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François Bache, Jean-Louis Olivet, Christian Gorini, Daniel Aslanian, Cinthia Labails, et al.. Evolution of rifted continental margins: The case of the Gulf of Lions (Western Mediterranean Basin). Earth and Planetary Science Letters, 2010, 292 (3-4), pp.345-356. 10.1016/j.epsl.2010.02.001 . insu-00464844

HAL Id: insu-00464844

<https://insu.hal.science/insu-00464844>

Submitted on 18 Feb 2011

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Evolution of rifted continental margins: The case of the Gulf of Lions (Western Mediterranean Basin)

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Abstract:

The formation of rifted continental margins has long been explained by numerous physical models. However, field observations are still lacking to validate or constrain these models. This study presents major new observations on the broad continental margin of the Gulf of Lions, based on a large amount of varied data. Two contrasting regions characterize the thinned continental crust of this margin. One of these regions corresponds to a narrow rift zone (40–50 km wide) that was highly thinned and stretched during rifting. In contrast with this domain, a large part of the margin subsided slowly during rifting and then rapidly after rifting. The thinning of this domain cannot be explained by stretching of the upper crust. We can thus recognize a zonation of the stretching in both time and space. In addition, the Provencal Basin is characterized by a segmentation of the order of 100–150 km. These observations have important consequences on the formation and evolution of the Gulf of Lions margin. Independently of the geodynamic context, we can propose some general features that characterize the formation of rifted continental margins.

Keywords: subsidence; passive margins; back-arc; rifting; erosion; stretching; thinning; Western Mediterranean; Gulf of Lions

34 **2. Introduction**

35
36 The formation of continental margins and rift basins is classically explained by lithospheric
37 extension. Mc Kenzie (1978) quantified the vertical motions that result from a uniform and
38 passive extension of the crust and lithosphere. The two main contributions to these motions
39 are subsidence, caused by crustal thinning, and uplift, caused by lithosphere heating. The
40 combination of these two factors explains an initial rapid subsidence during rifting, followed
41 by a slower thermal subsidence after rifting as the lithosphere cools down and returns to its
42 original thickness. However, this pattern is not always observed on continental margins. For
43 example, studies have demonstrated a rift-flank uplift of up to 1000 m in the Gulf of Suez
44 (Steckler, 1985) or uplift and erosion landward of a narrow hinge zone in the US Atlantic and
45 eastern Australian continental margins (Weissel and Karner, 1984; Steckler et al., 1988). A
46 greater degree of extension at depth rather than in the upper crust has been proposed to
47 account for these observations (Royden and Keen, 1980; Steckler, 1985; Steckler et al., 1988;
48 Davis and Kusznir, 2004; Reston, 2007; Huisman and Beaumont, 2008). Recent studies on
49 different margins allow us to compare the observations of late synrift sediments deposited
50 under shallow-water conditions offshore from the hinge zone to the oceanic domain (Moulin
51 et al., 2005; Dupré et al., 2007; Péron-Pinvidic and Manatschal, 2008; Aslanian et al., 2009;
52 Labails et al., 2009). However, the great diversity of margin morphologies leads us to
53 consider firstly the influence of the local geodynamic context (included inheritance) before
54 proposing general dynamic models of lithospheric extension. Unfortunately, this task is made
55 more difficult by the long and complex pre-rift history, often combined with poor-quality and
56 scattered geophysical and subsurface data. This last point has been repeatedly emphasized by
57 Watts (1981): “unfortunately, there is presently too little seismic and lithologic information
58 on the actual proportion of pre-rift and syn-rift to post-rift sediments (...) to constrain these
59 models”.

60 This study presents the young and weakly deformed Gulf of Lions continental margin, which
61 is covered by a dense network of observations. These data lead to a new model for the
62 formation of this margin and allow us to identify some major characteristics that can be
63 compared with observations made on other rifted continental margins.

64

65 **3. Geodynamic context and subsidence studies in the Gulf of Lions**

66

67 *3.1. The basin and its margins*

68

69 In the western Mediterranean, the Provencal Basin is a young oceanic basin created by a
70 Miocene counter-clockwise rotation of Corsica-Sardinian micro-plate (Smith, 1971; Auzende
71 et al., 1973; Dewey et al., 1973; Olivet, 1996; Gueguen et al., 1998; Gattacceca et al., 2007).
72 Along the north-western edge of this basin, the broad Gulf of Lions margin is bordered on
73 either side by the narrow Provence and Catalonian margins. On the south-eastern conjugate
74 edge, the broad Sardinian margin is intercalated between the narrow Nurra and Iglesias
75 margins. In this way, the Provencal Basin is characterized by a segmentation of the order of
76 100-150 km (Fig. 1).

77 The central part of the Provencal Basin shows magnetic anomalies and velocities related to
78 the presence of a typical oceanic crust (Le Douaran et al., 1984; De Voogd et al., 1991; Pascal
79 et al., 1993). This central oceanic domain (Fig. 1) is separated from the continental margins
80 by two domains of unknown nature without magnetic anomalies (or with low-amplitude
81 anomalies). These transitional domains appear to be an equivalent of the Ocean-Continent
82 Transition (OCT) as described on the Galicia margin (Boillot et al., 1980).

83 The opening of the Provencal Basin, followed by the Tyrrhenian Sea, took place in the back-
84 arc region of the south-eastward retreating Apennines-Maghrebides subduction zone (Réhault
85 et al., 1984; Malinverno and Ryan, 1986; Jolivet and Faccenna, 2000). Furthermore, the Gulf
86 of Lions is located at the eastern end of the Pyrenees and the southern end of the West
87 European Rift system (Rhine Graben, Bresse, Fig. 1). This margin is therefore the result of a

88 complex but well-known tectonic evolution (see (Gorini et al., 1993; Séranne, 1999; Guennoc
89 et al., 2000) for reviews).

90 91 3.2. *Pyrenean inheritance*

92
93 The Pyrenean orogeny affects the northern boundaries of the Iberian plate (Pyrenees) and the
94 Corsica-Sardinia plate (Languedoc-Provence) at the end of the Eocene (Arthaud and Séguret,
95 1981). In the Pyrenees, a shortening of 100 km or 150 km has been estimated, respectively, by
96 an analysis of the Ecors seismic profile (Roure et al., 1989) and by kinematic studies (Sibuet
97 and Collette, 1991; Olivet, 1996). Eastward of the Pyrenees, in the Languedoc-Provence
98 domain, various authors have estimated a shortening of the order of 50 km (Arthaud and
99 Séguret, 1981; Guieu and Roussel, 1990). Moreover, no deformation linked with this phase
100 has been reported in Corsica-Sardinia. NE-SW-trending Variscan and Tethyan structural
101 directions are preserved in the Gulf of Lions, thus corroborating these differences of
102 shortening. One important consequence is the activation of a major N-S strike-slip fault
103 between the Iberian and Corsica-Sardinia plates during the Late Cretaceous-Late Eocene
104 (Olivet, 1996). The Catalan and Igleziente margins seem to be directly related to this strike
105 slip fault (Chapter 5.1).

106 107 3.3. *Age of rifting*

108
109 At the end of the Eocene (Priabonian), the West European Rift system developed first in the
110 Rhine Graben, and then toward the south in the areas of Bresse and Valence. Séranne (1999)
111 has suggested an incipient structural development of the Camargue Basin during the West
112 European Rift phase. In the Gulf of Lions, the onset of rifting is attributed to the Oligocene,
113 contemporaneous with intraplate alkalic volcanism in Languedoc and andesitic volcanism
114 (related to the Apennines-Maghrebides subduction) in western Sardinia and offshore western
115 Corsica (Boccaletti and Guazzone, 1974; Gennessaux et al., 1974; Bellaiche et al., 1979;

116 Réhault et al., 1984). The end of the rifting is dated at between 23 and 19 Ma according to
117 numerous authors (Edel, 1980; Réhault et al., 1984; Ferrandini et al., 2003; Gattacceca et al.,
118 2007). The rifting of the Gulf of Lions is thus very short-lived (~9 Ma) in comparison to the
119 duration for other margins in extension (i.e., 10-160 Myr), which chiefly depends on the
120 interaction between lithospheric plates (Ziegler and Cloetingh, 2004).

121

122 3.4. *Subsidence of the basin*

123

124 In terms of subsidence, the Provencal basin has long been considered as an Atlantic-type
125 passive margin (Ryan, 1976; Steckler and Watts, 1980; Burrus, 1989). While uniform
126 extension models (McKenzie, 1978) were largely used to explain the evolution of such
127 margins, many discrepancies with the predictions of these models have been highlighted in
128 the Gulf of Lions. Steckler and Watts (1980) used biostratigraphic data from commercial
129 wells to study the subsidence history of the Gulf of Lions. They described a relatively small
130 volume of syn-rift sediments compared to post-rift sediments. For these authors, the small
131 amount of subsidence associated with rifting rules out any major stretching of the continental
132 crust, while the magnitude of the thermal subsidence requires widespread heating of
133 the lithosphere during rifting. Steckler and Watts (1980) concluded that mechanisms other
134 than passive heating related to stretching are required to account fully for these observations.
135 This first type of discrepancy was not corroborated by more recent studies, which described a
136 great thickness of synrift sediments (Bessis, 1986; Guennoc et al., 2000). Bessis (1986) and
137 Burrus (1989) pointed out that the evolution of the subsidence of the Gulf of Lions was
138 qualitatively (rapid initial subsidence during rifting, followed by a slower thermal subsidence
139 after rifting) but not quantitatively in agreement with the uniform stretching model proposed
140 by McKenzie (1978). In this way, they introduced the concept of “paradox of stretching” in
141 the Gulf of Lions: the high values of stretching required are inconsistent with the crustal
142 thinning ratio inferred from observations of the structural geology. For these latter authors

143 (*op. cit.*), stretching plays only a minor role and some other mechanisms appear to be
144 responsible for most of the crustal thinning. The discrepancy between observations and the
145 predictions of uniform extension models casts doubt on the validity of comparing the Gulf of
146 Lions margin to an Atlantic-type passive margin (assuming that uniform extension models
147 can be applied to Atlantic-type passive margins). Hence, various authors proposed an
148 influence due to the eastward retreat and roll-back of the Apennines-Maghrebides slab
149 (Faccenna et al., 2001; Jolivet et al., 2008; Yamasaki and Stephenson, 2008) and/or the
150 overthrusting of the Pyrenean Eocene units (Séranne, 1999).

151

152 **4. Data**

153

154 This study benefited from large amount of data collected in the area for both commercial and
155 academic purposes (Fig. 1). A partnership with Total gave us access a complete set of
156 conventional and high-resolution seismic reflection data from the coast to the deep sea
157 domain. Seismic interpretations were carried out based on the principles of seismic
158 stratigraphy (Vail et al., 1977). Additional data were obtained from the e-logs of nine oil-
159 industry boreholes that sampled the sedimentary cover down to the substratum. A detailed
160 micropaleontological study (Cravatte et al., 1974) compiles all the information on the
161 biostratigraphy and depositional environments of the Miocene, Pliocene and Quaternary
162 successions in four of the wells (Mistral1, Sirocco1, Autan1 and Tramontane1). The data from
163 these wells were brought together in a compilation of the drilling reports (Guennoc et al.,
164 2000). The Ecors programme (De Voogd et al., 1991) provided three general seismic sections
165 across the entire margin, supplemented by a series of Expanding Spread Profiles giving
166 estimates of the velocities (Pascal et al., 1993). Finally, we make use of the first results of the
167 recent Sardinia project, which imaged the deep structure of the Gulf of Lions and Sardinian
168 margins using wide-angle seismic data (Klingelhoefer et al., 2008; Gailler et al., 2009).

169

170 **5. Configuration of the Gulf of Lions margin**

171
172 The peculiarity of the Gulf of Lions margin is its wide area of continental shelf, which
173 contrasts with the narrow margins of Catalonia to the south-west and Provence to the north-
174 east. Seismic reflection data tied to the boreholes (Fig. 1) have provided a detailed
175 morphological map of the pre-Tertiary substratum (Fig. 2). In the present study, we first
176 describe the morphology and superficial structures of the substratum, and then its deep
177 structure using seismic refraction results (Pascal et al., 1993; Klingelhoefer et al., 2008;
178 Gailler et al., 2009). Finally, we present the characteristics of the sedimentary cover and the
179 areal extent of the synrift sediments.

180 181 *5.1. Morphology and faults*

182
183 Two distinct topographic regions can be recognized in the Gulf of Lions (Fig. 2): the elevated
184 north-eastern sector, represented in cross-section on Fig. 3A, is characterized by narrow
185 basins and marked topographic highs. The south-western sector, represented in cross-section
186 on Fig. 3B, is characterized by a relatively smooth basement topography and a broad
187 depression known as the “Graben Central”. Within these sectors (Fig. 4), three generations of
188 structural trends can be recognized which are inherited from the tectonic history. The NE-SW
189 direction corresponds to faults inherited from the Variscan orogeny (Arthaud and Matte,
190 1977b). These major faults delimit the Tethyan palaeo-margin (Lemoine, 1984) and were
191 reactivated during Pyrenean compression and at the end of the Miocene (Gorini et al., 1991;
192 Mauffret et al., 2001; Gorini et al., 2005). Surprisingly, these faults were not significantly
193 reactivated during the rifting except in the northern part of the Gulf of Lions and in the
194 Camargue Basin, at the junction with the West European Rift system (see Chapter 5.2). The
195 E-W to ENE-WSW directions characterize the north-eastern sector and its transition towards
196 the deep basin. They are probably the result of a Mid-Cretaceous Pyrenean deformation in the
197 prolongation of the North Pyrenean Fault Zone. These structures played a major role during

198 rifting, as indicated by the presence of a major ENE-WSW fault, separating the proximal
199 margin, which is in a high topographic position, from the more subsident distal margin (Fig.
200 3A). The N-S directions (Fig. 4) characterize the Catalan margin and its conjugate Iglesias
201 margin in its initial position before the opening of the basin (Fig. 5; Olivet, 1996). Many
202 studies (Gueguen et al., 1998; Gattacceca et al., 2007) support the hypothesis of a counter-
203 clockwise rotation (50-60° for Sardinia and 40-50° for Corsica during drifting).

204 Three structural domains can be highlighted extending from the coast to the oceanic crust
205 (Figs. 2 and 3). These three domains (I, II and III) are delimited by two major boundaries: B2
206 separates a sloping continental crust (in domains I and II) from the horizontal crust of domain
207 III, while B1 is well represented in the north-eastern sector by ENE-WSW major faults (B1s)
208 which mark out a zone of tilted blocks (domain II, Fig. 3A) distinct from domain I. However,
209 in the south-western sector of the margin, this limit is unclear at the top of the crust (Fig. 3B).

210 The study of crustal thickness variations allows us to clarify the nature of these major
211 transitions at depth and identify three structural domains going from the land toward the basin
212 (Fig. 3). A first major transition in crustal thickness (the hinge zone) separates a relatively
213 undeformed continental crust (> 30 km thick) from domain I farther offshore, which is ~100
214 km wide and characterized by a thinned continental crust (~20 km thick). The seaward limit
215 of the hinge zone corresponds to the onset of increasingly thick sedimentary deposits toward
216 the basin. Still farther offshore, domain II is characterized by a considerable thinning of the
217 crust (from 20 to 5 km) over a short distance (~50-70 km). This domain coincides with the
218 tilted blocks zone observed at the top of the crust (between B1s and B2) in the north-eastern
219 part of the margin, and represents the second major transition in crustal thickness (between
220 B1d and B2). Domains I and II taken together are termed the “continental crust slope” owing
221 to its morphology (sloping toward the basin) and the presence of upper continental crust. The
222 continental crust slope can thus be defined as a segment, seaward of the hinge zone, where the

223 continental crust is thinned and slopes down towards the basin. Domain II is marked by a
224 prominent reflector (reflector T) easily recognized at depth (De Voogd et al., 1991). A seismic
225 facies (with highly reflective and discontinuous reflections), which is recognized on domain I
226 and interpreted as the lower continental crust, pinches out on this reflector. Domain III marks
227 the transition between the continental crust slope and the oceanic crust. This 100-km-wide
228 domain exhibits a very thin (~5 km) crust of undetermined nature. Refraction data indicate
229 high velocities (~7.3-7.2 km/s) at its base, which are neither typical of a continental crust nor
230 of an oceanic crust (Pascal et al., 1993). The exact nature of this domain in the Gulf of Lions
231 is still the subject of intense debate. Recently, based on wide-angle seismic analysis, Gailler
232 et al. (2009) interpreted a high-velocity zone in this domain (Fig. 3B) either as representing
233 exhumed lower continental crust or a mixture of lower continental crust and upper mantle
234 material. In this study, we refer to domain III as “undetermined crust”. It corresponds to the
235 Ocean-Continent Transition (OCT), i.e. the transition between thinned continental crust and
236 oceanic crust (Boillot et al., 1980).

237 The faults bounding the depressions of domain I display a small displacement during rifting.
238 For example, a horizontal extension of around 10 km has been calculated in the wider and
239 deeper Camargue basin (Séranne et al., 1995). Assuming an initial thickness of the continental
240 crust of between 30 and 40 km (Gailler et al., 2009), we can estimate the thinning factor β
241 related to domain I (Fig. 3). The factor calculated in this way, which lies between 1.5-2 for
242 domain I assuming uniform extension, induces a theoretically horizontal movement of
243 between 33 and 50 km. In fact, we only observe 15-20 km of horizontal movement. Thus, we
244 can conclude that more than half of the thinning of domain I cannot be explained by upper
245 crustal extension. Conversely, the crustal configuration of domain II (tilted blocks) suggests a
246 large amount of crustal extension ($\beta = 4.5 - 6$) (Fig. 3).

247 To summarize the crustal observations, a major contrast occurs between domain I and domain
248 II on the Gulf of Lions continental crust slope. Domain I is characterized by a thinned
249 continental crust and weak stretching. Domain II (tilted blocks zone) is characterized by a
250 strongly thinned continental crust and major stretching. These domains can be recognized by
251 their crustal thicknesses and are delimited by a major fault at the top of the crust (fig. 3).
252 These observations are in line with the “stretching paradox” (Bessis, 1986; Burrus, 1989) in
253 the Gulf of Lions (see Chapter 3.4). The study of the sedimentary cover backs up these
254 observations as shown in the following.

255 256 5.2. *The sedimentary cover* 257

258 The sedimentary cover of the Gulf of Lions displays a thickness up to 8 km in the basin and
259 up to 5 km on the shelf (Fig. 3). This Oligocene to Recent succession is classically divided
260 into four major units according to seismic and borehole data interpretations. The lowermost
261 part the succession is made up of a synrift unit (in yellow on figures) which has been sampled
262 onshore in the Camargue basin. Thick silty marl and evaporite-bearing Oligocene deposits
263 have been described that are typical of a lagoonal lacustrine environment (Triat and Truc,
264 1983). Four wells have sampled the synrift unit offshore, but only in its upper part, so the total
265 thickness of the synrift deposits remains uncertain. The corresponding seismic facies exhibits
266 continuous to discontinuous reflectors. The second unit (Mi on figures), of Aquitanian to
267 Tortonian age, is characterized by sedimentation on a wide prograding shelf. This unit fills
268 pre-existing hollows in the relief, and displays morphologies with geometrical onlaps (Fig. 6)
269 and progradations toward the basin, forming features that are clearly recognized not only on
270 seismic data as clinoforms (between 80 and 100 km from the coast on Fig. 3B) but also on
271 dipmeter data in the Autan 1 well (Cravatte et al., 1974). These facies are made up of deltaic
272 deposits. The third unit (Me on figures), is restricted to the basin (Fig. 3), and corresponds to
273 Messinian terrigenous siliciclastic and evaporitic facies related to the major drawdown of sea

274 level in the Mediterranean after its isolation from Atlantic waters (Hsü, 1972; Cita, 1973;
275 Clauzon, 1973; Ryan, 1973). A recent detailed description and new interpretation of this unit
276 can be found in Bache et al., 2009. The fourth unit (PQ on figures), of Pliocene to Quaternary
277 age, records the restoration of open marine conditions at its base passing up into an overall
278 regressive sequence (Cravatte et al., 1974) characterized by the reconstruction of shelf-slope
279 geometries with prograding clinofolds.

280 The first point that we emphasize here concerns the thickness of the synrift deposits. The
281 Gulf of Lions margin has been described as an extensive area with deep grabens formed
282 during the Oligocene by normal faults that have reactivated older fault trends (Bessis, 1986;
283 Gorini et al., 1991; Séranne et al., 1995; Guennoc et al., 2000). Here, we propose a new
284 interpretation based on the depositional pattern and the highly contrasted seismic facies of
285 pre-rift and syn-rift sediments. On seismic profiles, syn-rift sediments (drilled or identified at
286 the outlet of the Camargue Graben) show a relatively continuous seismic facies (Fig. 6).
287 Mesozoic (Jurassic) series drilled in the Calmar (Fig. 6) and Cicindelle boreholes display a
288 highly reflective and discontinuous seismic facies. Borehole data, seismic facies and
289 sedimentary geometries allow us to differentiate the pre-rift and syn-rift sediments. According
290 to our interpretation, supported by the analysis of a huge seismic dataset, it appears that
291 synrift deposits are very thin on the Gulf of Lions margin (<1 s TWTT, Fig. 4), except in
292 some areas such as the “Camargue” and the “Marseilles” basins where more than 2 km of
293 synrift sediments have been drilled (Benedicto et al., 1996; Guennoc et al., 2000). The highly
294 reflective and discontinuous seismic facies previously interpreted as syn-rift deposits in the
295 Gulf of Lions (Bessis, 1986; Gorini et al., 1991; Séranne et al., 1995; Guennoc et al., 2000)
296 corresponds in fact to older Mesozoic sediments (Mz on figures). A smaller degree of
297 shortening in the Languedoc-Provence area than in the Pyrenees (see chapter on “Pyrenean
298 inheritance”) could explain the preservation of Mesozoic basins in the Gulf of Lions. This

299 new interpretation of synrift sediment thickness is in agreement with Steckler and Watts'
300 (1980) observations (see 3.4).

301 The second point concerns the presence of a major erosional surface at the top of the synrift
302 deposits or directly on the substratum. In the south-western part of the Gulf of Lions, this
303 surface erodes syn-rift deposits and is clearly distinguished from a more recent major erosion
304 surface (Fig. 7) attributed to the Messinian (Bache et al., 2009). In this part of the margin, the
305 Miocene shelf (Mi) is thick and preserved between the two surfaces (Fig. 7). In the elevated
306 north-eastern part of the Gulf of Lions, the substratum is directly eroded. The GLP2 basement
307 structure, located at the boundary between domain I and domain II, is eroded perpendicularly
308 to its main strike (Fig. 8), and thus demonstrates the importance of this erosion. Three major
309 axis of erosion can be outlined (in red on Figs. 2 and 4). In this part of the margin, there are
310 almost no Miocene deposits (Mi), so the two erosional surfaces are often merged. However,
311 two arguments lead us to link GLP2 substratum erosion to the early erosional phase identified
312 in the south-western part of the margin. (1) The first argument is based on paleogeography: no
313 Messinian fluvial network comparable to the Messinian Rhône, and capable of eroding the
314 GLP2 structure, has been found farther landward. However, we should not ignore the
315 presence of karst features comparable to those observed in Ardeche (Mocochain et al., 2006).
316 (2) The erosional surface also affects the top of the tilted blocks at the foot of the eroded
317 GLP2 high (Fig. 8). These blocks are overlain by Lower Miocene sediments (Mi) and were
318 therefore eroded and destabilized before the Messinian erosional event. To the East, the
319 margins of the Ligurian Sea are also cut by many canyons. These canyons were subaerial
320 during the Messinian crisis (Clauzon, 1978; Estocade-group, 1978; Ryan and Cita, 1978;
321 Savoye and Piper, 1991), and then re-eroded during the Quaternary (Cyaligure-group, 1979).
322 An older formation of these features could also be considered.

323 To summarize the sedimentary observations, the major part of the Gulf of Lions margin is
324 highly eroded and synrift deposits are either very thin or completely lacking (domain II and
325 seaward part of domain I). Landward of this early erosion, some significant but localised
326 synrift accumulations can be picked out (in yellow on Fig. 2).

327

328 **6. Discussion**

329

330 Our study highlights the major characteristics of the Gulf of Lions continental crust slope (see
331 5.1). Two major domains can be differentiated by their crustal structures and sedimentary
332 configurations (Figs. 2 and 3). Domain I is characterized by a thinned but weakly stretched
333 upper crust. This domain is characterized in its landward part by significant synrift
334 accumulations, and, in its seaward part, by early erosion affecting the top of thin synrift
335 deposits or cutting down directly into the substratum. Domain II, on the contrary, is
336 characterized by extremely thinned and stretched crust that can also be affected by the early
337 erosion. These domains can be recognized by their crustal thicknesses, and are sometimes
338 delimited by a major fault at the top of the crust. This configuration leads us to discuss the
339 following points.

340 *6.1. A high topographic position of the continental crust slope during* 341 *rifting*

342

343 The strong early erosion observed at the top of the synrift deposits or directly on the
344 substratum suggests that the erosion took place under subaerial conditions. In addition, the
345 generally thin development of synrift sediments (Fig. 4) suggests either that the margin did
346 not subside much during rifting or that it was uplifted at the end of rifting. The aggrading
347 shelf-slope geometries during the early to middle Miocene (Fig. 3B) indicate that the
348 morphology of the margin and the subsidence pattern changed after this early erosion and led
349 to the creation of accommodation. The micropaleontological study of borehole samples from
350 this Miocene shelf (Cravatte et al., 1974) reveals a deepening of the depositional environment

351 at this time. We can conclude that a large part of the Gulf of Lions margin subsided slowly
352 during rifting and rapidly after rifting, leading to the deposition of thick post-rift Miocene to
353 Quaternary deposits. Therefore, it appears that the synrift subsidence calculated by Bessis
354 (1986) and Burrus (1989) is excessive due to the overestimated thickness of synrift deposits.
355 Because of this, we reach the same conclusion as Steckler and Watts (1980): mechanisms
356 other than passive heating due to stretching are required to account fully for these
357 observations.

358 Figure 9 shows our view of the margin configuration at the end of rifting. We interpret the
359 tilted blocks zone (strongly thinned and stretched domain II) as corresponding to the main rift
360 (40-50 km wide, comparable with present-day width of the Rhine and East African rifts). The
361 seaward part of domain I (characterized by early erosion), separated from the tilted blocks
362 zone by a major fault, is interpreted as a rift flank uplifted and eroded during rifting. The
363 same configuration can be assumed in the Ligurian domain, where numerous canyons have
364 been described (see 5.2). In the Gulf of Lions and Sardinia, some grabens with synrift
365 deposits are observed flanking the rift shoulder (in yellow on Fig. 9), while no synrift deposits
366 have been identified in the main rift (domain II). A deflection of drainage systems away from
367 the main rift and into the continental interior can be suggested to explain this configuration.
368 The same pattern has been observed in the Red Sea (Frostick and Reid, 1989.), where it is
369 proposed as a possible mechanism explaining why the central parts of the Red Sea are
370 underfilled despite the massive evaporite precipitation following the major phase of extension
371 during the early Miocene (Bosence, 1998). After rifting, the entire Gulf of Lions margin was
372 affected by strong postrift subsidence and thick sedimentary accumulations. Polyphase
373 compressional deformation, which seems to be a common feature in the post-rift evolution of
374 many passive margins and rifts (Cloetingh et al., 2008), has not been observed here.

375

376 6.2. *Zonation of stretching*

377
378 The transition between the thinned but poorly stretched domain I and the extremely thinned
379 and stretched domain II is characterized by a major fault identified near the surface. The main
380 stretching phase of the crust is thus localized in the narrow domain II, seaward of this major
381 fault. The “necking zone” described on numerous margins has been similarly interpreted
382 (Sibuet, 1992; Lavier and Manatschal, 2006; Reston, 2007; Péron-Pinvidic and Manatschal,
383 2008). Domain I did not subside much during rifting and is characterized by a significant
384 thinning of the crust which cannot be explained by the stretching of the upper crust (see 5.1).
385 We can highlight a zonation of stretching between domains I and II, delimited by a major
386 fault. Moreover, a seismic facies interpreted as the lower continental crust pinches out on the
387 rising of the T reflector from domain I to domain II (Fig. 3). These observations are
388 incompatible with uniform extension, but are in better agreement with a larger extension at
389 depth than in the upper crust (Royden and Keen, 1980; Steckler, 1985; Steckler et al., 1988;
390 Davis and Kuszniir, 2004; Reston, 2007; Huisman and Beaumont, 2008). Other observations
391 compatible with a depth-dependant stretching model can be found in the South Atlantic
392 (Contrucci et al., 2004; Moulin et al., 2005; Dupré et al., 2007; Aslanian et al., 2009),
393 Australia (Driscoll and Karner, 1998) as well as the Central and North Atlantic (Davis and
394 Kuszniir, 2004; Funck et al., 2004; Labails et al., 2009).

395
396 6.3. *Segmentation of the margin*

397
398 The Provencal Basin is characterized by a segmentation of the order of 100-150 km (Fig. 1).
399 The wide Gulf of Lions-Sardinia segment is flanked on either side by the narrow Provence-
400 Nurra and Catalanian-Iglesiente segments. The Sardinia and Corsica blocks cannot be
401 dissociated to reduce the width of Gulf of Lions-Sardinia segment (Fig. 5) because of the
402 presence of a Permian dyke complex between Sardinia and Corsica (Arthaud and Matte,
403 1977a). Such a configuration poses a problem for kinematic reconstructions if we assume that

404 the thinning is directly linked to horizontal stretching. The same question arises for the
405 reconstruction of the Newfoundland and Iberian margins bordering the Atlantic, where the
406 independent movement of different blocks has been suggested. For example, (Sibuet et al.,
407 2007) have proposed the movement of Flemish Cap and Orphan Knoll in relation to the Great
408 Bank or the movement of Galicia Bank in relation to the Iberian margin. A segmentation of
409 the same order has been observed on the American and African conjugate margins, but the
410 movement of independent blocks seem unlikely (see (Sahabi et al., 2004) for a review).
411 Because of the young age of the Western Mediterranean, it is possible to study the
412 segmentation in more detail here than in old and complex margins. Our results suggest that
413 the segmentation observed in the Provençal Basin is linked to processes of thinning rather
414 than horizontal extension.

415

416 *6.4. A new model of evolution for the Gulf of Lions*

417

418 Observations in the Gulf of Lions are taken into account here to propose a model for the
419 formation of this crustal segment (Fig. 10). At first, most of the Gulf of Lions margin is
420 subaerially exposed during an early phase of rifting (Fig. 10A). A major fault separates the
421 40-50 km wide rift from domain I, which represents the uplifted footwall of this fault. The
422 seaward part of domain I (GLP2 structure) is subject to continuous erosion. Drainage is
423 directed away from the rift to external basins (in yellow). In a second stage (Fig. 10B), the
424 main break up occurs between the Gulf of Lions and Sardinia. This major stretching phase is
425 restricted to domain II (tilted blocks zone). During this stage, domain I remains at a high
426 topographic position despite significant thinning. From this stage onwards, the formation of
427 undetermined crust (domain III) is accompanied by a general subsidence of the margin. An
428 inversion of the drainage network occurs towards the centre of the basin, associated with thick
429 accumulations of postrift sediments. The last stage corresponds to the formation of typical

430 oceanic crust at the centre of the basin with sea-floor spreading (Fig. 10C). The different
431 morphological domains of the margin are summarized on Fig. 10.

432

433 **7. Conclusion**

434

435 The crustal structure and sedimentary facies of the Gulf of Lions margin allows us to
436 highlight two different domains on the continental crust slope (previously considered as a
437 single wide rift domain). A major fault differentiates a thinned and stretched narrow rift
438 domain (domain II, tilted blocks zone) from a thinned and poorly stretched domain (domain
439 I). This latter domain is characterized by a deficit of subsidence during rifting. The
440 identification of domain I provides a new insight into the formation of the Gulf of Lions
441 margin. The zonation of stretching and subsidence is accompanied by a 100-150 km
442 segmentation of the Provencal Basin, which suggests processes of thinning rather than simple
443 horizontal extension.

444 Numerous examples of thinned domains with limited subsidence during rifting have been
445 described on the “continental crust slope” of several Atlantic-type passive margins (Moulin et
446 al., 2005; Dupré et al., 2007; Péron-Pinvidic and Manatschal, 2008; Aslanian et al., 2009;
447 Labails et al., 2009). The evolution proposed here for the Gulf of Lions (located in a
448 particular geodynamic context) could be generalized to the formation of rifted continental
449 margins irrespective of their geodynamic context. This hypothesis could be further tested by
450 thermo-mechanical models and give mechanical constraints on the complex interplay between
451 subduction and roll-back processes in extensional basin formation (Cloetingh et al., 1995).

452 Different mechanisms have been proposed to explain rift flank uplift on extensional margins
453 landward of the hinge zone, including thermal processes (Royden and Keen, 1980; Keen,
454 1985; Steckler, 1985; Buck, 1986) and flexural isostatic rebound in response to mechanical
455 unloading of the lithosphere during extension (Watts, 1982; Weissel and Karner, 1989;
456 Gilchrist and Summerfield, 1990; Kooi et al., 1992; Ten Brink and Stern, 1992; Van Der

457 Beek and Cloetingh, 1992). In the Gulf of Lions, we find that the rift shoulder is located
458 seaward of the hinge zone (in a thinned domain). This domain remains in a high topographic
459 position during rifting and then undergoes strong subsidence. Our observations provide new
460 data to constrain these physical models.

461

462 **8. ACKNOWLEDGMENTS**

463

464 This work was funded by CNRS, IFREMER (F.B. scholarship) and the Action Marges
465 research programme. We thank Total for making their data available and in particular Jean
466 Loup Rubino and Jacqueline Camy-Peyret for their valuable help in working with the
467 database. We acknowledge the EPSL editor, Rob D. van der Hilst and journal reviewers for
468 advice and comments on the manuscript. We would also like to thank Laurent Jolivet and
469 Sylvie Leroy for their thoughtful comments. M.S.N. Carpenter post-edited the English style.

470

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732
733

734 **10.FIGURE CAPTIONS**

735

736 Figure 1: Topographic and bathymetric map of the West European Rift system and the
737 Provencal Basin (IOC et al., 2003), along with data base used for this study (detail inset). The
738 Provencal Basin was created by counterclockwise rotation of Corsica-Sardinia micro-plate
739 during the Miocene (see flowlines). Typical oceanic crust is shown at the centre of the basin.

740 Along its north-western edge, the Gulf of Lions margin is bracketed by the narrow Provence
741 and Catalonian margins. The Gulf of Lions represents a 150-km wide segment. GOL. Gulf of
742 Lions, P. Provence Margin, C. Catalonian Margin, N. Nurra Margin, S. Sardinian Margin, I.
743 Igleziante Margin, L. Languedoc, Pr. Provence. Boreholes: Ci. Cicindelle, Si. Sirocco, Ca.
744 Calmar, Mi. Mistral, Am. Agde Maritime, Tr. Tramontane, Ra. Rascasse, Au1. Autan 1,
745 GLP2. Golfe du Lions Profond 2.

746

747 Figure 2: Morphological map of the pre-Tertiary substratum (depth in TWTT s) in the Gulf of
748 Lions. The north-eastern sector is characterized by narrow basins and marked topographic
749 highs. The south-western sector exhibits fewer topographic highs, but is characterized by a
750 broad depression known as the “Graben Central”. Domains I, II and III are delimited by two
751 major boundaries extending across the entire Gulf of Lions. B2 separates a sloping continental
752 crust (domains I and II) from the horizontal crust of domain III. B1 is characterized by a
753 ENE-WSW-trending major fault at the top of the crust (B1s) and/or by the onset of a major
754 transition in crustal thickness at depth (B1d). Three major axes are indicated (in red) showing
755 areas where the substratum is directly affected by early erosion. Synrift deposits with a
756 thickness of more than 0.5 s TWTT are mainly located landward of these axes of erosion. CB:
757 Camargue Basin. MB: Marseilles Basin.

758

759 Figure 3: (A) Line drawings of the ECORS profile (north-eastern sector) and (B) LRM16-
760 Ligo20 profiles (south-western sector) converted into km (velocities indicated in km/s from
761 Pascal et al, 1993 and from Gailler et al, 2009, location of the base of the crust from
762 Klingelhofer et al., 2008). The continental crust slope (domains I and II) is affected by the
763 early erosion (in red). Domain I is characterized by a thinned continental crust and weak
764 stretching, in contrast to domain II (hachured) characterized by a strongly thinned continental

765 crust and major stretching (tilted blocks zone). Location of profiles on Fig. 2. PQ: Pliocene-
766 Quaternary. Me: Messinian. Mi: Miocene. Mz: Mesozoic.

767

768 Figure 4: Isopach map of synrift sediments. Synrift deposits are very thin on the Gulf of Lions
769 margin (<1 s TWTT), except for some areas such as the “Camargue” and “Marseilles” basins
770 where more than 2 km of synrift sediments have been drilled. Three structural directions can
771 be distinguished using topographic highs (NE-SW, ENE-WSW and N-S).

772

773 Figure 5: Position of the Corsica-Sardinia micro-plate before the opening of the basin
774 (slightly modified after Olivet, 1996). The Gulf of Lions-Sardinia segment is wider than the
775 Provence-Nurra and Catalanian-Iglesiente segments. The Sardinian-Corsica block cannot be
776 dissociated from the reconstruction to reduce (as much as the other segments) the width of the
777 Gulf of Lions-Sardinia segment, because of the presence of a Permian dyke complex between
778 Sardinia and Corsica (Arthaud and Matte, 1977a). However, in this position, we can pick out
779 a 50-km wide domain on all the segments (including domain II of the Gulf of Lions), which is
780 bordered by major faults. Domain I in the Gulf of Lions and its conjugate domain on the
781 Sardinia margin thus represent a “distinctive feature” in comparison with the other segments.

782

783 Figure 6: Seismic profile showing the highly reflective and discontinuous seismic facies
784 interpreted in this study as Mesozoic substratum. Location of profiles and boreholes on Fig. 4.
785 PQ: Pliocene-Quaternary. Mi: Miocene. Mz: Mesozoic.

786

787 Figure 7: Seismic profile showing effects of early erosion (erosional truncations) at the top of
788 synrift deposits in the south-western sector of the margin. Location of profiles on Fig. 4. PQ:
789 Pliocene-Quaternary. Me: Messinian. Mi: Miocene

790

791 Figure 8: Seismic profiles showing a major axis of early erosion affecting the substratum of
792 the elevated north-eastern sector of the margin. The GLP2 basement structure is eroded
793 perpendicularly to the main strike direction, and thus reveals the importance of this erosion.
794 Location of profiles on Fig. 4. PQ: Pliocene-Quaternary. Me: Messinian. Mi: Miocene.

795

796 Figure 9: Palaeogeographic map of the Provencal-Ligurian rift. The tilted blocks zone
797 (strongly thinned and stretched domain II) is interpreted as the main rift (40-50 km wide). The
798 seaward part of domain I (characterized by early erosion) is interpreted as the rift flank
799 uplifted and eroded during rifting. Synrift deposits are located on the flanks of the rift
800 shoulder (in yellow), while no synrift deposits are identified in the main rift. this
801 configuration may be explained by a deflection of drainage systems away from the main rift
802 and into the continental interiors (major axis of erosion in red).

803

804 Figure 10: Model of evolution of the Gulf of Lions margin. A. Early rifting. The major part of
805 the Gulf of Lions margin was subaerially exposed during an early phase of rifting. Domain I
806 is separated from the 40-50 km wide rift by a major fault, and represents the uplifted footwall
807 of this fault. B. Break-up. This major stretching phase is restricted to domain II (tilted blocks).
808 At this time, domain I remains at a high topographic position despite the significant thinning.
809 Subsequently, the initial stages of formation of undetermined crust (domain III) are
810 accompanied by a general subsidence of the margin (subsidence phase). C. Present-day
811 configuration, after the formation of typical oceanic crust at the centre of the basin, associated
812 with sea-floor spreading (drifting phase).

Figure1
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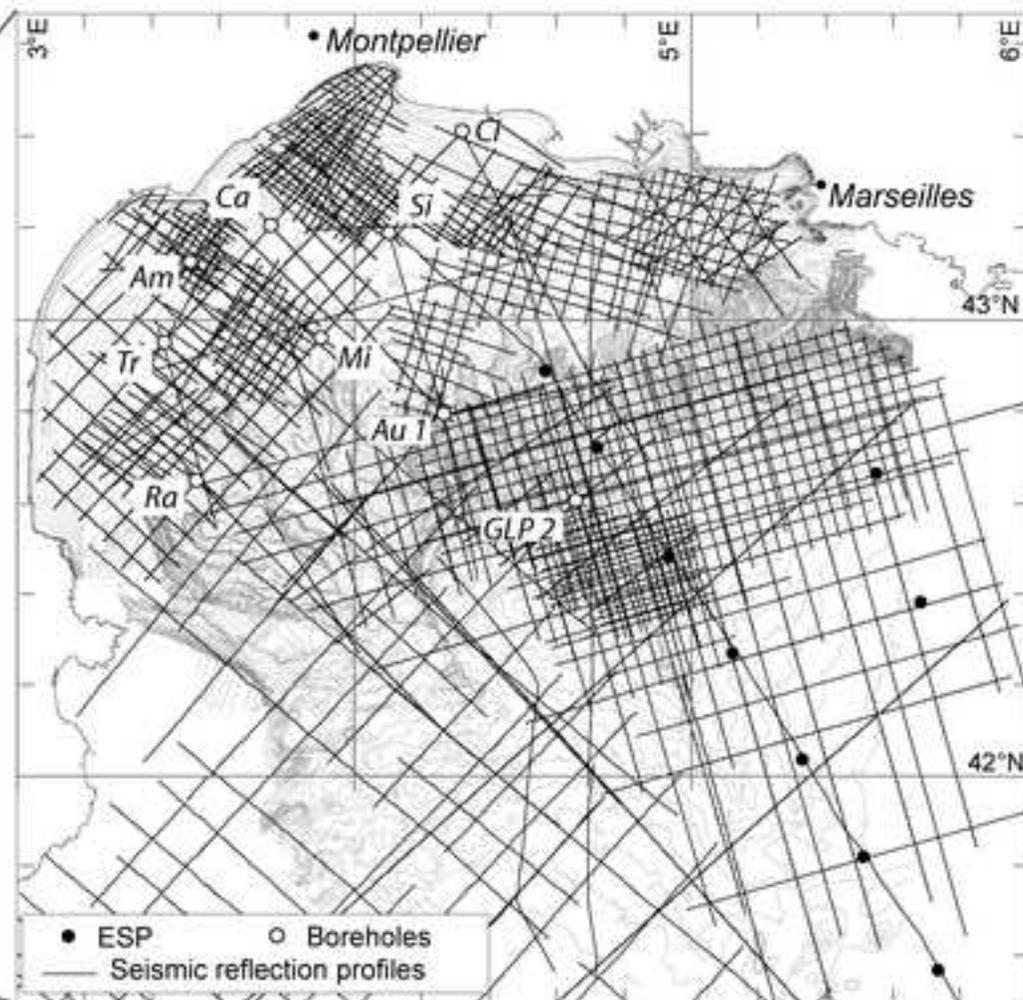
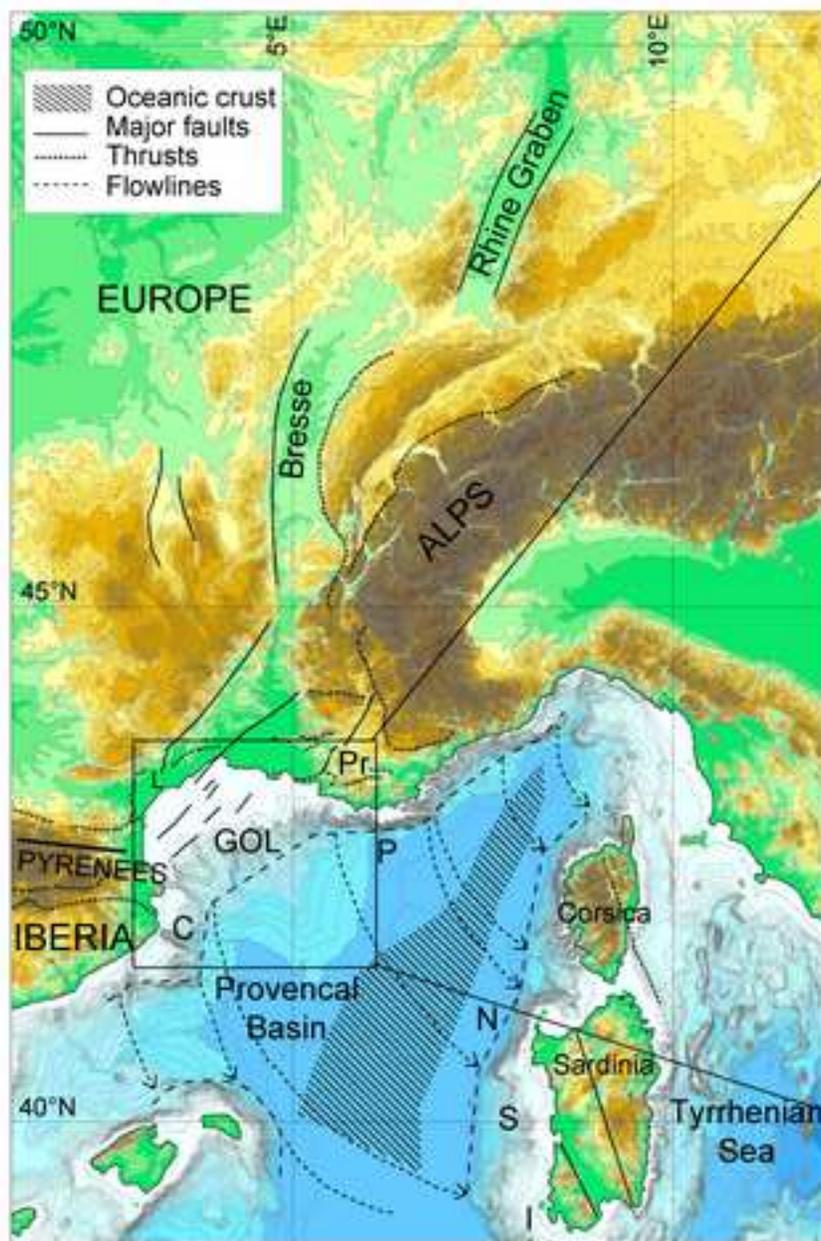


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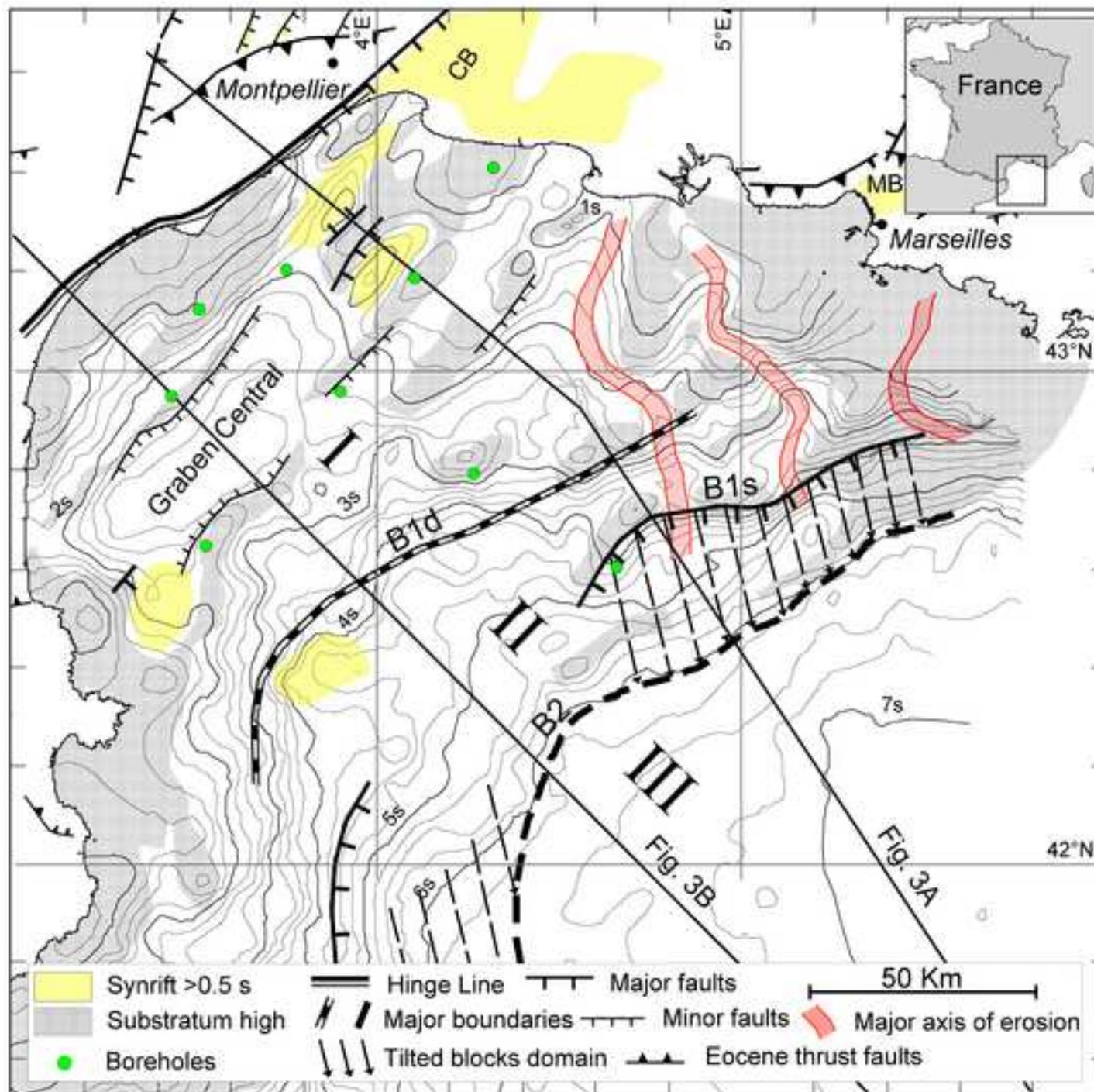


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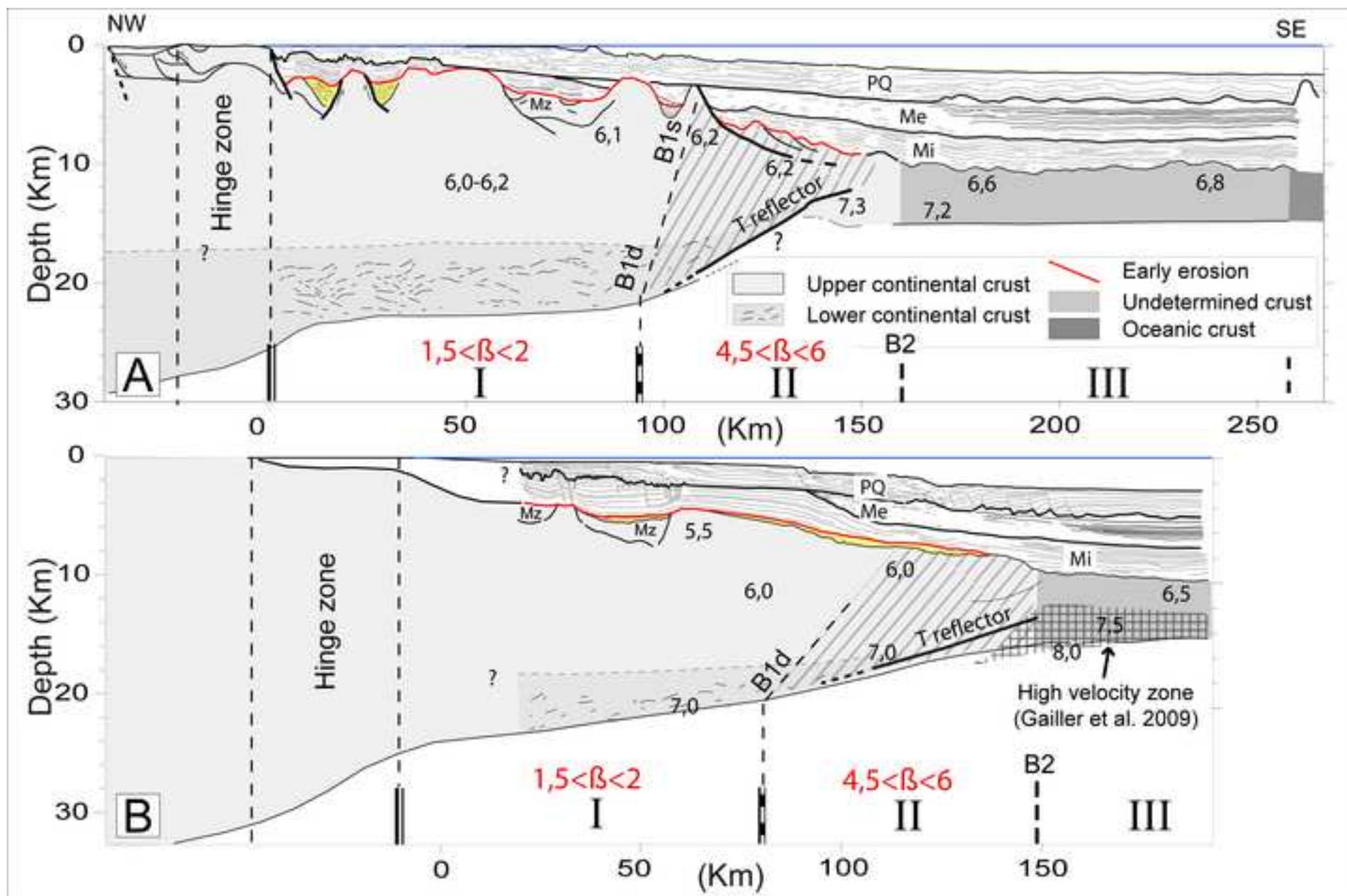


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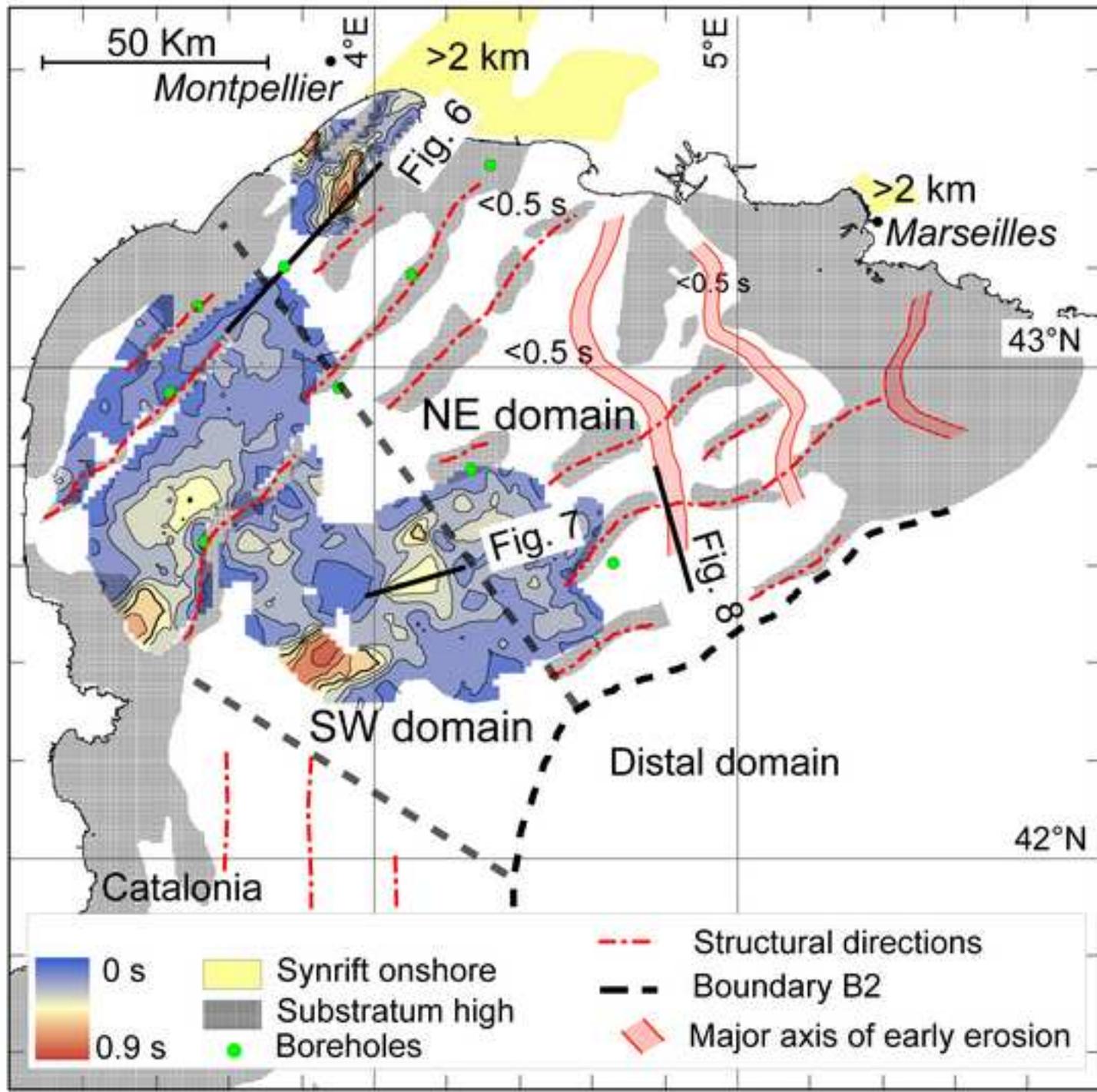


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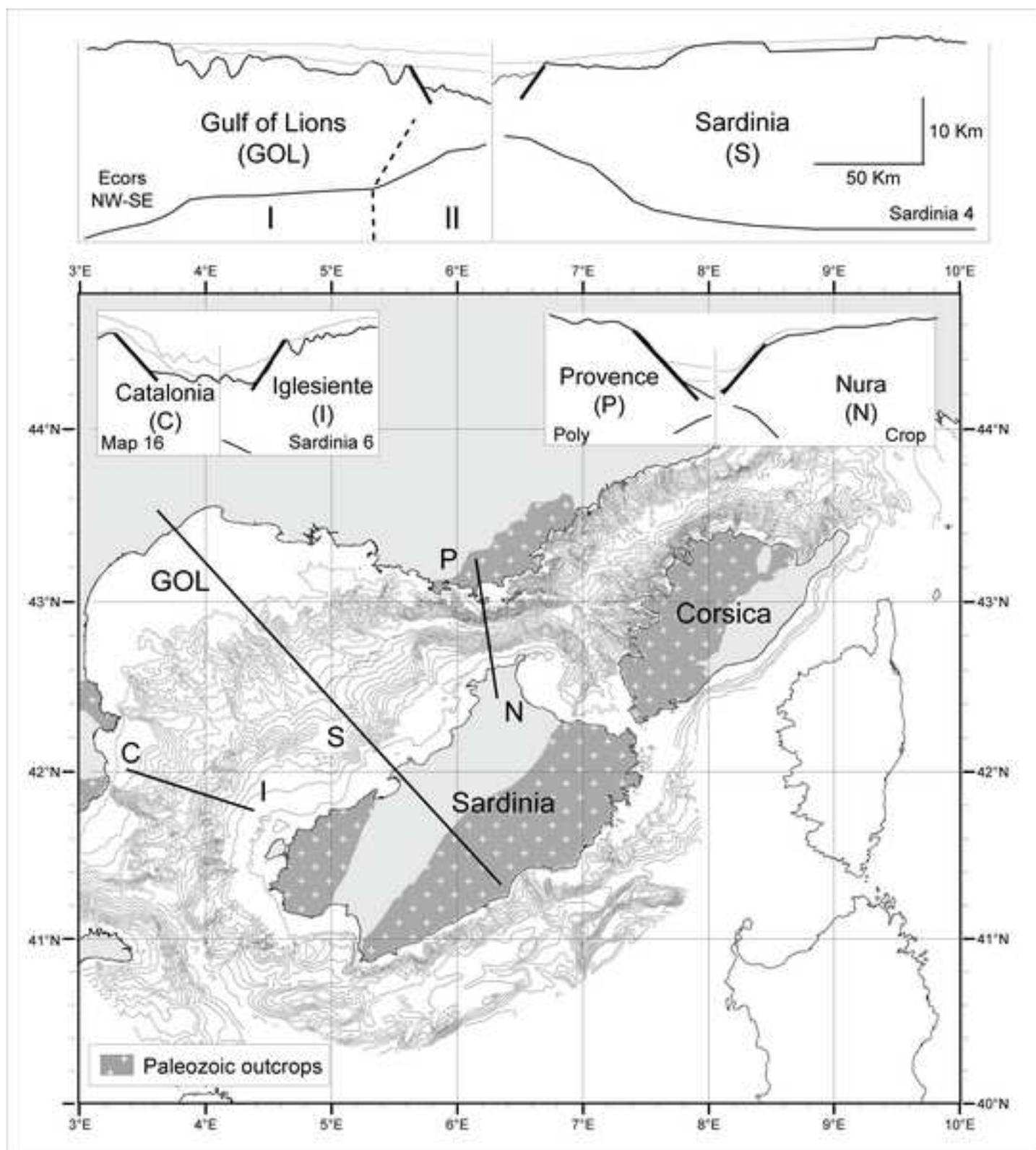


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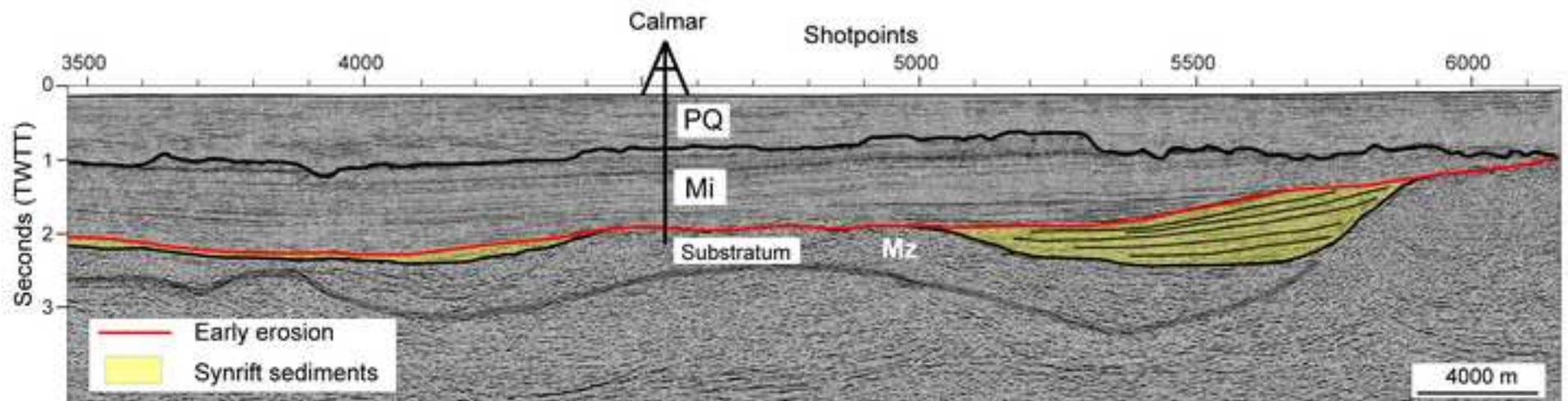


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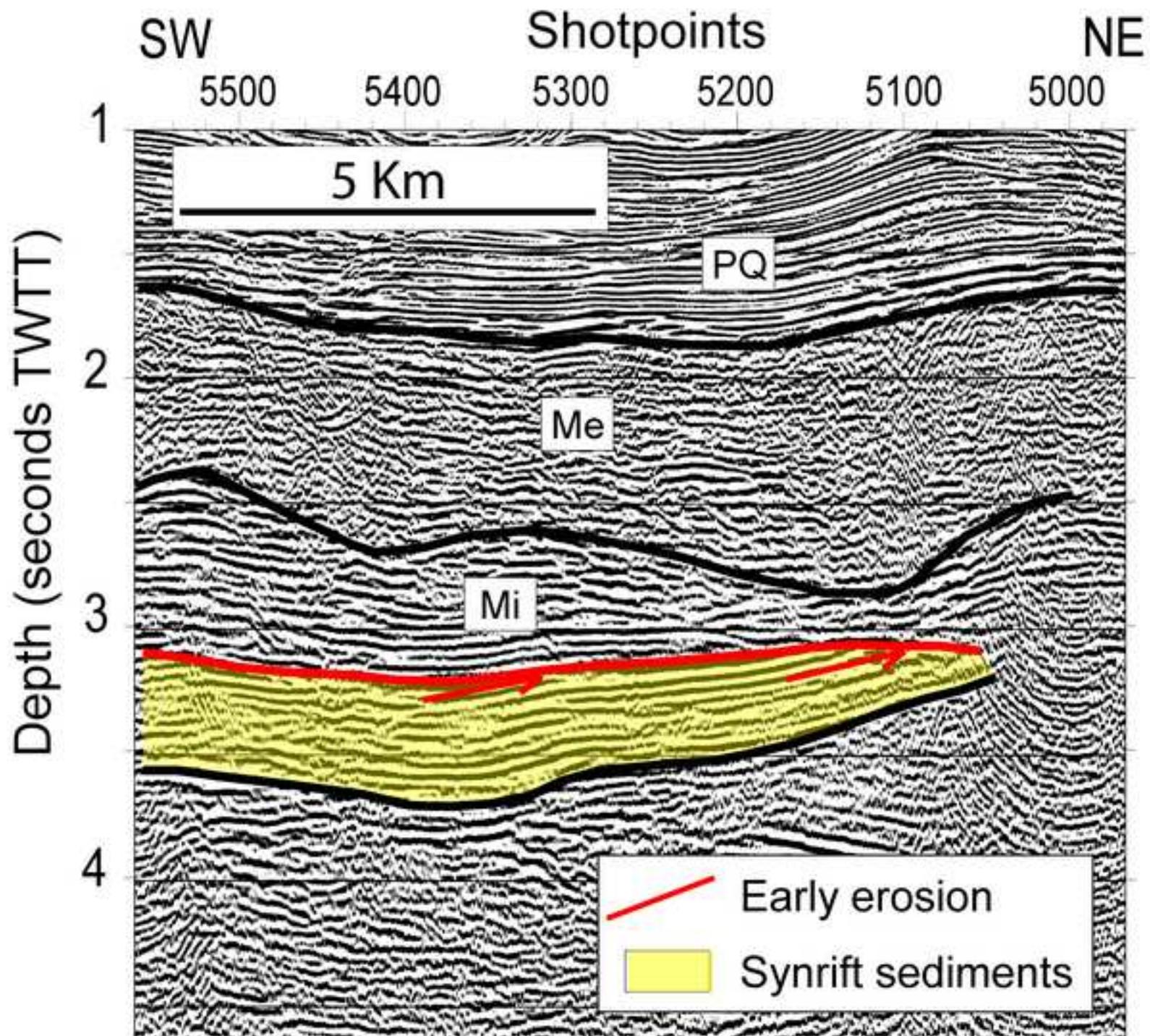


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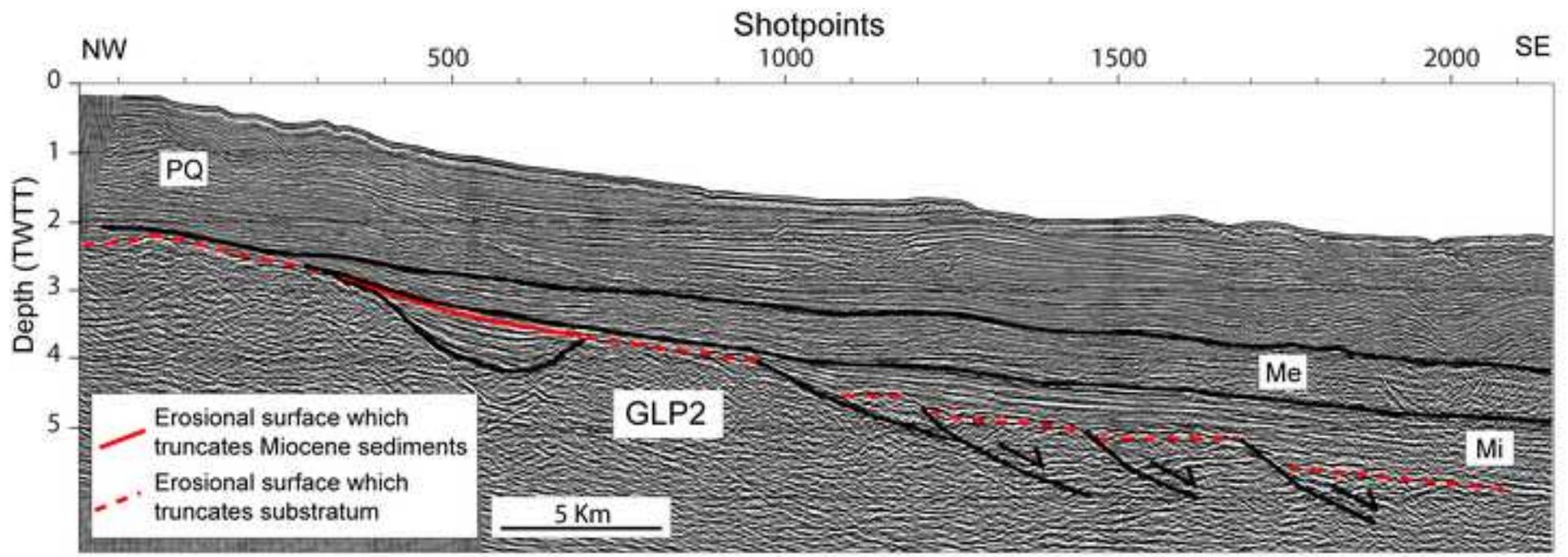


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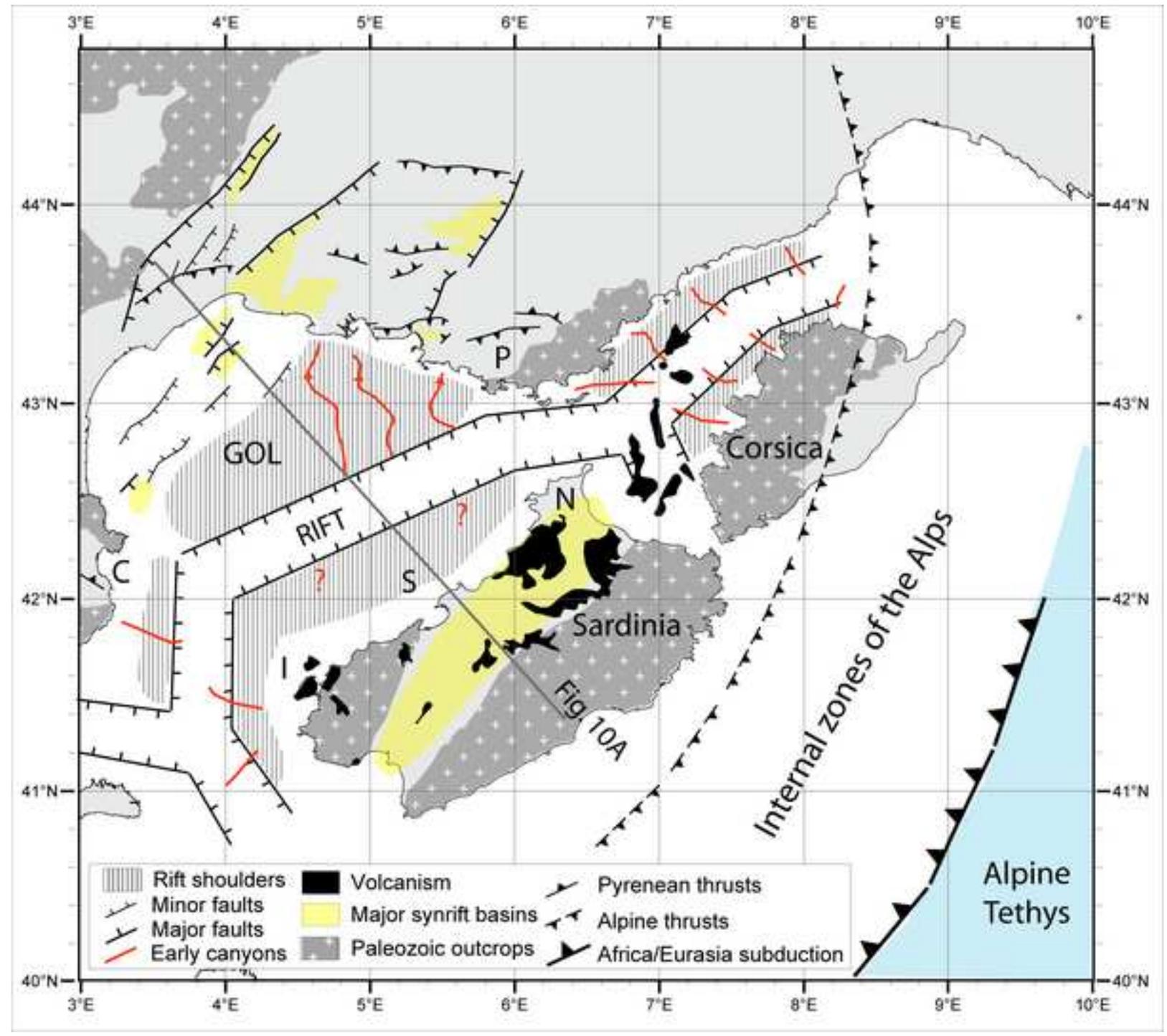


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