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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 km<sup>2</sup>), 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 km<sup>3</sup> 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 km<sup>2</sup> 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 ( $1500 \text{ km}^3$ ) compared to the high volume of estimated erosional sediments ( $3000 \text{ km}^3$ ) 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 5<sup>th</sup> order dendritic drainage (Gennesseaux 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 km<sup>3</sup> 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 km<sup>3</sup> 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 Km<sup>2</sup>), we can assume the eroded volume to be much  
269 higher (~10 000 Km<sup>3</sup>). 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  $9400 \text{ km}^3$ . 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 km<sup>3</sup> (with an average velocity of 2000 m/s) or 3000 km<sup>3</sup>  
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 km<sup>3</sup>).
- 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 than 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 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 km<sup>3</sup> and probably around 10



894 000 km<sup>3</sup>) 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 km<sup>3</sup>) is of the same order of magnitude as the eroded  
899 volume (around 10000 km<sup>3</sup>). 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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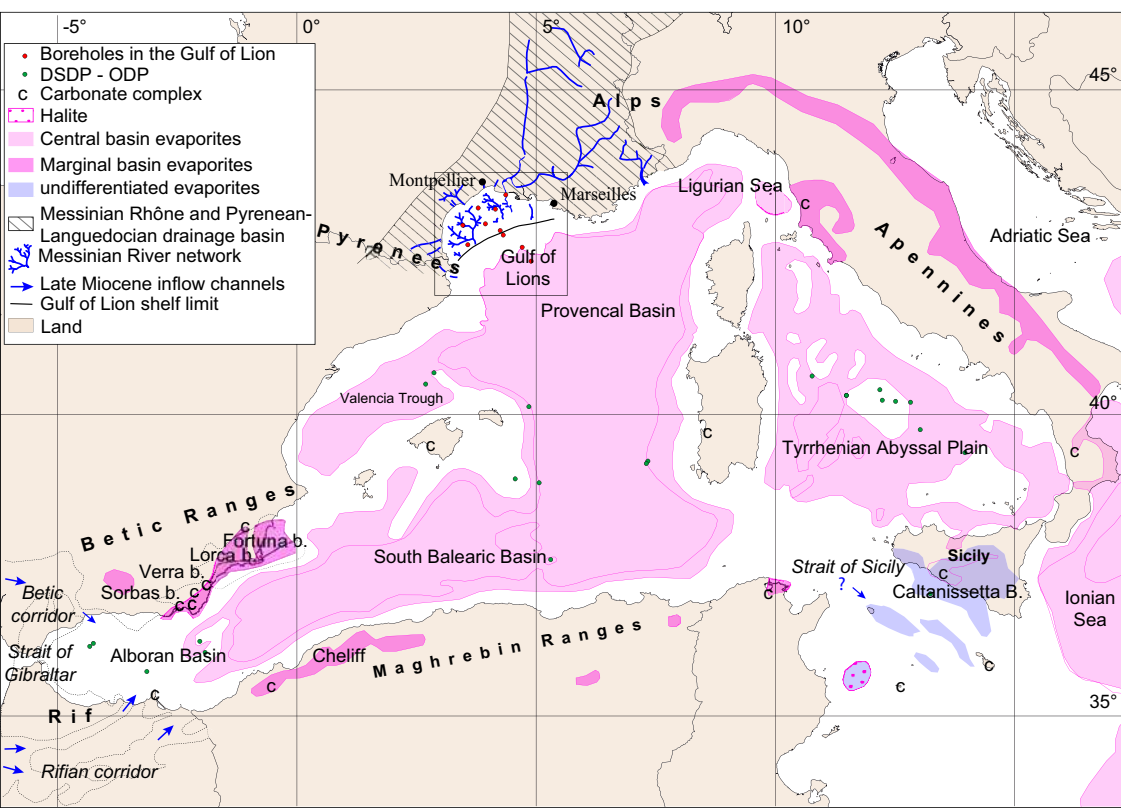
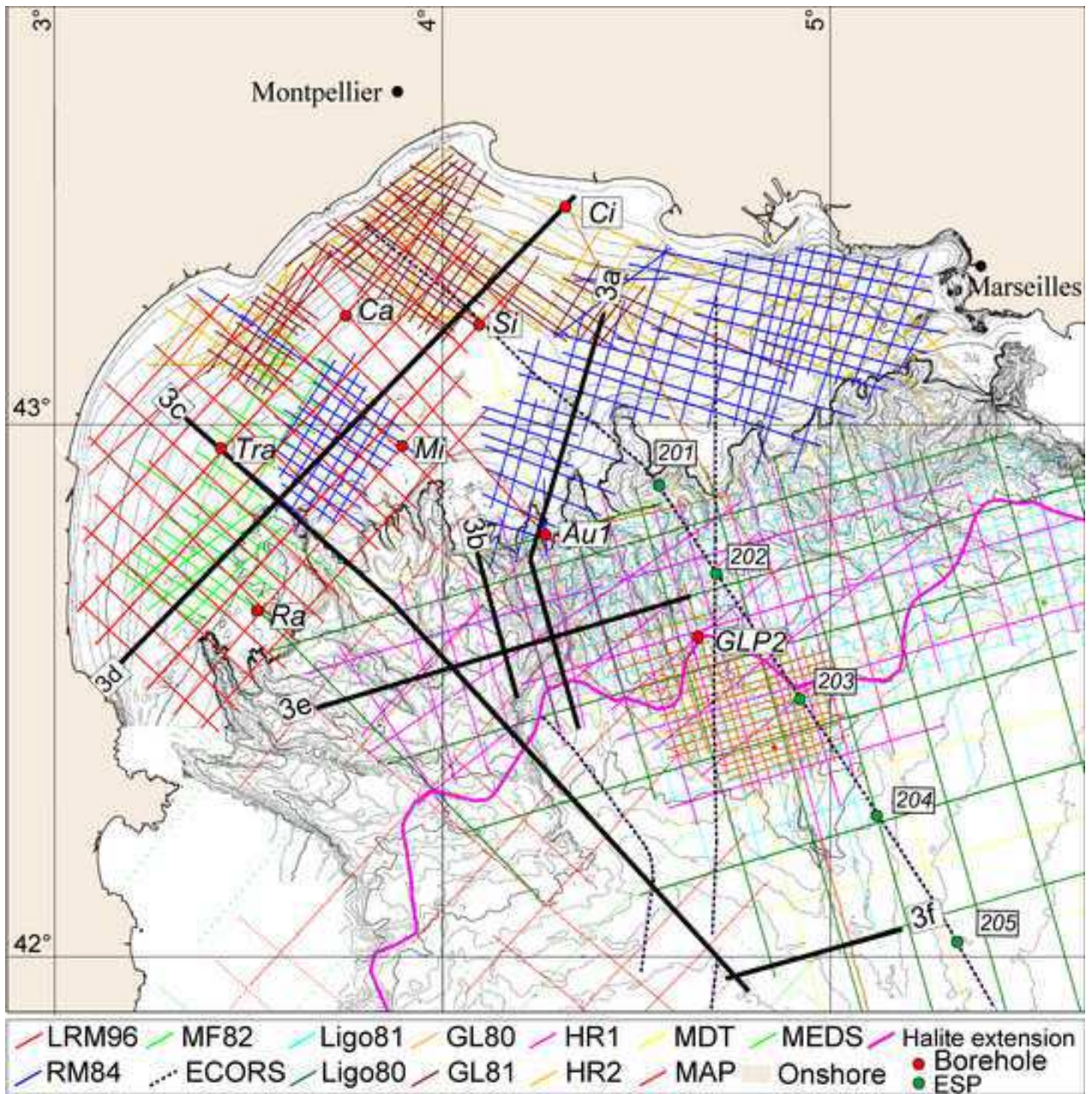


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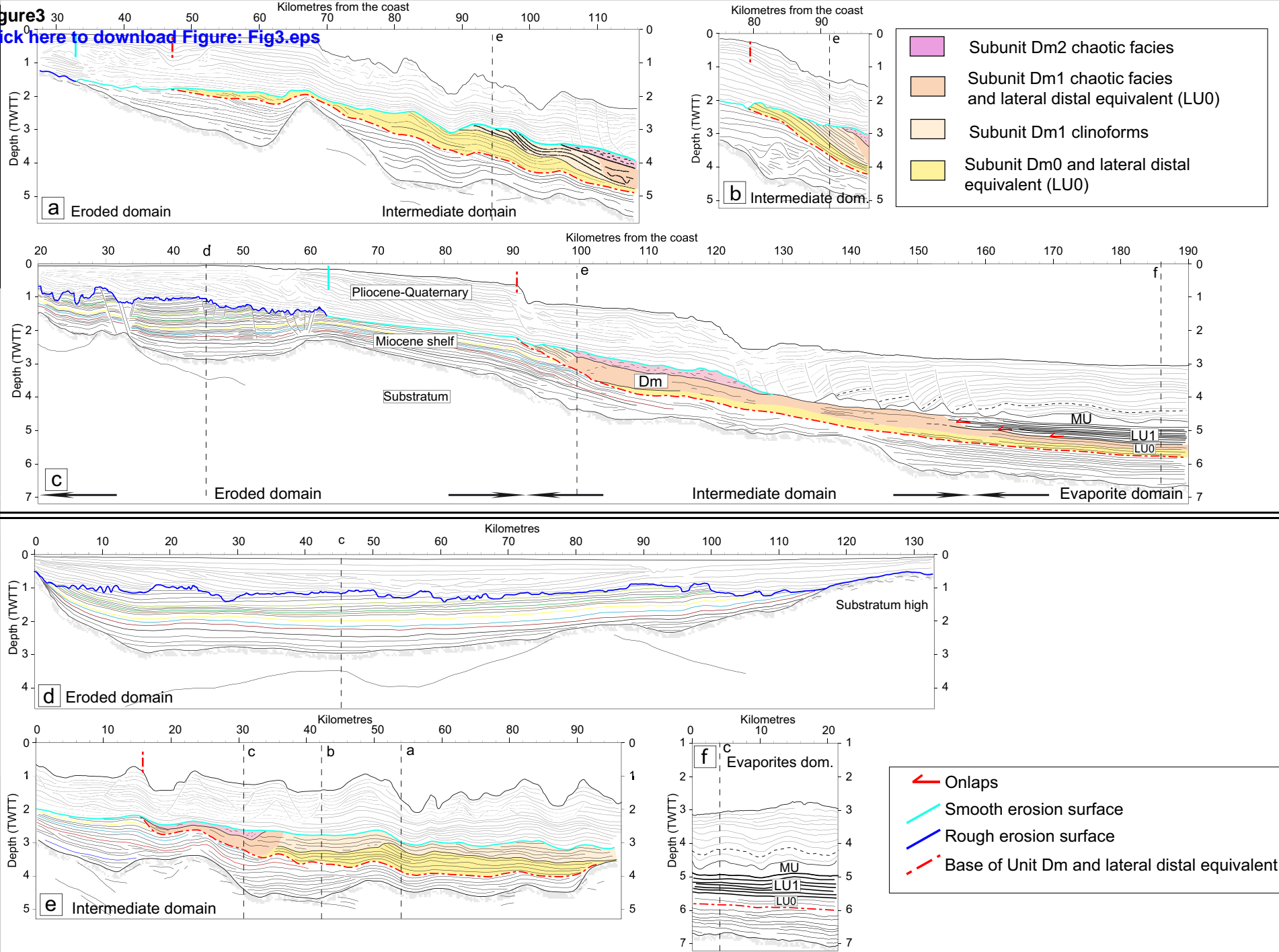


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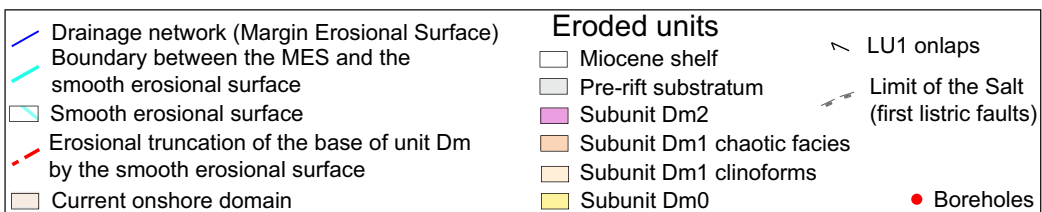
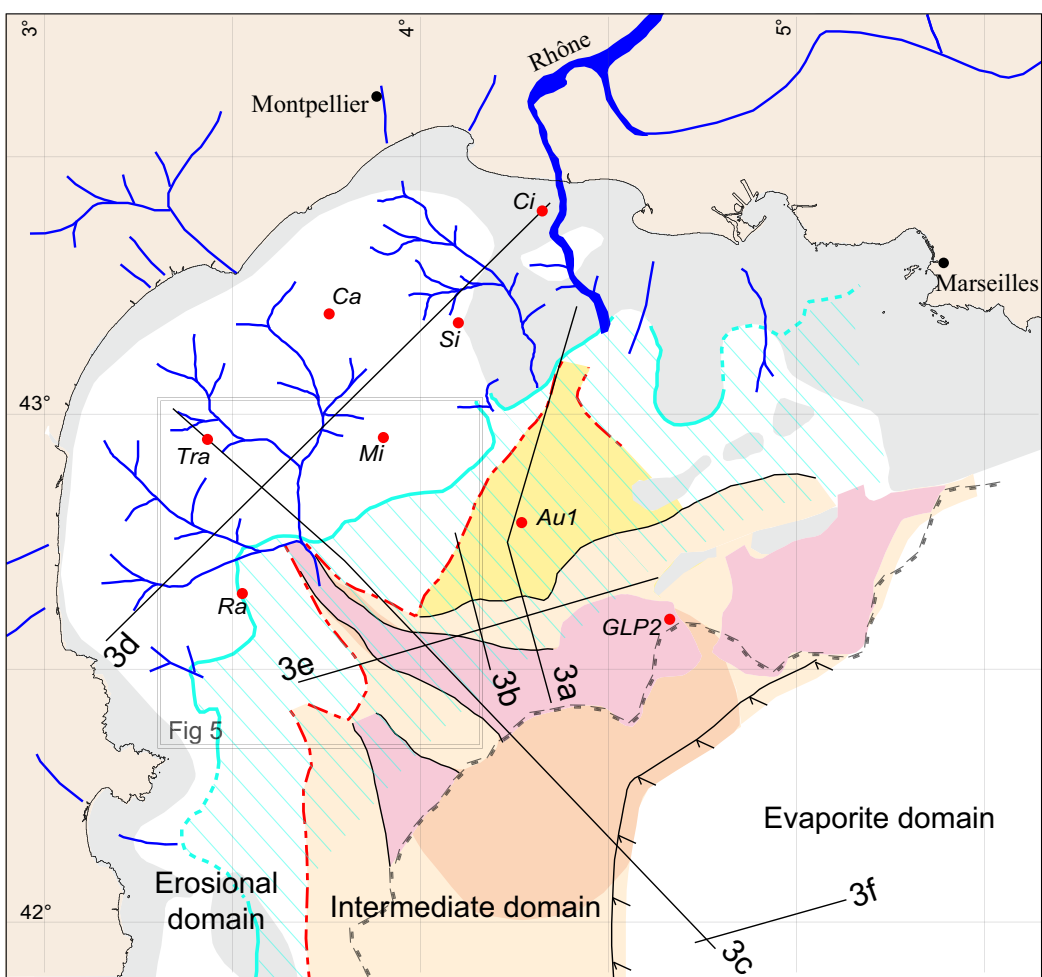


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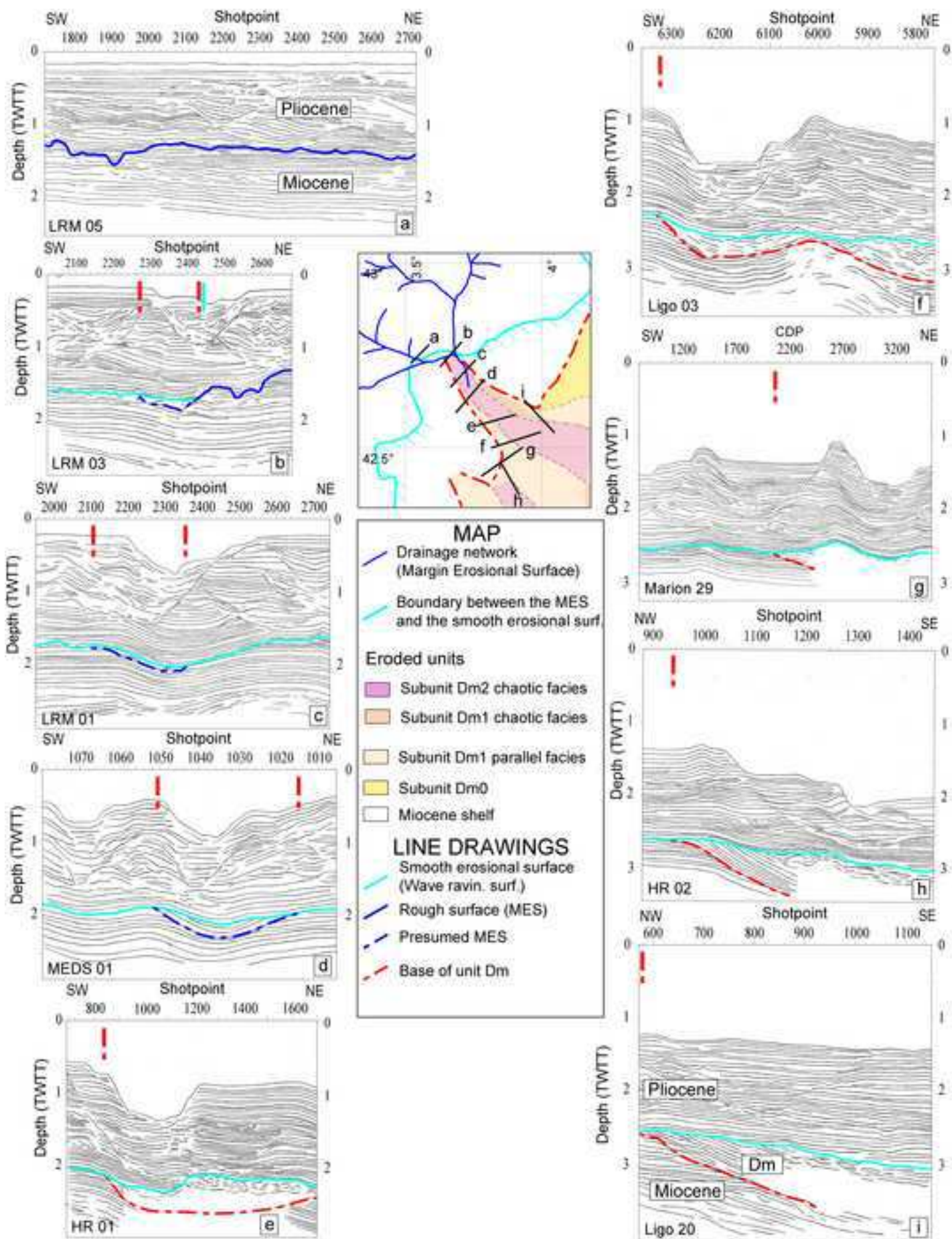


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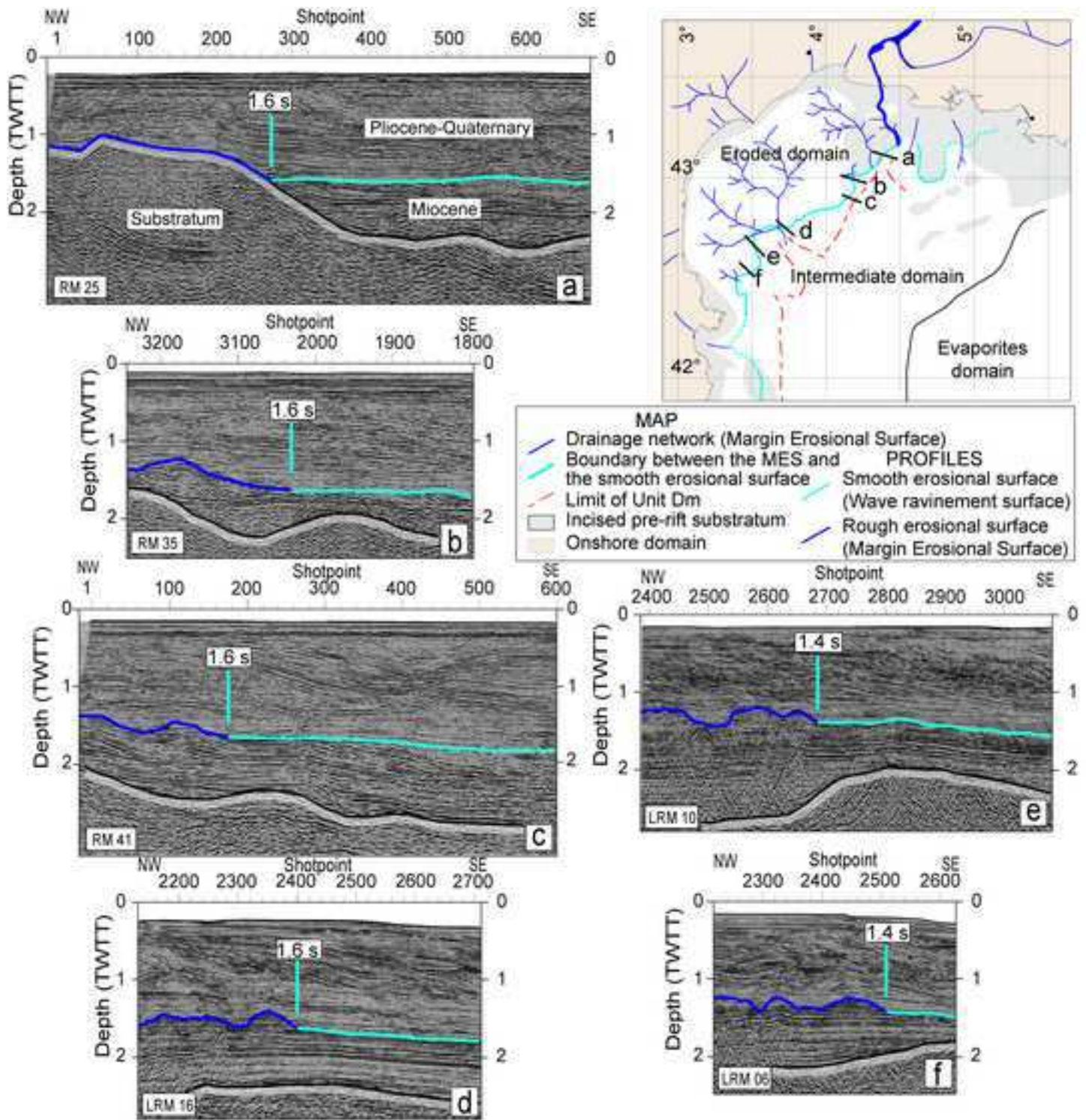




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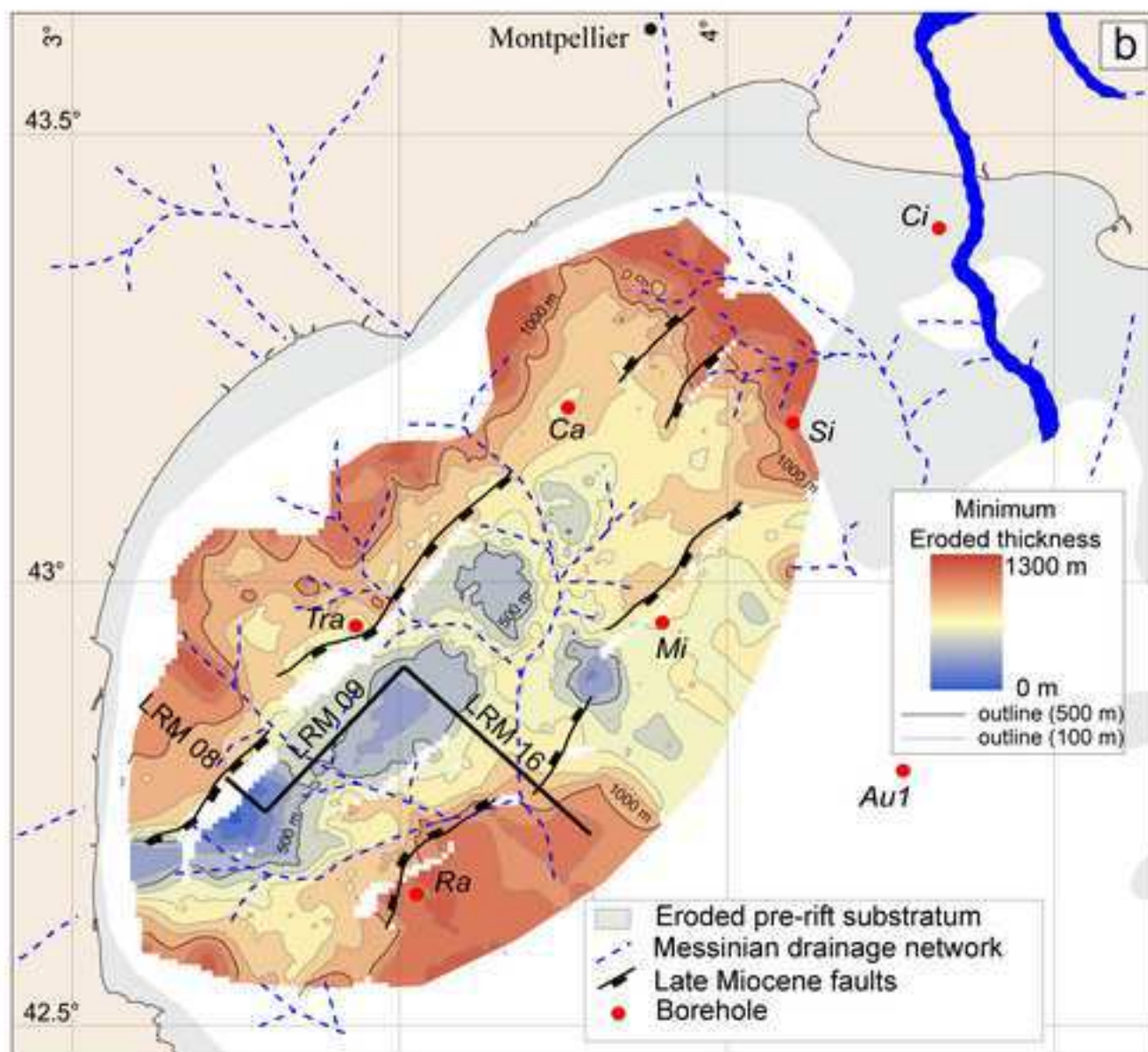
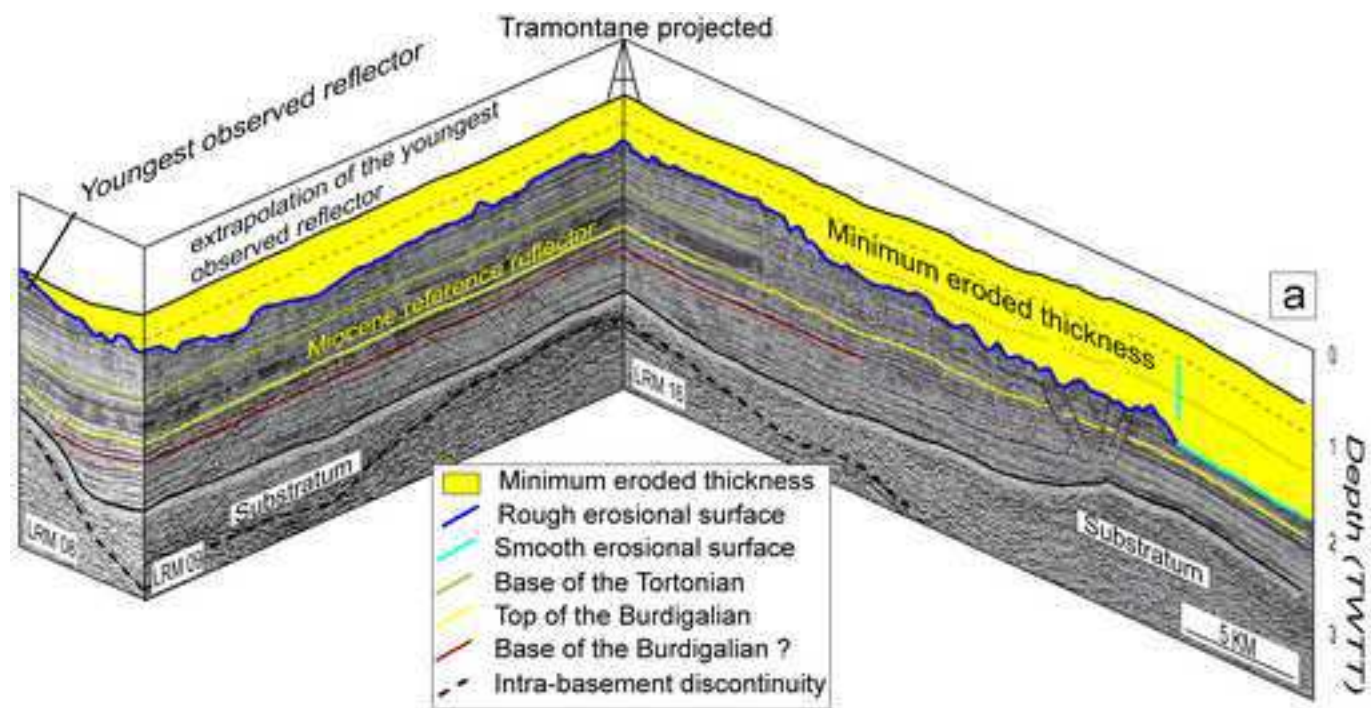
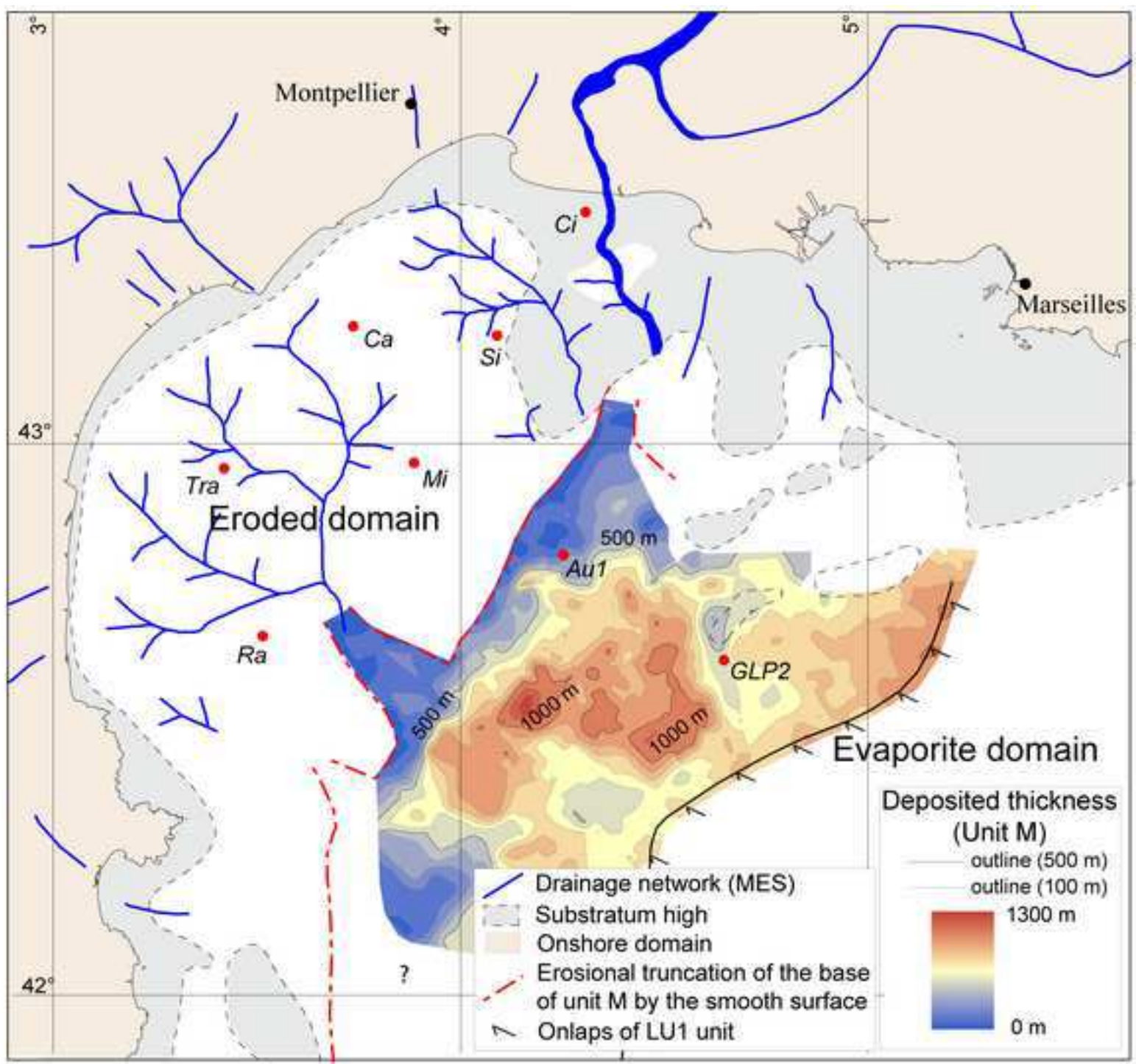
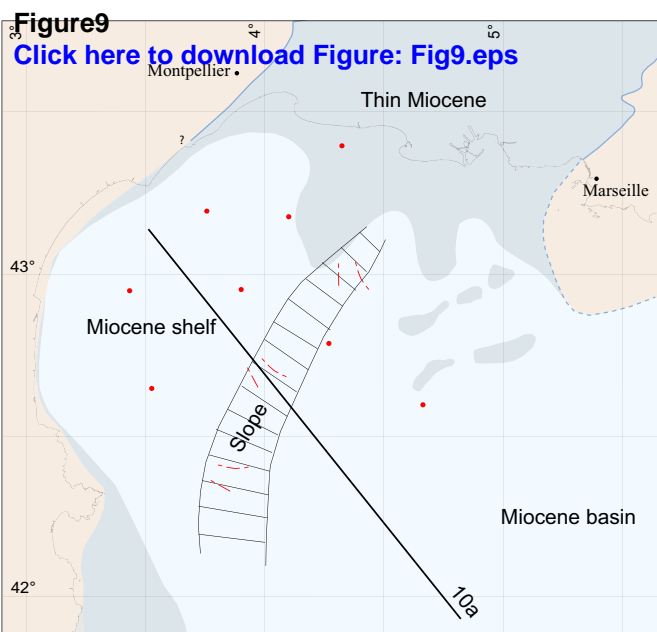


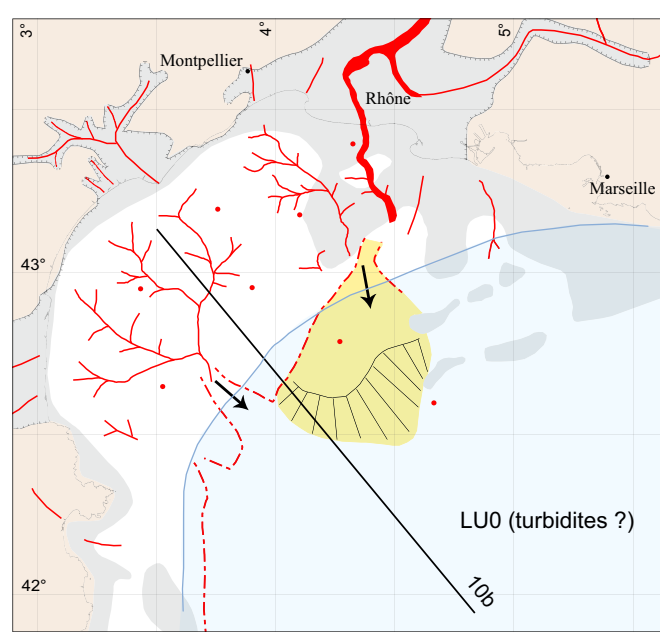
Figure8

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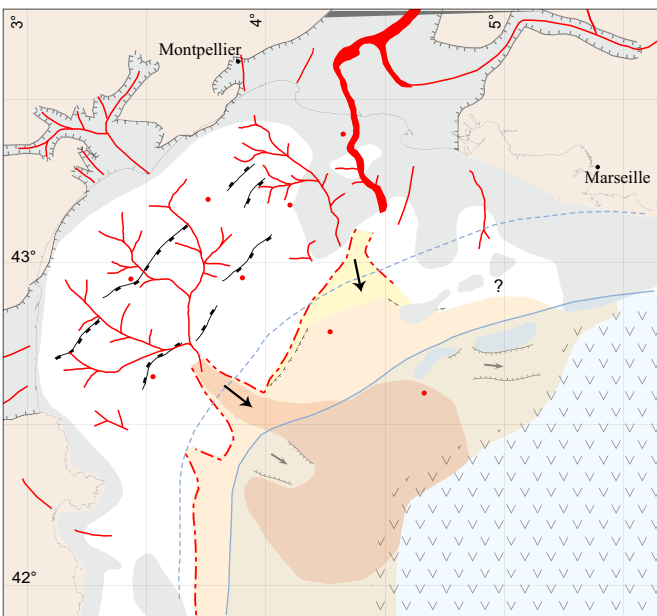


**Figure9**[Click here to download Figure: Fig9.eps](#)

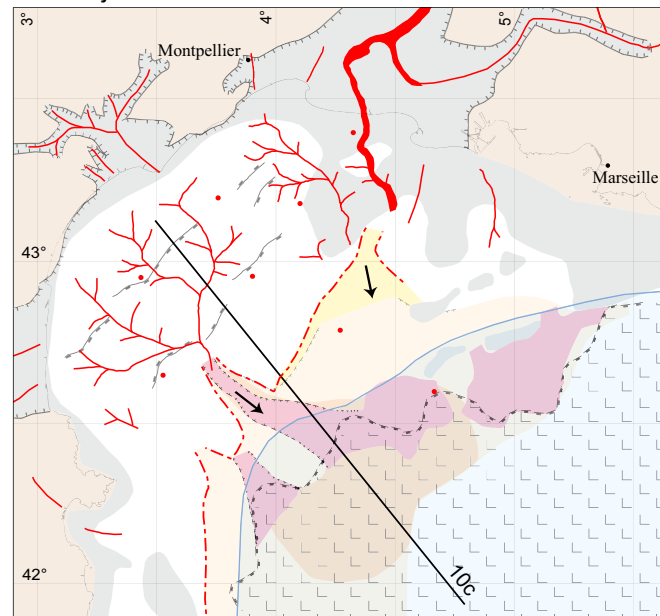
A/ Miocene shelf gently incised before the major Messinian drawdown



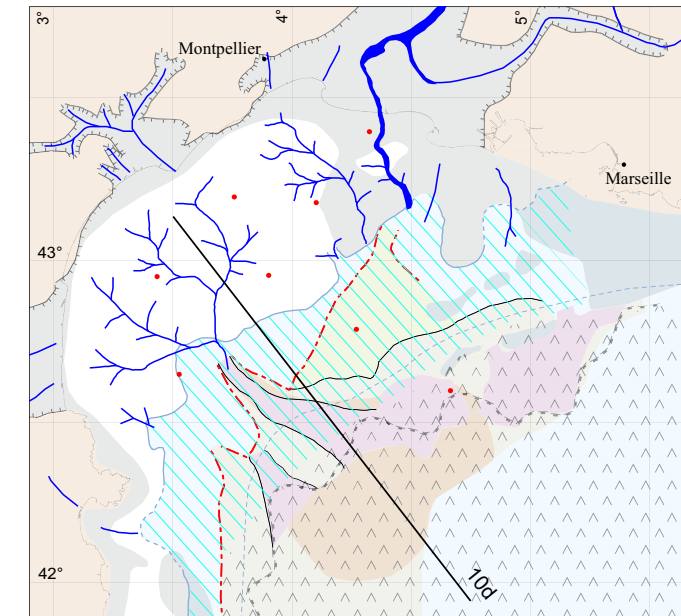
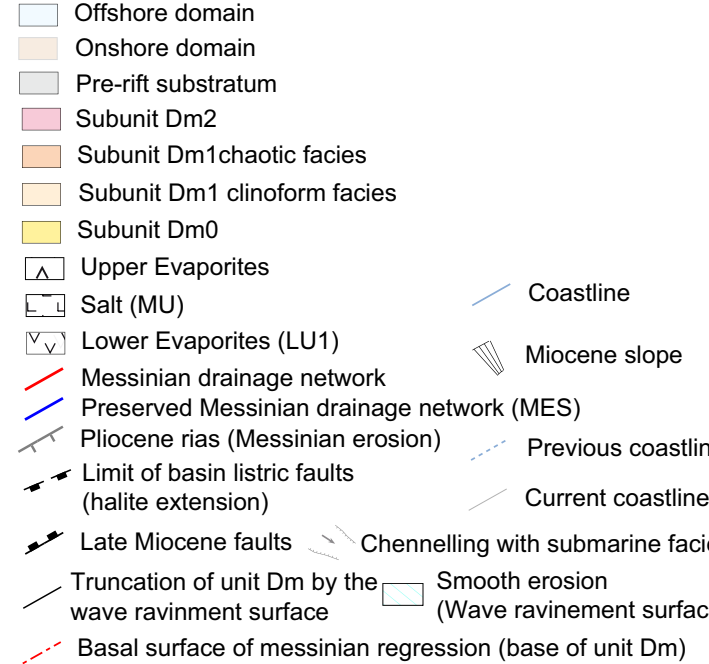
B/ Beginning of the major Messinian drawdown major sediment transfer



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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