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Messinian erosional and salinity crises: View from the Provence Basin (Gulf of Lions, Western Mediterranean)

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Abstract:

Though the late Miocene “Messinian Salinity Crisis” has been intensely researched along the circum-Mediterranean basins, few studies have focused on the central part of the Mediterranean Basin and, especially, the pre-salt deposits. To improve our knowledge of the Messinian events, it is imperative to better understand this domain. In this study, we provide a more complete understanding of this central domain in the Provence Basin. We were able to recognize: a) thick marine detrital series (up to 1000 m) derived from the Messinian subaerial erosion which is partly prolonged in the distal part by b) a thick unit of deep marine deposits (up to 800 m) prior to the evaporites; c) a thick presumed alternation of detritals and evaporites (1500 m) below the mobile halite; and d) a two-step transgression at the end of the Messinian. Spatially, we document the eroded shelf to the deep basin (and from the western to the eastern parts of the Gulf of Lions), and temporally, we extend the interpretations from the early deposition of detritic sediments to the final sea-level rise. The results provide a new basis for discussion not only for the development of the Messinian Salinity Crisis but also for the reconstruction of the subsidence history of the Provence Basin.

Keywords: Messinian; Salinity Crisis; Gulf of Lions; Mediterranean; Provence Basin; Miocene; detrital deposits; erosion

30 **2 Introduction**

31 The reduced inflow of Atlantic Ocean water through the Betic and Rifian corridors (Fig. 1) at
32 the end of the Miocene, together with a high evaporation rate, led to a significant lowering of
33 the Mediterranean Sea's base level and gave rise to one of the most prominent episodes of the
34 Sea's history, known as the "Messinian Salinity Crisis". This Salinity Crisis continues to raise
35 questions and arouse interest. First, because of the wide geographical extent of the extreme
36 environment, the Messinian gave rise to one of the largest evaporite basins known (2.5
37 millions km²), comparable in size to the North Sea Permian basins (Ziegler, 1982). Its
38 comparatively younger (Neogene) age also makes it much more accessible to analysis and
39 modelling than older and deeper large known basins. Second, the volume of the Messinian
40 evaporite series is greater than 1 millions km³ in the Mediterranean Basin (Ryan, 1973). The
41 Messinian (evaporitic and erosional) events are also distinctive in that they occurred in a
42 relatively brief period of ~ 0.63 My (Hilgen et al., 2007) and during the history of an oceanic-
43 type basin which is at least 15 millions years old.

44 A supply of oceanic water to the basin is necessary to explain the thickness of the evaporite
45 layer. In view of the absence of connections with the Indian Ocean, the history of the eastern
46 Mediterranean Basins (e.g. Tyrrhenian, Ionian) is linked intimately to the western basin.
47 Within the western Mediterranean Sea, the Gulf of Lions is exceptional in that its sedimentary
48 strata have not been deformed. In addition, the Gulf of Lions is characterized by relatively
49 constant subsidence with continuous accommodation space for sediment accumulation. This
50 margin is also characterized by a gentle slope, which prevents major remobilization and
51 gravitational movements. This configuration, together with the availability of a vast data base,
52 enables us to describe full geometries of the stratal patterns of Miocene series (from the
53 intensely eroded geomorphologies on the shelf to the well preserved successions in the basin).
54 Previous studies have focused on "marginal" or "peripheral" basins (mainly present-day
55 onshore areas) rather than on the "central" basins (present-day offshore areas). The central

56 basins are relatively of wide extent and contain thick evaporitic sequences, while marginal
57 basins are much smaller with reduced evaporitic sequences (Fig. 1). These basins have also
58 been studied with two very different approaches due to their accessibility: outcrop studies,
59 and some mines and boreholes in marginal basins and remote geophysical techniques in the
60 central basins. So far the central Mediterranean Basin has been poorly known, due to its
61 relative inaccessibility and lack of integration of available data.

62 **3 Overview of previous works**

63 Pioneer works based on field studies described a huge incision in the Rhône River valley at
64 the end of Miocene (Fontannes, 1882; Depéret, 1890, 1893; Denizot, 1952). The isolation of
65 the Mediterranean at that time, a drop in sea level, the subsequent invasion of the sea in the
66 fluvial network in earliest Pliocene and the idea that a salinity crisis could have occurred were
67 proposed very early (Denizot, 1952; Ruggieri, 1967). The development of reflection profiling
68 techniques and increasing exploration established the existence of a mobile layer capable of
69 generating diapirs beneath the floor of most of the central basins of the Mediterranean Sea
70 (Alinat and Cousteau, 1962; Hersey, 1965; Menard et al., 1965; Glangeaud et al., 1966; Ryan
71 et al., 1966; Leenhardt, 1968; Mauffret, 1970; Montadert et al., 1970; Auzende et al., 1971;
72 Ryan et al., 1971). The origin of this layer was largely interpreted as related to salt deposition.
73 However, different interpretations were proposed for the age of salt deposition and its
74 disposition (Glangeaud et al., 1966; Cornet, 1968; Ryan, 1969; Mauffret, 1970; Montadert et
75 al., 1970). Using new and high quality seismic data acquired in the Mediterranean Basin in
76 1970, Auzende et al. (1971) proposed that the salt was late Miocene in age, following earlier
77 suggestions from Denizot (1952) and Ruggieri (1967). At the same time, the salt was cored
78 during Leg 13 of the Deep Sea Drilling Project in 1970 along with its cover of gypsum,
79 anhydrite, lacustrine mud and marls with clastics reworked from the margin. This layer was
80 dubbed the “Upper Evaporites” by the Leg scientists. All these deposits were indisputably

81 dated and interpreted for the first time as deep-basin products of the Messinian Salinity Crisis
82 (Ryan et al., 1970; Hsü, 1972b; Hsü et al., 1973b). Two models, both based on the deposition
83 of evaporites in shallow water depth were proposed and initiated a heated debate in the
84 scientific community: the “shallow water, shallow-basin desiccation model” (Nesteroff,
85 1973); and the “desiccated, deep basin model” (Hsü, 1972b; Cita, 1973; Cita and Ryan, 1973;
86 Hsü, 1973; Hsü et al., 1973a; Ryan, 1973).

87 The first model suggests the existence of a shallow basin (several hundred meters deep)
88 before the Salinity Crisis. This model envisioned vertical tectonic movement during the
89 Pliocene that would have deepened the basin after the crisis (Bourcart, 1962; Pautot, 1970;
90 Auzende et al., 1971; Buroillet and Byramjee, 1974; Stanley et al., 1974; Rouchy, 1980,
91 1982). But considering that different basins that make up the Mediterranean are of different
92 ages —some much older (such as the Ionian Sea), others much younger (such as the
93 Tyrrhenian Sea) — this Alpine tectonic model soon became obsolete. The second model
94 suggests the existence of a deep basin (over 1500 meters deep) before the Messinian crisis
95 (Argand, 1924; Cita, 1973; Hsü, 1973; Hsü et al., 1973b; Hsü and Bernoulli, 1978; Montadert
96 et al., 1978; Stampfli and Höcker, 1989) and a sea-level drop of around 1500 m. Three
97 arguments were used to strengthen this theory: the tidal nature of the evaporites recovered in
98 all the major basins (Hsü, 1972a, 1972b); the pan-Mediterranean distribution of seismic
99 reflector M, that was calibrated with the abrupt contact between the evaporites and the
100 overlying Early Pliocene marls (Ryan, 1973), and the open marine, deep bathyal nature of the
101 pelagic sediments immediately superposed on the evaporites (Cita, 1973).

102 The deep basin model could also be defended by kinematic and geodynamic considerations:
103 such a basin, opened by the rotation of a microcontinent during the Oligocene time (at around
104 30 My) in the general framework of African-European convergence (Smith, 1971; Dewey et
105 al., 1973) can at the time of the Messinian only have been deep. A final decisive argument in

106 favour of this spectacular hypothesis came from studies on the marginal erosion coeval with
107 the central basin evaporites all around the Mediterranean (Barr and Walker, 1973; Chumakov,
108 1973; Clauzon, 1973, 1974; Cita and Ryan, 1978; Clauzon, 1978; Rizzini et al., 1978; Ryan
109 and Cita, 1978; Clauzon, 1979; Barber, 1981; Clauzon, 1982). The convergence of
110 observations has made it possible to exclude regional tectonic factors and confirm that the
111 eustatic fall of more than 1500 m sculpted the Mediterranean river systems during the
112 Messinian Crisis. This result was obtained mainly from onshore observations but it has also
113 been supported by seismic reflection surveys over a width of some hundred kilometres on the
114 Gulf of Lions shelf (Burolet and Dufaure, 1972; Biju-Duval et al., 1974; Burolet and
115 Byramjee, 1974; Genesseeux and Lefebvre, 1980; Lefebvre, 1980). The “Desiccated, deep
116 basin model” (Hsü, 1972b; Cita, 1973; Hsü, 1973; Hsü et al., 1973a) was therefore widely
117 accepted at that time. Some years later, Gorini (1993) and Guennoc et al (2000) compiled a
118 map of the subaerial erosion surface over some 15,000 km² in the shelf of the Gulf of Lions.
119 This confirmed, over a distance of some 100 km, the existence of a major Languedocian
120 paleoriver. In the eastern part of the shelf they also mapped the channel of a paleo-Rhône
121 (Fig. 1). These observations although likely to provide us information on the paleoshorelines
122 of the Messinian basin, were, unfortunately only mapped down to the upper continental slope.

123

124 Messinian evaporites have been described as three different sub-units from the top to the base:
125 1) The “Upper Evaporites” sequence with high amplitude reflectors (M reflectors) at its top, it
126 has only been sampled in its upper part in the deep basin (Ryan et al., 1973); 2) The massive
127 salt layer which has never been cored, its limits have long been recognized thanks to seismic
128 interpretations (Mauffret et al., 1973; Ryan, 1976); 3) A lower unit with high amplitude, well
129 stratified reflections was first interpreted as a velocity artefact and then named “Lower
130 Evaporites” using a simple analogy with the two evaporitic units observed in Sicily which are

131 accessible for outcrop studies (Decima and Wezel, 1971). A thickness on the order of 500 m
132 has been proposed (Montadert et al., 1978).

133

134 Some major questions remain concerning the beginning of the crisis in the central
135 Mediterranean Basin. The geometric physical link between the evaporitic series identified in
136 marginal basins accessible for field studies and the evaporitic series of the central basins has
137 never been made. The many interpretations concerning the marginal and central Messinian
138 deposits are well summarized in a review article by Rouchy and Caruso (2006). Two major
139 groupings are evident: one that favours a synchronous deposition of the first evaporites in all
140 the basins before the major phase of erosion (Krijgsman et al., 1999); and the other that
141 favours a diachronous deposition of the evaporites through more than one phases of
142 desiccation which would first have affected the marginal basins and later the central basins
143 (Clauzon et al., 1996; Riding et al., 1998; Butler et al., 1999). In spite of conflicting
144 interpretations, most workers agree with a three-phase progression: 1) a period of partial
145 confinement leading to a limited regression (onset of evaporite deposition in the marginal
146 basins at 5.96 Ma (Gautier et al., 1994; Krijgsman et al., 1999; Sierro et al., 1999); 2) a period
147 of near desiccation (major regression); 3) followed by the Pliocene reflooding. Estimates
148 differ on the age and duration of phase 2: beginning at 5.6 Ma (Clauzon et al., 1996;
149 Krijgsman et al., 1999; Rouchy and Caruso, 2006), or slightly earlier (Butler et al., 1999). The
150 reflooding of the Mediterranean Basin is considered to have been sudden during the earliest
151 Pliocene (Hsü et al., 1973a; Clauzon and Cravatte, 1985; Pierre et al., 1998; Blanc, 2002; Lofi
152 et al., 2005) and a precise age has been proposed at 5.33 Ma (Hilgen and Langereis, 1993;
153 Van Couvering et al., 2000; Lourens et al., 2004).

154

155 Surprisingly, detritic deposits in the Gulf of Lions that must have originated during the huge
156 erosional event were not described until 2002. Savoye and Piper (1991) identified some
157 deposits in the Var region, but Lofi (2002) first identified detrital sediments in the Provence
158 Basin at the outlet of the Languedoc paleoriver. The small volume of the detrital products
159 (1500 km^3) compared to the high volume of estimated erosional sediments (3000 km^3) was
160 explained by the deposition of a part of detritus in the basin (intercalated with gypsum and
161 anhydrite in the “Lower Evaporites” below the salt) (Lofi et al., 2005). Recently, Lofi and
162 Berné (2008) described pre-Messinian submarine paleo-canyons just below the detritals. We
163 will refer to this proposition later in the Discussion Section. Sage et al. (2005) and Maillard et
164 al. (2006) have also described detritals on the Sardinian and Valencia margins.

165 **4 Data and method**

166 One of the major assets of this study has been the large amount of data collected in the area
167 for both industrial and academic purposes. A partnership with Total gave us access to an
168 exceptional set of conventional and high-resolution seismic reflection data from the coast to
169 the deep domain (Fig. 2). Seismic interpretations have been performed using the principles of
170 seismic stratigraphy (Vail et al., 1977). We identified seismic units based on stratal
171 terminations and configurations of seismic reflections. The large coverage of seismic data
172 enabled us to map the units in 3D throughout the Gulf of Lions from Cap Creus to Provence
173 and from the present day coast to the basin area ($\sim 2500 \text{ m}$ water depth).

174 Additional data were obtained from the e-logs of nine industrial boreholes that sampled the
175 sedimentary cover down to the substratum (Fig. 2). A detailed micropaleontological study
176 (Cravatte et al., 1974) provided information on the biostratigraphy and depositional
177 environments of the Miocene, Pliocene and Quaternary successions in four of the wells
178 (Mistral1, Sirocco1, Autan1 and Tramontane1). The data from these wells were synthesized in
179 a compilation of all the drilling reports (Guennoc et al., 2000).

180 The Ecors programme (De Voogd et al., 1991) provided three general seismic sections across
181 the entire margin, completed by a series of ESP (Expanding Spread Profiles) (Pascal et al.,
182 1993). ESP data and average velocities in wells were used to obtain propagation velocities
183 from which it was possible to estimate the thickness of the series from the seismic data (time-
184 depth conversion), thus giving access to volume estimates of the units involved.

185 **5 Results: from the eroded Gulf of Lions shelf and slope** 186 **domain to the evaporite domain**

187 Here, we will describe the depositional geometries of the Gulf of Lions from its eroded
188 margin to the evaporite domain. Although these two domains have been known for many
189 years, they were studied separately and the direct geometrical link between them was not
190 established for all of the sedimentary series. We categorize three characteristic domains from
191 the shoreline to the centre of the basin (Figs. 3 and 4):

- 192 • The eroded domain, characterized by a single discordant surface between the Miocene
193 deposits and the Plio-Pleistocene deposits (without any Messinian deposits).
- 194 • A complex intermediate domain, at the bottom of the continental slope, corresponding
195 to the area in which the Messinian erosion products were deposited (Lofi et al., 2005).
- 196 • The evaporite domain characterized by a continuity of the succession throughout the
197 Messinian period and by the presence of evaporites.

198 **5.1 The eroded domain**

199 A pervasive erosional surface (dark blue lines on Fig. 3) has long been identified in the Rhône
200 Valley (Denizot, 1952; Clauzon, 1973, 1982) and on the Gulf of Lions shelf where it is very
201 clearly discernable in the seismic reflection profiles (Ryan and Cita, 1978; Genesseeux and
202 Lefebvre, 1980; Lefebvre, 1980; Gorini, 1993; Guennoc et al., 2000; Lofi, 2002; Lofi et al.,
203 2005). This erosion surface, i.e. the discordant contact between the Miocene deposits and the

204 overlying prograding Plio-Pleistocene sequence beneath the shelf and slope, was named
205 “Margin Erosion Surface” (MES) by Lofi et al. (2005) and Lofi and Berné (2008).

206 **5.1.1 The Miocene eroded series**

207 The cross sections in Figure 3 (c, d, e) show that a large part of the Gulf of Lions is buried
208 beneath a pre-Messinian sedimentary cover. Reflections are planar and parallel and show
209 good continuity with few thickness variations. Landward, in the direction of Provence and the
210 Pyrenees, the reflections terminate as onlaps on rises of pre-rift substratum (Fig. 3d);
211 basinward, they prograde or lap out approximately up to the present-day slope (Fig. 3c). The
212 pre-Messinian succession is eroded and slightly deformed, except close to the Pyrenees in the
213 West where faults and roll-over tilting are observed (Mauffret et al., 2001; Lofi et al., 2005).
214 Boreholes show that the erosion surface of the shelf truncates sediments of the Miocene age
215 and is covered by sediments of the earliest stage of the Pliocene (Cravatte et al., 1974). Up to
216 7 My of the Upper Miocene sediment record are missing in Autan borehole at the shelf edge
217 where youngest deposits are dated at ~12 My (post last occurrence of *Globorotalia*
218 *peripheroronda*), having been removed by erosion during the Messinian Salinity Crisis.
219 However, the youngest Miocene sediments were found in the Tramontane well and were
220 dated as Tortonian (Cravatte et al., 1974). In the Cicindelle borehole we found that the entire
221 Miocene was removed so that the Pliocene lies directly on the substratum (Fig. 3d). The Gulf
222 of Lions can be sub-divided into two main areas (Fig. 3d): a Languedoc area in the southwest
223 where substratum was highly subsident so that an accommodation of 2000 to 3000 m was
224 available for the Miocene sediments, and a Provence area where the substratum is in a much
225 higher position and lack of accommodation prevented deposition and/or preservation of thick
226 Miocene strata. It is also deeply incised.

227 **5.1.2 Morphology of the Margin Erosion Surface**

228 A large part of the MES had already been mapped and interpreted in the past. The mapping
229 revealed a pattern of up to 5th order dendritic drainage (Genesseaux and Lefebvre, 1980;
230 Gorini et al., 1993; Guennoc et al., 2000; Gorini et al., 2005; Lofi et al., 2005) with two main
231 systems (Fig. 4). One to the East, corresponding to the Rhône (which was located East of
232 present day Rhône River) together with a network from the region of Montpellier, both join
233 up downstream into a single valley. The other to the West, with headwards extending from the
234 Languedoc and Roussillon region. The Rhône largely incised the Mesozoic limestone
235 substratum, whereas the Languedoc cuts mainly into the Miocene marls. In both cases, several
236 hundred metres depth can be observed between the thalweg and the interfluves. This height
237 however does not represent the total amount of erosion by the rivers, as interfluves themselves
238 are eroded, so the total amount of erosion could be much greater (see next section).

239 The drainage networks (MES) have sculpted a “rough” or “badland” morphology (Ryan,
240 1978). In this study we also observed that this morphology gives way basinward to a planar
241 and “smooth” surface that is locally conformable with the underlying Miocene series but that
242 is also locally erosional as it truncates the underlying succession of the intermediate domain
243 (unit Dm on Fig. 3). This smooth surface slightly deepens seaward and extends over 60-70
244 km. The transition between the two morphologies (rough and smooth) is very clear and lies at
245 a constant two-way traveltime depth of 1.6 seconds over most of the shelf (Fig. 6), albeit
246 slightly less at the edges of the basin (1.4 seconds two-way traveltime in Provence and
247 Catalonia). An interpretation of this change in morphology will be proposed later in the
248 Discussion Section.

249 **5.1.3 Volume eroded by the Margin Erosion Surface**

250 It is possible to obtain a minimum volumetric estimate of the Miocene sediments that have
251 been removed by erosion in the western part of the Gulf of Lions. Figure 7 shows the
252 measurement method and the estimated values. The Miocene deposits, wherever they are

253 observed, are extremely regular over a large part of the continental shelf and the first signs of
254 a progradation only occur at approximately 90 km from the coast (Fig. 3c). Consequently, up
255 to this point, one can simply extrapolate the intervals removed by erosion. This technique was
256 used earlier by Mauffret et al. (2001) and Lofi et al. (2005) but only in the Languedoc and
257 Roussillon areas which led to a minimum estimate of about 3000 km³ of eroded sediments.
258 An average velocity of 2000 m/s (Lofi et al., 2005) was used for the evaluation of thicknesses
259 within the Miocene and Messinian series. Here, we extended this technique to the East, to the
260 Rhône area as far as the regional reference marker exists. Figure 7a gives a perspective view
261 of three selected profile segments from the seismic coverage. LRM 08 on Figure 7 intersects
262 the Miocene succession where it is best preserved. We extended the youngest observed
263 horizon (Late Miocene) parallel to a regional marker horizon preserved within the series over
264 the entire area. The minimum eroded thickness through extrapolation is shown in yellow on
265 Figure 7. This new evaluation provides an estimated volume of 4000 km³ of eroded sediments
266 (Fig. 7b). Note that this amount of sediments does not take into account the entire eroded area.
267 If we consider the whole Rhône Valley and shelf of the Gulf of Lions where the erosion
268 surface has been observed (> 20 000 Km²), we can assume the eroded volume to be much
269 higher (~10 000 Km³). Note also that this volume does not take into account the direct input
270 from the Rhône River. This volume of eroded sediment must have been transported
271 downstream and deposited into the deep basin.

272 5.2 The intermediate domain (between the eroded shelf and the 273 evaporite domain)

274 The intermediate domain is characterized by a seismic unit (unit Dm) sandwiched between
275 the prograding Miocene deposits below and the Pliocene deposits above and bounded both at
276 its base and top by discontinuities (Figs. 3a, b, c and e). One thus passes from an eroded
277 domain, characterized by a single “rough” (MES) then “smooth” erosion surface occurring

278 between Miocene and Pliocene sediments, to a more complex, intermediate domain where the
279 Miocene and Pliocene sediments are separated by the unit Dm.

280 **5.2.1 Description of unit D-geometries**

281 The edge of the Miocene shelf is truncated by a surface inclined ($\sim 2.5^\circ$) towards the basin
282 (surface in red in Figures 3a, b, c, e). This surface characterizes the base of unit Dm that
283 shows a major incision (up to 1500 m) at the outlets of the Rhône and of the Pyrenees-
284 Languedoc drainage networks (Fig. 5). The incision is less marked between these two areas.
285 Three subunits can be recognized in unit D whose extension has been mapped (Figs. 3 and 4).

- 286 • Subunit Dm0 is the lower member of unit Dm and can be seen at the outlet of the
287 Rhône. It is characterized by clinoforms that dip steeply basinward and extend deep
288 beneath the salt. The clinoforms are up to 1 km in height, they are truncated upstream
289 by the smoother surface described earlier (Fig. 3a, b).
- 290 • Subunit Dm1, lying unconformably on subunit Dm0, is present over the entire margin
291 at the outlet of the Roussillon-Languedoc valleys and the Rhône valleys one. Like
292 subunit Dm0, it is characterized by basinward dipping clinoforms (also up to 1 km in
293 height) and also truncated upstream. Basinward, down-dip from the strata, we observe
294 two distinct seismic facies (Fig. 3e): a chaotic facies located mainly on the outlet of
295 the erosional valleys (on the western side); and a facies characterized by more or less
296 continuous reflections (on the eastern side). This facies difference is probably due to
297 whether or not the area had a direct connection with the drainage systems. On Figure 4
298 we can see rises of the substratum that most likely isolated the eastern side from a
299 direct input of the Rhône and Languedoc sediments, so that sediments are more
300 homogenous and probably more shalier. In both cases, the upper part of subunit Dm1
301 extends beneath the salt and becomes imbricated in a continuous high-amplitude
302 reflector (LU1) present in the evaporite domain.

303 • The upper subunit, Dm2, is characterized by a chaotic high-amplitude seismic facies
304 (called “CU” in Lofi et al., 2005) located at the immediate outlet of the Languedoc
305 drainage network. A direct connection with the Rhône system and a deposition of
306 coarse deposits can be assumed. This subunit is also truncated in its upstream part.
307 The base of subunit Dm2 ties in basinward with the base of the mobile salt unit (MU).

308 **5.2.2 Description of unit D in the boreholes**

309 Two boreholes cross the unit Dm (Fig. 4). Autan1 is localized on the edge of shelf and GLP2
310 on the slope, at the limit of the salt deposit.

311 • Autan1 (Cravatte et al., 1974) indicates, for the interval corresponding to the unit Dm
312 (2424-2997 m), sandy carbonated clay with rare foraminiferas which are often broken
313 and of small size. The lack of significant planktonic foraminiferas prevents precise
314 dating for this interval, however an Upper to Middle Miocene age with marine
315 environment is suggested (Cravatte et al., 1974). A gap of Messinian and Tortonian is
316 also assumed. Cravatte et al. (1974) added that the cuttings of drilling are often not
317 representative because of the significant contamination and the conditions of drilling.
318 The only representative samples are the slabs (one side core drillings) but they were
319 few in number.

320 • GLP2 presents many reworkings at all levels of the borehole which made
321 interpretation very tricky (Brun et al., 1984). Under salt and anhydrite deposits related
322 to Messinian, carbonated clays (sometimes with silt) are described. This interval,
323 corresponding to unit Dm (3703-4856 m), provides limited information. An uncertain
324 Burdigalian to Tortonian age is suggested.

325 Autan1 and GLP2 boreholes therefore provide poor fossil associations for the interval
326 corresponding to the unit Dm. On top of that, reworkings described in GLP2 and Autan1
327 (broken forams) lead us to remain cautious on ages (undifferentiated Burdigalian to

328 Tortonian, see 5.2.2). Samples in regressive seals, which are made of reworked and mixed
329 material are known to be poor intervals for age credibility (B. Haq, personal communication).
330 Both ages given by these two boreholes are doubtful, and have not been used by us. A
331 Messinian age for the deposits (reworking previous sediments) can not be rejected.

332 **5.2.3 Volume of Unit Dm**

333 Figure 8 shows the isopach map of Unit Dm. The maximum observed thickness is more than
334 1000 m, with the depocentre located downstream of the outlet of the Roussillon-Languedoc
335 rivers and the Rhône River. The corresponding volume can be estimated at $\sim 4700 \text{ km}^3$ if we
336 consider the average velocity of 2000 m/s used by Lofi et al. (2005). In fact, a velocity of
337 3000-4000 m/s is probably more appropriate (Fahlquist and Hersey, 1969; Leenhardt, 1970),
338 so that the volume of unit Dm could even reach values of 9400 km^3 . This does not include the
339 most distal deposits located in the very deep basin area nor the lateral equivalent of the shelf-
340 edge prisms Dm0, Dm1, Dm2 towards the East.

341 **5.3 The evaporite domain**

342 Directly below the Pliocene and Quaternary sediments (Fig. 3c, f), the upstream extension of
343 the “Upper Evaporites” is marked by onlaps onto the top of unit Dm. These “Upper
344 Evaporites” made-up of intercalated beds of anhydrite and clay (Ryan et al., 1973) and also
345 named “Upper Unit” (Lofi and Berné, 2008), have been deformed by creeping and sliding of
346 the underlying salt and by listric faults.

347 The massive salt underlying the “Upper Evaporites” is the most representative facies of the
348 Messinian in the basin. It is characterized by a transparent seismic facies forming salt domes,
349 formed as the salt flows since the early Pliocene and during the deposition of the Pliocene and
350 Quaternary turbidites (Dos Reis et al., 2005). Its original upstream extension (before
351 movement) can be considered as the limit between the listric faults (which sole out at the base

352 of the salt) and subunit Dm2 (see on Figure 3). This unit is named the “Mobile Unit” (MU) by
353 Lofi et al. (2005).

354 Below the mobile salt (MU) we found a unit characterized by continuous parallel high-
355 amplitude reflections (LU1). The upper part of this unit was described and interpreted as
356 “Lower Evaporites” by analogy to the seismic facies of the “Upper Evaporites” and by
357 analogy to the evaporite trilogy in Sicily (Montadert et al., 1978). The reflections clearly
358 onlap the lower part of unit Dm (Dm0 and Dm1, Fig. 3c). The facies is thick in the basin (it
359 reaches 0.6 seconds two-way travelttime) and thins over unit Dm in the intermediate domain.
360 The upper part of LU1 is imbricated with the upper part of subunit Dm1 (lateral facies
361 transition).

362 Beneath the LU1 unit, we found a facies with average-amplitude reflections that are more or
363 less continuous. This facies (LU0) is the lateral distal equivalent of the lower part of Unit Dm
364 (subunits Dm0 and Dm1). The base of this distal unit is marked by a high-amplitude reflector
365 that becomes erosive toward the intermediate domain and which corresponds to the base of
366 unit Dm. The lowermost sediments (below LU0) rest directly on the basement and represent
367 the deep deposits of the Miocene post-rift margin.

368

369 To summarize, we have described and correlated three major seismic domains. The first is
370 characterized by intense erosion (MES), the second by deposition at the outlet of the river
371 valleys (unit Dm), and the third by an evaporitic deposition. It should be noted that the base of
372 unit Dm, characterized by major erosion in the intermediate domain, extends conformably and
373 widely into the basin below LU0 unit (Fig. 3c).

374 **6 Discussion**

375 The results that we discuss here include the recognition of thick marine detritic deposits that
376 provides the evidence of a huge detritic phase prior to the evaporite deposition in the central

377 basins; the presence of presumed evaporites, with a thickness of up to 1500 m, located below
378 the thick halite; and finally the evidence of a two-step transgression at the end of the
379 Messinian.

380 6.1 The detrital succession derived from Messinian subaerial erosion

381 The analysis of depositional geometries provides evidences of a huge phase of subaerial
382 erosion in the Rhône Valley and on the continental shelf of the Gulf of Lions (MES). A major
383 drawdown was thus necessary to deeply incise these domains and particularly the Miocene
384 shelf. We assume that only the major Messinian drawdown was able to produce this huge
385 phase of erosion. This major drawdown (~ 1500 m) has been strongly argued in the past
386 (Ryan and Cita, 1978; Gennesseaux and Lefebvre, 1980; Lefebvre, 1980; Clauzon, 1982;
387 Gorini, 1993; Guennoc et al., 2000; Lofi, 2002; Gorini et al., 2005; Lofi et al., 2005). This
388 estimate mainly results from observations done during dives realized by Savoye and Piper
389 (Savoye and Piper, 1991) and is now largely accepted as shown by the recent published
390 “Consensus” about the MSC scenario (CIESM, 2008). However, no evidence had been
391 produced of corresponding detrital deposits before 2002. Several studies have since proved
392 (Lofi et al., 2005; Sage et al., 2005; Maillard et al., 2006) its existence between the evaporite
393 domain and the foot of the continental slope. Nevertheless, the limit of its lower boundary
394 (due to lack of seismic penetration) or its lateral correlation to the deep basin succession (due
395 to the lack of lateral seismic data) have remained undetermined.

396 Unit Dm that we described is sandwiched between the Miocene shelf deposits and the
397 Pliocene and Quaternary cover (Fig. 3). A major unconformity characterizes the base of unit
398 Dm and other minor surfaces can also be observed within this unit (Fig. 3e). Two conflicting
399 interpretations (depending on the position of the “Basal Erosion Surface” (Maillard et al.,
400 2006), i.e., the discordant contact between the pre-salinity crisis deposits and the syn-crisis
401 deposits) can be proposed and will be discussed here about the age of unit Dm.

- 402 • Lofi and Berné (2008) interpreted these discontinuities as paleo-submarine canyons
403 that pre-date the initiation of the Messinian drawdown phase. Only the upper part of
404 unit Dm (characterized by a chaotic high-amplitude seismic facies) is attributed to
405 Messinian detrital deposits. Nevertheless, the volume of these chaotic deposits,
406 estimated at around 1500 km³ (with an average velocity of 2000 m/s) or 3000 km³
407 (with 4000 m/s) by the same authors (Lofi et al., 2005) is far less than the estimated
408 volume of eroded material in the entire Rhône Valley and Gulf of Lions shelf (~10
409 000 km³).
- 410 • On the contrary, we suggest that all of unit Dm is Messinian and that the major
411 unconformity observed at its base should be linked to the beginning of the main
412 Messinian drawdown of the Mediterranean Sea (Bache, 2008). The full unit Dm,
413 which has a volume of the same order of magnitude as the estimated volume of eroded
414 material, is a probable candidate for the detrital deposits from the Messinian erosion.
415 Several other considerations support our interpretation:

416 ***6.1.1 Pre-Messinian vs Messinian fluctuations of sea level***

417 The main Messinian drawdown is the most prominent such event to occur in the
418 Mediterranean and probably in the world. The consequences of this drawdown had dramatic
419 effect leading to abnormal amounts of erosion in the Rhône Valley and sediment transfer into
420 the basin. Numerous sea-level fluctuations occurred before the period of the Messinian
421 drawdown (Haq et al., 1987) but none of them are comparable (100-200 m at the maximum).

422 The lower part of Unit Dm (Dm0 and the base of Dm1, the greatest in volume) correlates with
423 LU0 (Fig. 3c). The Dm0-LU0 depositional sequences are genetically related sediments
424 bounded by unconformity (base Dm0) and their correlative conformity (base of LU0). This
425 phase therefore corresponds to a major sediment transfer, which built detrital wedges of
426 thickness as much as 1000 m at the outlet of the Messinian rivers, and in the order of 800 m in

427 the basin. A Messinian origin for only the upper part of unit Dm (characterized by a chaotic
428 high-amplitude seismic facies) would mean that the erosive base of unit Dm (which is a
429 regional major erosional surface that truncates the Miocene shelf) is not connected to the all
430 important Messinian event but to a previous event. In this scenario the Messinian event would
431 thus have produced less prominent unconformities (within the unit Dm) whereas the major
432 regional erosional surface would have been produced by a previous event of lesser severity.
433 To us this scenario seems unlikely. Instead, the most likely interpretation in the context of the
434 regional distribution of unit Dm and its erosive base is that it is a product of the major
435 Messinian drawdown. The surface resulting from this major drawdown would have
436 overshadowed all previous events. In the case in the Provence Basin this is certainly true
437 where the MES sometimes erodes up to the substratum.

438 **6.1.2 Position of the unit Dm**

439 The mapping of unit Dm and its basal erosional surface identified three subunits at the outlet
440 of Rhône and Roussillon-Languedoc Messinian paleo-rivers (Fig. 4). The MES represents this
441 preserved subaerial landscape just before the Zanclean refilling of the basin, i.e., the terminal
442 Messinian exposed landscape. The first unit (Dm0) is principally located at the outlet of the
443 Rhône network. The others (Dm1, Dm2) are also located at the outlet of Roussillon-
444 Languedoc network. These locations can be explained by a drawdown so extensive that he
445 first impacted the Rhône Valley (Dm0) and then the Gulf of Lions shelf (Dm1-Dm2) with the
446 Roussillon-Languedoc rivers that became a major source of sediment supply (Figs. 9 and 10).

447
448 Thus, seismic sequence geometries are consistent with a Messinian age for unit Dm and
449 therefore we favor to attribute the major unconformity at its base to the onset of the major
450 Messinian drawdown. Nevertheless, we do not rule out the occurrence of smaller erosional
451 events (prior to the main Messinian drawdown) which may not have been preserved on the

452 Messinian shelf edge; i.e., in the transitional domain. This interpretation have strong
453 implications on the Messinian Salinity Crisis scenario.

454 6.2 The Messinian scenario as viewed from the "central" basin

455 We must emphasize that the two-step scenario of the MSC proposed by Clauzon et al. (1996)
456 is now widely recognized as the valid one by the respective authors of the Mediterranean-
457 scale MSC scenarios mostly discussed during the last years, as illustrated by the “Consensus
458 report” recently published (CIESM, 2008). We illustrate our interpretation of the Messinian
459 evolution of the Provence Basin in Figures 9 and 10. Following an initial and limited
460 Messinian regression (Clauzon et al., 1996) (Figs 9a and 10a), we recognize four major
461 phases as described below.

462

463 The first phase is marked by a major detrital event, underlying the lowermost evaporite
464 (LU1), and related to the major Messinian drop in the Mediterranean sea level (yellow areas
465 in Figures 9b and 10b). This pre-evaporite step implies that thick evaporites in the central
466 basin (visible at the seismic resolution) deposited after the subaerial exposition of the Gulf of
467 Lions, certainly under low bathymetry. Loget et al. (2005) have shown that consecutive
468 intense regressive erosion developed inevitably in the Gibraltar area. It should be a likely
469 process to explain a continuous input of marine waters necessary to precipitate enough
470 evaporites in the desiccated Mediterranean Basin. The assumption that central basin
471 evaporites partly deposited under a high bathymetry and before the major phase of erosion
472 (Krijgsman et al., 1999; Meijer and Krijgsman, 2005; Krijgsman and Meijer, 2008; Govers,
473 2009; Govers et al., 2009) should imply the observation of a major detritic event above
474 evaporites in the basin. Such a depositional geometry has not been observed.

475

476 The second phase (Figs. 9c and 10c) corresponds to a strong change in the sedimentary
477 regime as shown by the onlaps of the sediments during this phase (LU1) onto the underlying
478 detritic layer. Sedimentation evolves from the first detrital event (phase 1) to a massive salt
479 deposition (at the top of LU1 unit) resulting from an increase of salt concentration and
480 continuous input of marine waters within the almost desiccated basin. The corresponding
481 seismic facies is comparable to that of the Upper Evaporites facies comprising of halites,
482 gypsum, anhydrite, lacustrine mud and marls with clastics reworked from the margin.
483 Therefore, we attributed LU1 to the onset of evaporite/detrital deposition in the central
484 Provence Basin. These “Lower Evaporites” present a thickness of ~1500 m, much higher than
485 what was assumed previously (500 to 600 m) (Montadert et al., 1978; Lofi et al., 2005). Such
486 a thickness of Lower Evaporites must be tested in future quantitative studies of the Messinian
487 Salinity Crisis.

488

489 The third and the fourth phases correspond to a two-step transgression at the end of the crisis.
490 An initial relatively slow sea level rise (Figs 9d and 10d) permitted the development of a
491 transgressive surface with smooth topography (light blue line) identified previously on
492 seismic profiles. These flatten the top of regressive prisms (Dm0, Dm1, Dm2) and represent
493 the limit between Messinian and Pliocene deposits (Fig. 6). During this relatively slow
494 landward migration of the Messinian shoreline, the continuous action of waves and tides
495 smoothed the reliefs of the Messinian erosional surface. This interpretation is supported by
496 the presence of 50 m of azoic sand at the top of the evaporites in the GLP2. This unit,
497 described by Gorini (1993), could correspond to the transgressive sand from the upstream
498 marine abrasion by wave ravinement. The fourth phase corresponds to the Zanclean rapid
499 reflooding (Hsü et al., 1973a; Clauzon and Cravatte, 1985; Pierre et al., 1998; Blanc, 2002;
500 Lofi et al., 2005) and has been precisely dated at 5.332 Ma (Hilgen and Langereis, 1993; Van

501 Couvering et al., 2000; Lourens et al., 2004). It is clearly marked by the transition between
502 two morphologies (rough and smooth), at a constant two-way traveltime/depth of 1.6 seconds
503 over the entire shelf (Fig. 6). Up to this two-way traveltime depth, the irregular 'rough' or
504 badland topography (of MES) illustrates the Messinian paleogeography as it was at the end of
505 the Messinian erosional period (Figs. 9d and 10d, in dark blue). This rapid reflooding implies
506 a cessation of the action of waves, which has preserved badland morphologies (Fig. 10e). The
507 change in morphology corresponds therefore to the transition between a subaerial erosion
508 (rough morphology) and a submarine erosion (smooth morphology). In this scenario, the 1.6
509 second limit corresponds to the position of the paleoshoreline at 5.332 Ma and is an
510 appropriate marker for subsidence studies.

511 **7 Conclusion**

512 Our results support the deep-desiccated evaporite basin hypothesis (Hsü et al., 1973a): thick
513 detrital deposits at the outlet of the Messinian Rhône and Messinian Languedocian and
514 Pyrenean rivers are, as would be expected (Ryan and Cita, 1978; Clauzon, 1982), present at
515 the transition between the Miocene shelf and basin. On the basis of depositional geometries,
516 studied for the first time over the entire margin and down to the central basin of the Western
517 Mediterranean, we are able to underscore the following points:

- 518 • the evidence of a pre-evaporite phase corresponding to a prominent erosional crisis
519 responding to a major drawdown of the Mediterranean seawater. Assuming that this
520 major drawdown corresponds to the major Messinian drawdown, we can conclude that
521 the Mediterranean bathymetry significantly decreased before the precipitation of
522 central basins evaporites. A deep water formation seem unlikely.
- 523 • the presence of a thick probable “Lower Evaporites” series (with a thickness up to
524 1500 m) located below the salt sequence. This implies that the total thickness of
525 Messinian deposits in the basin should be as much as 3500 m (including the pre-evaporite

526 phase and the salt). This thickness also implies that the relief from shelf to basin floor
527 was already significant at the time of their deposition. The basin was gradually filled
528 during the Messinian Salinity Crisis. This infilling would have had a significant effect
529 on the vertical movements of the basin.

530 • the characteristics of the final discontinuity surface and of two types of morphology
531 (rough and smooth) provides evidence of the basin being resubmerged at the end of
532 the Messinian Crisis. This refilling was first moderate accompanied by transgressive
533 ravinement and later rapid so as to “preserve” the paleoshoreline at 5.332 My and the
534 Margin Erosion Surface. These markers of a two-step reflooding observed in the Gulf
535 of Lions provide remarkable points of reference for subsidence studies. It will be
536 necessary to correlate them at the scale of the whole Western Mediterranean, as well
537 as within the Eastern basin.

538 Several authors have tried to study the subsidence in the Provence Basin and the isostatic
539 readjustments related to the Messinian Crisis (Ryan, 1976; Steckler and Watts, 1980; Burrus
540 and Audebert, 1990; Meijer and Krijgsman, 2005; Krijgsman and Meijer, 2008; Govers,
541 2009; Govers et al., 2009). The view that we outline provides new fodder for the study of
542 subsidence of the Provence Basin and better understanding its structural evolution. An other
543 interesting perspective of this work could be the study of the lithospheric response to strong
544 and rapid variations of weight during the Messinian Erosional and Salinity crises.

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555

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842

843

844 **10 Figure Captions**

845

846 Figure 1: Location of the Messinian evaporite series (halite and other evaporites) in the
847 Western Mediterranean (modified for the Gulf of Lions from Montadert et al., 1978 and
848 Rouchy and Caruso, 2006) and the area drained by the Messinian rivers in Southeastern
849 France (hatched). The Late Miocene Betic and Rifian corridors (dotted line) are taken from
850 Martin et al, 2001. The study area is outlined in black.

851

852 Figure 2: Seismic data and boreholes used for this study. The bold lines represent the location
853 of the line drawings in Figure 3.

854

855 Figure 3: Line drawings perpendicular and parallel to the margin of the Gulf of Lions
856 (locations shown in Figure 2). The Messinian crisis is recorded distinctly in three domains
857 illustrated on profiles a, b and c basinward from the coast: an eroded domain, an intermediate
858 domain and an evaporite accumulation domain. These domains are crossed by profiles d, e
859 and f respectively. The eroded domain corresponds to the Miocene shelf with a 'rough'
860 subaerial erosion surface (in blue). The intermediate domain is characterized by the presence
861 of a sedimentary unit (unit Dm) that shows up well on Profile b. The unit is bounded at its
862 base by an erosion surface (in red) that truncates the Miocene slope, and at its top by a
863 'smooth' erosion surface (in pale blue) that truncates unit Dm (characteristic of the
864 intermediate domain) and the Miocene shelf at the end of the Messinian time. The deep basin
865 is characterized by the presence of salt (MU, transparent seismic facies) with underlying
866 reflectors (LU1). The reflectors are continuous, high amplitude, and clearly onlap Unit Dm.

867

868 Figure 4: Map showing the sedimentary units and the erosion located just below the Pliocene.
869 The drainage network (Margin Erosion Surface) dominates on the shelf. The 'rough-smooth'

870 erosion boundary is in pale blue. Below the smooth erosional surface, one can see the
871 extension of unit Dm. The evaporite domain transgresses this intermediate domain.

872

873 Figure 5: Detail of the transition from the eroded domain (a, b) to the intermediate domain (c,
874 d, e, f, g, h, i) on the Languedoc side. In the eroded domain, the 'rough' subaerial erosion
875 surface separates the Miocene shelf from the Pliocene units. In the intermediate domain, Unit
876 Dm occurs inserted between the Miocene series and the Pliocene series. We thus find erosion
877 in the first domain and a more complex history in the intermediate domain, which shows an
878 initial episode characterized by a major discontinuity (at the base of Unit Dm), although it is
879 difficult to determine down to which point subaerial erosion was active.

880

881 Figure 6: Detail of the transition from the 'rough' erosion surface (Margin Erosion Surface) to
882 the 'smooth' erosional surface. The 'rough-smooth' boundary is located at a constant two-way
883 travelttime depth of 1.6 seconds over the entire margin (a, b, c, d). Near the Pyrenees, the
884 'rough-smooth' boundary is located around a two-way travelttime depth of 1.4 seconds (e, f).

885

886 Figure 7: Estimated thickness of Miocene sediments eroded during the Messinian Event.

887 A: The continuity and parallelism of the Miocene series (aggradation) under the Messinian
888 erosion surface make it possible to estimate the eroded thickness. The estimation was made by
889 projecting a reference Miocene reflector onto the last seismically observable Miocene layer.

890 B: Isopach map of the eroded thickness. This thickness could only be estimated in the area
891 where the reference Miocene reflector was still visible. The thickness of sediments eroded in
892 the areas where the substratum is directly affected (Rhône side) is not taken into account. The
893 significant, but minimum, estimated volume (more than 4000 km³ and probably around 10

894 000 km³) is to be compared with the volume of unit Dm located downstream in the
895 intermediate domain.

896

897 Figure 8: Estimate of the volume of unit Dm deposited in the intermediate domain. One
898 should note that this volume (9400 km³) is of the same order of magnitude as the eroded
899 volume (around 10000 km³). Unit Dm is thus the only unit that corresponds to the volume
900 eroded upstream.

901

902 Figure 9: Paleogeographic synthesis of the observations made over the entire Gulf of Lions
903 margin arranged in chronological order.

904 A: Reconstruction of the Miocene margin before the major Messinian drawdown. The
905 Miocene sea drowned part of the Rhône Valley. The Miocene coastline in the Rhône Valley is
906 taken from Besson et al. (2005). The shelf ended as onlaps on the basin edges, where the
907 substratum was in a higher position. Minor erosions related to previous minor drawdowns can
908 be assumed.

909 B: The drop in the Mediterranean sea level gave rise to subaerial erosion on the shelf (Margin
910 Erosion Surface). Downstream, a submarine erosion surface (base of unit Dm) across which
911 the first detrital deposits (turbidites?) transited.

912 C1: The sea-level drop continues to its lowest level. The Messinian rivers carry large amounts
913 of sediment from the Miocene shelf toward the intermediate domain. This sedimentary
914 transfer brought about basinal subsidence and a readjustment of the shelf lightened by
915 erosion. Within the basin, a supply of seawater concentrated with salt, plus evaporation, led to
916 the precipitation of evaporites which would onlap unit Dm and fill the available space created
917 by the subsidence. Where the substratum is steep, as in Provence or on the Catalonian margin,
918 the detrital series are thin and the basin evaporite series directly onlap the substratum.

919 Isostatic readjustment could have been the cause of the fracturing seen within the Miocene
920 shelf series.

921 C2: The sea level is still at its lowest level. Salt precipitates at the height of the Crisis.

922 D: The morphology of the 'smooth' erosion surface present in the intermediate domain
923 suggests transgression of the coastline. This transgression would bring about abrasion of the
924 underlying series up to the 'rough-smooth' boundary. The 'smooth' surface is thus interpreted
925 as a marine ravinement surface. The Upper Evaporites would be related to a change in the
926 basin's salinity conditions (Lago Mare?).

927

928 Figure 10: Synthetic cross section of the observations made over the entire Gulf of Lions
929 | arranged in chronological order. See Figure 9 for section locations and explanations.

Figure1

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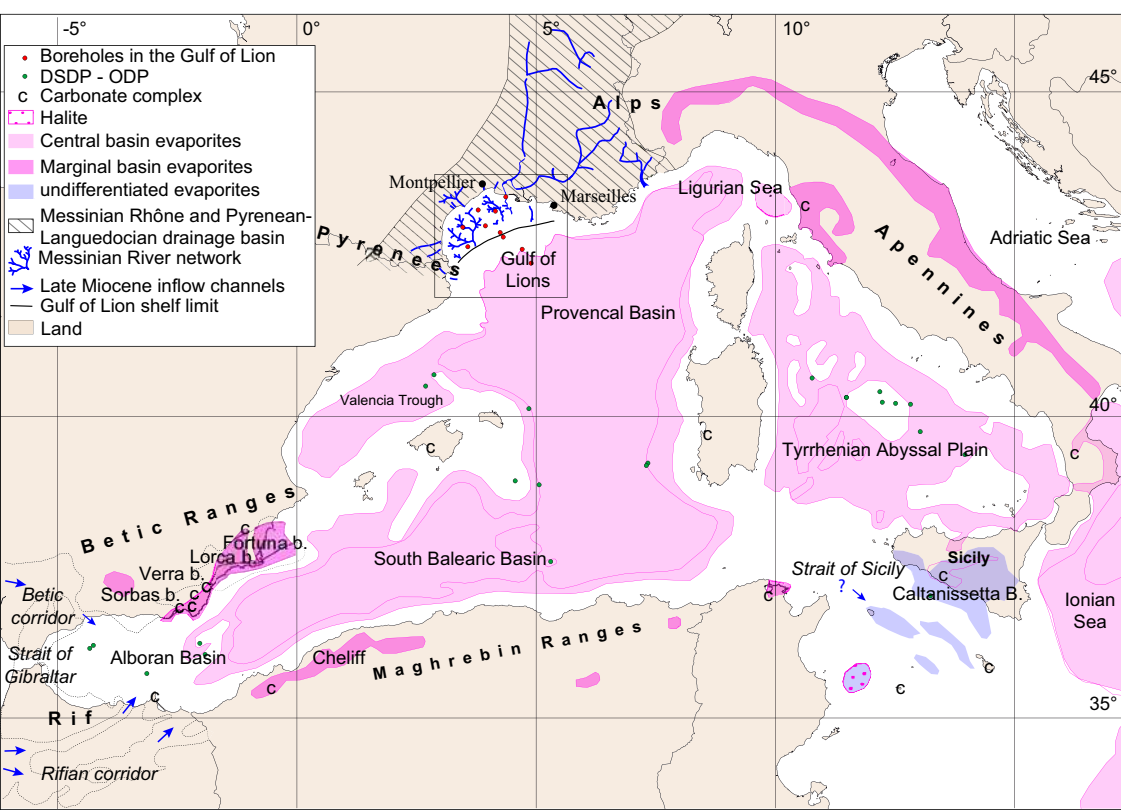


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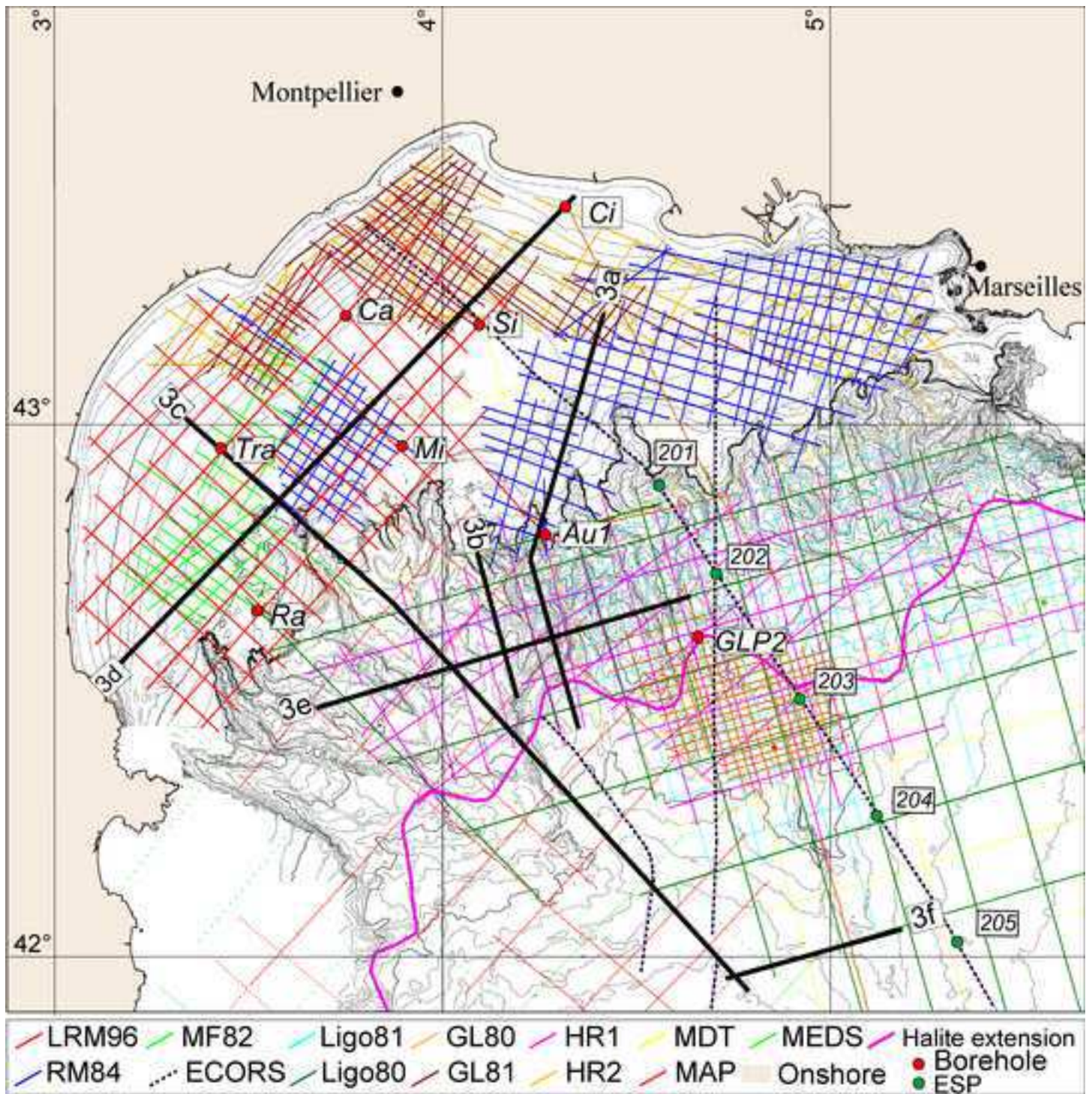


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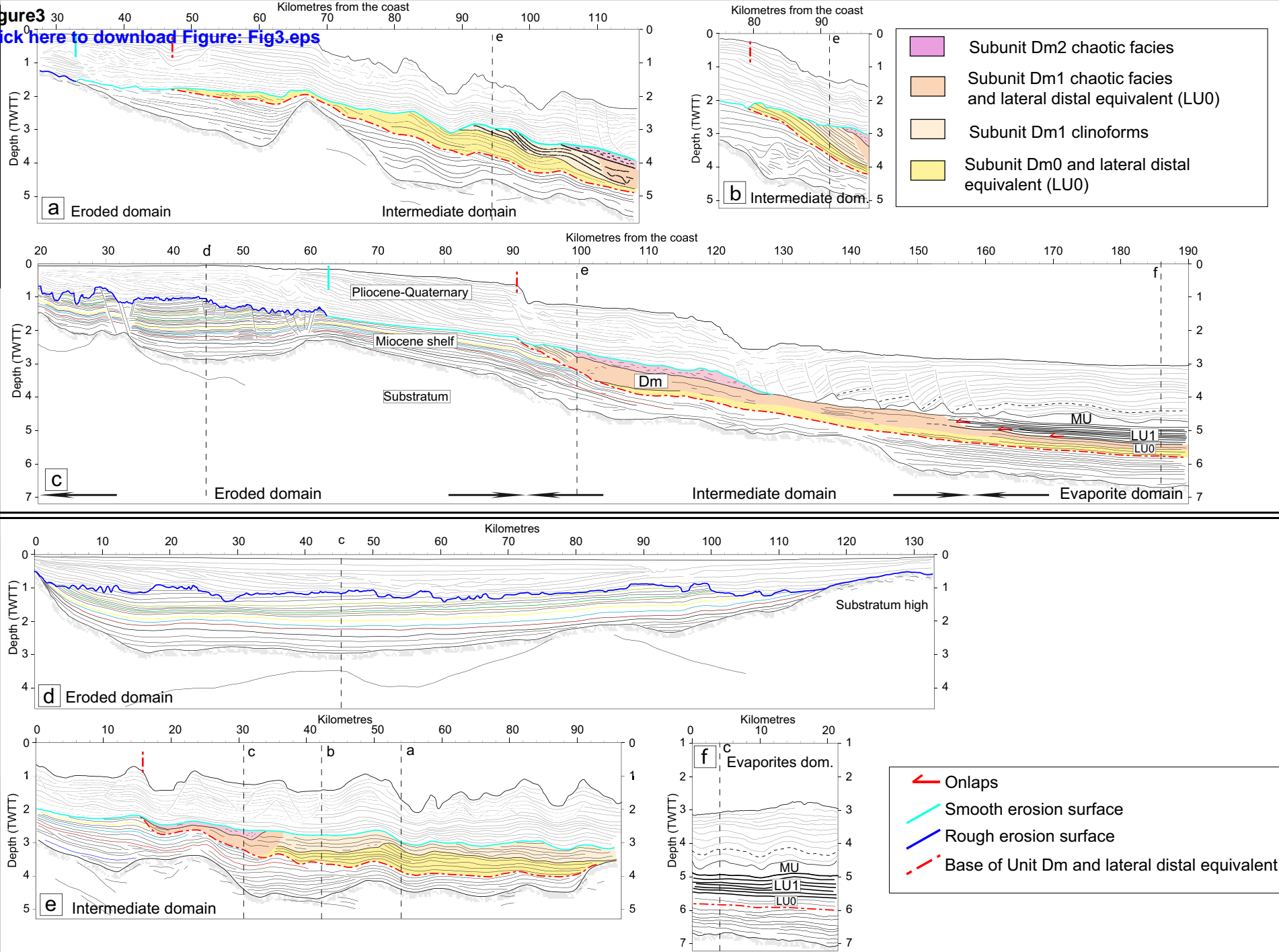


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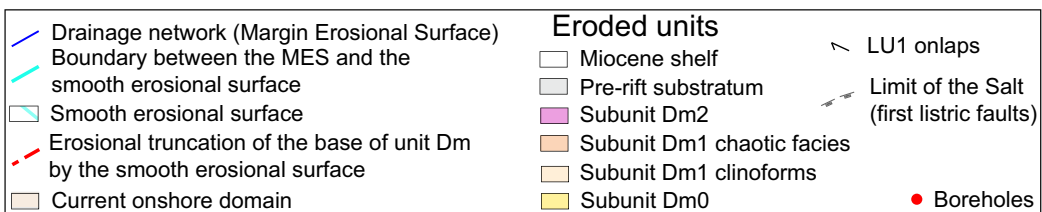
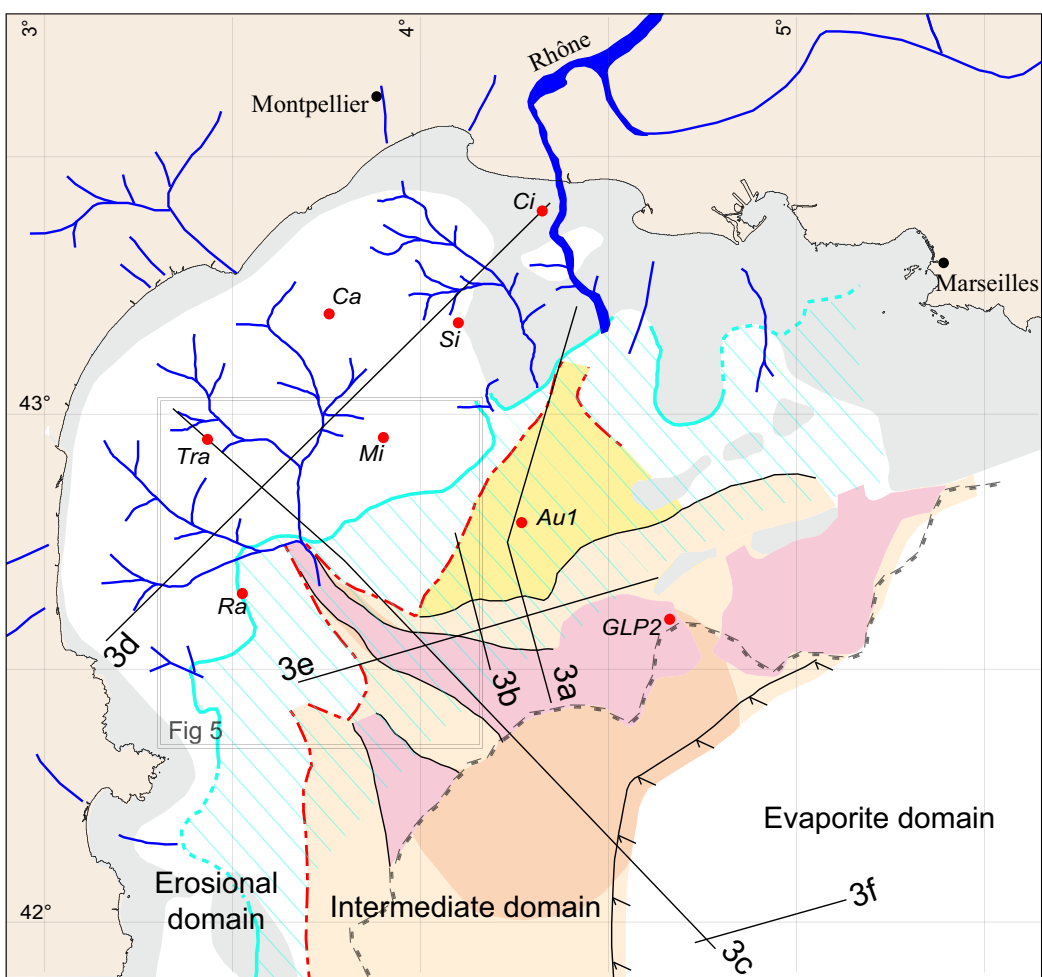


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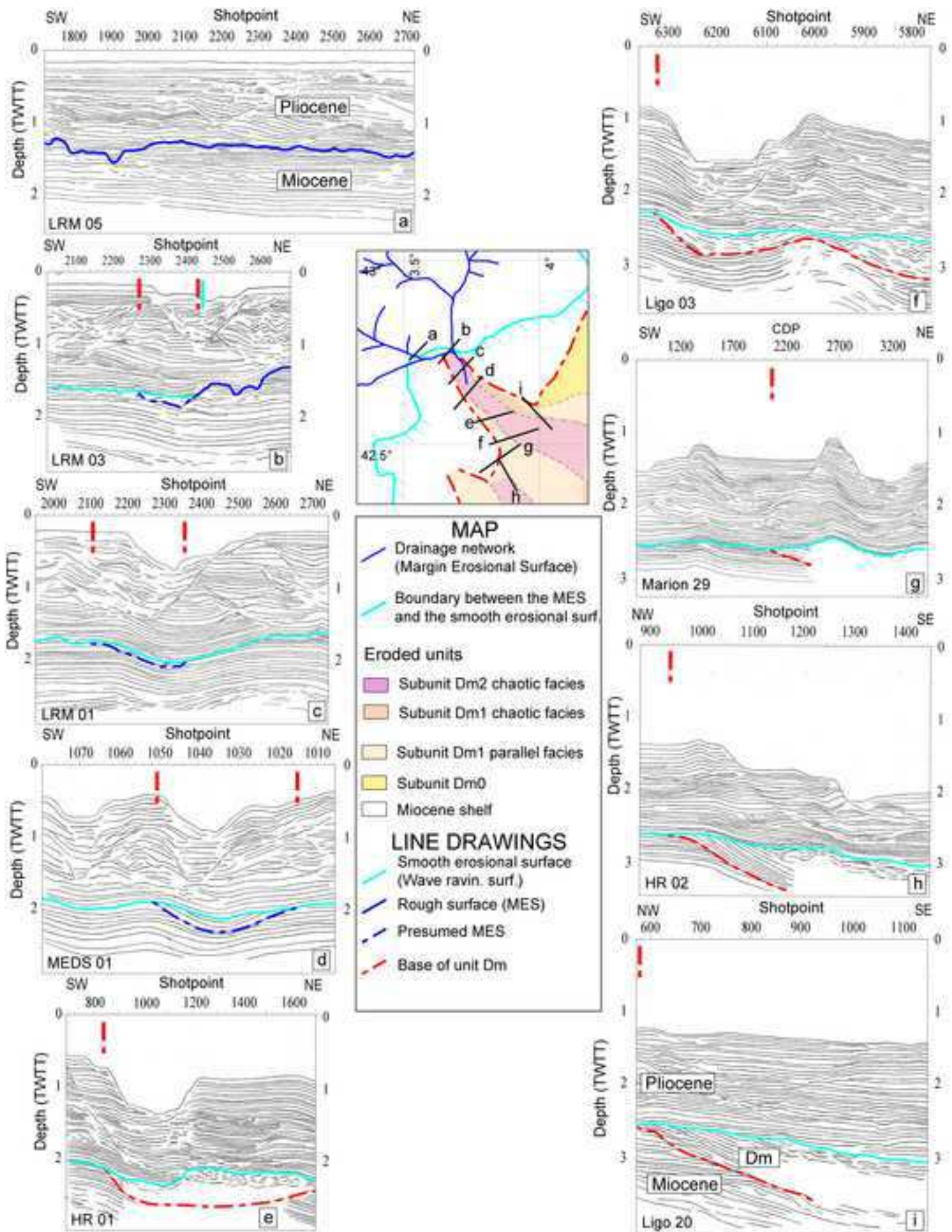


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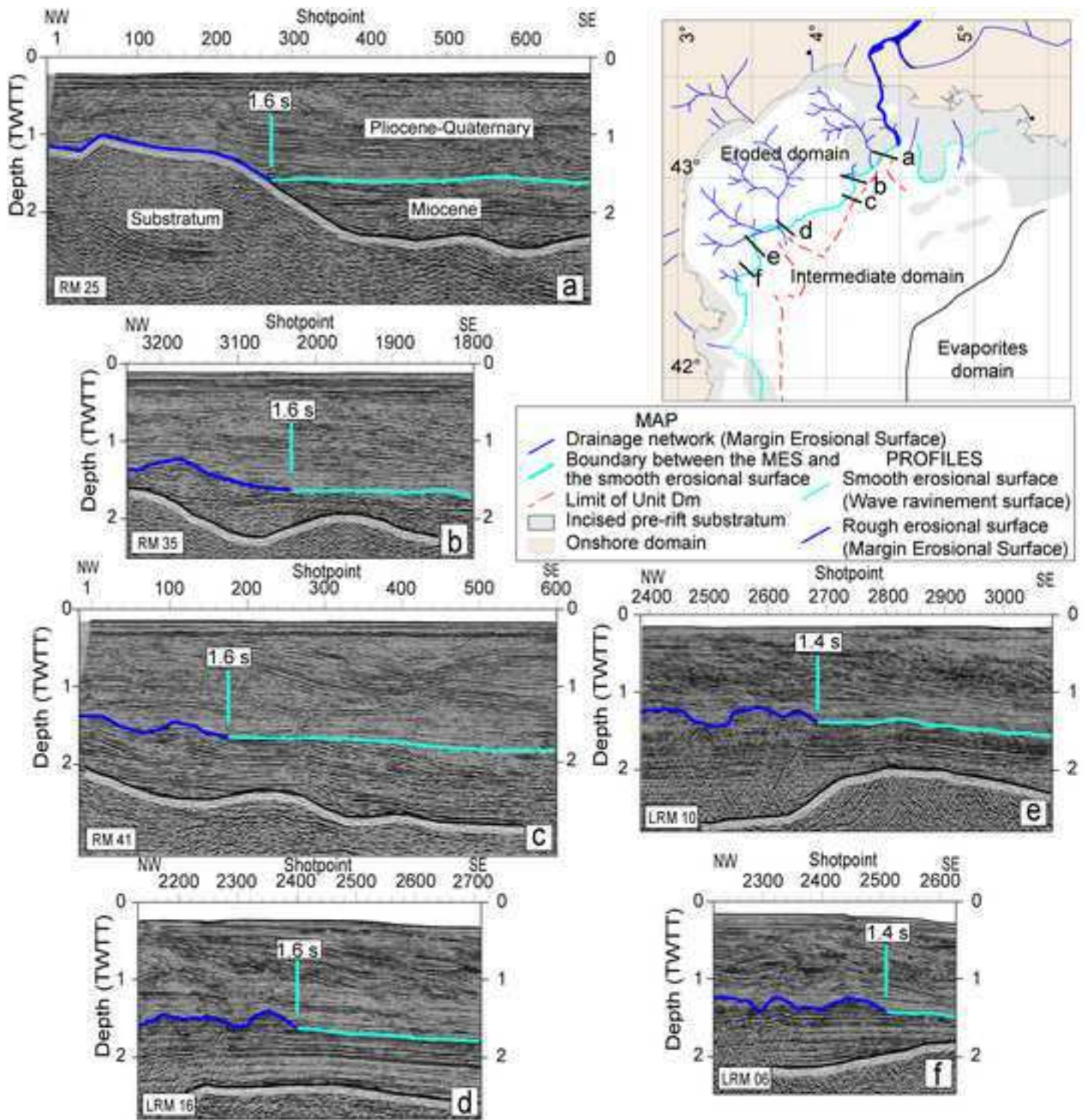


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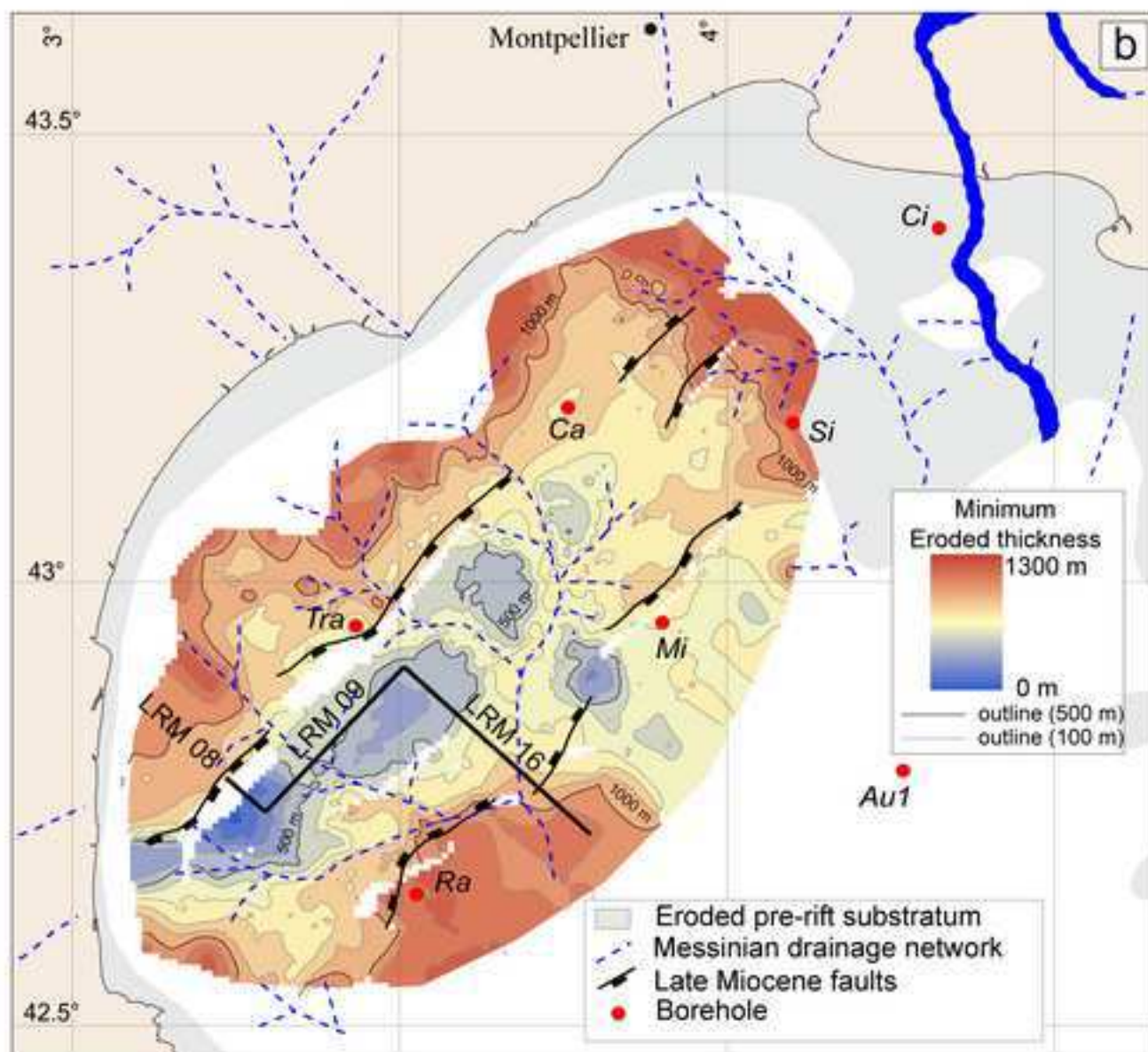
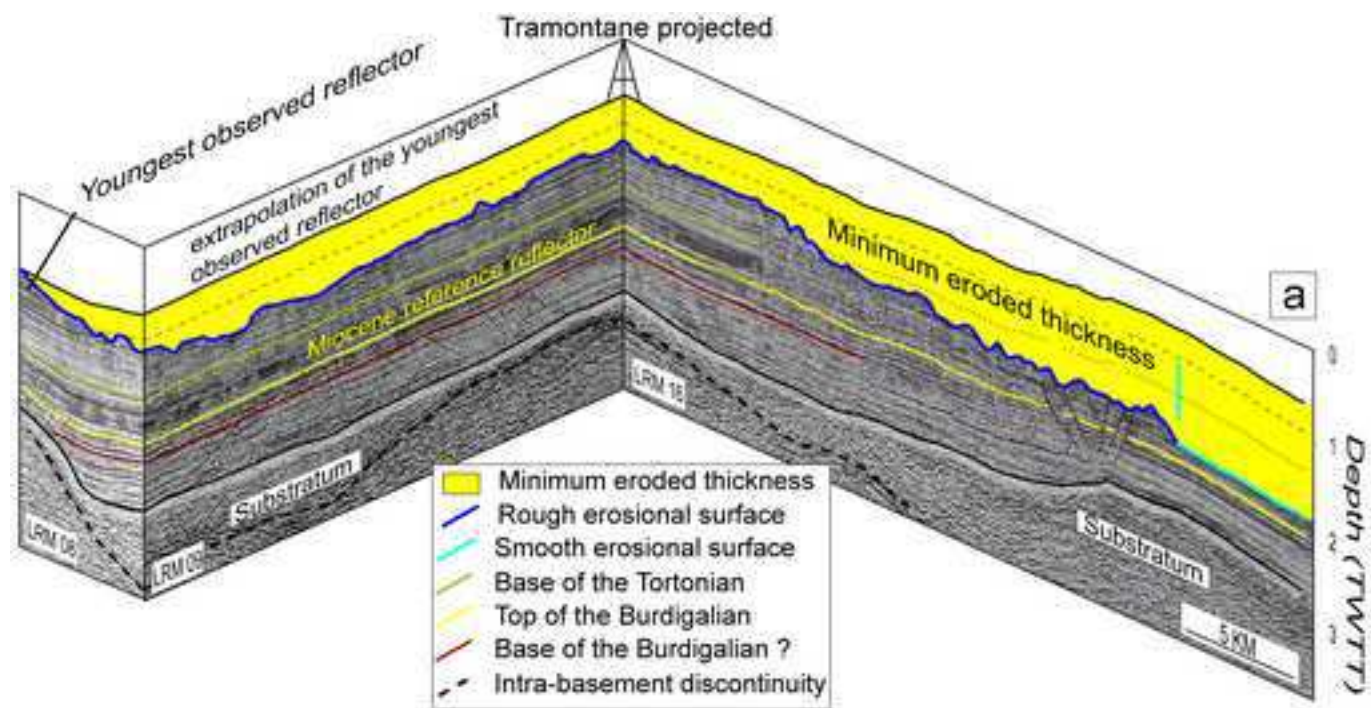


Figure8

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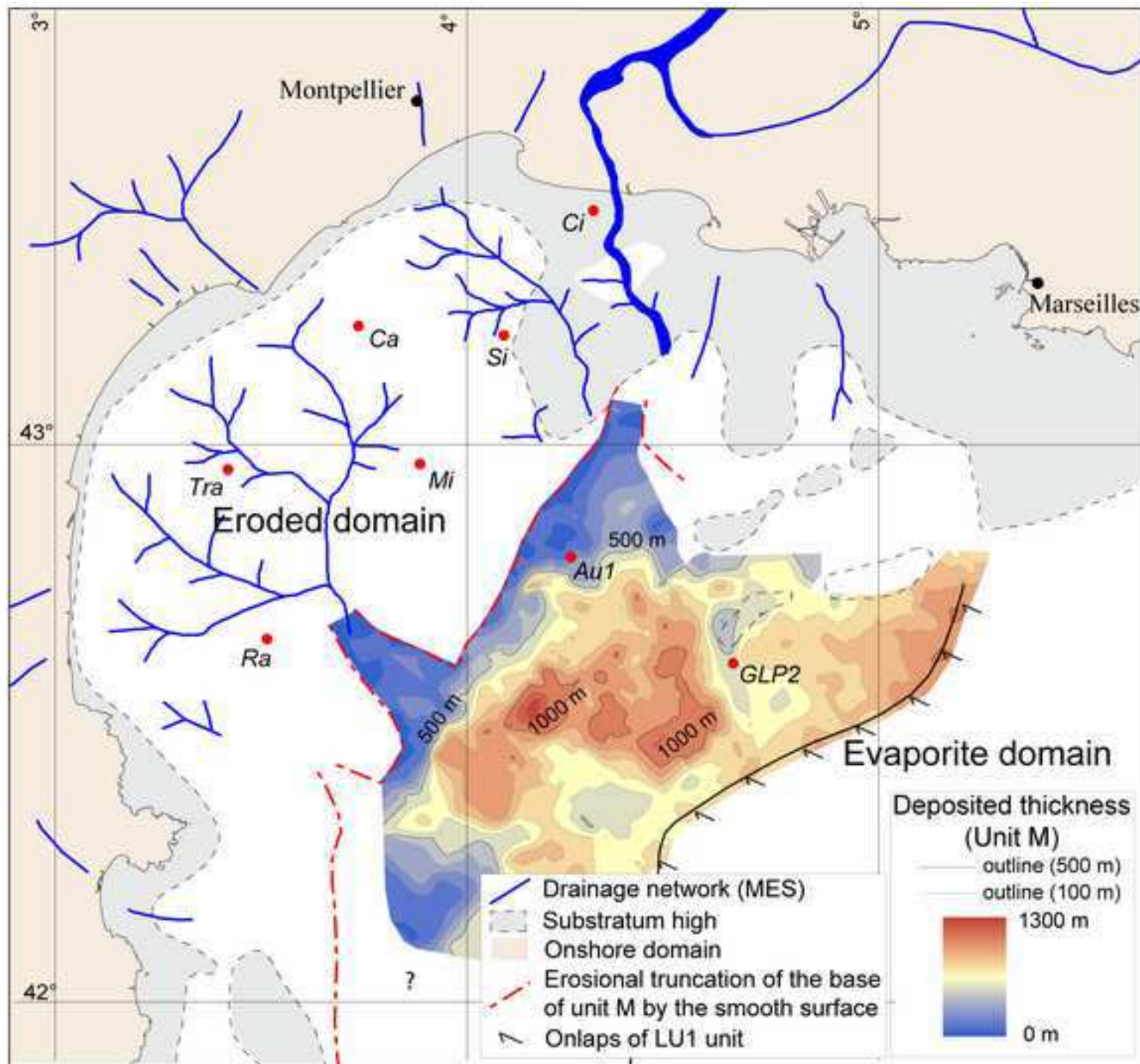


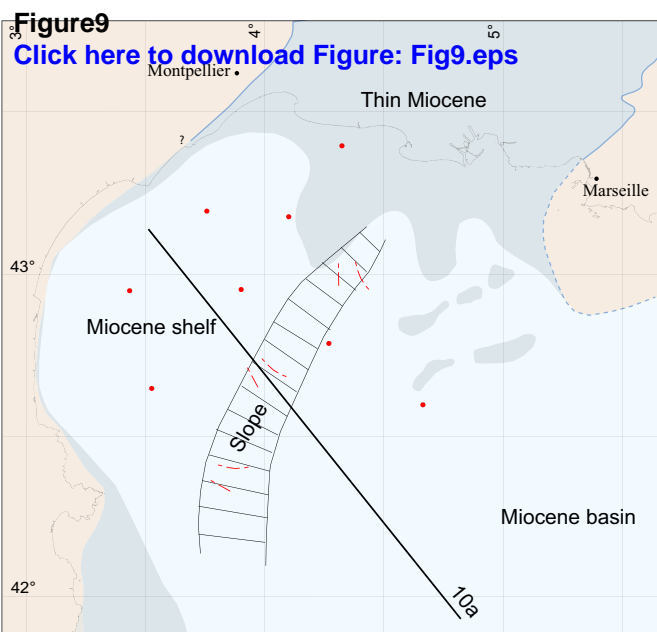
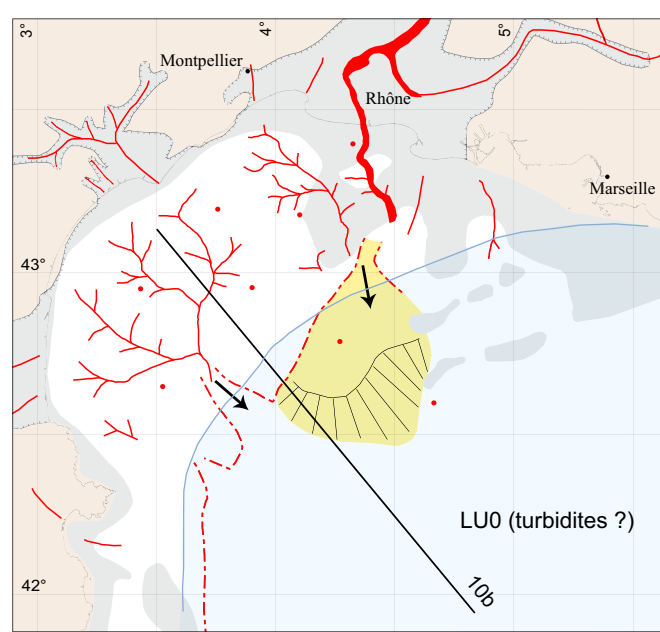
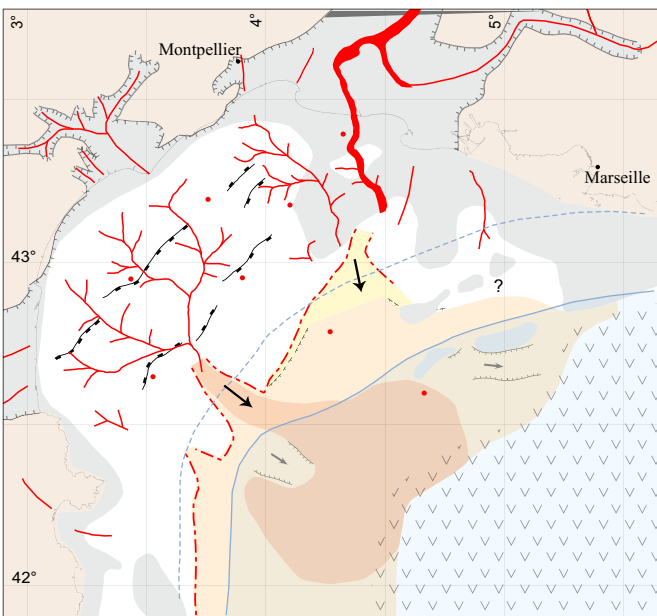
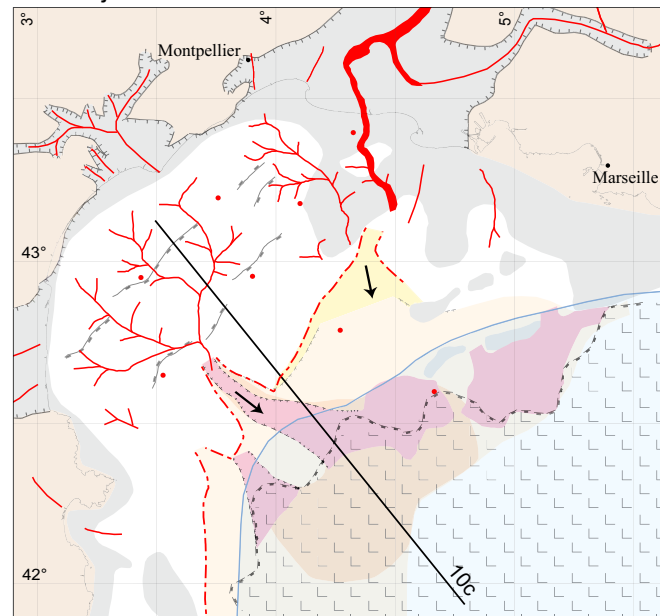
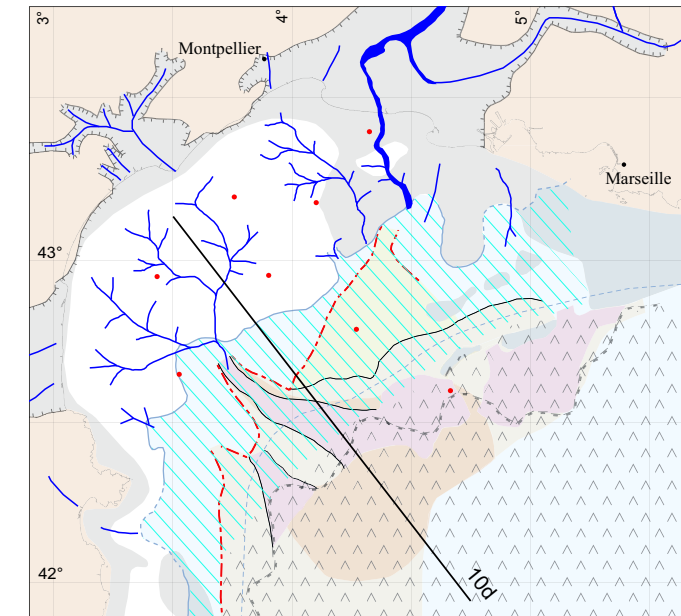
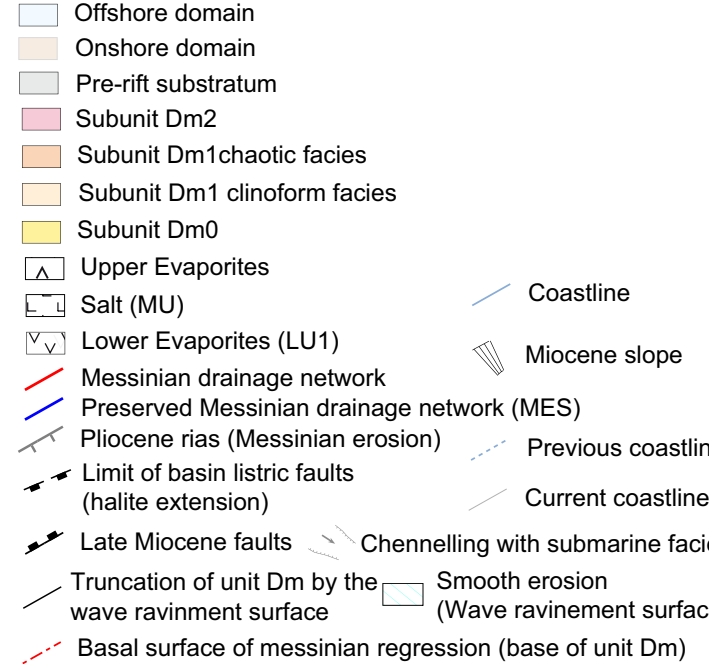
Figure9[Click here to download Figure: Fig9.eps](#)**A/** Miocene shelf gently incised before the major Messinian drawdown**B/** Beginning of the major Messinian drawdown major sediment transfer**C1/** Beginning of desiccation - Low sea level**C2/** Desiccation - Lowest sea level - Salt deposition**D/** Rise of sea level accompanied by smooth erosion

Figure10
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