularly (but not systematically) superimposed on the typical cross-section
224 described above i.e. a ridge that can be observed along certain scarp crests (indicated by black
225 arrows in Fig. 6), similar to elongated hillocks. We did not find any relation between the heights
226 of the hillocks and the height of the straight slope or any other distinctive dimensions. The hillock
227 / straight-slope height ratio is usually < 0.2 , although around 10 LAPSs, mostly concentrated in
228 the far-east side of UL, have a ratio > 0.5 . However, note that the hillocks remain extremely flat,
229 as they are stretched horizontally over 2 to 5 km.

230

231 * Location of Fig. 5 (as wide as possible).

232 * Location of Fig. 6 (as wide as possible).

233

234 **5. Stratigraphy**

235

236 The behavior of the internal structure of any geological formation is necessary to understand its
237 origin. Consequently the structure of the PLD beneath the LAPS and information from
238 subsurface radar are essential. However, as noted in section 3, the layers detected by SHARAD in
239 the UL region correspond to faint signals. To support the radar observations, we compared them
240 with visible images from HiRISE and HRSC. These cross-analyses made it possible to draw a
241 partial pattern for the polar layers.

242 Figure 7 shows two LAPS cross-sections associated with two SHARAD radargrams. HRSC
243 images of the surface along the groundtracks are also shown. The radargram of cross-section 5-5'
244 clearly shows horizontal layers on the straight-slope side (right side of the picture), leading to the
245 hypothesis that the scarp includes outcrops there. On the other side, the layers below the convex
246 slope are curved, parallel to the surface and plunging. Unlike the case on the straight-slope side,
247 no outcrops are expected on the convex slope. On the HRSC image associated with this cross-
248 section, polar layer outcrops can be distinguished as gathered lines of various albedos
249 perpendicular to the ground-track. The change in albedo is due to slope and dust content
250 variations from one layer to another. The cross-section locates these outcrops in an area
251 corresponding exclusively to the straight slope, confirming the radar observation. Conversely, the
252 HRSC image does not show any such signature on the convex slope, consistent with the previous
253 hypothesis that the layers are curved downward and do not outcrop on this side. Cross-section 6-
254 6' shows similar behavior, although the bending of the convex-slope layers is not as clear on the

255 radargram because of the faint detection signals. However the associated HRSC image reveals
256 that outcrops occur only on the straight slope, implying that the convex-slope layers also plunge
257 downward as supposed.

258 This asymmetric behavior of the polar layers (outcrops on the straight slope and downward
259 bending below the convex slope) cannot be verified by radar data for the entire set of LAPSs
260 because of the poor layer detection in the UL region as mentioned above. However, visual
261 inspection of available images shows that outcropping on the straight slope only is a common
262 signature of the LAPSs. Figure 8 is an example of a HiRISE image over two successive LAPSs.
263 The asymmetric outcrop is clear for both; however the cross-section path cuts the end of the
264 second LAPS leading to progressive fading of the outcrops.

265 Finally, it is not possible to comment on the structure just under the LAPS troughs given that no
266 formation is detected by radar. This does not necessarily mean that no reflector is present. It is
267 more likely due to the straight slope, refracting most of the back-wave power offside with respect
268 to the instrument, making underlying features hard to detect. In addition, the recurrent clutter
269 echoes at this location could be strong enough to hide faint signals from the subsurface.

270

271 * Location of Fig. 7 (as wide as possible).

272 * Location of Fig. 8 (as wide as possible).

273

274 **6. Interpretations**

275

276 The results of the morphologic description of the LAPS surface and the stratigraphic study are
277 summarized in Fig. 4. The different indicators support that Fig. 4 is a roughly general model for
278 the LAPS morphology. We will now look at the possible origins of the LAPSs.

279

280 6.1. *Crater filling as a possible origin of LAPSs*

281

282 The arched shape of the LAPSs naturally suggests a possible link with craters. Some of the
283 circular objects on UL are obviously buried craters that lay either on buried layered deposits
284 (paleo-surface) or on the bedrock. Subsequent accumulation of deposits of ice on these
285 irregularities would lead to an increasingly smooth surface topography that would nevertheless
286 conserve a spatial signature of the initial formations with a decreasing vertical relief. In
287 particular, the common hillocks observed along the crests could be easily interpreted in terms of
288 crater rim prominences. However, the observed LAPSs are just semi-circular with no sign of an
289 opposite and symmetric formation to complete the circle. Nevertheless, it should be possible to
290 fill a particular crater or bedrock formation with successive deposits of layers in order to obtain a
291 LAPS morphology. One possibility would be to start with a crater that has been asymmetrically
292 eroded. Uneven deposition of ice on a crater is another mechanism that could produce a LAPS by
293 accumulation of the deposits preferentially on one side. However, even if a LAPS production
294 process based on crater filling can be imagined, it does not easily explain the spatial repetitions
295 that are observed (Howard, 2000). The repetition and similar dimensions of the LAPSs as well as
296 their local layout in aligned formations does not support craters as the origin given that crater
297 locations and diameters are basically random.

298

299 6.2. *Erosion processes as a possible origin of LAPSs*

300
301 Howard (2000) performed a complete survey of optical images in order to detect surface
302 signatures of eolian processes over the PLDs. He noticed similarities between the arched shape of
303 LAPSs and barchan dunes formed by deposition of wind-transported sand. Since this study, the
304 availability of an accurate digital elevation model (MOLA) allows us to show that LAPSs are
305 instead deep depressions in the ice. This raises the possibility of LAPS formation by erosion of
306 the ice, which could be driven either by eolian processes or sun sublimation.

307 The long-term efficiency of the wind loaded with abrasive particles to shape the surface of the ice
308 is well known (e.g. Howard, 2000; Koutnik et al., 2005). Wire brush terrains, snakes, and trailing
309 grooves are especially common eolian formations encountered on Planum Australe. They extend
310 for hundreds of kilometers and are associated with a decameter vertical scale (Koutnik et al.,
311 2005). The objects thus formed have a vertical / horizontal ratio several orders of magnitude
312 smaller than the typical dimensions of LAPSs. However, the relatively uniform orientation of the
313 LAPSs is consistent with an eolian origin, except for the quasi-perpendicular LAPSs found in a
314 single region as shown in Fig 2.

315 At the North Pole, Planum Boreum exhibits numerous spiral troughs in its margin. Their
316 asymmetric cross-sections are quite similar to those of the LAPSs. Although their precise origin
317 is not yet well understood, northern troughs are thought to be sustained by a process involving
318 solar sublimation of the exposed slope together with deposition of water vapor on the pole-facing
319 slope, leading to an asymmetric outcrop (e.g. Pelletier, 2004 and references therein). Ice flow and
320 katabatic winds could also play a key role in their evolution (Fisher et al., 2002; Smith et al., 2010).

321 In particular, Smith et al. (2010) suggest trough migration to explain the asymmetric stratigraphy
322 of the troughs. They suggest that katabatic winds remove material from the upwind slopes of a
323 trough and carry it to the downwind slope. However, northern troughs have linear shapes up to

324 hundreds of kilometers long, roughly arranged in a spiral leading out from the pole all around the
325 cap, while LAPSs are individually restricted to a 20-km arch shape in the heart of a single region
326 of Planum Australe. In addition, the hillocks often observed along the crests of the LAPS are not
327 observed on the northern troughs. Thus, spatial shape and distribution considerations do not
328 contribute to a common origin of the northern and southern scarps. Furthermore, LAPS
329 orientations are not preferentially sunward and a number of them have their straight slope with
330 outcrops almost parallel to longitudes, meaning that sun sublimation is not likely to have initiated
331 them.

332

333 6.3. *Tectonic scenario*

334

335 On Earth, a common mode of crustal extension consists in the development of listric normal fault
336 and their associated rollover anticline. Because of their crucial importance for commercial
337 prospecting (hydrocarbon traps in faulted/folded strata), these structures have been studied
338 extensively (e.g. Dula, 1991; Poblet and Bulnes, 2005; Shelton, 1984).

339 Listric faults can be defined as curved normal faults in which the fault surface is concave
340 upwards, its dip angle decreasing with depth. These faults occur in extension zones where there is
341 a main detachment fracture following a curved path that connects to a horizontal décollement.

342 The hanging-wall may develop a syn-tectonic rollover anticline classically interpreted as a direct
343 consequence of layer bending during hanging-wall displacement above the listric normal fault
344 (Fig. 9). The rollover geometry is conventionally interpreted as a direct consequence of the
345 gradual bending of the strata of the hanging-wall moving along the listric normal fault. The shift
346 changes with a horizontal component that increases with depth to become parallel to the

347 décollement. It is generally accepted that the latter is a level where fluid pressure is abnormally
348 high or where materials are weak.

349 The morphology of the LAPSs observed on Mars is very similar to the above listric fault
350 formation on Earth. They show a topographic asymmetry with a steeply dipping scarp facing a
351 gentle flexure that flattens with elevation, producing a convex morphology. The radargram
352 cross-section confirms this similarity by revealing the subsurface layer geometry. The similarity
353 with a terrestrial example is striking (see Fig. 10). The footwall compartment clearly shows
354 horizontal layers that appear to intersect with the escarpment, while the hanging-wall shows a
355 flexural geometry with a gradual downward bending of layers toward the scarp.

356

357 * Location of Fig. 9 (1 column width).

358 * Location of Fig. 10 (1 column width).

359

360 The LAPS morphology on Mars thus appears to correspond to the formations produced around a
361 listric normal fault on earth. The length of the scarp may correspond to the fault slip. The fault
362 has a strong dip angle with respect to the outcrop, which decreases with depth to reach a level
363 that may be the ice/bedrock interface.

364 Figure 9C shows a more complex evolution of the system with some subsequent faulting and
365 tilting of individual blocks (Davison, 1986; Hauge and Gray, 1996; Song and Cawood, 2001;
366 Williams and Vann, 1987). It is similar to the surface characteristics observed on cross-sections
367 4a-4a' and 4b-4b'. The presence of this rollover geometry suggests extensive regional tectonic
368 activity related to the slow sliding of Planum Australe on a geological time scale. In some
369 particular situations, the semi-circular topographic scarp may correspond to some pre-existing
370 impact crater rims associated with a circular and normal faulting system. Such structural systems

371 favor the preferential sliding of the UL polar layered region. The implied horizontal displacement
372 would be substantial (several kilometers, depending on the LAPS length) and mainly directed
373 toward the quadrant of the circular histogram Fig. 3.

374 The rollover hypothesis can be tested by modeling the tectonic process, for instance using the
375 area balance technique conventionally used for the restoration of a balanced cross-section
376 (Davison, 1986; Faure and Seguret, 1988; Gibbs, 1983). The principle is based on the concept of
377 plane strain or volume conservation of cross-sectional area. In Fig. 9B, it consists in measuring
378 the area below the regional datum (area A) which is, in the case of volume conservation, equal to
379 the volume displaced (area B). The latter is the product of the horizontal extension and the depth
380 of the décollement ($A = B = h \times d$). In such a model, it is assumed that the hanging-wall deforms
381 by simple shear and that the footwall remains undeformed throughout the extension (White et al.,
382 1986). The horizontal displacement (H_r in Fig. 11) can be directly inferred from the cross-
383 sections (if the latter is parallel to the tectonic strike). Indeed, in the case of a listric fault, the
384 deformation of the hanging-wall must be similar to simple shear deformation. Most of the shear
385 angles used for earth materials are around 60° (Dula, 1991). Compensation to 60° of potential
386 gap implies that the cutoff point of the hanging-wall is projected at 60° with respect to the surface
387 of the listric fault (Fig. 11). The horizontal displacement can be calculated as:
388 $H_r = H_a + h_v/\text{tg}(60^\circ)$. In some case, due to slight curvature, the cutoff point may be difficult to
389 locate. We chose to use a range of possibilities between a minimum position and a maximum
390 position (Fig. 11). Thus, we can deduce a range for the depth of the décollement level which can
391 be compared to the range of the ice/bedrock interface depth inferred by MARSIS.

392

393 * Location of Fig. 11 (1 column width).

394
395 Using the geometric and topographic data, we built various LAPS models. Table 1 and associated
396 Fig. 12 gives the results of the 8 profiles tested. For each profile, we calculated the minimum,
397 maximum and average values of the décollement level vs depth of the bedrock interface. From
398 Fig. 12, it appears that the depths of the décollement levels, deduced from the above models, are
399 in good agreement with the regional depths of the bedrock interface, except for profiles 3a-3a'
400 and 4b-4b'. For these last profiles, the depth of décollement is overestimated or underestimated
401 by about 1 km compared to the depth of the bedrock. Of course, these disagreements could be
402 produce by local singularities of the bedrock topography that cannot be detected by Marsis. A
403 byproduct of this test is the horizontal displacement H_r . It appears that the listric fault scenario
404 agrees with a substantial (4-5 km on the average) horizontal displacement of the ice,
405 corresponding approximately to 0.5 to 1% of the UL width. These values are consistent with
406 those usually encountered for terrestrial rollover analogs. For instance, the seismic profile
407 presented in Fig. 10 corresponds to a horizontal displacement of about 10 km (Zhang, 1994).

408

409 * Location of Table 1.

410 * Location of Fig. 12 (1 column width).

411

412 **7. Discussion and conclusions**

413

414 We have provided a complete description of particular polar scarps observed in the ice of UL, a
415 large outlying region of Planum Australe. Cross-analyses of topographic data, optical images, and
416 subsurface radar observations were used to derive a morphologic and stratigraphic scheme for

417 these scarps that we refer to as LAPS (Large asymmetric polar scarps) because of their particular
418 cross-section with a trough between a straight and a convex upward slope, along with outcrops on
419 the straight slope only. Although the scarps have a weak slope, they commonly reach more than
420 half the thickness of the PLD made up of 1 to 1.5 km of stacked ice. The LAPSs are numerous
421 and widespread over UL, but they all have similar dimensions.

422 Surface features on Martian PLDs are usually explained in terms of depositional and/or erosion
423 processes. (e.g. Fisher et al., 2002; Howard, 2000; Koutnik et al., 2005; Smith and Holt, 2010).

424 As an alternative process, we suggest a mechanical failure of the ice for the LAPSs origin, based
425 on their striking similarities in shape and size with rollover anticlines above listric normal faults.

426 A quantitative model, based on area balance technique, has been briefly introduced to roughly
427 test this hypothesis by computing some dimensions of a few basic geometries (Davison, 1986;

428 Faure and Seguret, 1988; Gibbs, 1983). It appears that the expected depth of the décollement
429 agrees with the bedrock depth inferred by Marsis for most of the LAPSs. It would be of interest

430 to extend this method in the future to all the LAPSs. This system is also associated with
431 horizontal displacement, computed to be 4-5 km on average for the LAPSs. This result agrees

432 with what is usually observed for terrestrial rollover analogs, and would imply a substantial
433 global outward sliding of the PLD. Such sliding has already been suggested by Murray et al.

434 (2001) based on fractures observed along with undeformed layers outcropping from Planum
435 Australe margins. Such peripheral fractures could be damping structures resulting from an

436 outward sliding from the heart of UL. The sliding of an ice sheet is a process requiring a weak
437 basal shear stress. Such conditions could be met in case of (i) incompetent basal sediments, (ii)

438 basal sediments softened by melt-water, (iii) over-loaded salt acting as lubricant (Jackson et al.,
439 1994), or (iv) a lower yield stress of Martian ice compared to Earth ice (Banks and Pelletier,

440 2008). No information is available to determine whether such sliding could occur at present day
441 or not.

442 Why the PLD exhibits an outward motion is also a major question resulting from the sliding
443 hypothesis. Possible explanations include (i) an active tectonic displacement of the underlying
444 bedrock, (ii) a simple gravitational readjustment of the accumulated ice stack, or (iii) a fluid
445 basal-material naturally dragged up and drained outward by the weight of the glacier.

446 The link between the tectonic hypothesis and the hillocks often observed along the LAPS crests
447 remains to be determined. The hillocks are possibly related to (i) a post-deposition of icy
448 materials, in which case the LAPS topography, under the dominant wind-stream, would generate
449 depressions and cold traps along the crests, ~~(ii) a slight elastic rebound of the footwall after the~~
450 ~~breaking of the ice, as is commonly observed for Terrestrial tectonic phenomenon (e.g. Weissen~~
451 ~~and Karner, 1989; Westaway, 1992) and could be in our Martian case a natural consequence of~~
452 ~~istic faulting, the magnitude of which holds information on the ice rheology;~~ (ii) a rheological
453 response to a change in basal conditions as observed around subglacial lakes on Earth (Remy et
454 al., 1999).

455 A deeper study of possible tectonic activity in UL should be undertaken because of its
456 implications on the ice rheology and PLD basal conditions. In particular, it could be a macro-
457 expression of fundamental differences between ice-sheet behavior under Martian and Terrestrial
458 conditions, given that the viscosity of ice on Earth would not be expected to generate such
459 faulting.

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633 **Table 1.** Depth of the décollement level determined for 8 LAPS profiles.

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Profile	Min. value (km)			Max. value (km)			Measured area (km ²)	Depth of décollement (km)			Depth of bedrock (km)		
	H _a	h _v	H _r	H _a	h _v	H _r		Min. slip	Max. slip	Mean	Min.	Max.	Mean
1aa'	2.31	0.26	2.46	3.23	0.26	3.38	3.67	1.49	1.09	1.29	0.90	1.30	1.10
1bb'	2.98	0.28	3.14	3.70	0.27	3.86	1.87	0.60	0.48	0.54	0.20	0.60	0.40
2aa'	3.00	0.43	3.25	4.10	0.45	4.36	4.37	1.35	1.00	1.17	0.70	1.11	0.91
2bb'	3.20	0.35	3.40	3.80	0.34	4.00	2.75	0.81	0.69	0.75	0.70	1.11	0.91
3aa'	2.10	0.19	2.21	3.70	0.22	3.83	2.29	1.04	0.60	0.82	1.08	1.50	1.29
3bb'	5.70	0.40	5.93	8.80	0.40	9.03	5.82	0.98	0.64	0.81	0.36	0.76	0.56
4aa'	4.40	0.58	4.74	5.90	0.57	6.23	5.33	1.12	0.86	0.99	0.65	1.05	0.85
4bb'	3.80	0.55	4.12	6.90	0.55	7.22	8.11	1.97	1.12	1.55	0.67	1.04	0.86

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650 **Figure captions**

651

652 **Fig. 1.** Shaded topography of UL (stereographic projection with illumination from the bottom-
653 right). The white line is the Planum Australe boundary. The bottom-right insert locates UL within
654 the entire polar plateau. Five black boxes delimit the regions that are enlarged in Fig. 5.

655

656 **Fig. 2.** Arch-shaped features are indicated in bold red. The arches marked by X's are LAPSs that
657 exhibit a convex slope with a more complex topography (see section 4.2 for details). White
658 arrows indicate an example of neighboring LAPSs with strictly different orientations.

659

660 **Fig. 3.** (Top) Histogram of the LAPS azimuths. The Y-axis is the number of occurrences. A
661 concavity facing north has an azimuth equal to 0° . A concavity parallel to a longitude and facing
662 decreasing west-longitudes has an azimuth equals 90° . (Bottom) Circular histogram of the
663 relative orientation of the LAPSs in a regional context. The circle border represents 25
664 occurrences. See section 4.1 for details.

665

666 **Fig. 4.** 3D view of a LAPS (located at the lower right corner of Fig. 5A). Illumination is from the
667 upper-left. Keep in mind that the vertical scale is exaggerated by a factor of 10. The volume is 45
668 km x 40 km x 1800 m. The bottom gray area depicts the expected position of the bedrock
669 detected by MARSIS (Plaut et al., 2007), taking into account the ± 200 m uncertainty. Note the
670 typical asymmetric cross-section, perpendicular to the spatial arch shape, with a straight slope

671 facing a convex slope. The general behavior of the polar layers deduced from the stratigraphic
672 study was added to create a typical model of a LAPS cross-section. The outcrops on the straight
673 slope are outlined, while the downward bending of the subsurface layers is visible below the
674 convex slope. The question mark beneath the LAPS is a reminder that no radar data regarding the
675 subsurface structure are available at the corresponding location (see section 4.2 for details).
676 Hillocks are also present.

677
678 **Fig. 5.** Five enlargements (A-E) for the corresponding regions indicated in Fig.1. The background
679 map is the unshaded MOLA elevation map. Contour lines are separated by 50 m. Elevation color
680 coding and the spatial scale are the same for all boxes. The black lines locate the cross-sections
681 shown in Fig. 6. The three white rectangles delimit the extent of the images corresponding to the
682 cross-sections in Fig. 7. An example of merging craters that were not taken into account for
683 LAPS counting can be seen at the bottom left of box B (see section 4.1 for details).

684
685 **Fig. 6.** Cross-sections of some LAPSs. The cross-section locations are indicated in Fig. 5. Black
686 lines are the surface and gray areas depict the expected position of the bedrock as retrieved from
687 the interpolated MARSIS map (Plaut et al., 2007), taking into account the 200 m uncertainty.
688 Elevations are indicated in meters, while horizontal lengths are in kilometers. Black arrows show
689 hillocks when present (see section 4.3 for details). Each cross-section is represented by two
690 profiles: (Bottom) Vertical scale multiplied by 10 to highlight the surface shape, (Top) No
691 exaggeration of vertical scale to emphasize the relative flatness and thinness of the system.

692
693 **Fig. 7.** Cross-sections (5-5' and 6-6') of two LAPSs, associated with HRSC pictures (DLR/FU
694 Berlin/ESA) and SHARAD radargrams (NASA/ASI). Illumination is from the left. See Fig. 5 for

695 locations. The first radargram from the top has its vertical scale multiplied by 10. The last two
696 have a vertical scale multiplied by 30 to emphasize the subsurface echoes. The colored lines in
697 the bottom radargram highlight the behavior of detected subsurface layers. The blue lines are
698 polar layered deposits and the red lines are the putative bedrock deduced by correlation between
699 the SHARAD radargram and the MARSIS basal topography. Black arrows indicate strong echoes
700 that are clutters generated by off-nadir surface reflections.

701
702 **Fig. 8.** Cross-section (7-7') of two successive LAPSs, associated with the HiRISE picture
703 PSP_06222_1055 (NASA/JPL/University of Arizona). Illumination is from the bottom-right. See
704 Fig. 5 for locations. Outcrops of layers occur only on the straight slope of the LAPSs, especially
705 clear on the LAPS on the left. For the LAPS on the right, the cross-section path cuts the end of
706 the LAPS leading to progressive fading of the outcrops.

707
708 **Fig. 9.** Sketches illustrating the typical geometric evolution of hanging-wall deformation in a
709 listric normal fault system. (A) An outward stress breaks the layered material. The dip angle of
710 the resultant fault decreases down to the level of the décollement. (B) Gradual bending of the
711 hanging-wall leads to a rollover anticline geometry. (C) Antithetic faults can follow either
712 directly steps (A) or (B) (modified from Song and Cawood (2001)).

713
714 **Fig. 10.** Seismic profile of a rollover fold associated with a listric fault in the Bohai Gulf of
715 northern China. The vertical scale is in seconds. Note that LAPSs observed on Mars are only
716 made up of pre-tectonic deposits. This rollover fold corresponds to a horizontal displacement of
717 about 10 km. 1 s is equivalent to 700 m on the vertical scale. Modified from Zhang (1994).

718

719 **Fig. 11.** Area balance for extension. *Top:* Relationship between the undeformed and deformed
720 lengths. The cutoff points are the intersection between the stratigraphic boundaries and the listric
721 fault. For a given stratigraphic horizon, we can identify a footwall cutoff point and a hanging wall
722 cutoff point. The real horizontal extension (H_r) is the sum of the apparent horizontal extension
723 (H_a) and the projected cutoff point position (H_c). *Bottom:* Because of the low curvature of the
724 listric fault and the rollover geometry, the position of the cutoff point is uncertain. Two extreme
725 positions are used giving two values of apparent horizontal extension (H_a). Uncertainty on the
726 position of the bedrock is represented by a gray band.

727
728 **Fig. 12.** Graphic illustration of the minimum, maximum and average depth of the décollement
729 level according to the minimum, maximum and average position of the bedrock for the 8 profiles
730 tested.

Figure 1

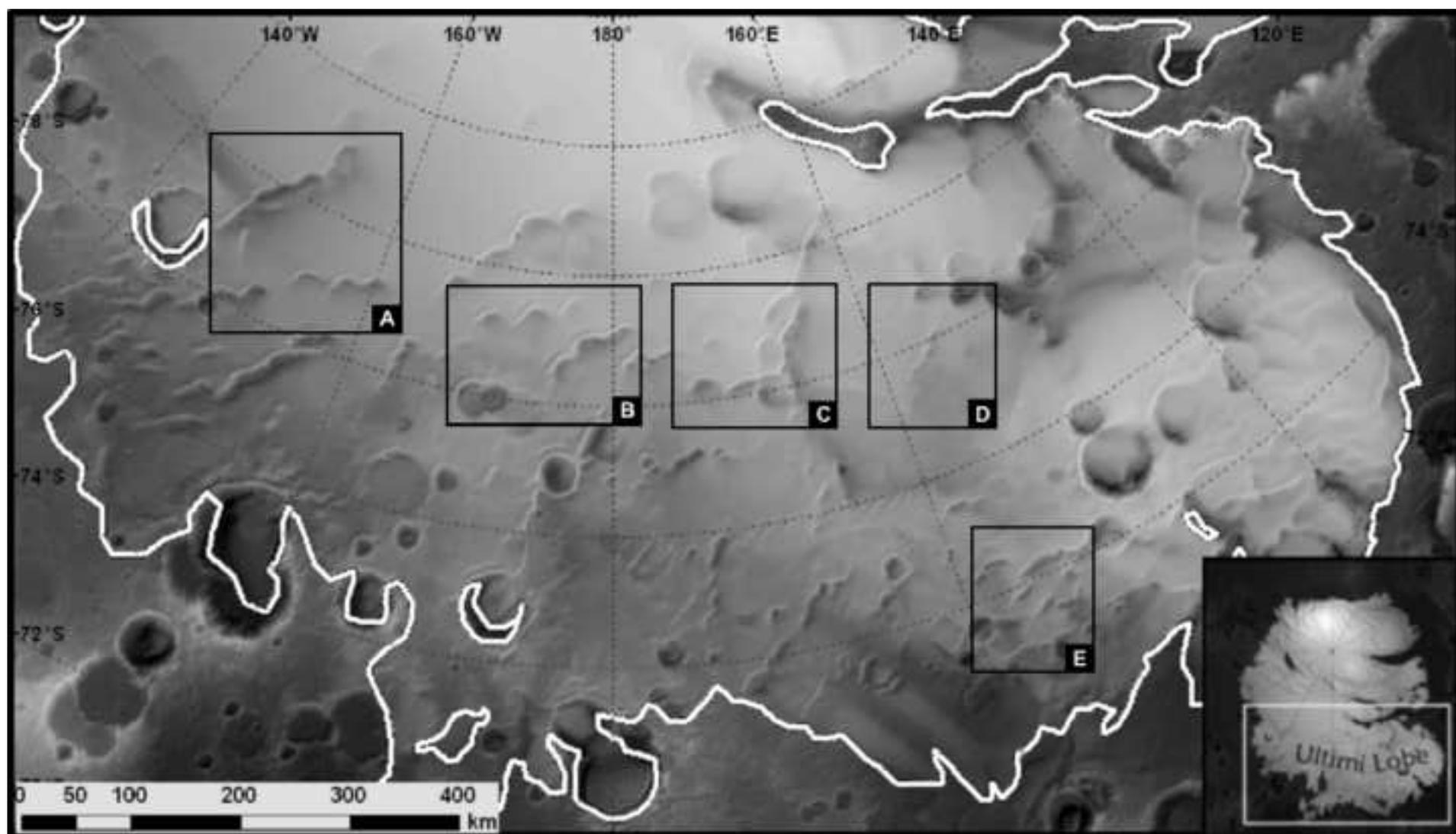
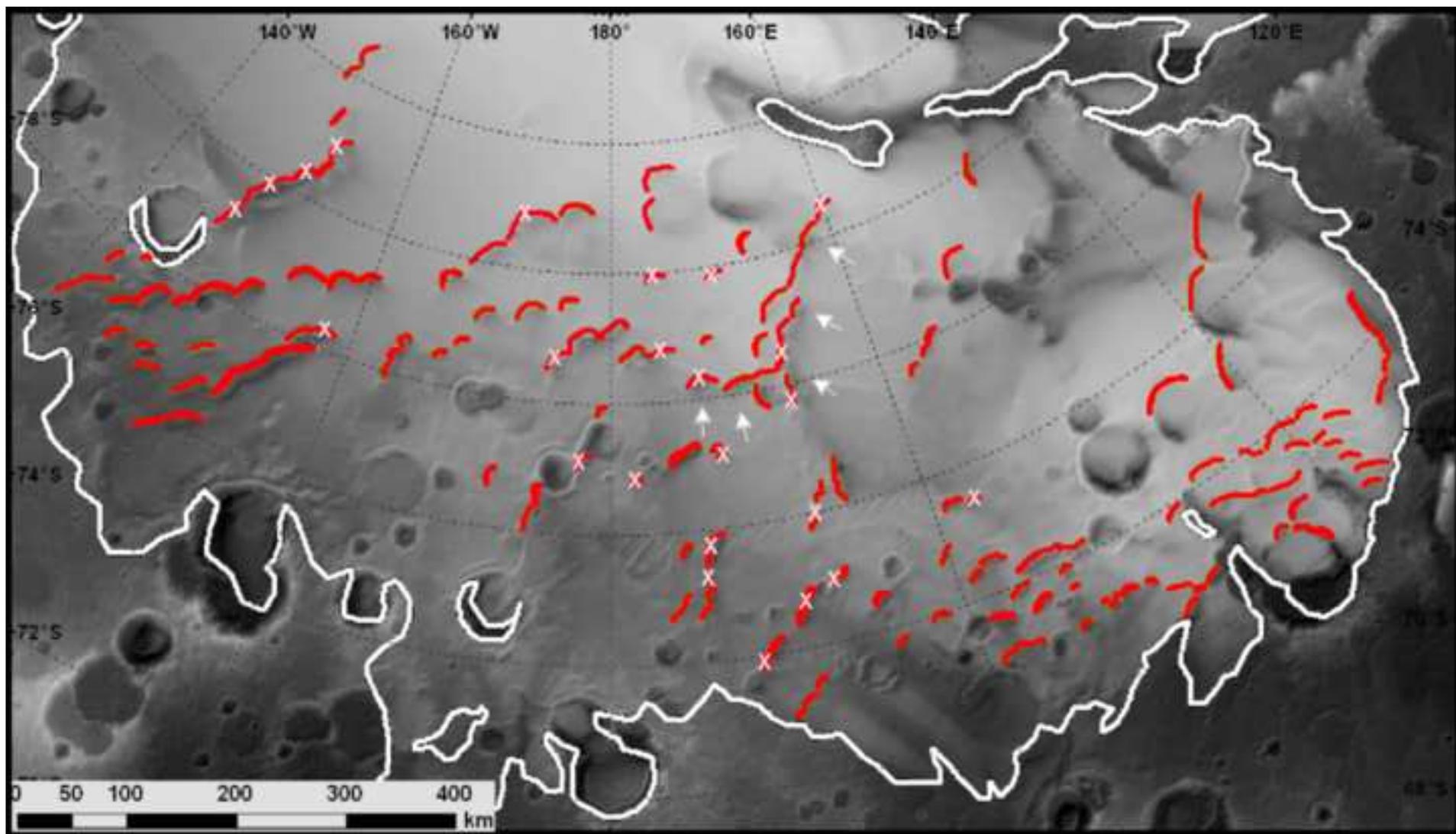


Figure 2



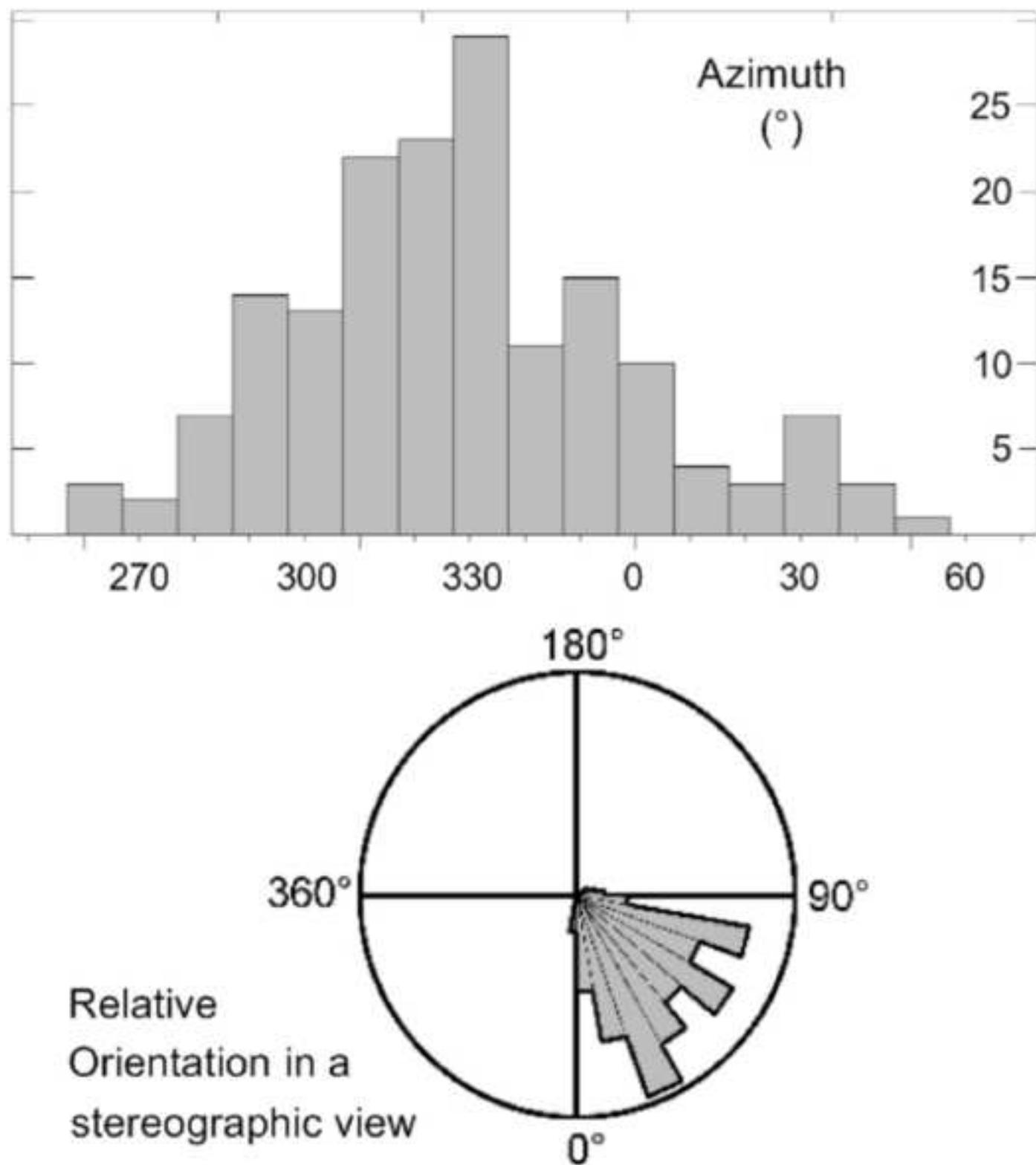
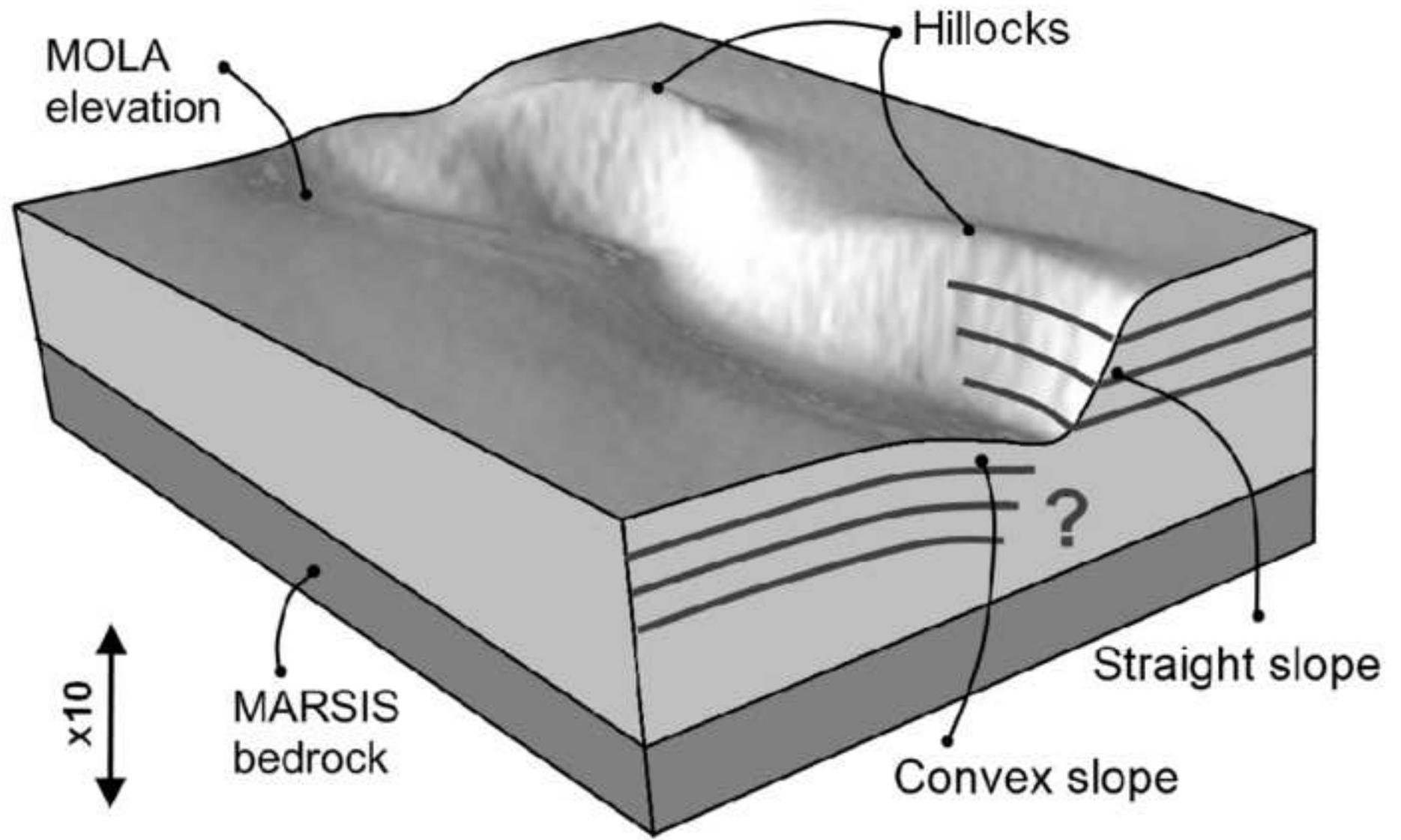
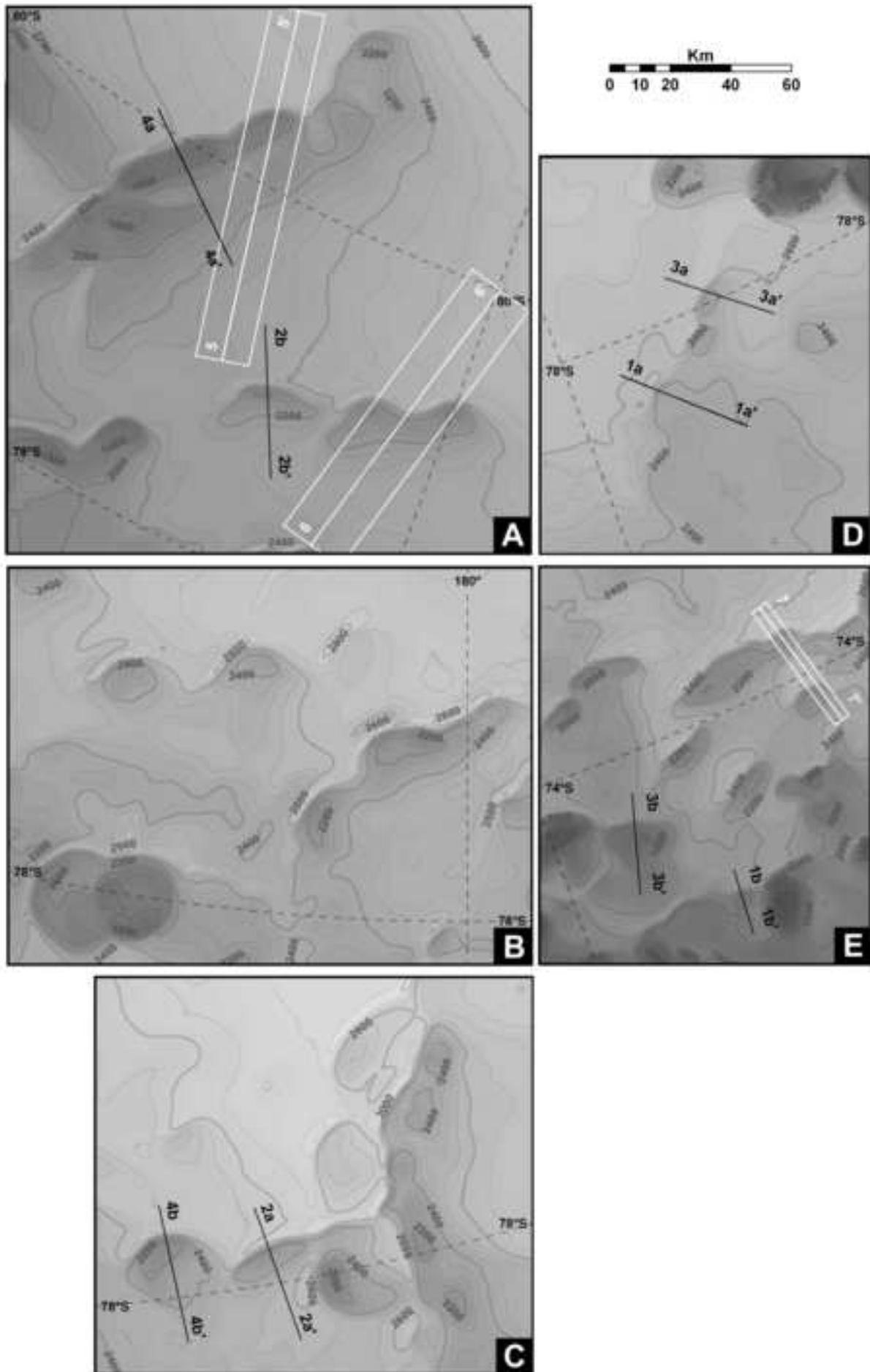


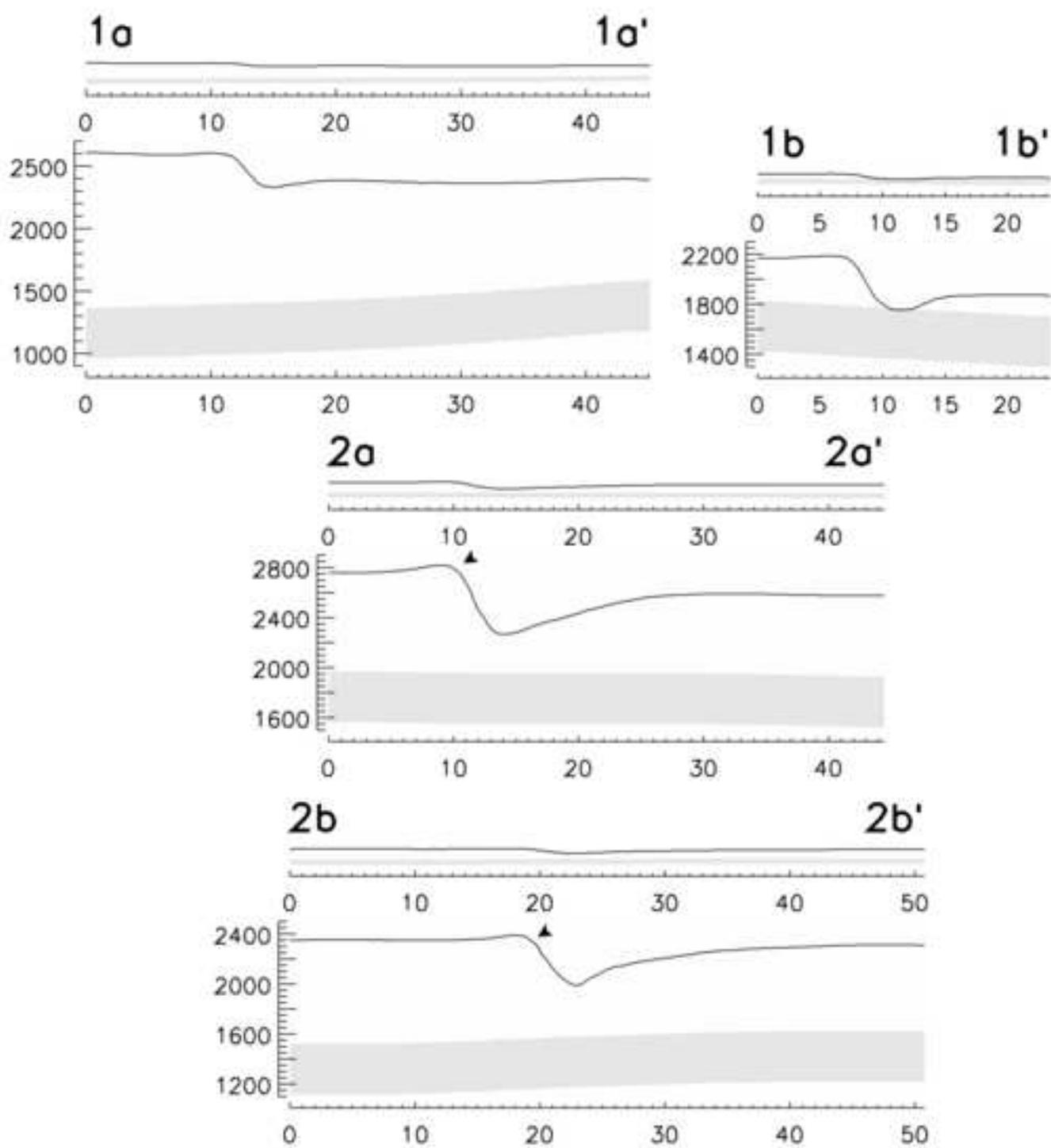
Figure 4



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Figure 5





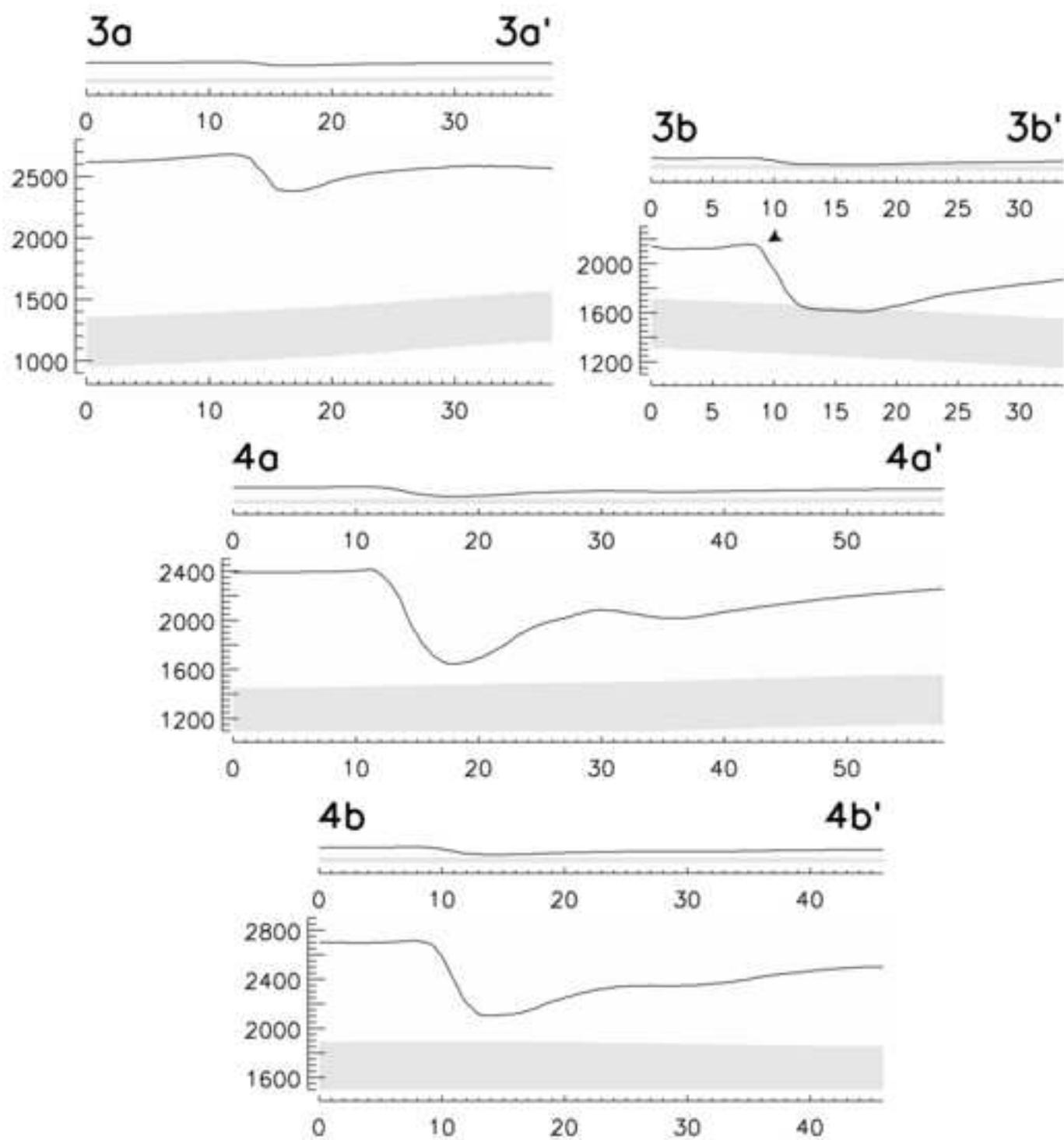
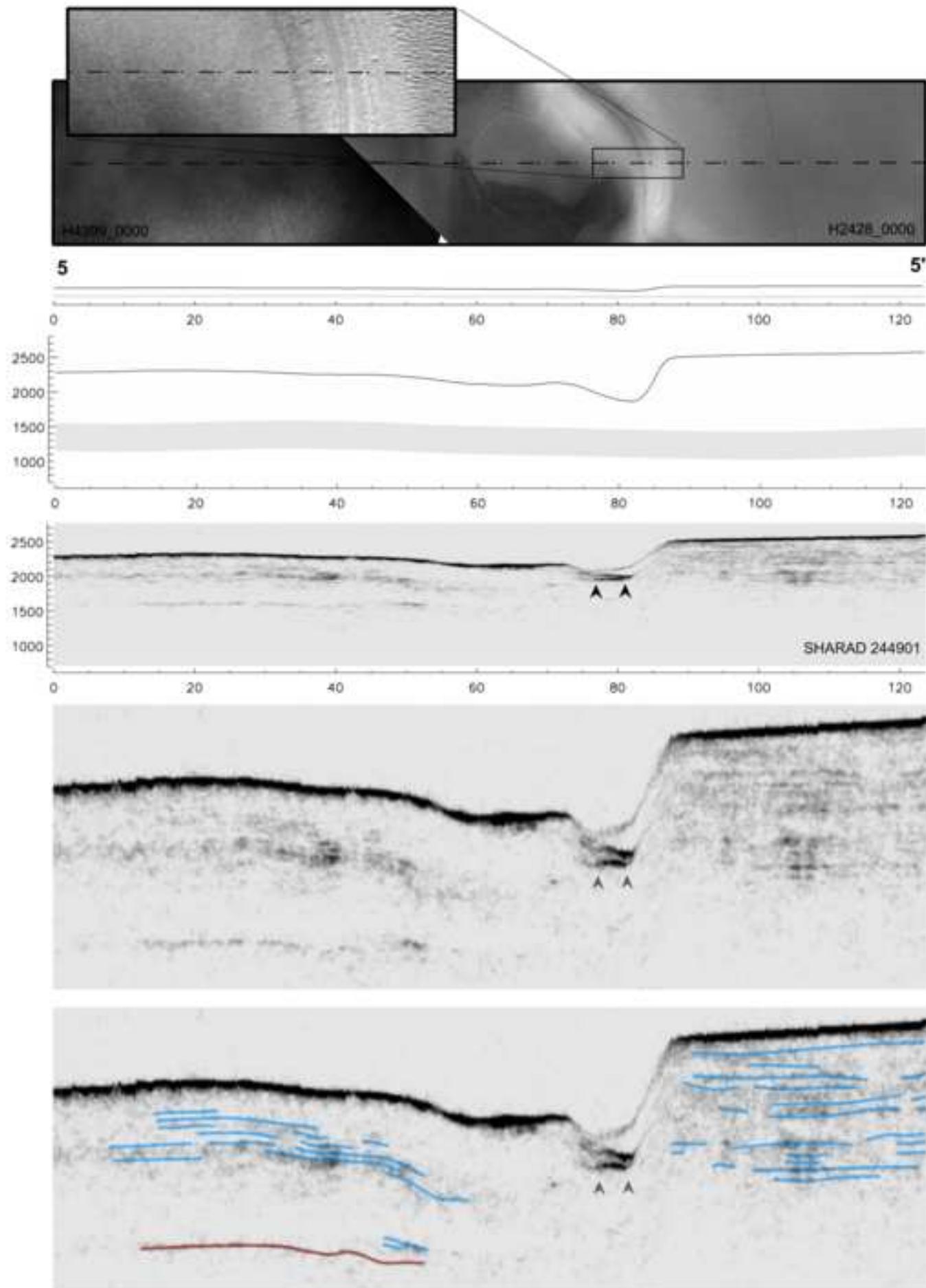


Figure 7



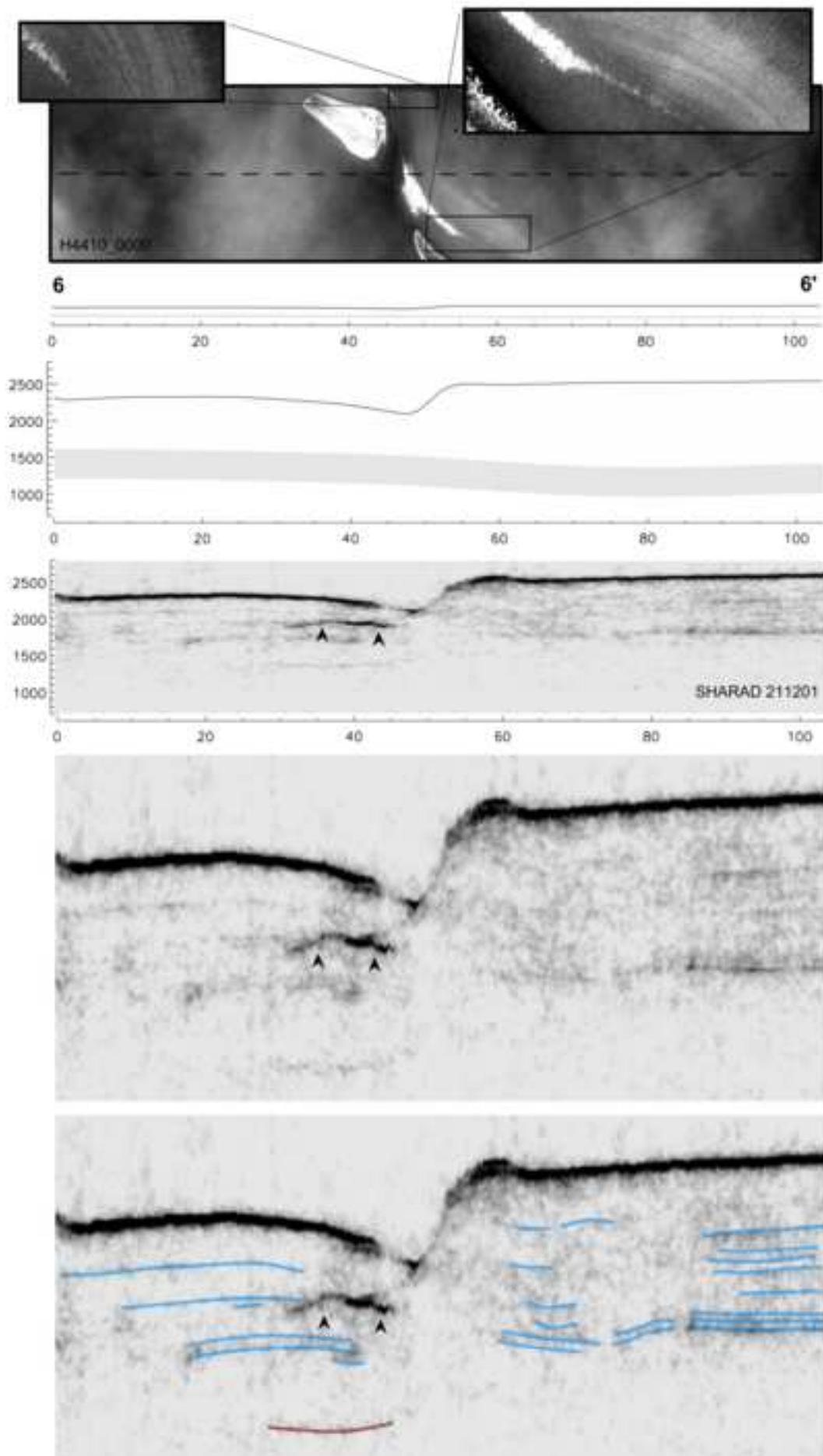
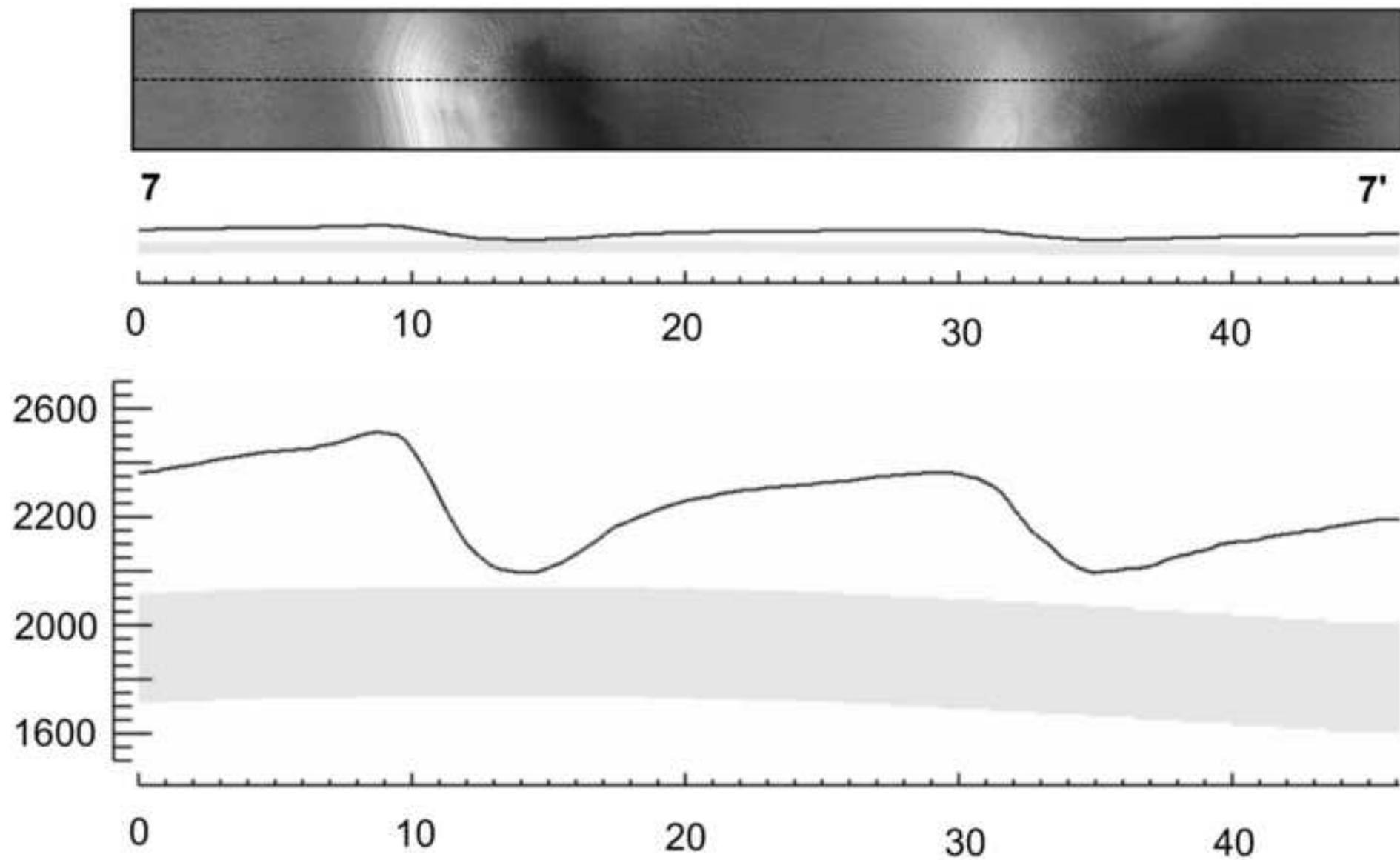
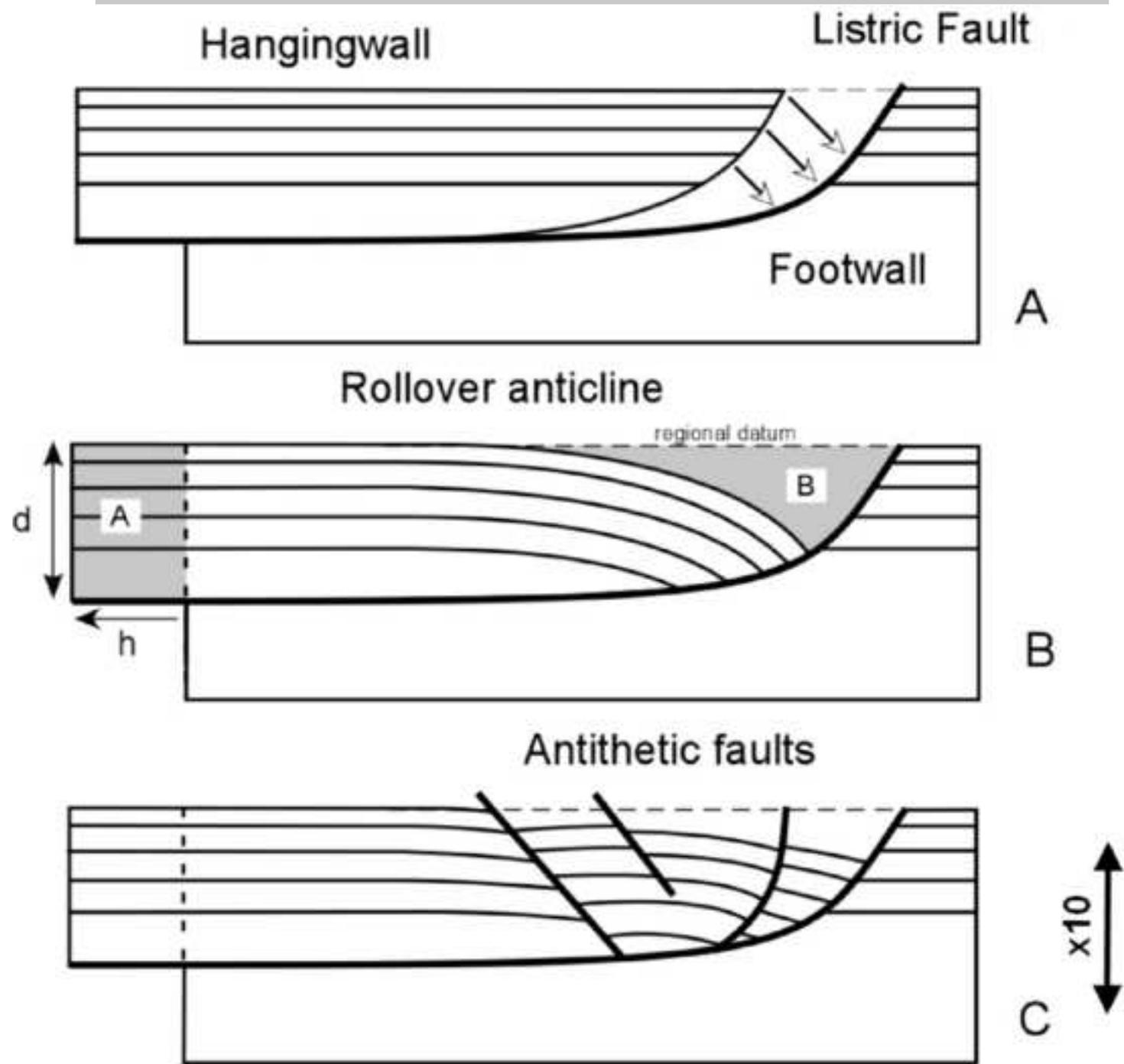


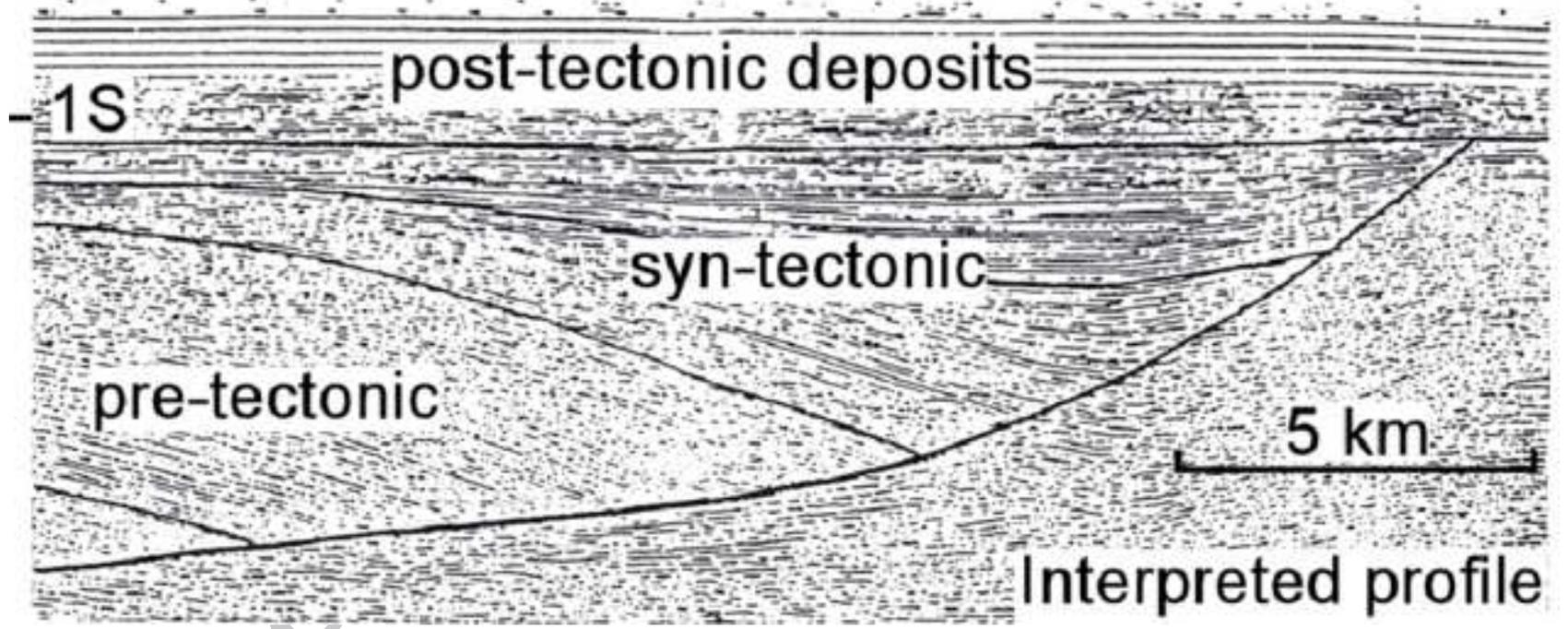
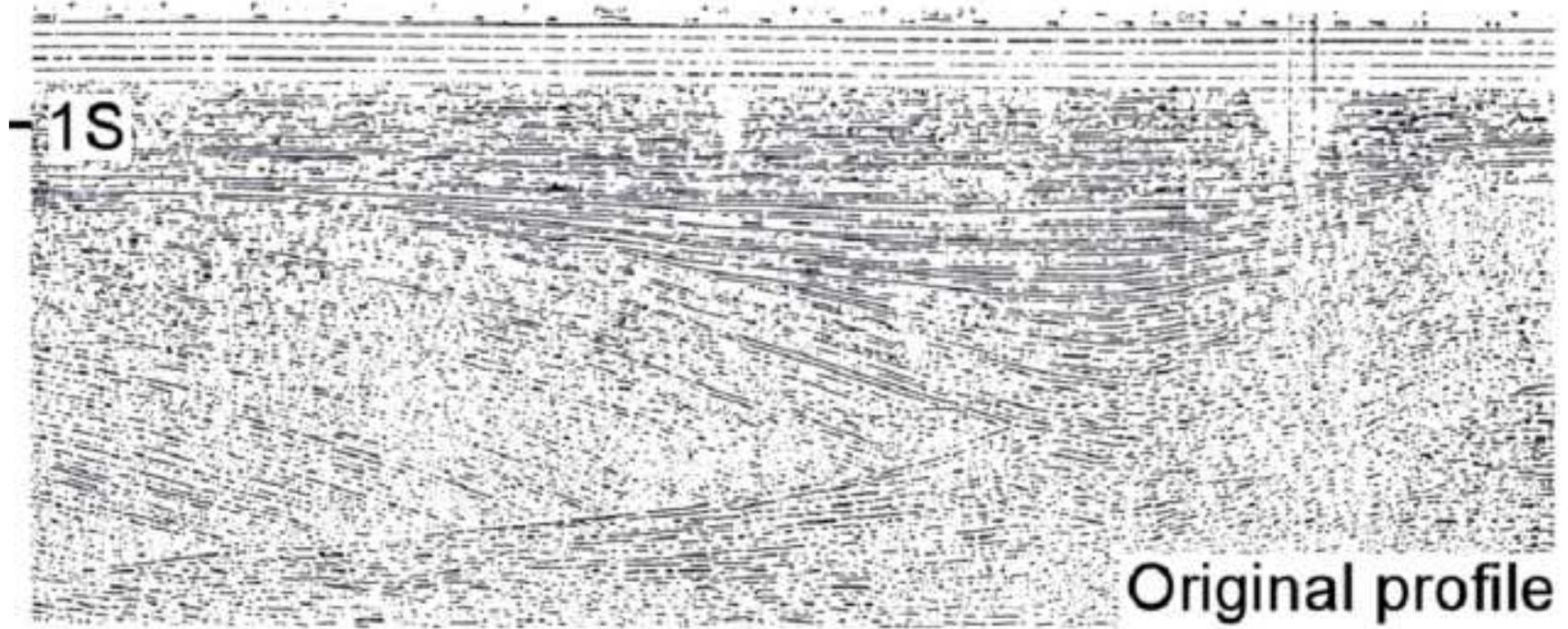
Figure 8

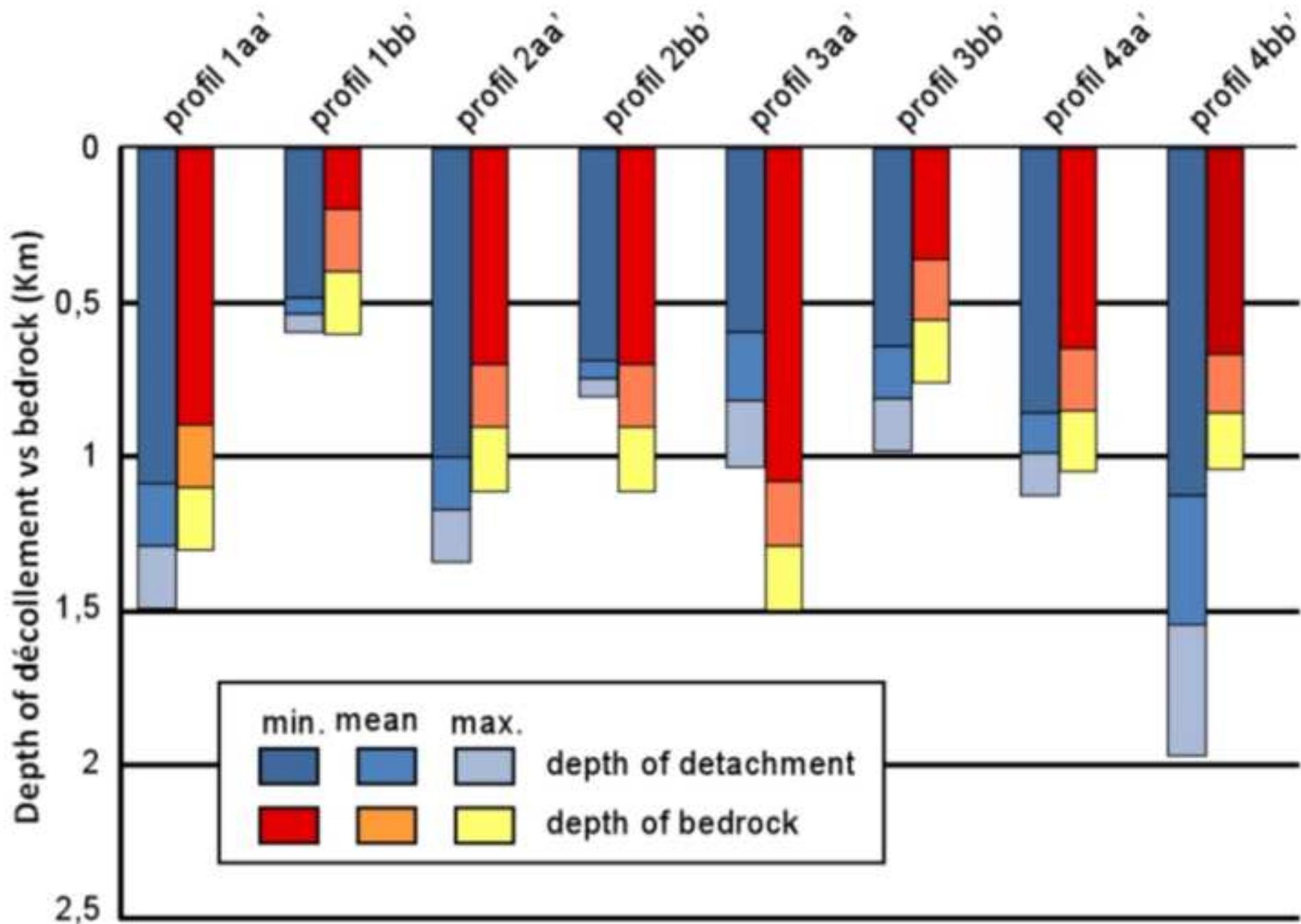


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Figure 9







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Research Highlights

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735 • The ms makes a new and complete geomorphologic description of intriguing scarps of Planum
736 Australe, using jointly different set of data.

737

738 • This description is similar to the cross-section of a listric normal fault. This allows proposing a
739 new hypothesis regarding the formation process of these scarps, implying a mechanical failure of
740 the ice and a subsequent basal sliding.

741

742 • It is emphasized that this process should be study more deeply because of its implications on the
743 ice rheology and basal conditions

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