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Crustal structures and salt tectonics on the margins of the western Algerian Basin

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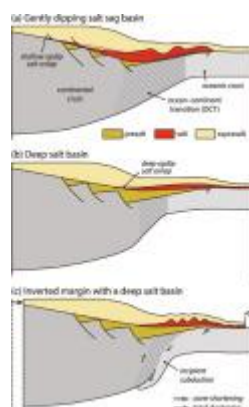
Abstract :

We present an overview of the crustal architecture of the continental margins of the oceanic Algerian Basin in the westernmost Mediterranean Sea. During the Cenozoic, and with a variable oblique convergence between the African and Eurasian plates during the Cenozoic, the Western Mediterranean Sea has experienced thinning and extension behind a tight orogenic arc formed by the Betics, Rif, and Tell Cordilleras. This study is focused on the structural style affecting the Messinian salt layer, which is mostly restricted to the deep domains of the Algerian Basin, where it is floored by a thin oceanic crust of probable Miocene age.

Using deep-penetrating seismic profiles and wells from offshore western Algeria to southeastern Spain, we have analyzed the crustal structures affecting the domains close to the oceanic-continent transition on the three margins of the western Algerian Basin. Since the Early Miocene, active shortening in the Tell-Atlas domain has accommodated most of the plate convergence in the basin, whereas the Alboran margin in the west and the Iberian margin in the north experienced eastward and southward crustal extension and thinning, respectively, accompanied by volcanism. The Algerian margin in the south shows incipient thrusting of African continental crust over oceanic crust. This shortening occurred since at least the Late Miocene, also promoting decoupling and contraction of the deep, sub-horizontal Messinian salt layer. The salt exhibits diapir squeezing and suprasalt folding, whereas the presalt sequence preserves partially-inverted half-grabens. Salt tectonic processes along the northern and western margins of the Western Mediterranean Basin show contrasting structural styles formed by narrow extensional and transtensional domains with gentle salt anticlines.

This region shows therefore a somewhat unusual salt-tectonic style, departing from the gravity-driven model typical of continental margins that contain an initial continuous, gently-dipping salt layer. In the Algerian Basin, salt is mostly restricted to deep water domain floored by oceanic crust, so it does not participate in significant gravity-driven deformation. Instead, Messinian salt and the suprasalt sequences underwent significant shortening along the southern margin, simultaneous with thick-skinned extension involving the Messinian evaporites in the northern and eastern margins.

Graphical abstract



Highlights

► Crustal structure of the W Algerian Basin is reviewed by the first time. ► Seismic interpretation to unravel the crustal structures of the basin and margins. ► How the Messinian salt layer is deformed in the oceanic floor of the basin. ► How the deformation occurring in the margins affected the deep-seated salt layer. ► Restoration to evaluate timing, magnitude, and rate of post-6 Ma deformations.

Keywords : Salt margins, salt folded belts, thick-skinned deformation, crustal extension, tectonic inversion, Messinian, Western Mediterranean, Algerian Basin

65 **1. Introduction**

66 Our study is focused on reviewing the overall structure of the oceanic Algerian (or South
67 Balearic) Basin in the westernmost Mediterranean Sea to provide, for the first time, a
68 comprehensive review of the crustal structure of the basin and its continental margins (Fig. 1).
69 To simplify the terminology for the three margins of the Algerian Basin, we use Algerian
70 margin, Alboran margin, and Iberian margin when referring to the southern, western, and
71 northern margins, respectively. The first two terms refer to the so-called North Algerian (or
72 Algeria) margin and the western transition from the East Alboran Sea to the Algerian Basin.
73 For some of the basin margins, the overall crustal structure, the main crustal characteristics,
74 and principal stages of the Neogene evolution are very well established. For example,
75 numerous studies document the crustal configuration of the long Algerian margin (reviews by
76 Strzeczynski et al. [2010], Leffondré et al. [2021], and Klingelhofer et al. [2022]), and many
77 authors have inspected the geophysical characteristics of the continent–ocean transition in the
78 Alboran margin (Comas et al., 1997; Booth-Rea et al., 2007, 2018; Medaouri et al., 2014;
79 Gómez de la Peña et al., 2018, 2020, 2021). In contrast, understanding of the crustal
80 architecture, tectonic structures, and recent evolution in the Iberian margin is poorly
81 established. There are some regional sections (Driussi et al., 2015b; Kumar et al., 2021) and
82 local studies of recent processes affecting the sea-floor and the most recent sediments (Acosta
83 et al., 2001; Lastras et al., 2004, 2006; Camerlenghi et al., 2009). Nevertheless, it remains
84 unknown which structures mainly affect the different segments of the Iberian margin, and
85 some researchers even debate the margins' kinematics. Most authors suggest strike-slip
86 motion (mostly due to right-lateral faulting) for the structures affecting the studied sector of
87 this margin (Mauffret et al., 1992; Camerlenghi et al., 2009; Maillard and Mauffret, 2013;
88 Driussi et al., 2015a; Kumar et al., 2021).

89 We have conducted the first complete regional synthesis of the western Algerian Basin and its
90 margins by interpreting multi-channel seismic profiles from both industrial and academic
91 sources. Seismic interpretation is based in a revision of the stratigraphic information provided
92 by all the available wells in the region, coming from both African and Iberian offshore areas
93 (Fig. 1). The interpretation of the structural styles and our inferences about the magnitude and
94 timing of the Neogene (mostly Upper Miocene to recent) deformation are integrated into the
95 tectonic scenario of the region, which has also been summarized through review of previous
96 publications in the area.

97 Our tectonic analysis of the crustal configuration and structure of the western Algerian Basin
98 and its margins also studies how the Messinian evaporites are deformed in the region, a topic
99 that has received little attention to date (e.g., Bellucci et al., 2021). The seismic data we use
100 vary in quality, because we have used vintage commercial seismic reflection profiles on the
101 Iberian margin, a single section on the Alboran margin, and a complete set of commercial and
102 scientific lines on the Algerian margin. Due to this data-quality issue, our study of salt
103 structures, together with the presalt and suprasalt sequences, is necessarily incomplete and of
104 variable precision. In the Algerian margin, for example, we could complete a structural
105 restoration of a selected seismic interpretation. However, our approach to the salt tectonic
106 processes affecting the Alboran and Iberian margins is preliminary and will require future re-
107 evaluation pending on the availability of better and more modern seismic datasets.

108 The position, geometry, and nature of the Messinian salt layer in the Algerian Basin has been
109 known for many years (e.g., Biju-Duval et al., 1978; Lofi et al., 2018). Nevertheless,
110 researchers debate how evaporite precipitation in the deep basin was connected to the
111 sedimentary systems operating in the surrounding continental platforms during the Messinian
112 Salinity Crisis (MSC) and whether evaporites were also deposited along the costal and
113 continental regions (e.g., Meijer and Krijgsman, 2005; Bache et al., 2009; Garcia-Castellanos
114 et al., 2009; Raad et al., 2021). The Messinian salt was deposited throughout the
115 Mediterranean Basin due to a gradual restriction of water exchange with the Atlantic Ocean in
116 Late Miocene time, and due to a generalized sea level drop and a basin-wide desiccation,
117 according to several authors. Together, these factors led to extreme paleoenvironmental
118 changes during the climax of the MSC (5.97–5.33 Ma) (see reviews by Lofi et al. [2011],
119 Bache et al. [2012], Flecker et al. [2015], Lofi [2018], and Andreetto et al. [2021]). The
120 isolation of the overall Mediterranean Basin during the short MSC (~660 kyr) made possible
121 the deposition of the Messinian salt in the deepwater domains of the basin (e.g., Haq et al.,
122 2020).

123 Key questions addressed in this contribution include: What is the overall structural
124 configuration of the Algerian Basin and its margins? What is the role played by Neogene
125 crustal thinning and extension versus igneous intrusions and volcanism on the Alboran
126 margin? What is the main structural style of the Iberian margin? Is the Iberian margin affected
127 by strike-slip faulting or by normal faulting? What is the role played by the Messinian salt
128 during the most recent evolution of the basin? What is the magnitude and timing of salt-
129 detached deformation, compared to the presalt? And finally, can we use modern concepts of

130 salt tectonics to unravel these processes and provide a complete view of the western Algerian
131 Basin and its margins?

132

133 **2. A review of the tectonic setting of the Western Mediterranean**

134 The Algerian Basin and its margins are part of the Gibraltar Arc System (Figs. 1, 2). The
135 Gibraltar Arc System is a tight, Alpine orogenic loop in the westernmost Mediterranean,
136 formed by the mountain belts of the Betic in southern Spain, the Rif in northern Morocco, and
137 the continuation towards the east along the Tell in northern Algeria (Fig. 3) (e.g., Biju-Duval
138 et al., 1978; Bouillin et al., 1986; Comas et al., 1999; Frizon de Lamotte et al., 2000;
139 Chalouan et al., 2008; Leprêtre et al., 2018; Jolivet et al., 2015, 2021a; Haidar et al., 2022).
140 This system embraces the Alboran Basin, which is floored by stretched continental crust, and
141 the oceanic Algerian Basin further to the east. The Alboran Basin constitutes a Mediterranean
142 back-arc-type basin formed by extensional collapse of the Gibraltar Arc (e.g., Dewey et al.,
143 1989; García-Dueñas et al., 1992; Vissers et al., 1995; Platt et al., 1998, 2013). There is a
144 general consensus that the Neogene orogenic processes shaping both the mountain regions
145 and the offshore basins of the Gibraltar Arc System are as follows:

- 146 1. Peripheral thrusting imbricating the former South-Iberian and Maghrebian passive
147 margins over the Iberian and African (Hercynian) forelands, respectively (Figs. 3, 4).
- 148 2. Westward migration, imbrication, and exhumation of diverse metamorphic continental
149 terranes forming the Alboran Domain or Internal Zones, which extend from the
150 Internal Betics and Rif to the Kabylies in northern Algeria.
- 151 3. Thrust-sheet imbrication within the Alboran Domain, forming a progressively tighter
152 orogenic arc as it migrates westward.
- 153 4. Simultaneous collapse of the Alboran Domain flooring the thick depocenter of the
154 West Alboran Basin (e.g., Fig. 4).
- 155 5. Extreme crustal stretching accompanied by abundant calc-alkaline and tholeiitic (14–6
156 Ma) to intraplate-type alkali (6.0–0.8 Ma) volcanism flooring the East Alboran Basin
157 (Fig. 3) (e.g., see review by Soto et al., 2008).
- 158 6. Oceanic spreading, possibly during the Lower–Middle Miocene, forming the Algerian
159 Basin, well behind the Gibraltar Arc System.

160 The Algerian Basin is a large, deepwater abyssal plain with a constant depth of about 2600 m
161 (Fig. 1), which is floored by thin (avg. ~5 km) oceanic crust (Hinz, 1973; Gallart et al., 1997;

162 Sàbat et al., 1997; Driussi et al., 2015b; Kumar et al., 2021). The age of this crust is debatable,
 163 assigned to the Oligocene to Lower Miocene (Biju-Duval et al., 1978; Mauffret et al., 1992;
 164 Haidar et al., 2022) or Middle Miocene (Rehault et al., 1984; Gueguen et al., 1998; Carminati
 165 et al., 2012; Driussi et al., 2015a, 2015b; dal Cin et al., 2016). Nevertheless, all these authors
 166 agree that the oceanic crust was completely accreted in the Tortonian time. This crust was
 167 formed by very-rapid oceanic accretion ($\sim 5 \text{ cm} \times \text{yr}^{-1}$) (Mauffret et al., 2004; Jolivet et al.,
 168 2021a; Haidar et al., 2022; Klingelhoefner et al., 2022). The gravity anomaly map in this basin
 169 also shows a rather constant value, close to zero, which tends to decrease slightly (-10 to -20
 170 mGal) towards the northern and eastern limits of the oceanic crust (Fig. 2). Conversely, the
 171 Algerian margin, with a steep slope and abrupt continental rise, coincides with a west-east
 172 elongated domain with negative gravity values (~ -100 to -120 mGal; Fig. 2) (Auzende et al.,
 173 1975; Mauffret et al., 2004; Mauffret, 2007; Badji, 2014; Hamai et al., 2015; Leffondré et al.,
 174 2021; Klingelhoefner et al., 2022).

175 In contrast to the eastern Algerian Basin (Bayer et al., 1973; Galdeano and Rossignol, 1977;
 176 Schettino and Turco, 2006; Driussi et al., 2015b; Haidar et al., 2022), the available magnetic
 177 anomaly data for the western Algerian Basin do not depict a clear pattern of linear features
 178 that can be associated with oceanic crust formed along linear segments of oceanic ridges ($\sim -$
 179 100 to -120 mGal). Conversely, the reduced-to-pole magnetic data displays irregular patches,
 180 with contrasting magnetic anomalies in the oceanic crust, which can be interpreted as
 181 scattered volcanic edifices associated with oceanic spreading centers or as post-accretion
 182 magmatism related to deep, partial melting of a metasomatized mantle (Medaouri, 2014;
 183 Medaouri et al., 2014; Aïdi et al., 2018; Klingelhoefner et al., 2022).

184 (insert here Fig. 1)

185 **Fig. 1.** *Topography of the Western Mediterranean region in the area between south Iberia and*
 186 *northern Africa, including the connection through the Strait of Gibraltar with the Atlantic Ocean in*
 187 *the Gulf of Cádiz. In the Western Mediterranean, the Algerian Basin in particular is bounded by*
 188 *the narrow and steep Algerian margin, the Alboran margin (in the transition to the East Alboran*
 189 *Basin), and the Iberian margin. The Iberian margin in particular contains different segments with*
 190 *varied orientations, like the concave and narrow margin that connects the Almería margin with the*
 191 *west-east oriented Mazarrón Escarpment, and the continuation towards the east along the southern*
 192 *slope of the islands of Ibiza and Mallorca. Elevation data merge information from the General*
 193 *Bathymetric Chart of the Oceans–Bathymetric Compilation Group 2019 (GEBCO, 2019) for the*
 194 *offshore regions with the Global Bathymetry and Topography at 15 ArcSec (SRTM15+, v. 12.1) for*
 195 *the onshore areas (Tozer et al., 2019). Image created using a grid spacing of 1 km and a light*
 196 *source oriented $135^\circ/60^\circ$ (azimuth and elevation, respectively). Bathymetry contours are every 500*
 197 *m, and undersea names are according to GEBCO (2019). Seismic lines (gray lines) used in this*
 198 *study come from the ATH database (ATH, 2020) for Spain and from various sources for the*
 199 *Algerian margin (Badji, 2014; Medaouri, 2014; Medaouri et al., 2014; Badji et al., 2015;*
 200 *Klingelhoefner et al., 2022). Thick black lines mark the position of the different figures and the*

201 *interpreted seismic lines shown in Figs. 8–17. Studied wells (Fig. 6) are located in the Alboran*
 202 *margin, the Iberian margin, and the Algerian margin. Inset shows the location of the study area*
 203 *(red rectangle) in the Mediterranean region.*

204

205 (insert here Fig. 2)

206 **Fig. 2.** *Gravity anomaly map of the same area depicted in Fig. 1. Gravity anomaly from satellite*
 207 *altimetry is taken from Sandwell et al. (2013, 2014) (v. 28.1). Image created using a grid spacing*
 208 *of 1 km and a light source oriented 135°/70° (azimuth and elevation, respectively). Main tectonic*
 209 *contacts are taken from Fig. 3. Thick black lines mark the positions of the different figures and the*
 210 *interpreted seismic lines shown in Figs. 8–17. Undersea names and wells are as in Fig. 1. Inset*
 211 *shows the location of the study area (red rectangle) in the Mediterranean region.*

212

213 2.1 Crustal structure of the Algerian Basin margins

214 The Algerian Basin in our study area has three margins with different orientations and
 215 different crustal structures (Figs. 1–3). Hereafter, we will use these names to refer to the three
 216 margins: (1) the Algerian margin, which is the southern margin of the basin, has a linear trend
 217 and a general west-southwest orientation, which has a narrow continental platform (<15 km)
 218 and steep slope connecting with the oceanic plain; (2) the Alboran margin, which is the
 219 western margin, contains abundant outcropping volcanic edifices; and (3) the Iberian margin,
 220 which is the northern part of the basin, is also formed by a series of segments with contrasting
 221 orientations, physiography, and (probably) crustal configuration.

222 2.1.1 Algerian margin

223 In comparison with the other margins, the Algerian margin is very-well studied, and
 224 numerous works document its characteristics such as seafloor features and the general
 225 structure of its sedimentary cover (Déverchère et al., 2005; Domzig et al., 2006, 2009;
 226 Mauffret, 2007; Strzeczynski et al., 2010; 2021; Medaouri et al., 2012, 2014; Medaouri, 2014;
 227 Arab et al., 2016; Leffondré et al., 2021; Haidar et al., 2022), the crustal structure (Leprêtre et
 228 al., 2013; Badji, 2014; Badji et al., 2015; Bouyahiaoui et al., 2015; Aïdi et al., 2018;
 229 Klingelhofer et al., 2022), and the recent tectonic processes that explain the distribution and
 230 nature of the earthquake activity (Aoudia et al., 2000; Yelles-Chaouche et al., 2006;
 231 Kherroubi et al., 2009, 2017; Soumaya et al., 2018; Ousadou and Bezzeghoud, 2019).

232 For the purposes of this work, the following are the main characteristics of this margin that
 233 are especially relevant for our study:

- 234 1. The physiography of the basin floor of the Algerian Basin in the vicinity of the
 235 continental rise documents the existence of subcropping, elongated (west-southwest–
 236 east-northeast and west-east) salt diapirs that deform the seafloor (Fig. 3) (e.g.,
 237 Domzig et al., 2006; Mauffret, 2007; Obone-Zue-Obame, 2009; Badji et al., 2015;
 238 Leffondré et al., 2021).
- 239 2. The sedimentary cover of this margin, particularly in the domain of the abyssal plain,
 240 contains diapirs involving the Messinian salt, although their three-dimensional
 241 geometry and the tectonic processes shaping these structures is still poorly understood
 242 (e.g., Bellucci et al., 2021).
- 243 3. The age of the sedimentary cover is mostly Messinian to recent, although older
 244 Miocene (and possibly Oligocene) sediments have been locally reported in the margin,
 245 filling depocenters with an unclear geometry and a debatable timing for their
 246 associated rifting events (e.g., Medaouri et al., 2014; Arab et al., 2016; Haidar et al.,
 247 2022).
- 248 4. The pre-Messinian sequence thickens progressively from the abyssal plain towards the
 249 continental rise (e.g., Bellucci et al., 2021; Leffondré et al., 2021).
- 250 5. The abyssal plain is floored by oceanic crust that was probably formed during the
 251 Miocene (certainly before the Tortonian) (e.g., Mauffret et al., 1992, 2004; Haidar et
 252 al., 2022).
- 253 6. The crustal structure of the margin contains a narrow, and possibly steep boundary
 254 between the continental and oceanic crusts, with an abrupt crustal thinning (within ~80
 255 km) from ~28 to 8 km (Leprêtre et al., 2013; Badji, 2014; Badji et al., 2015;
 256 Bouyahiaoui et al., 2015; Klingelhofer et al., 2022).

257

258 (insert here Fig. 3)

259 **Fig. 3.** Tectonic map of the Gibraltar Arc orogen in the Western Mediterranean Sea and the transition
 260 to the oceanic domains of the Algerian Basin in the east and the accretionary wedge of the Gulf of
 261 Cádiz in the west. Numerous sources are compiled in this map, which is based on the synthesis of
 262 Comas et al. (1999), Fernández-Ibañez and Soto (2017), and Flinch and Soto (2017). The map
 263 includes results from this study and additional sources of information for the Algerian margin
 264 (Domzig et al., 2006, 2009; Medaouri et al., 2014; Leffondré et al., 2021), the Iberian margin,
 265 from Almería to Ibiza (Comas et al., 2000, 2006a, 2006b; Woodside et al., 2000; Giaconia et al.,
 266 2015), the Alboran Sea (Mazzini et al., 2003; Martínez-García et al., 2011, 2013; Martínez-
 267 García, 2012), the Tell (Domzig et al., 2006, 2009; Yelles-Chaouche et al., 2006; Ansberque, 2011;
 268 Leprêtre et al., 2018), the Rif (Flinch, 1993, 1996; Chalouan et al., 2008), the Betics (Rodríguez
 269 Fernández et al., 2015), and the Gulf of Cádiz (Flinch, 1993; Medialdea et al., 2004, 2009;
 270 Zitellini et al., 2009). Mud volcanoes and shale diapirs, together with sub-outcropping salt diapirs
 271 (involving the Triassic or the Messinian evaporites) in the offshore areas, are taken from various

272 *authors (Comas et al., 2003; Sautkin et al., 2003; Somoza et al., 2003, 2012; Talukder et al., 2003;*
 273 *Van Rensbergen et al., 2005; Domzig et al., 2006; Fernández-Puga et al., 2007; Medialdea et al.,*
 274 *2009; Soto et al., 2010, 2012). For the sake of clarity, the Flyschs units in the Tell region include*
 275 *the Tello Nappes (e.g., Leffondré et al., 2021). Approximate distribution of the compressional*
 276 *folded belt in the Algerian Basin is marked with a stippled pattern. Thick black lines mark the*
 277 *position of the different figures and the interpreted seismic lines shown in Figs. 8–17. Undersea*
 278 *names and wells are as in Fig. 1. Abbreviations: AP= Alicante Platform; AR= Alboran Ridge;*
 279 *DP= Djibouti Plateau; EAB= East Alboran Basin; EBE= Émile Baudot Escarpment; IC= Ibiza*
 280 *(Eivissa) Channel; MC= Mallorca Channel; ME= Mazarrón Escarpment; PF= Palomares fault*
 281 *system; WAB= West Alboran Basin; YF= Yusuf fault system.*

282

283 Several other well-established observations have been made concerning the crust beneath the
 284 Algerian Basin. First, the basin has a rather standard and homogenous oceanic crust that is
 285 anomalously thin (~5.5 km). According to tomographic inversion models, this oceanic crust
 286 has an upper layer with sediments grading downwards to basalts (V_p varies progressively
 287 from 4.8 to 6.0 km \times s⁻¹) and a lower oceanic layer that is most probably formed of gabbroic
 288 rocks rather than by components of serpentized mantle (V_p increases from 6.1 to 7.2 km \times s⁻¹)
 289 (e.g., Badji et al., 2015; Bouyahiaoui et al., 2015; Klingelhofer et al. 2022). Second, the
 290 boundary between the oceanic and continental crusts is one of the singularities of this margin,
 291 because it is always accompanied by a narrow transition (~5.5 km wide) between them. The
 292 wide-angle refraction profiles in this domain, together with tomographic inversion data, show
 293 that the crust in the narrow ocean–continent transition (OCT) has sonic velocities intermediate
 294 between those of the bounding oceanic and continental crusts. In particular, the OCT has a
 295 strong velocity gradient in the upper crust and the deep crust has velocities similar to the
 296 lower continental crust (Leprêtre et al., 2013; Badji, 2014; Badji et al., 2015; Bouyahiaoui et
 297 al., 2015; Klingelhofer et al., 2022). Some segments of the Algerian margin even document
 298 the existence of a small domain with a relatively thicker oceanic crust (Moho at 12–13 km
 299 depth), showing a local thickening of the lower layer of the oceanic crust (e.g., Bouyahiaoui et
 300 al., 2015). The narrow ocean–continent boundary has been interpreted as a result of two
 301 processes: the occurrence of a general transcurrent plate boundary along this margin (a
 302 subduction transform edge propagation–fault [STEP–fault] margin) (Badji, 2014; Medaouri,
 303 2014; Medaouri et al., 2014; Badji et al., 2015; van Hinsbergen et al., 2014; Spakman et al.,
 304 2018; Jolivet et al., 2021a, 2021b; Leffondré et al., 2021) and the occurrence of a moderate
 305 underthrusting of the Algerian oceanic crust beneath the continental African plate (Auzende et
 306 al., 1975; Déverchère et al., 2005; Mauffret, 2007; Leprêtre et al., 2013; Badji et al., 2015;
 307 Hamai et al., 2015, 2018; Leffondré et al., 2021).

308 2.1.2 Alboran margin

309 The transition of the Algerian Basin to the East Alboran Basin on the Alboran margin
310 coincides with a broad, north–south-trending domain of a thin continental crust (14–10 km
311 thick) with abundant Neogene calc-alkaline and tholeiitic volcanism with isotopic ages
312 ranging from the Serravallian to the Messinian (12–6 Ma), which evolves to intraplate-type
313 alkali basalts of latest Messinian–to–early Pliocene age (6.0–0.8 Ma) (see reviews of Savelli
314 [2002], Duggen et al. [2003, 2004], and Soto et al. [2008]). The abundance of volcanism
315 together with the geophysical properties of this crust, such as high heat flow (Polyak et al.,
316 1996; Poort et al., 2020), high Vp velocities (typically >6.0 and sometimes ranging between
317 7.1 and 7.3 km×s⁻¹) (Booth-Rea et al., 2007, 2018), and relatively low densities (2,820–2,840
318 kg×m⁻³) (Soto et al., 2008), have been used to postulate that the East Alboran Basin is flooded
319 by a highly stretched continental crust (Hatzfeld et al., 1978; Comas et al., 1997; Medaouri et
320 al., 2014) or even with a volcanic arc-type continental crust (Booth-Rea et al., 2007, 2018;
321 Gómez de la Peña et al., 2018, 2020, 2021). According to the half-graben geometries
322 identified in the Neogene sedimentary cover (typically <2 km thick, in places <1 km thick)
323 above this crustal domain, workers have suggested that west-east crustal stretching was active
324 there during the Miocene (possibly during the Middle Miocene) (Mauffret et al., 1992;
325 Medaouri et al., 2014). Nevertheless, the magnitude of extension, three-dimensional geometry
326 of the extensional faults, and the exact timing of the rifting and crustal stretching are still not
327 well established.

328 In addition to the rifting structures, two important crustal-scale (> 180 km long) strike-slip
329 fault systems deform the East Alboran Basin (Fig. 3). One of these systems is the
330 transtensional, right-lateral Yusuf fault, which trends west-northwest and connects two
331 compressional domains, the Alboran Ridge towards the west (Fig. 4) and the Algerian margin
332 towards the southeast (Mauffret et al., 1992; Fernández-Ibáñez et al., 2007; Medaouri et al.,
333 2012; Martínez-García et al., 2013). The other fault system is the Carboneras fault system,
334 which is formed by various transpressional, left-lateral fault segments. These segments trend
335 southwest–northeast and extend from the Djibouti Plateau to the onshore volcanic province of
336 Cabo de Gata (e.g., Gràcia et al., 2006, 2012) to finally connect eastward with the north–
337 south, left-lateral Palomares fault. This latter fault runs subparallel to the coastline, shaping a
338 north–south continental margin in the eastern Betics (Comas et al., 2006a, 2006b; Giaconia et
339 al., 2015). These two crustal-scale strike-slip faults probably have been active since the
340 Middle and Upper Miocene, and according to seismicity, faulting along them continues up to

341 the present (e.g., Mauffret et al., 1992; Fernández-Ibáñez et al., 2007; Medaouri et al., 2012;
 342 Gómez de la Peña et al., 2018; Spakman et al., 2018).

343 (insert here Fig. 4)

344 **Fig. 4.** *Cross section from the western Betics and the West and South Alboran Basins to the African*
 345 *foreland (modified from Flinch and Soto, 2017). Crustal thickness is according to Torne et al.*
 346 *(2000) and Soto et al. (2008). Structures in the offshore region are from various sources (Soto et*
 347 *al., 2010; Martínez-García, 2012; Fernández-Ibáñez and Soto, 2017). Location of the section is*
 348 *shown in Figs. 1–3.*

349

350 2.1.3 Iberian margin

351 The Iberian margin is composed of several segments with varied orientations and possibly
 352 with different tectonic styles, and contains the eastern continuation of the Betic Cordillera
 353 (Fig. 3). From west to east in the study area, this margin is formed by three segments: (1) a
 354 narrow north–south segment that includes the Palomares fault system, which we mentioned
 355 previously; (2) the steep west–east segment identified along the Mazarrón Escarpment; and
 356 (3) the gently dipping continental talus developed south of the Balearic Islands of Ibiza and
 357 Mallorca, which contains the southwest–northeast-trending Émile Baudot Escarpment.

358 The Palomares segment has a very narrow continental platform (<10 km in width) and a steep
 359 continental slope that is incised by deep, west–east canyons and some elongated volcanic
 360 highs (e.g., the Abubacer and Maimonides High; Fig. 1) that are accompanied by local
 361 positive gravity anomalies (Fig. 2). The few studies of this margin document the existence of
 362 very recent (Pliocene) and seismically active, high-angle, left-lateral strike-slip faults. These
 363 faults are similar in orientation, kinematics, and timing to the onshore segment of the
 364 Palomares fault system (Fig. 3) (Mauffret et al., 1992; Comas et al., 2000, 2006a, 2006b;
 365 Gómez de la Peña et al., 2018). Some studies also document the existence of a moderate
 366 compressional deformation associated with the strike-slip faults, developing southwest–
 367 northeast volcanic highs and anticlines (e.g., Abubacer High) that affect the thin Pliocene-to-
 368 Quaternary cover of this margin (Giaconia et al., 2015). The overall structure of the
 369 Palomares segment is interpreted to correspond to a north–south narrow continental margin
 370 with active, left-lateral transpressional strike-slip faulting (Comas et al., 2000, 2006b;
 371 Fernández-Ibáñez et al., 2007; Giaconia et al., 2015).

372 The Palomares segment changes abruptly to a narrow, west-trending slope that corresponds to
 373 the Mazarrón Escarpment. This segment of the margin is relatively unexplored, and the few
 374 studies there reflect the occurrence of massive submarine slides activated by steep, west-

375 trending normal faults (Fig. 3) (Mauffret et al., 1992; Comas et al., 2000; Woodside et al.,
376 2000; Maillard and Mauffret, 2013). The segment also includes an isolated volcanic edifice
377 known as the Águilas Seamount (Fernández Soler et al., 2000), limited by a northwest-
378 trending, high-angle normal fault (the Tiñosa fault), which does not have a significant
379 associated gravity anomaly (Figs. 1–3). The Mazarrón Escarpment constitutes the continental
380 slope of a larger continental platform, which extends southeast and east of Murcia and
381 Alicante. Sufficient geophysical information (seismic profiles and wells) is available to
382 confirm that the Alboran Domain of the eastern Betics continues offshore beneath this
383 continental platform (Fig. 3) (Comas et al., 2000, 2006b; Fernández Soler et al., 2000; Alfaro
384 et al., 2002; Roca et al., 2004; Maillard and Mauffret, 2013; Driussi et al., 2015a, 2015b;
385 Kumar et al., 2021). The height of the Mazarrón Escarpment diminishes eastward, vanishing
386 in an area where we interpret the presence of an embayment of the oceanic crust (at ~lat
387 37.5°N, long 0.5°E). This embayment forms a northward continuation of the abyssal plain of
388 the Algerian Basin, which connects with the next segment of the margin, which is marked by
389 the Émile Baudot Escarpment.

390 The easternmost domain of the Iberian margin in the study area contains two continental
391 platforms around the Ibiza and Mallorca islands and exhibits a common gentle continental
392 slope featuring a rugose seafloor with abundant slide scars (Acosta et al., 2001; Lastras et al.,
393 2004, 2006; Camerlenghi et al., 2009) and some isolated volcanic highs near the continental
394 rise (e.g., the Prunes Seamount; Figs. 1, 2). The trend of this segment of the margin is
395 approximately west–east up to the Prunes Seamount, changing progressively to be
396 southwesterly along the Émile Baudot Escarpment. Multiple researchers suggest that the
397 External and Internal domains of the eastern Betics continue eastward, maintaining a west-
398 southwest trend (Sàbat et al., 1997; Alfaro et al., 2002; Lastras et al., 2004; Maillard and
399 Mauffret, 2013; Maillard et al., 2014). The continent–ocean transition (OCT) occurs along a
400 narrow crustal boundary (Sàbat et al., 1997; Roca et al., 2004; Driussi et al., 2015b) that has
401 been interpreted as a transcurrent margin, associated with right-lateral strike-slip faulting
402 (Mauffret et al., 1992, 2004; Camerlenghi et al., 2009; Dal Cin et al., 2016; Jolivet et al.,
403 2021b) that is accompanied by recent volcanic intrusions (Acosta et al., 2001; Maillard and
404 Mauffret, 2013).

405 Our interpretation of the limit of the oceanic crust in the Algerian Basin is included in Figs. 2
406 and 3. Three types of observations have been used to map this limit: (1) our interpretation of
407 the crustal structure according to seismic profiles; (2) the fact that most of the diapiric

408 structures affecting a thick Messinian salt layer occur above the oceanic crust (e.g., Biju-
409 Duval et al., 1978; Mauffret et al., 1992, 2004; Comas et al., 1997, 2000, 2006a, 2006b;
410 Camerlenghi et al., 2009; Maillard et al., 2014; Dal Cin et al., 2016; Pellen et al., 2016; Haq et
411 al., 2020; Bellucci et al., 2021), although some authors suggest that salt pinches out above the
412 deeper parts of the adjacent thinned continental crust (Driussi et al., 2015b); and (3) the
413 distribution and magnitude of the gravity anomalies. The northern limit of oceanic crust
414 coincides clearly with a domain where the polarity of the gravity anomaly changes, being
415 positive in the continental domain and moderately negative or zero in the oceanic domain
416 (also in Driussi et al. [2015b]). In contrast, the southern limit of the continental crust, along
417 the Algerian margin, is marked by a narrow negative anomaly (~50–70 mGal) that runs
418 parallel to the continental rise. The origin of this anomaly has been interpreted as the
419 combination of two processes: a larger sedimentary thickness of the pre-Messinian sediments
420 (i.e., a static contribution to the gravity field) and the effects of the incipient subduction of
421 oceanic crust below the overriding continental crust of the African plate (i.e., a dynamic
422 contribution due to flexure of the subducting oceanic crust) (e.g., Leprêtre et al., 2013;
423 Bouyahiaoui et al., 2015; Hamai et al., 2015).

424

425 *2.2 Plate-tectonic scenario*

426 Numerous authors have reconstructed the relative motions of the bounding plates in the
427 Western Mediterranean Sea. All these studies document that, with respect to a fixed position
428 of the Eurasian plate, the Africa (Nubia) plate migrated towards the east and southeast starting
429 in the Middle Jurassic, changed direction to move towards the east-northeast (~85–80 Ma)
430 and finally towards the north in the Upper Cretaceous (since the Maastrichtian, at 70 Ma).
431 This relative drift of Africa is illustrated in Fig. 5 using the plate reconstruction model of
432 Rosenbaum et al. (2002). To reconstruct the positions of Africa with respect to Eurasia (Fig.
433 5c) and compute the trajectories of two singular points of the study area (Figs. 5a, 5b), we
434 have used the dataset of these authors and the standard method to reconstruct plate trajectories
435 in a sphere described by many authors (e.g., Le Pichon et al., 1973).

436 To illustrate the implications of plate motions in the area of interest, we have computed the
437 trajectories followed since 165 Ma (Callovian) of two representative points (Fig. 5c): one is
438 selected to show the motion of the Algerian margin (presently situated at lat 35°N, long
439 1.5°E), and the other is representative of the final position of the western Betics, particularly

440 the West Alboran Sea (currently situated at lat 36°N, long 4°W). Importantly, the trajectory of
 441 the latter point does not reflect orogenic processes like the large allochthonous westward
 442 migration of the Alboran Domain nor its Neogene collapse.

443 (insert here Fig. 5)

444 **Fig. 5.** Relative motion of the African plate with respect to a fixed Eurasia plate, using the plate-
 445 tectonic reconstruction of Rosenbaum et al. (2002). (a) Plot with the orientation of the convergence
 446 azimuth for the African plate during the past 50 Ma (Ypresian, early Eocene time), computed for
 447 two singular points: one in the West Alboran Basin (with a present-day position of lat 36°N, long
 448 4°W; blue curve) and the other in the onshore region of Algerian margin (lat 37.5°N, long 1.5°E;
 449 green curve). (b) Plot with the velocity (in $\text{mm}\times\text{yr}^{-1}$) of the African plate motion for the same points
 450 used for (a). Both plots include the present-day conditions for the African plate motion according
 451 to current plate-motion models (Nuvel-1A from DeMets et al. [1994] and Deos-2k from Fernandes
 452 et al. [2003]). The two components of the overall vector of the plate convergence in the west–east
 453 and north–south orientations are also included in the plot, with discontinuous and dotted lines,
 454 respectively. Messinian salt precipitation during the MSC (5.97–5.55 Ma; e.g., Andreetto et al.
 455 [2021]) is included in both plots for reference. (c) Map representing the relative motion of the
 456 African plate with respect to a fixed Eurasian plate and the trajectories from 165 Ma to present
 457 (beginning in Callovian, Middle Jurassic time) of the two singular points used to compute plots (a)
 458 and (b). The trajectories followed by these two points during the past 50 million years, which are
 459 detailed in (a) and (b), are marked with a thicker colored line. The actual boundary between the
 460 two plates is omitted for the sake of clarity. Abbreviation: Pl-Q= Pliocene–Quaternary.

461

462 Although other models reconstruct the plate motions of Africa and Eurasia in the Western
 463 Mediterranean Sea (Dewey et al., 1989; Srivastava et al., 1990; Roest and Srivastava, 1991;
 464 Mazzoli and Helman, 1994; Capitanio and Goes, 2006; Schettino and Turco, 2006, 2009;
 465 Handy et al., 2010; Jolivet et al., 2015, 2021; Hosseinpour et al., 2016; Macchiavelli et al.,
 466 2017; Romagny et al., 2020; van Hinsbergen et al., 2020; Frasca et al., 2021), researchers
 467 have achieved consensus concerning the following important points:

- 468 1. During most of the Mesozoic (at least from 180–80 Ma) the motion of Africa with
 469 respect to a fixed Eurasia was a continuous drift towards the southeast, maintaining
 470 the north–south dimensions of a relatively narrow corridor that represented the
 471 western termination of the Tethys Basin.
- 472 2. From the latest Cretaceous to the earliest Eocene (80–55 Ma), the African plate
 473 changed its trajectory, initiating a northwest–north-northwest-directed convergence
 474 with Eurasia.
- 475 3. During a short interval in the early Eocene (55–50 Ma), Africa moved suddenly
 476 towards the southwest, promoting a moderate stretching of the narrow basin between
 477 the two plates.

478 The post-Eocene evolution of the two plates is of particular interest to our study (Rosenbaum
479 et al., 2002; DeMets et al., 2015; Romagny et al., 2020) because the African plate moved
480 continuously towards the north-northeast from 45 to 25 Ma (from the middle Eocene to the
481 latest Oligocene), with an increasing rate of convergence with Eurasia peaking at 9–12
482 $\text{mm}\times\text{yr}^{-1}$ at 25 Ma (Fig. 5b). During the Lower and Middle Miocene (25–15 Ma), an
483 important modification of the plate convergence occurred because Africa moved towards the
484 northeast and west-northwest down to 4 $\text{mm}\times\text{yr}^{-1}$ (Figs. 5a, 5b). Since then, from the Upper
485 Miocene to the present, the convergence of the African plate was oblique, with an average
486 trend of convergence that evolved from being west-northwesterly in the latest Middle
487 Miocene to northwesterly in the present day (average azimuths 100° – 135°), according to the
488 geodetic models of DeMets et al. (1994) and Fernandes et al. (2003), and the GPS
489 determinations of Bougrine et al. (2019).

490 After the deposition of the Messinian salt (at ~ 5.5 Ma), the plate convergence rate diminished
491 slightly through time, being at present slightly higher along the Algerian margin than in the
492 West Alboran Basin (5.5 and 4.7 $\text{mm}\times\text{yr}^{-1}$, respectively) (Fig. 5b). During this recent epoch
493 (<5.5 Ma), a slight change in the convergence vector between the two plates can be
494 interpreted, evolving from north-northwest to northwest convergence (Fig. 5a). The average
495 trends for plate convergence in this period, changed from 127° to $\sim 115^{\circ}$ for the point in the
496 West Alboran Basin and from 140° to 130° for the Algerian margin.

497

498 **3. Dataset and methods**

499 We used a large dataset of commercial and scientific wells and seismic profiles (of about 280
500 lines, representing a total length of $\sim 8,000$ km), from both offshore Spain and Algeria (Fig.
501 1). Wells selected for this study come from two scientific drillings conducted by the Ocean
502 Drilling Program (ODP) in the East Alboran Basin and a commercial well near the basin's
503 northern margin (Comas et al., 1999), six wells on the eastern continental shelf in Spain
504 (south of Valencia to Murcia) (acquired through Archivo Técnico de Hidrocarburos [ATH,
505 2020]), and three commercial wells along the Algerian margin (Buroillet et al., 1978;
506 Medaouri et al., 2012, 2014). We used these wells to produce the correlations between the
507 Algerian Basin margins shown in Fig. 6. These correlations show synthetic stratigraphic
508 sections in the offshore continuation of the eastern Betics (wells Javea-1, Calpe-1, Alicante A-
509 1, and Muchamiel-1; Fig. 6a), the northern East Alboran Basin (well Andalucía A-1 and ODP

510 Sites 978 and 977; Fig. 6b), and the variation along-strike in the Algerian margin (wells
511 Habibas-1, Arzew-1, and Alger-1; Fig. 6c).

512 The 2D seismic lines selected to illustrate this work were acquired from a variety of sources.
513 Seismic for the northern margin of the Alboran Basin in Spain were obtained through ATH
514 (2020). For the Algerian margin in the south, we have selected various commercial and
515 scientific lines reproduced in works like Badji (2014), Medaouri (2014), Medaouri et al.
516 (2014), Badji et al. (2015), and Klingelhoefer et al. (2022). The Alboran margin has been
517 studied using one of the deep seismic profiles of Comas et al. (1997), which was later
518 processed and interpreted by Booth-Rea et al. (2007, 2018) and Gómez de la Peña et al.
519 (2018).

520 Our seismic interpretation had four goals:

- 521 1. Characterize the structures involving the Messinian salt using salt tectonic concepts
522 and theory (e.g., Jackson and Hudec, 2017).
- 523 2. Reconstruct the geometry of the suprasalt sequences (i.e., Messinian to recent) to
524 evaluate the relationships among deformation, halokinesis, and sedimentation.
- 525 3. Where seismic has enough resolution, evaluate the geometry of the presalt sequences
526 and determine the basement-involved structures.
- 527 4. Establish the general structural style of the deformation affecting the basement and
528 identify the reflections marking the crust–mantle boundary to compare with other
529 sources of information for this discontinuity.

530 The correlation of horizons between seismic lines along the Algerian margin was conducted
531 using a dense grid of seismic profiles (Fig. 1). We then used the relatively few intersections
532 between seismic lines from the Iberian and Algerian margins to correlate the horizons from
533 the south to the north. We are conscious of the relatively poor quality of the vintage seismic
534 lines in the Iberian margin, so our interpretations there, particularly those related to salt
535 geometries, should be accepted with caution.

536 One of the seismic interpretations from the Algerian margin has been converted to depth
537 using the seismic velocities established in the sedimentary cover of the region (Badji et al.,
538 2015; Bouyahiaoui et al., 2015; Klingelhoefer et al., 2022). Details about the depth
539 conversion, as well as the procedure to make the restoration, are provided in Section 6.

540

541 4. Seismic stratigraphy

542 The seismic stratigraphy scheme used for our study follows the stratigraphic framework
 543 established by previous workers in the region. For the East Alboran Basin, for example, we
 544 use data from Comas et al. (1992, 1997, 1999), Medaouri et al. (2012, 2014), and Gómez de
 545 la Peña et al. (2021). Information about the seismic facies of the sedimentary cover along the
 546 Iberian margin is taken from Maillard and Mauffret (2013), Maillard et al. (2014), and
 547 Giaconia et al. (2015), together with the detailed Messinian stratigraphy established there by
 548 Driussi et al. (2015a, 2015b) and Ochoa et al. (2015). The seismic stratigraphy of the Algerian
 549 margin follows information provided by Strzeczynski et al. (2010, 2021), Badji (2014),
 550 Medaouri (2014), Mihoubi et al. (2014), Badji et al. (2015), Haidar et al. (2022), and
 551 Klingelhofer et al. (2022). In addition, we have made revisions based on information
 552 provided from the following wells: Andalucía A-1 and ODP Sites 977 and 977 (with data
 553 from Comas et al. [1999]), Javea-1 (Texas Pacific Oil Co., 1977), Calpe-1 (Texas Pacific Oil
 554 Co., 1975), Alicante A-1 (Upton and Young, 1984), Muchamiel-1 (ESSO, 1981), Torrevieja
 555 Marino C-1 (ENIEPSA, 1979), Habibas-1 (Medaouri et al., 2012, 2014; Medaouri, 2014), and
 556 Alger-1 and Arzew-1 (Buroillet et al., 1978). In wells Calpe-1 and Muchamiel-1, we also used
 557 the detailed revision of the Upper Miocene sequences conducted by Ochoa et al. (2015).

558 The stratigraphic correlation that we established among the three margins of the Algerian
 559 Basin according to well information is presented in Fig. 6.

560 All the aforementioned information was extrapolated and tied to the studied seismic profiles,
 561 resulting in a seismic stratigraphy scheme that is illustrated in Fig. 7. The seismic facies along
 562 the continental rise of the Algerian Basin are shown in Figs. 7a and 7b using a seismic
 563 window from the Algerian margin. The domain of the basin floored by oceanic crust is
 564 exemplified in Figs. 7c and 7d.

(insert here Fig. 6)

566 **Fig. 6.** Well correlation in the study area along the three margins of the Algerian Basin: (a) a north–
 567 south transect (wells Javea-1, Calpe-1, Alicante A-1, and Muchamiel-1) in the Iberian margin,
 568 documenting the offshore continuation of the eastern Betics; (b) a northwest–southeast transect
 569 (wells Andalucía A-1, ODP Site 978, and ODP Site 977) in the East Alboran Basin towards the
 570 Algerian Basin; and (c) west-southwest–east-northeast transect (wells Habibas-1, Arzew-1, and
 571 Alger-1) along strike of the Algerian margin. The diagram shows the correlation for the base of the
 572 Pliocene–Quaternary section (the Messinian or M unconformity) as well as the position and nature
 573 of the Messinian sequences, differentiating the occurrence of evaporite-dominated (in red;
 574 distinguishing when gypsum or anhydrite are the more abundant minerals) and mud-dominated
 575 sequences (in light yellow). Inset shows the correlation lines of the three transects, using wells
 576 (black dots) as they are located in Fig. 1. Distance between wells is shown between the lithological
 577 columns. Stratigraphic and paleontological information in these wells is extracted from: Comas et

578 *al. (1999) (well Andalucía A-1 and OPD Sites 978 and 977); Medaouri et al. (2012, 2014) (well*
 579 *Habibas-1); Burollet et al. (1978) (wells Arzew-1 and Alger-1); Texas Pacific Oil Co. (1977) (well*
 580 *Javea-1); Texas Pacific Oil Co. (1975) and Ochoa et al. (2015) (Calpe-1); Upton and Young*
 581 *(1984) (well Alicante A-1); and ESSO (1981) and Ochoa et al. (2015) (well Muchamiel-1).*
 582 *Approximate boundary positions are marked with discontinuous lines. Abbreviations: LU= Lower*
 583 *Messinian series; UU= Upper Messinian series.*

584

585 The Pliocene–Quaternary section thickens towards the center of the Algerian Basin. On the
 586 Algerian margin, these series also thickens towards the East Alboran Sea; i.e., towards the
 587 west-southwest (cf. change from Arzew-1 to Habibas-1 wells in Fig. 6c). We have interpreted
 588 three seismic units within the Pliocene–Quaternary sequence, bounded by unconformities.

589 The Pliocene–Quaternary sequence lies above a Mediterranean Basin–wide regional
 590 unconformity known as the “M reflector” (e.g., Hsü et al., 1977; Biju-Duval et al., 1978;
 591 Ryan and Cita, 1978). Below this unconformity, the sedimentary section consists of a
 592 Miocene sequence of variable thickness, being up to 1.1 km thick in the shallow portion of the
 593 Algerian margin and 2.4 and 2.6 km thick in the continental platforms of the northern and
 594 southern East Alboran Basin, respectively (according to data from wells Andalucía A-1 and
 595 Habibas-1). The offshore continuation of the External Betics along the Iberian margin consists
 596 of a variable sequence of Upper Miocene, fine-grained detritic sediments (with a maximum
 597 thickness of 0.95 km in the well Calpe-1) above Jurassic–Paleogene limestones and Triassic
 598 evaporites (Fig. 6).

599 In the shallow portion of the studied margins, the Messinian sequence locally comprises reef
 600 buildups, but is characterized in most places by marls, calcareous claystones, and fine-grained
 601 siltstones with intercalations of gypsum and eventually anhydrite that becomes more abundant
 602 basinward (e.g., wells Calpe-1, Muchamiel-1, and Alger-1; Burollet et al., 1978; Martínez del
 603 Olmo, 2011a; Ochoa et al., 2015; Raad et al., 2021). The Messinian evaporite sequence is
 604 formed by gypsum-rich marls that grade downward to anhydrite-rich marls and clays (e.g.,
 605 well Arzew-1). This gypsum-rich sequence in the Iberian margin is referred to as the bedded
 606 units (BU) (Lofi et al., 2011a, 2011b; Maillard et al., 2014; Driussi et al., 2015a, 2015b;
 607 Ochoa et al., 2015; Raad et al., 2021), which are commonly correlated by these authors with
 608 the primary lower gypsum (PLG) unit, with an estimated age of 5.971–5.61 Ma, formed
 609 during Stage 1 of the MSC (e.g., Andretto et al., 2021).

610 None of the available wells in the area cut the Messinian salt (mostly halite, but possibly also
 611 with other evaporites like gypsum and anhydrite) sequence that was deposited in the deepest
 612 portion of the basin, flooring the abyssal plain of the Algerian Basin (e.g., Biju-Duval et al.,

613 1978; Mauffret et al., 1992, 2004; Driussi et al., 2015b; Gorini et al., 2015; Dal Cin et al.,
614 2016; Lofi et al., 2018; Haq et al., 2020), which is commonly referred as the mobile unit
615 (MU) (Lofi et al., 2011a, 2011b; Lofi, 2018).

616 For the Messinian series, we have distinguished the salt layer (equivalent to the MU unit) and
617 two subunits within the Upper Messinian sequence; the so-called UU unit (“Unité Supérieure
618 Messinienne” or “Evaporites supérieures”) (*sensu* Lofi et al., 2011a, 2011b; Lofi, 2018;
619 Leroux et al., 2019; Andreetto et al., 2021). The salt unit has semitransparent seismic facies
620 with some scarce discontinuous and strong positive reflections that suggest the existence of
621 other evaporites or lithologies in addition to pure halite (e.g., Raad et al., 2021). The base of
622 the salt corresponds to a weak reflection with a higher amplitude towards the basin margins
623 (e.g., Fig. 7a). The UU unit is represented by layered seismic facies with a pair of strong
624 positive reflections at the top. We have differentiated two seismic units within the UU, an
625 upper UU unit (UU2) with strong parallel reflections and a lower UU unit (UU1) with weak
626 parallel reflections and some patches of transparent seismic facies (in line with a comparable
627 differentiation made in other Messinian deep basins in the Western Mediterranean Sea; e.g.,
628 Obone-Zue-Obame et al. [2011], Geletti et al. [2014], and Dal Cin et al. [2016]).

629 Some wells document also the occurrence of thin intervals of anhydrite and gypsum within
630 the uppermost Tortonian sediments (e.g., wells Alicante A-1 and Alger-1). This evidence may
631 relate to observations in some of the onshore basins in Algeria (e.g., Chlef Basin) and
632 southeastern Iberia (Bajo Segura Basin), showing local deposition of evaporites during the
633 late Tortonian Age (e.g., Krijgsman et al., 2000; Rouchy et al., 2007; Ortí et al., 2014; García-
634 Veigas et al., 2020). Nevertheless, recent studies in some of the offshore wells (Muchamiel-1
635 and Calpe-1) suggest that all the evaporites (gypsum) can be assigned to the PLG unit of the
636 MSC (Martínez del Olmo, 2011b; Ochoa et al., 2015). In spite of this debate, our summary in
637 Fig. 6 reproduces the available paleontological data, suggesting local deposition of evaporites
638 (with gypsum and anhydrite) in the shallow basins of the Algerian Basin margins during the
639 uppermost Tortonian Age.

640 The presalt sedimentary sequence is locally identified along the Algerian margin and the
641 Alboran margin, either below the Messinian series (Fig. 7) or under the regional unconformity
642 marked by the strong M reflector, which has associated deep erosion (e.g., Soto et al., 2010;
643 Estrada et al., 2011; Garcia-Castellanos and Villaseñor, 2011; Just et al., 2011; Martínez del
644 Olmo, 2011a, 2011b; Martínez-García et al., 2011, 2013; Do Couto et al., 2016; Booth-Rea et
645 al., 2018) and local deposition of conglomerate deposits around emergent basement highs

646 (e.g., ODP Site 977; Comas et al., 1999). The distribution of the seismic dataset makes it
 647 impossible to establish a precise lateral correlation of the presalt sequence age. Our
 648 interpretation of the age of this sequence incorporates the information provided from the
 649 available wells in the region (Fig. 6). Based on this information, we assume that the presalt
 650 sequences in the Algerian Basin margins are of Middle Miocene–Tortonian age. Some of
 651 these sequences could locally include Lower Miocene sediments, as has been suggested
 652 further to the east in the Algerian margin (e.g., Medaouri et al., 2014; Arab et al., 2016;
 653 Haidar et al., 2022).

654 (insert here Fig. 7)

655 **Fig. 7.** *Seismic examples and interpretation illustrating the different seismic units and regional*
 656 *reflections differentiated in this study. (a) Seismic window in the continental rise of the Algerian*
 657 *margin. (b) Seismic interpretation of (a). (c) Seismic window in the oceanic domain of the Algerian*
 658 *Basin. (d) Seismic interpretation of (c). Three Messinian sequences are distinguished in this work,*
 659 *following Lofi et al. (2011a, 2011b) and Lofi (2018), where UU refers to the “Unité Supérieure*
 660 *Messinienne” of these authors (Table 1). Discontinuous lines mark internal reflections within the*
 661 *differentiated seismic units and uncertain seismic reflectors. Double arrows correspond to*
 662 *positively inverted normal faults, with the open arrow indicating the sense of displacement of the*
 663 *previous normal fault. Locations of the seismic windows are detailed in Fig. 17.*

664

665 In summary, we have used the following age boundaries for the seismic units (Table 1): (1)
 666 top of the Late Pliocene unit: 3.6 Ma; (2) intra-Pliocene discontinuity: ~4.0 Ma; (3) top of the
 667 UU2 unit: 5.33 Ma; (4) top of the UU1 unit: ~5.42 Ma; (5) top and base of salt: 5.55 and ~6
 668 Ma (5.971 Ma), respectively; and (6) presalt sequences, containing Middle Miocene–
 669 Tortonian sediments (up to ~7.5 Ma). The age we use for the Messinian units follows the
 670 regional stratigraphy established in the Mediterranean Basin for the MSC (Krijgsman et al.,
 671 1999, 2018; Lofi et al., 2011a, 2011b; Bache et al., 2012; Roveri et al., 2014, 2019; Lofi,
 672 2018; Leroux et al., 2019; Andreetto et al., 2021). For the age of the base of salt, we have
 673 preferred to use 6.0 Ma (according to 5.971 Ma), instead of 5.6 Ma (Meilijson et al., 2019).
 674 So, we assume that salt deposition (precipitation) occurred in the Algerian Basin from the
 675 beginning of the MSC. This excludes a more complex scenario of sedimentation of presalt
 676 Messinian sediments in which other evaporites (selenite), euxinic shales, and dolostones
 677 would correspond with the lower evaporites (LU) unit (MSC Stage 1, *sensu*, e.g., Roveri et al.
 678 [2014]). This assumption also has been followed by previous studies in the area (e.g.,
 679 Bouyahiaoui et al., 2015; Dale et al., 2021).

680

681

| Units | Age (Ma) ⁽¹⁾ | Lithology | Porosity ⁽²⁾ | | V _p (m×s ⁻¹) | ρ (kg×m ⁻³) |
|----------------------------------|-------------------------|----------------------|-------------------------|-----------------------|-------------------------------------|-------------------------|
| | | | φ ₀ | c (km ⁻¹) | | |
| Sea water | 0 | - | 0 | 0 | 1500 | 1030 |
| Quaternary | 0 | shale | 0.53 | 0.56 | 1900 | 2720 |
| Upper Pliocene | 3.60 | shale | 0.45 | 0.56 | 2100 | 2720 |
| Lower Pliocene | 4.00 | sand | 0.40 | 0.56 | 2200 | 2650 |
| UU2 (Mess.) | 5.33 | shale ⁽³⁾ | 0.38 | 0.56 | 2500 | 2720 |
| UU1 (Mess.) | 5.42 | silt ⁽³⁾ | 0.36 | 0.56 | 2750 ⁽⁴⁾ | 2680 |
| Messinian salt | 5.55 | salt | 0 | 0 | 4500 ⁽⁵⁾ | 2200 ⁽⁶⁾ |
| Presalt | ~7.50 ⁽⁷⁾ | silt | 0.56 | 0.39 | 3500 ⁽⁸⁾ | 2680 |
| Continental crust ⁽⁹⁾ | 28 | - | 0 | 0 | 6500 | 2820 |
| Oceanic crust ⁽¹⁰⁾ | 35 | - | 0 | 0 | 7000 | 2890 |

Notes:

(1) Age for the top of the unit. See text for sources.

(2) Using [Sclater and Christie \(1980\)](#).

(3) Approximate lithologies used for backstripping analysis (see note [2]).

(4) Some studies suggest V_p values in the UU unit of up to 3100 ([Dal Cin et al., 2016](#)), 3300 ([Dale et al., 2021](#)), 3400 ([Bouyahiaoui et al., 2015](#)) or 3600 m×s⁻¹ ([Lefondré et al., 2021](#)).(5) Sonic velocities in the Messinian salt are quite variable, varying from 4200 to 5100 m×s⁻¹ ([Montadert et al., 1978](#); [Dal Cin et al., 2016](#); [Dale et al., 2021](#)), although some authors infer lower velocities of 3800–4030 m×s⁻¹ ([Bouyahiaoui et al., 2015](#); [Haq et al., 2020](#); [Lefondré et al., 2021](#)).(6) Close to the average density of 2130 kg×m⁻³ estimated by [Dale et al. \(2021\)](#).

(7) Assuming the occurrence of late Tortonian sediments below the MSC series.

(8) The deepest sediments in the Algerian margin could have velocities of 4800 m×s⁻¹ ([Bouyahiaoui et al., 2015](#); [Klingelhoefer et al., 2022](#)).(9) Properties according to [Christensen and Mooney \(1995\)](#) and the average density established in the region by [Soto et al. \(2008\)](#).(10) Properties according to [Carlson and Raskin \(1984\)](#). Measured sonic velocities in the Algerian margin are slightly lower, ~6750 m×s⁻¹ (e.g., [Klingelhoefer et al., 2022](#)).

682 **Table 1.** Characteristics of the different seismic units of this study and values used to conduct the
 683 restoration (Fig. 18):

684

685 5. Structural interpretation of the seismic profiles

686 Our interpretation of the general structure of the Algerian Basin margins is presented through
 687 selected profiles that illustrate the structural configuration of the Iberian margin in the north
 688 (Figs. 8-10), the Alboran margin in the west (Figs. 11-13a), and the structure of the Algerian
 689 margin in the south (Figs. 13c-17). All seismic profiles are in two-way time (TWT) and were
 690 acquired at different times (from the 1970s to the 2010s) using diverse sources and processed
 691 with different workflows.

692

693 5.1 Seismic sections along the Iberian margin

694 The structure of the Iberian margin is shown through two northwest–southeast dip lines (Figs.
 695 8, 9) and a cross-cutting, west-southwest–east-northeast strike line (Fig. 10).

696 The configuration of the margin from the southernmost domain of the Gulf of Valencia and
 697 the Ibiza Channel, across the continental slope containing the Provençaux Bank, and finally

698 the abyssal plain of the Algerian Basin, is shown in Fig. 8. A parallel section from the
 699 continental platform east of Alicante and across the slope, situated just east of the Mazarrón
 700 Escarpment, is shown in Fig. 9. In these sections, we interpret the general structure of the
 701 offshore continuation of the External Betics as a series of NW-directed stacked thrust sheets
 702 imbricating the Mesozoic cover (similar to Sàbat et al. [1997], Roca et al. [2004], Maillard
 703 and Mauffret [2013] and Driussi et al. [2015a, 2015b]), which are later inverted as low-angle
 704 normal faults (Fig. 8b). The same style of extensional tectonics is seen along the offshore
 705 continuation of the Internal Betics (or Alboran Domain). Severe extension is seen in both
 706 crustal domains through rotated blocks limited by extensional faults that extend downward,
 707 probably merging along the middle (and possibly the lower) continental crust. Some of the
 708 rotated fault blocks support half-grabens filled by Messinian sediments (BU or PLG units of
 709 the MSC that we simplify, correlating them with the UU2) and Pliocene to recent sequences
 710 (e.g., half-grabens of the El Cid, Elche, and Formentera Basins in Fig. 8b and of San Pedro
 711 and Cogedor basins in Fig. 9b). Although these extensional faults could have a lateral
 712 component of displacement, we interpret that the large size of these listric faults is more in
 713 agreement with a main downdip displacement. This interpretation contrasts with the strike-
 714 slip (right-lateral) motion suggested by other authors for the continent–oceanic boundary in
 715 this portion of the margin (e.g., Mauffret et al., 1992; Camerlenghi et al., 2009; Maillard and
 716 Mauffret, 2013; Driussi et al., 2015b).

717 (insert here Fig. 8. Landscape orientation of the page)

718 **Fig. 8.** (a) Northwest–southeast seismic section and (b) interpretation of the line MEDS-29 (seismic
 719 line from ATH [2020]) across the offshore continuation of the eastern Betics, showing the structure
 720 of the Iberian margin and the northern sector of the Algerian Basin. Notice the occurrence of
 721 various perched Messinian half-grabens, bounded by crustal-scale listric normal faults, developed
 722 behind the orogenic, thrust front of the External Betic Cordillera, and the occurrence of high-
 723 extensional riders and low-angle detachment faults thinning the offshore continuation of the
 724 Alboran Domain (Internal Betics) near the transition to the oceanic crust of the Algerian Basin.
 725 Seismic units and symbols are detailed in Figs. 7 and 14 and Table 1. Location of the seismic
 726 profile and wells used to tie the interpretation are shown in Figs. 1–3. Volcanic edifices (vr) have
 727 been found locally along the Émile Baudot Escarpment (Mauffret et al., 1992; Acosta et al., 2001;
 728 Camerlenghi et al., 2009; Maillard and Mauffret, 2013; Driussi et al., 2015b).

729

730 (insert here Fig. 9. Landscape orientation of the page)

731 **Fig. 9.** (a) Northwest–southeast seismic line and (b) interpretation of the line MEDS-31 (seismic line
 732 from ATH [2020]) across the Iberian margin and the northern sector of the Algerian Basin,
 733 showing also the offshore continuation of the Internal Betics in this margin. It is interpreted
 734 various perched Messinian half-grabens bounded by crustal-scale listric normal faults thinning the
 735 Alboran Domain (Internal Betics) near the transition to the oceanic crust of the Algerian Basin.

736 *Seismic units and symbols are detailed in Figs. 7 and 14 and Table 1. Location of the seismic*
 737 *profile and well used to tie the interpretation is shown in Figs. 1–3.*

738

739 (insert here Fig. 10. Landscape orientation of the page)

740 **Fig. 10.** (a) Southwest–northeast seismic line and (b) interpretation of the line MEDS-7D (seismic line
 741 from ATH [2020]) along the continental rise of the Iberian margin. In this strike section, we
 742 interpret the occurrence of various perched Messinian half-grabens bounded by crustal-scale
 743 listric normal faults, which promote a severe thinning of the offshore continuation of the Alboran
 744 Domain (Internal Betics) near the transition to the oceanic crust of the Algerian Basin. Notice the
 745 occurrence also of various presalt half-grabens. Seismic units and symbols are detailed in Figs. 7
 746 and 14 and Table 1. Location of the seismic profile is shown in Figs. 1–3.

747

748 Our interpretation of the seismic profiles, which is tied by wells like Calpe-1, Muchamiel-1,
 749 and Torre Vieja Marino-1, indicates that crustal extension, rotated fault blocks, and half-graben
 750 formation has continued after the Messinian (Figs. 8b, 9b). The presalt sequences seem also to
 751 be bounded by these extensional faults, which is consistent with the formation of a highly
 752 stretched continental crust in the transition to oceanic crust (Fig. 10b). Salt deposition
 753 occurred during the Messinian Age only at the base of the continental slope and above the
 754 thin oceanic crust of the Algerian Basin (total thickness, including the sedimentary sequence,
 755 of ~2.2 s TWT).

756 The geometry of the presalt half-grabens also suggests that crustal stretching has occurred
 757 since the Tortonian and possibly during the Middle Miocene (e.g., Mauffret et al., 1992). The
 758 position and geometry of the upper Messinian sequences (UU2), filling half-grabens that are
 759 progressively higher towards the north (Raad et al., 2021), show that crustal stretching during
 760 Messinian time was also accompanied by tectonic uplift and deep erosion (Just et al., 2011).
 761 This inference agrees with detailed studies of the Messinian series conducted in this margin,
 762 suggesting the occurrence during the MSC of various intermediate, perched basins situated at
 763 different depths, connecting the peripheral onshore basins with the deep salt basin (Rouchy
 764 and Caruso, 2006; Ryan, 2008; Maillard and Mauffret, 2013; Maillard et al., 2014; Driussi et
 765 al., 2015a; Raad et al., 2021).

766 At the base of the continental slope, the Messinian salt pinches out against the gently dipping
 767 top of the basement, corresponding to the highly stretched continental crust of the Internal
 768 Betics (or Alboran Domain). With respect to the salt structures, we cannot interpret their
 769 geometries with confidence due to the low quality of these commercial seismic profiles. The
 770 data suggest the occurrence of broad diapiric culminations and salt-cored anticlines, possibly

771 with some salt-pillow geometries. Some of the geometries seem to indicate the existence of
772 local diapirs discordant with the two UU sub-units and the lower Pliocene sequences (e.g.,
773 Figs. 8b, 9b). Suprasalt sequences seem to thin progressively towards the anticline crests,
774 documenting growth since the deposition of the salt layer, and continuing through Pliocene–
775 Quaternary time. Away from diapir highs and anticline culminations, the salt layer has a
776 rather constant thickness of 0.2–0.27 s TWT above the top of the oceanic crust (~450–610 m
777 using an average velocity of $4,500 \text{ m}\times\text{s}^{-1}$; Table 1).

778 Our interpretation of the crustal thickness and the location of the continent–ocean boundary,
779 which could correspond with a narrow and sub-vertical contact, agrees with other geophysical
780 observations and models of this margin (Gallart et al., 1997; Sàbat et al., 1997; Vidal et al.,
781 1998; Roca et al., 2004; Maillard and Mauffret, 2013; Driussi et al., 2015b; Kumar et al.,
782 2021).

783

784 *5.2 Seismic section across the Alboran margin*

785 The structural configuration of the Alboran margin has been inspected through a single
786 seismic section that is part of the ESCI-ALB 2C deep-seismic profile (using data from Comas
787 et al. [1997] and Booth-Rea et al. [2007, 2018]). This portion of the seismic line shows the
788 transition from the relatively thicker continental crust of the East Alboran Basin to the oceanic
789 crust of the Algerian Basin (Fig. 11a). The transition between the two domains includes
790 abundant volcanic edifices (Comas et al., 2000, 2006a, 2006b; Gómez de la Peña et al., 2018).

791 Our interpretation of the deep structure of the margin, shown in Fig. 11b, suggests a
792 progressive eastward thinning of the thin continental crust of the East Alboran Basin (with a
793 Moho depth shallowing from 7.5 s to 6.75 s TWT in about 70 km of horizontal distance).
794 Structures associated with crustal thinning involve basinward-dipping low-angle extensional
795 faults that describe extensional horses and rotated fault blocks with lenses of possibly upper-
796 crustal rocks, lying along the deep crust and close to the Moho boundary. The transition to
797 oceanic crust is interpreted to occur through a crustal neck (*sensu* Péron-Pinvidic and
798 Manatschal, 2009; Chenin et al., 2018). Deep seismic tomography also suggests that the
799 continent–oceanic boundary coincides with this narrow crustal neck and that crustal thinning
800 is also produced by progressive thinning of the ductile deep crust (e.g., Booth-Rea et al.,
801 2007, 2018; Gómez de la Peña et al., 2020).

802 The seismic image of the pre-Messinian sequences shows abundant lateral diffractions and
 803 seismic noise. In spite of that, we are confident on the existence of a thin remnant of the
 804 presalt sequence filling the stretched continental crust (in the crustal neck), and the western
 805 domain of the oceanic crust with onlap geometries. If this geometry is confirmed by future
 806 seismic observations, it would suggest that crustal stretching occurred on this margin during
 807 the Middle Miocene, evolving to a final sag-basin geometry just before the MSC.

808 Salt structures are better imaged here than on the Iberian margin, and occur in two domains. A
 809 thin, perched salt basin is observed in the west, where the base of salt dips to the east. Most
 810 structures are low-relief salt pillows, although we do interpret one salt roller. Growth of these
 811 pillows is dated by progressive thinning of the two UU subunits over the crests of the
 812 structures.

813 One of the open salt pillows lies above a basement step, and shortening of this salt structure is
 814 shown by progressive thinning of the two UU subunits toward the crest, which is
 815 accompanied by basinward thrusting of the salt roof (Fig. 12b). These geometries suggest the
 816 existence of a linked kinematic system resulting in local thrusting above salt highs. The
 817 existence of salt-detached extension at the updip end of the line also suggests the existence of
 818 some downdip gliding of the suprasalt series above the thinned continental crust. Thinning of
 819 Early Pliocene units towards the west indicates that the eastward regional dip existed at that
 820 time (i.e., from 5.5 to 4.0 Ma). Shortening in the UU sequence above salt pillows suggests
 821 that this dip may have been in existence at that time as well, and that downslope gliding began
 822 shortly after salt deposition. Shortening at the downdip end of this system may also have
 823 caused some of the growth of the salt pillows.

824 (insert here Fig. 11. Landscape orientation of the page to reproduce the illustration and its
 825 maximum size)

826 **Fig. 11.** (a) West-southwest–east-northeast seismic line and (b) interpretation of the line ESCI-ALB
 827 2C (seismic line from Comas et al. [1997] and Booth-Rea et al. [2007]) illustrating the Alboran
 828 margin. Seismic units and symbols are detailed in Figs. 7 and 14 and Table 1. The continent–
 829 oceanic boundary is suggested according to the tomography model created by Gómez de la Peña et
 830 al. (2020) using wide-angle seismic data. Location of the seismic profile is shown in Figs. 1–3. Red
 831 rectangles mark the position of the seismic windows shown in Figs. 12 and 13.

832

833 The second domain of salt structures is further to the east, in the oceanic Algerian Basin.
 834 Here, we interpret the occurrence of salt pillows and diapirs (Figs. 13a, 13b). The existence of
 835 isopachous prekinematic sediments over the crests of some pillows in this seismic line, should
 836 be taken with care as it is oriented almost normal to the regional shortening direction.

837 Nevertheless, shortening is suggested by some of the diapirs exhibiting arched roofs or being
 838 pinched off to form disconnected teardrops with sub-vertical secondary welds (Figs. 13a,
 839 13b). Thickness variations in the UU sequences over pillow crests and against the flanks of
 840 diapirs are probably apparent due to the orientation of the seismic line. Shortening then began
 841 in Pliocene time, as indicated by pinchout of Pliocene units over the crests of many diapirs
 842 and pillows.

843 (insert here Fig. 12)

844 **Fig. 12. (a)** Seismic example and **(b)** interpretation of the salt structures in the updip domain of
 845 the salt basin in the Alboran margin. Seismic units and symbols are detailed in Fig. 7 and Table 1.
 846 Various lenticular bodies with possible channel deposits within the Lower Pliocene unit are also
 847 differentiated in (b). The structure of the presalt sequences and the approximate position of the top
 848 of basement is included with dotted lines. Location of the seismic window is detailed in Fig. 11.

849

850 From these observations, we conclude that salt was slightly thicker on the oceanic (eastern)
 851 side of this margin (≤ 0.20 s TWT; i.e., ~400–450 m) and that a moderate basinward
 852 (eastward) tilting began immediately after the deposition of the Messinian salt and continued
 853 throughout the Pliocene Epoch (Fig. 12). This tilting then caused: a progressive thinning of
 854 the Pliocene and the UU2 units towards the west and a modest eastward gliding of the
 855 suprasalt section. However, this modest gliding is unlikely to have caused the more intense
 856 shortening we observe on the eastern end of the seismic line. Instead, below we will suggest
 857 that the shortening is probably caused by deformation originating along the Algerian margin
 858 (Figs. 13a, 13b).

859 (insert here Fig. 13)

860 **Fig. 13. (a)** Seismic examples and **(b)** interpretation of the salt structures in the compressional domain
 861 of the Algerian Basin, which is associated to active compression along the Algerian margin.
 862 Seismic units and symbols are detailed in Fig. 7 and Table 1. Presalt structures have been omitted
 863 for the sake of simplicity. Locations of the seismic windows are detailed in Figs. 11 and 14.

864

865 5.3 Seismic sections along the Algerian margin

866 The structure of the Algerian margin is shown using four high-quality seismic profiles. All
 867 northwest-trending seismic profiles have been interpreted by previous authors, and abundant
 868 information is available concerning the geophysical properties of the crust and the nature and
 869 position of the continent–ocean boundary (Leprêtre et al., 2013; Badji et al., 2015;
 870 Bouyahiaoui et al., 2015; Aïdi et al., 2018; Klingelhoefer et al., 2022). Our interpretations
 871 include these aspects of the geology, but salt structures are here explored for the first time

872 using modern salt tectonic principles (Figs. 13–17). A similar approach has been also used
873 recently in the eastern domain of this margin using seismic data and analogue modeling (e.g.,
874 Travan et al., 2021).

875 The Algerian margin has a narrow OCT domain, showing an abrupt change from a uniformly-
876 thick oceanic crust (~ 3 s TWT thickness with ~ 2 s TWT of sediments, equal to ~ 3.5 – 5.25 km
877 of crystalline oceanic crust with ~ 2.7 – 3.0 km of sediments using average velocities of $7,000$
878 and $2,700 \text{ m}\times\text{s}^{-1}$, respectively; Table 1) to a relatively thick continental crust that thins
879 smoothly basinward. In most areas, excluding the water column, the continental crust thins
880 basinward from 8 s to 4.5 s TWT, including a sedimentary column of ~ 1 – 2 s TWT (i.e., from
881 ~ 27 – 28 km to ~ 16 – 18 km, using an average velocity of $6,500$ and $2,700 \text{ m}\times\text{s}^{-1}$, respectively;
882 Table 1) in about 50 – 55 km, which represents a general dip for the Moho boundary of about
883 7° or 8° towards the south (some refraction studies reconstruct local dips of up $\sim 45^\circ$, e.g.,
884 Badji et al. [2015]). Deep seismic experiments and tomographic models show a narrow OCT
885 that occurs in a margin-parallel band situated in the abyssal plain around 20 – 25 km north of
886 the base of the continental rise.

887 The oceanic crust in this sector of the Algerian Basin is immediately overlain by a presalt
888 sequence that locally fills half-grabens thickening into high-angle, basinward normal faults
889 (e.g., Fig. 15b). The exact age and nature of the presalt sediments is unknown, although well
890 information from the continental shelf and regional interpretation of the age of the oceanic
891 crust suggest that they correspond to layered, fine-grained detritic sediments of Middle (and
892 possibly Lower?) Miocene to Tortonian age (Fig. 6) (Medaouri et al., 2014; Badji et al., 2015;
893 Haidar et al., 2022). The presalt sequence thickens towards the base of the Algerian
894 continental slope (i.e., southward), as it was also suggested in previous studies of the margin
895 (e.g., Mauffret, 2007; Arab et al., 2016; Leffondré et al., 2022). This sequence achieves a
896 maximum thickness (0.4 – 0.5 s TWT; equal to ~ 0.9 – 1.1 km) in the OCT region (Figs. 14b,
897 15b and 16b; see recent reviews by Haidar et al. [2022] and Klingelhofer et al. [2022]).
898 Beneath the continental slope, the presalt sequence thins progressively southward on top of
899 the continental basement and could be deformed above a basement step formed by a deep,
900 north-directed reverse fault (Fig. 17b; in agreement with many previous studies, e.g.,
901 Déverchère et al. [2005], Mauffret [2007], Kherroubi et al. [2009, 2017], Leffondré et al.
902 [2021], and Strzeczynski et al. [2021]). Although we do not have direct evidence on the nature
903 of these sequences, regional information suggest that they could be pelagic marly sequences

904 with some interbedded sandstones and limestone layers of Langhian(?) to Tortonian age (Fig.
905 6c; Burollet et al., 1978; Medaouri et al., 2014; Arab et al., 2016).

906 The Messinian series are highly deformed on this margin, with structures ranging from diapirs
907 and salt-cored folds near the base of the slope to gentle salt-cored folds further out in the
908 basin. The basinward decrease in salt-structure amplitude and structural height, suggests that
909 the salt was thickest near the base of the slope and thinned basinward (Figs. 14b, 17b).

910 Salt onlaps against the base of the slope, and the overlying postsalt sequence onlap
911 progressively further up the continental basement of the margin. However, the margin also
912 contains local perched, upper Messinian basins in the shelf areas (e.g., Figs. 14b–16b).

913 (insert here Fig. 14)

914 **Fig. 14.** (a) Northwest–southeast seismic section and (b) interpretation of the line ALWG02-169
915 (seismic line from Badji [2014]) illustrating the structure of the Algerian margin and the narrow
916 transition to the Algerian Basin. Notice the basinward decrease in the height of the salt structures,
917 and how they change progressively from salt pillow, salt walls and diapirs, to smooth, detached
918 salt anticlines with roof thrusting. It is interpreted a presalt trough with a maximum thickness
919 situated above the OCT region. Seismic units and symbols are detailed in Fig. 7 and Table 1. The
920 continent–oceanic boundary is taken from wide-angle refraction and deep seismic reflection
921 tomography studies (Badji et al., 2015). Location of the seismic profile and well used to tie the
922 interpretation is shown in Figs. 1–3. Red rectangle marks the position of the seismic window shown
923 in Fig. 13.

924

925 (insert here Fig. 15)

926 **Fig. 15.** (a) Northwest–southeast seismic section and (b) interpretation of the line SPI-02 (seismic line
927 from Badji et al. [2015]) illustrating the structure of the Algerian margin and the narrow transition
928 to the Algerian Basin. Salt structures are here seen clearly detached along the salt base, with a
929 proximal salt roller, followed basinward by the salt wall of the Ameer diapir. Above the oceanic
930 crust the salt anticlines are probably deformed by low-angle thrusts forming allochthonous salt
931 sheets. We also suggest the occurrence of squeezed salt diapirs with an upper bulb and a narrow
932 sub-vertical feeder. The presalt series show a similar geometry to the one seen in Fig. 14. Seismic
933 units and symbols are detailed in Fig. 7 and Table 1. The continent–oceanic boundary is taken
934 from wide-angle refraction and deep seismic reflection tomography studies (Badji et al., 2015).
935 Location of the seismic profile is shown in Figs. 1–3.

936

937 (insert here Fig. 16)

938 **Fig. 16.** (a) Northwest–southeast seismic section and (b) interpretation of the line ALWG02-165
939 (seismic line from Badji [2014]) illustrating the structure of the Algerian margin and the narrow
940 transition to the Algerian Basin. In this section, the updip salt pinchout is deformed by a buried
941 thrust involving the basement. Above the OCT region is observed a symmetric, detached salt
942 anticline (with a geometry that resembles a “Napoleon chat”). Some of the salt diapirs are
943 probably thrust basinward above the UU1 series (e.g., in the Ameer diapir). The presalt
944 sequences have again their maximum thickness in the OCT region. We interpret also the
945 occurrence of some high-angle normal faults affecting the oceanic crust and the presalt sequences.
946 Seismic units and symbols are detailed in Fig. 7 and Table 1. The continent–oceanic boundary is

947 taken from wide-angle refraction and deep-seismic reflection tomography studies (Badji et al.,
948 2015). Location of the seismic profile is shown in Figs. 1–3.

949

950 (insert here Fig. 17. Landscape orientation of the page to reproduce the illustration and its
951 maximum size)

952 **Fig. 17.** (a) Northwest–southeast seismic section and (b) interpretation of the line SPI-04 (seismic line
953 from Badji et al [2015]) illustrating the structure of the Algerian margin and the narrow transition
954 to the Algerian Basin. In this case, the marginal domain of the salt basin with the salt pinchout and
955 associated salt rollers, is clearly deformed by the buried thrust, which produces basement
956 overthrusting above the presalt sequences and a differential uplift and tilt of the suprasalt section
957 above the thrust hangingwall. The geometry of the suprasalt series above the OCT resembles an
958 expulsion rollover, with an asymmetric Pliocene infill, tilted basinward by simultaneous salt
959 evacuation forming finally a primary salt weld. Basinward there is broad domain of salt diapirs
960 (~25 km) with multiple evidence of contractional deformation, forming pinched-off diapirs, thrust
961 secondary welds, and possibly detached upper salt bulbs. A basinward decrease in the height of the
962 salt structures is clearly evidenced, due possibly to a local thinning of the Messinian source layer.
963 The oceanic crust is here deformed by diverse high-angle normal faults, which bound asymmetric
964 presalt half-grabens. Seismic units and symbols are detailed in Figs. 7 and 14 and Table 1. The
965 continent-oceanic boundary is taken from wide-angle refraction and deep-seismic reflection
966 tomography studies (Badji et al., 2015). Location of the seismic profile is shown in Figs. 1–3. Red
967 rectangles mark the positions of the seismic windows shown in Fig. 7.

968

969 Both the UU1 and the UU2 sequences thin against the diapirs and over the crest of the pillows
970 and salt anticlines (Figs. 13c, 13d). These observations document growth of salt structures
971 during UU time. There are no diagnostic criteria to indicate whether this growth was purely
972 halokinetic (by active diapirism) or compressional (a problem that was also discussed in other
973 areas of the Mediterranean Sea by Gaullier et al. [2014]). However, there are a number of
974 clearly imaged thrust geometries with Pliocene growth (Figs 13c, 13d). In addition, many
975 pillows and diapirs show significant roof uplift during the Pliocene (Figs. 14–17). Together,
976 these observations provide clear evidence for shortening during the Pliocene. This history is
977 similar to the one that we inferred for the structures shown in the eastern end of Fig. 11,
978 suggesting that the compressional deformation there was part of the same fold belt that we see
979 along the Algerian margin (see stippled area in Fig. 3 for map distribution of the belt).

980 Our seismic interpretation shows only minor extension at the landward end of the salt basin
981 (also identified by Bellucci et al. [2021]), which occurred during the late Messinian (mostly
982 coinciding with the deposition of the UU2 unit) and continued through the Pliocene Epoch
983 (Fig. 7b). The absence of major extension at the landward end of the system is consistent with
984 the restriction of salt to the deep basin. Because the salt layer exhibits little structural relief,
985 little driving force existed for gravity-driven translation.

986 This extension is clearly of insufficient magnitude to have caused all of the Pliocene–
987 Quaternary shortening affecting the salt structures of the margin. If the shortening was not
988 produced by a salt-detached, gravity-driven system, what caused it?

989 We see that the base of the Messinian series is clearly uplifted and deformed by basement-
990 involved thrusts that imbricate the continental crust over the oceanic domain (Figs. 7b, 17b;
991 also identified by Mauffret [2007]). This basement shortening in combination with the well-
992 documented basinward tilt and uplift of the margin (Hamai et al., 2015, 2018; Recanati et al.,
993 2019) suggests that basement shortening could be the cause of the salt deformation observed
994 along the Algerian margin of the basin. If so, salt-detached shortening is related to
995 convergence between the African and Eurasian plates. This convergence has been ongoing
996 throughout the Cenozoic Epoch (Fig. 5), so it seems likely that salt-detached shortening did
997 not suddenly begin in the Pliocene. We therefore hypothesize that growth of salt structures
998 during UU deposition was also related to shortening, although we cannot prove this. We
999 investigate this hypothesis in the next section through structural restoration of a selected
1000 section across the margin.

1001

1002 **6. Cross section restoration in the Algerian margin**

1003 We have selected a representative section of the Algerian margin on which to conduct a
1004 sequential restoration to explore the hypothesis that suprasalt shortening has been ongoing
1005 since the end of salt deposition (Fig. 14b). This section contains a good representation of both
1006 the style of the salt structures and a relatively simple presalt configuration. Our restoration of
1007 the section starts with a depth conversion of the seismic interpretation using constant-layer
1008 properties and the average sonic velocities computed using well-logging information from
1009 wells (Table 1). We have also corrected the pull-up effects seen locally at the salt base below
1010 the higher salt structures (cf. dotted lines in Fig. 18a). Restoration follows the standard
1011 process used to balance salt-bearing cross sections, as summarized by Rowan and Ratliff
1012 (2012) and Jackson and Hudec (2017). Restoration was conducted with MOVE software (v.
1013 2018) using a successive decompaction of the sedimentary sequences assuming a local (Airy)
1014 isostasy model and ignoring global variations of the sea level. Lithological parameters are
1015 from Sclater and Christie (1980) (Table 1). Folds are restored using flexural slip (consistent
1016 with our hypothesis that they formed by shortening), whereas high-angle and low-angle faults
1017 are restored assuming fault-parallel slip and simple shearing, respectively. Parameters used
1018 for depth conversion and layer decompaction are detailed in Table 1.

1019 The results of the restoration are presented graphically in Fig. 18. Values of the incremental
1020 and total shortening are also summarized in Table 2. We have also computed the average
1021 deformation rate for every interval using the incremental shortening measured for the base of
1022 the unit and the time interval of the seismic unit (Table 2).

1023 We make several assumptions in the restoration: (1) all units on the basin floor were deposited
1024 horizontally; (2) the pinch-out of the salt layer at the base of the continental slope is fixed
1025 (circled number 1 in Figs. 18e, 18f); (3) in the case of exposed salt structures, salt diapirs
1026 exhibit a reasonable minimum width (circled number 2 in Figs. 18d, 18e); and (4) shortening
1027 is accommodated on different structures in the suprasalt and subsalt sequences. Because salt-
1028 detached extension is insufficient to drive the shortening observed on the basin floor,
1029 basement shortening is required to balance the section. This basement shortening was
1030 accomplished on a gently dipping detachment surface situated in the deep continental crust of
1031 the margin. The location and geometry of this thrust is tentative, because it is derived from the
1032 line-balancing technique used for the restoration. Notably, our restoration reconstructs only
1033 the latest evolution of the Algerian margin, since the early stages of the MSC (early
1034 Messinian to recent time).

1035 Our restoration indicates that the original geometries of the stratigraphic units in the margin
1036 are as follows:

- 1037 1. The presalt unit (Tortonian and possible older strata) was deposited in an asymmetric
1038 trough, with the thickest accumulations just above the transition from oceanic to
1039 continental crust (the OCT), thinning landward and basinward (circled number 3 in
1040 Figs. 18f, 18g).
- 1041 2. Originally, the salt layer had a maximum thickness of 1.5 km close to the landward
1042 limit of the oceanic crust, pinching out landward on top of the presalt sequences
1043 (circled number 4 in Fig. 18f). The exact position of the salt pinchout should be taken
1044 with care, as we cannot rule out the existence of salt dissolution, particularly in the
1045 landward limit of the Messinian basin (e.g., Kirkham et al., 2020).
- 1046 3. The UU1 unit (5.55–5.42 Ma) was deposited forming small minibasins and troughs
1047 between small salt structures (Figs. 13c, 13d and circled number 5 in Fig. 18e).
- 1048 4. Minibasins subsidence is also recorded by the UU2 unit, although this unit covers
1049 most of the salt structures (circled number 6 in Fig. 18d), thus indicating a progressive
1050 reduction of salt flow during this epoch (5.42–5.33 Ma). These geometries can be

1051 formed either by passive diapirism with local salt withdrawal forming local minibasins
 1052 or by moderate shortening.

1053 5. Pliocene and Quaternary units (<5.33 Ma) show a general basinward thinning of the
 1054 sequences, although they developed a thick depocenter at the continent–ocean
 1055 boundary, with an internal asymmetric geometry (circled number 7 in Figs. 18a–18c)
 1056 that documents the basinward evacuation of the salt layer.

1057 The main tectonic findings of the restoration are these:

- 1058 1. Suprasalt shortening in the deepwater part of the margin was caused by over-thrusting
 1059 of the continental crust above the oceanic domain.
- 1060 2. Basement-involved thrusting (thick-skinned tectonics) is also associated with the
 1061 inversion of the presalt half-graben situated above the OCT (circled number 8 in Figs.
 1062 18b–18e). The main fault limiting this half-graben was probably active during
 1063 Tortonian and earliest Messinian presalt deposition (circled number 9 in Figs. 18f,
 1064 18g).
- 1065 3. This inverted fault propagated upward to connect with the base of salt. This surface
 1066 acted as a major detachment surface, so that the shortening was then accommodated
 1067 by formation of salt-cored buckle folds and minor salt-detached thrusts (circled
 1068 numbers 10–14 in Figs. 18b–18e).
- 1069 4. Suprasalt shortening was most intense during Pliocene to recent times, with late
 1070 Messinian shortening producing only folding.
- 1071 5. Extensional deformation in the cover is insignificant and is restricted to the landward
 1072 salt pinch-out. A few listric faults detach onto the salt layer, forming small salt rollers.
 1073 The base of the salt is here uplifted and tilted basinward due to the overthrusting of
 1074 continental crust over oceanic crust. The activity of these salt rollers seems to be
 1075 restricted to deposition of the UU2 unit to the Upper Pliocene (i.e., 5.33 to ~3.6 Ma)
 1076 (circled number 15 in Figs. 18b–18d).

1077 Contractional deformation on the Algerian margin has the following characteristics (Table 2):

- 1078 1. Continuous contraction since the deposition of the Messinian salt (6–5.55 Ma) arising
 1079 from the continuous African-Eurasian plate convergence (Fig. 5); the section records
 1080 a total shortening of 1.15 km.
- 1081 2. Shortening continued immediately after salt deposition and during the late Messinian
 1082 age, achieving a maximum rate of deformation during the sedimentation of the two
 1083 UU units, with a peak of $4.67 \text{ mm} \times \text{yr}^{-1}$ at 5.33–5.42 Ma (coinciding with deposition

1084 of UU2 unit). The shortening magnitudes estimated for UU should be taken with
 1085 some care because our approach for the restoration does not differentiated between
 1086 pure shortening (conducted through layer folding and thrusting) and minibasin
 1087 sinking with vertical differential subsidence (linked to halokinetic deformations and
 1088 salt withdrawal).

1089 3. Shortening decreases abruptly and monotonically from the Lower Pliocene time
 1090 onward ($\sim 0.1 \text{ mm}\times\text{yr}^{-1}$ during the Pliocene Epoch and $<0.003 \text{ mm}\times\text{yr}^{-1}$ during the
 1091 Quaternary Period), accompanying the progressive uplift and basinward tilt of the
 1092 continental margin.

1093

1094 (insert here Fig. 18, occupying the complete page)

1095 **Fig. 18.** *Sequential restoration of the section shown in Fig. 14, documenting the structure of the*
 1096 *Algerian margin. (a) Depth converted section; (b) restoration for the Late Pliocene (3.6 Ma); (c)*
 1097 *restoration for the Early Pliocene (~ 4 Ma); (d) restoration for the UU2 unit (Messinian, 5.33 Ma);*
 1098 *(e) restoration for the UU1 unit (Messinian, ~ 5.42 Ma); (f) restoration for the top of the Messinian*
 1099 *salt (Messinian, 5.55 Ma); and (g) restoration for the base of the Messinian salt (possibly at 5.97*
 1100 *Ma). Seismic units are detailed in Fig. 7 and Table 1. Details of the restoration, the depth*
 1101 *conversion, and an explanation of the circled numbers are provided in the text. Red and blue*
 1102 *numbers mark observations about the stratigraphy of the units and the tectonic processes,*
 1103 *respectively, as detailed in the text. Approximate correction of the pull-up effects observed below*
 1104 *major salt structures is marked with dotted lines in (a). Uncertain elements of the restorations (b–*
 1105 *g) are marked with discontinuous lines. Numerical results of the restoration are summarized in*
 1106 *Table 2.*

1107

1108 Since the deposition of the Messinian salt, the overall plate-tectonic scenario consists in an
 1109 oblique (northwest) convergence of the African (Nubia) plate. On the Algerian margin, we
 1110 estimate that the average rate of convergence during the MSC was $\sim 6.5 \text{ mm}\times\text{yr}^{-1}$
 1111 (corresponding to a north–south convergence of $\sim 4.5 \text{ mm}\times\text{yr}^{-1}$; Fig. 6b), diminishing to ~ 5.5
 1112 $\text{mm}\times\text{yr}^{-1}$ at present. These values are close to the shortening rates measured in our restoration
 1113 for the postsalt MSC epoch ($3.6\text{--}4.7 \text{ mm}\times\text{yr}^{-1}$) and also follow the magnitudes inferred for the
 1114 Pliocene–Quaternary period ($\leq 0.12 \text{ mm}\times\text{yr}^{-1}$; Table 2). This decrease of the shortening rate
 1115 also matches the previous observations made at the Algerian margin toe, where only a limited
 1116 tectonic shortening affecting the seafloor has been reported (Domzig et al., 2009; Medaouri et
 1117 al., 2014; Leffondré et al., 2021).

1118 We suggest, then, that most (if not all) of the plate convergence in this margin was
 1119 accommodated by basement overthrusting and suprasalt shortening, with a deformation that

1120 accompanied the MSC and continued through the Pliocene and decreasing to almost zero
 1121 during the Quaternary.

| Units | Age (Ma) ⁽¹⁾ | Shortening (m) | | Deformation rate (mm×yr ⁻¹) ⁽²⁾ |
|----------------|----------------------------|----------------|-------|---|
| | | Incremental | Total | |
| Quaternary | 0 | - | - | <0.003 |
| Upper Pliocene | 3.60 | ~10 | 10 | 0.12 |
| Lower Pliocene | 4.00 | 50 | 60 | 0.06 |
| UU2 (Mess.) | 5.33 | 80 | 140 | 4.67 |
| UU1 (Mess.) | 5.42 | 420 | 560 | 3.55 |
| Messinian salt | 5.55 | 461 | 1021 | 0.30 (2.52) ⁽³⁾ |
| Base of salt | 5.97 (5.60) ⁽³⁾ | 126 | 1147 | |

Notes:

(1) Age for the top of the unit (Table 1), except for (3).

(2) Computed using the incremental shortening and the time interval corresponding to the deposition of the unit.

(3) First age considers that salt deposition initiated with the MSC. Value in parenthesis is taken assuming that there is a presalt Messinian sequence, the LU unit (i.e., including the MSC Stage 1). See text for discussion.

1122 **Table 2.** *Estimated shortening of the Algerian margin according to the restoration shown in Fig. 18:*

1123

1124

1125 **7. Tectonic summary and salt-tectonic implications**

1126 The varied structure of the Algerian Basin margins in the Western Mediterranean Sea is
 1127 illustrated with two regional sections that contain a simplified version of our seismic
 1128 interpretation (Fig. 19). One of the main simplifications in these regional sections is that we
 1129 simplify the two UU subunits into a single unit. Fig. 19a joins the interpretations in Figs. 9
 1130 and 17 to show a continuous north–south section from the Algerian margin to the Iberian
 1131 margin in the central domain of the study sector of the Algerian Basin. The western domain of
 1132 the basin is illustrated in Fig. 19b, connecting two highly oblique sections: one west–east
 1133 across the Alboran margin (Fig. 11) and the other north–south across the westernmost sector
 1134 of the Algerian margin (Fig. 14). To further support the regional analysis of the basin, we
 1135 have generated depth conversions of these sections (Fig. 20). These depth sections schematize
 1136 the salt structures and incorporate results from other geophysical studies that document the
 1137 position of the crust–mantle boundary and provide information about the depths of the main
 1138 stratigraphic discontinuities, like top of basement, base of salt, and thickness of the suprasalt
 1139 layer. Results from gravity models and data from seismic refraction and tomography have
 1140 been included in these sections, coming from studies on the Algerian margin (Badji et al.,
 1141 2015; Klingelhoefer et al., 2022), the East Alboran Basin (Booth-Rea et al., 2018; Gómez de
 1142 la Peña et al., 2020), and the Iberian margin (Hinz, 1973; Gallart et al., 1997; Sàbat et al.,
 1143 1997; Driussi et al., 2015b; Kumar et al., 2021).

1144 Sections in Figs. 19 and 20 necessarily do not capture the possible component of lateral-
 1145 motion component along faults and even along the continent–oceanic boundary but
 1146 summarize the main results of our study. The complete view of the Algerian Basin, from the
 1147 African to the Iberian margins, makes possible the extraction of the following summary
 1148 remarks.

1149 The Algerian margin contains a narrow OCT domain accompanied by a steep geometry of
 1150 Moho discontinuity. In addition, this margin shows multiple evidence for shortening since the
 1151 Middle Miocene that continues to the present (according to the seismicity, e.g., Aoudia et al.
 1152 [2000], Yelles-Chaouche et al. [2006], Kherroubi et al. [2009, 2017], and Soumaya et al.
 1153 [2018]). Our observations are summarized as follows (Figs. 19, 20):

1154

1155 (insert here Fig. 19. Landscape orientation of the page to reproduce the illustration and its
 1156 maximum size)

1157 **Fig. 19.** Sections (in TWT) of the Algerian Basin and its margins merging a simplified version of
 1158 seismic interpretations. (a) North–south section from version from the Algerian margin to the
 1159 Iberian margin containing the offshore continuation of the Internal Betics (Alboran Domain) (Figs.
 1160 9b, 17b). (b) Composite section in the westernmost Algerian Basin, showing the west–east section
 1161 in the Alboran margin and the north–south structure of western Algerian margin (Figs. 11b, 14b).
 1162 Double arrows correspond to positively inverted normal faults, with the open arrow indicating the
 1163 sense of displacement of the previous normal fault. Locations of the profiles are shown in Figs. 1–
 1164 3.

1165

1166 (insert here Fig. 20. Landscape orientation of the page to reproduce the illustration and its
 1167 maximum size)

1168 **Fig. 20.** Synthetic depth sections of the Algerian Basin and its margins, emphasizing the salt
 1169 structures. (a) North–south section from version from the Algerian margin to the Iberian margin
 1170 (according to Fig. 19a). (b) Composite section in the westernmost Algerian Basin, showing the
 1171 west–east section of the Alboran margin joined with a north–south section across the western
 1172 Algerian margin (according to Fig. 19b). Approximate depth conversion of the sedimentary
 1173 sequences is generated using average velocities for seismic units (Table 1) and information
 1174 provided by diverse tomographic studies in the Algerian margin (particularly Badji et al. [2015]
 1175 and Klingelhoefer et al. [2022]), the Alboran margin (using Booth-Rea et al. [2018] and Gómez de
 1176 la Peña et al. [2020]), and the Iberian margin (according to Driussi et al. [2015b] and Kumar et
 1177 al. [2021]). Thick arrows mark the plate convergence imposed by the northwest convergence of the
 1178 African plate, occurring since the Miocene Epoch (Fig. 5), and the inferred basement uplift and
 1179 tilting of the North African margin. Locations of the profiles are shown in Figs. 1–3.

1180

1181 1. The presalt series (Middle Miocene to Tortonian time) is deposited in inverted half-
 1182 grabens that are thickest near the OCT (continent–ocean transition). These presalt

- 1183 basins can be interpreted as flexural forebulge basins (Leprêtre et al., 2013; Hamai et
 1184 al., 2015; Leffondré et al., 2021) formed in response to the northward thrusting of
 1185 African crust over the oceanic crust of the Algerian Basin.
- 1186 2. Inversion of these presalt basins is accomplished by basement folding and inversion of
 1187 pre-existing normal faults.
 - 1188 3. Margin uplift accompanied basement-involved shortening, as is expressed by a
 1189 moderate basinward tilting of the salt and cover at the landward end of the basin.
 - 1190 4. Moderate basinward gliding and extension of the cover is accomplished through salt
 1191 rollers and rafts, in a narrow distal domain of the continental basement.
 - 1192 5. Shortening linked to basement shortening forms a wide salt-detached fold belt in the
 1193 oceanic domain and leads to formation of salt-cored folds, pinched-off diapirs, and
 1194 some associated salt thrusts. Shortened salt diapirs are preferentially located near the
 1195 OCT. All these structures are detached along the base of the salt and were mostly
 1196 formed by early contraction synchronous with the sedimentation of the UU unit (5.55–
 1197 5.33 Ma, with a rate of shortening of 3.6–4.7 mm×yr⁻¹), continuing with a moderate to
 1198 low rate of shortening up to the present (from 4 Ma at a rate of ≤0.1 mm×yr⁻¹) (Fig.
 1199 18, Table 2).

1200 The structure of the western and northern margins of the Algerian Basin contains marked
 1201 differences from the Algerian margin because crustal thinning and extension is the dominant
 1202 structural style in both cases. The Alboran margin in the west has the following characteristics
 1203 (Figs. 19b, 20b):

- 1204 1. A progressive eastward thinning of the continental crust (the Moho discontinuity rises
 1205 from 12 to 10 km depth in about 80 or 90 km), which has abundant intrusions of
 1206 volcanic rocks.
- 1207 2. The OCT is marked by a crustal neck (Fig. 11b).
- 1208 3. Crustal thinning and eastward extension are accomplished by low-angle faulting,
 1209 which forms extensional duplexes and a series of presalt half-grabens. The age of the
 1210 infilling sediments is uncertain, but on the basis of regional considerations and the
 1211 available information from nearby wells (Fig. 6), we suggest that most of the crustal
 1212 thinning and necking occurred during Middle to Upper (pre-MS) Miocene time.
- 1213 4. The MSC series dips gently basinward, showing an opposite (westward) progressive
 1214 thinning of the salt and the UU unit.

1215 5. Subsidence of the oceanic domain with respect to the buoyant continental crust of the
1216 East Alboran Basin since the MSC is expressed by progressive basinward thickening
1217 of the Pliocene–Quaternary strata and the UU units and by salt gliding towards the
1218 oceanic domain.

1219 The Iberian margin has been explored here through several vintage seismic profiles (Figs. 8–
1220 10). In spite of the relatively low quality of the seismic data and the locations of sparse
1221 number of available wells on the platform, we suggest that this margin has the following
1222 characteristics (Figs. 19a, 20a):

- 1223 1. The margin platform, and the transition to the north to the Valencia Trough (Fig. 8), is
1224 deformed by gently south-dipping thrusts and open, west–southwest-trending folds
1225 that document compression in the offshore continuation of the orogenic front of the
1226 Betics (Alfaro et al., 2002; Maillard and Mauffret, 2013).
- 1227 2. The continental crust gently thins towards the Algerian Basin. Crustal extension is
1228 seen as rotated crustal blocks limited by south-dipping listric faults that affect the
1229 offshore continuation of the Internal Betics (Alboran Domain) and part of the External
1230 Betics domain.
- 1231 3. These faults define perched half-grabens that are filled by asymmetric wedges of
1232 Messinian–Quaternary-age, and possibly Tortonian-age sediments (Figs. 9b–11b).
1233 Although the age of the Messinian sequences in these perched basins is under debate
1234 (see discussion in Driussi et al. [2015a], Ochoa et al. [2015], and Raad et al. [2021]),
1235 and some of the sequences (particularly towards the east, near the island of Mallorca)
1236 might even have a thin salt layer (Maillard et al., 2014; Driussi et al., 2015a; Raad et
1237 al., 2021), we are inclined to assign them to the UU unit. Given that interpretation, we
1238 conclude that crustal thinning and extension on this margin has occurred from late
1239 MSC time (5.33 Ma) to the present, on the basis of minor crustal extension also
1240 documented on this margin in the form of high-angle faults that have been active from
1241 Pliocene to recent time (Acosta et al., 2001; Camerlenghi et al., 2009; Just et al., 2011;
1242 Maillard and Mauffret, 2013; Driussi et al., 2015a; Ochoa et al., 2015).
- 1243 4. Salt structures consist of gentle pillows and smooth salt-cored anticlines developed in
1244 the oceanic domain. The salt layer pinches out landward at the base of the continental
1245 slope and is overlain by progressive landward thinning and onlap of the UU units
1246 (Figs. 8b, 9b). The salt at the base of the margin appears to be deformed into salt-cored
1247 folds, but the data are too poor to infer their timing or genesis with confidence.

1248 In the Algerian Basin, we suggest that a deepwater salt-cored folded belt is developed on the
 1249 Algerian margin, where the Messinian salt was originally thicker (Fig. 20). The northward
 1250 convergence of the African plate during the Neogene and Quaternary Periods in the Western
 1251 Mediterranean Sea (Fig. 5) caused basement-involved thrusting along the Algerian margin,
 1252 which linked to the salt detachment to form the fold belt. This shortening also caused limited
 1253 inversion of the presalt (Middle Miocene–Tortonian) “foredeep” flexural basin. In contrast,
 1254 the northern and western margins of the Algerian Basin were differentially stretched by
 1255 extensional faulting, causing moderate downslope (eastward) gliding of the MSC series in the
 1256 transition to the Alboran margin and creating a series of perched, Messinian half-grabens on
 1257 the Iberian margin. Both margins of the Algerian Basin document a long-lived history of
 1258 Miocene crustal extension and differential subsidence that continues to the present.

1259 One intriguing possibility for the salt-detached folds observed at the downdip end of the
 1260 Iberian margin is that they are compressional structures marking the extreme distal end of the
 1261 fold belt formed at the Algerian margin. We cannot disprove this, although the fact that a
 1262 wide swath of undeformed strata lies between the Algerian and Iberian margins implies and
 1263 argument against such interpretation.

1264 Salt layers are well known to be important controls on the structural styles of passive margins.
 1265 In addition to serving as effective decoupling levels between the salt and the overlying
 1266 sequences, on many margins, gravity instability of the suprasalt cover generates a
 1267 combination of updip and thin-skinned extension linked to downdip detached shortening in a
 1268 deepwater fold belt (Fig. 21a) (e.g., Vendeville and Jackson, 1992; Letouzey et al., 1995;
 1269 Rowan et al., 2004; Hudec and Jackson, 2007; Morley et al., 2011; Jackson and Hudec, 2017).
 1270 Our case deviates from this scenario because the salt layer was originally deposited
 1271 horizontally in the deep oceanic domain of the margin (Fig. 21b). We have documented how
 1272 under this initial configuration, plate convergence promoted shortening by moderate
 1273 subduction and overthrusting along the Algerian margin, nucleated along the OCT domain
 1274 (e.g., Auzemery et al., 2021). This thick-skinned shortening linked upward to the salt
 1275 detachment, originating a fold belt close to the proximal salt pinch-out (Fig. 21c).

1276

1277 (insert here Fig. 21)

1278 **Fig. 21.** Configuration and processes in salt continental margins, illustrating the case of deformations
 1279 affecting a salt layer that was deposited after rifting. (a) Continental margin with a continuous and
 1280 gently dipping salt layer. Gravity gliding and sliding generate suprasalt updip basinward extension
 1281 and a linked, deepwater fold belt with salt inflation and local salt withdrawal in synclines (e.g.,

1282 *Rowan et al., 2004; Jackson and Hudec, 2017). (b) Continental margin with a deep and*
 1283 *subhorizontal salt layer, with an inland pinch out situated close to the continent–oceanic transition*
 1284 *(OCT). A suprasalt wedge prograding from the continental shelf above the salt layer generates an*
 1285 *expulsion rollover and a broad salt folded belt in the deepwater region, which could affect the*
 1286 *sequences lying above the oceanic crust (e.g., Vendeville, 2005; Zucker et al., 2020). (c) Possible*
 1287 *configuration of a deep salt continental margin (case shown in [b]) after a moderate inversion by*
 1288 *horizontal compression, which also generates an incipient subduction of the oceanic crust and*
 1289 *pervasive shearing around the OCT domain. Initial position of the top of salt is marked in all the*
 1290 *cases with a dotted purple line.*

1291

1292 **8. Conclusions**

- 1293 1. The Messinian evaporites (including salt) in the westernmost Mediterranean Sea were
 1294 deposited during the MSC between ~6.0 and ~5.55 Ma over oceanic crust flooring the deep
 1295 Algerian Basin.
- 1296 2. Along the Iberian margin, the upper (postsalt) Messinian sediments (possibly equivalent to
 1297 the UU unit) onlap and thin progressively above several rotated extensional blocks,
 1298 shaping a series of perched basins deepening progressively towards the oceanic Algerian
 1299 Basin.
- 1300 3. Listric normal faults merging towards the deep crust, accommodated crustal thinning of the
 1301 Iberian margin and affect here the offshore continuation of the Internal Betics. Syn-
 1302 extensional presalt (Middle Miocene to Tortonian) half-grabens, together with the
 1303 geometry of the crustal listric faults, suggest that the Iberian margin was severely stretched
 1304 southward beginning in the Middle Miocene and during the MSC.
- 1305 4. Crustal thinning also occurred in the Alboran margin through basinwards (eastward) low-
 1306 angle normal faults and extensional duplexes, which supporting presalt half-grabens filled
 1307 with probable Middle Miocene to Tortonian sediments. Continent–oceanic transition
 1308 (OCT) in this margin is accompanied by abundant Neogene–Quaternary volcanism and
 1309 crustal necking. Salt and suprasalt sequences thin westward, documenting the existence of
 1310 a differential subsidence between the continental East Alboran Basin and the oceanic
 1311 Algerian Basin since at least the MSC.
- 1312 5. Since the deposition of the MSC evaporites, the Messinian salt layer served as a
 1313 detachment during the ongoing plate convergence between the African and Iberian
 1314 (Eurasia) plates. North-northwest-directed overthrusting of continental crust over the
 1315 oceanic domain in the Algerian margin tilted the continent seaward, produced limited

1316 northward gliding along the salt layer, and shortened the suprasalt section, developing
1317 tighter and higher structures close to the ocean–continent boundary.

1318 6. The Messinian salt layer constituted an effective decoupling level during deformation,
1319 promoting synsedimentary shortening in the suprasalt sequence, which is detached from
1320 partially inverted presalt half-grabens filled by Middle Miocene–Tortonian sediments.

1321 7. The general scenario of the Algerian Basin and its contrasting margins constitutes a
1322 valuable example of a deep salt basin deformed after salt deposition by convergence-
1323 induced overthrusting of the continental crust in the southern margin. Shortening
1324 propagated along the basal detachment formed by the Messinian salt layer, causing
1325 synsedimentary folding of the suprasalt sequences.

1326

1327

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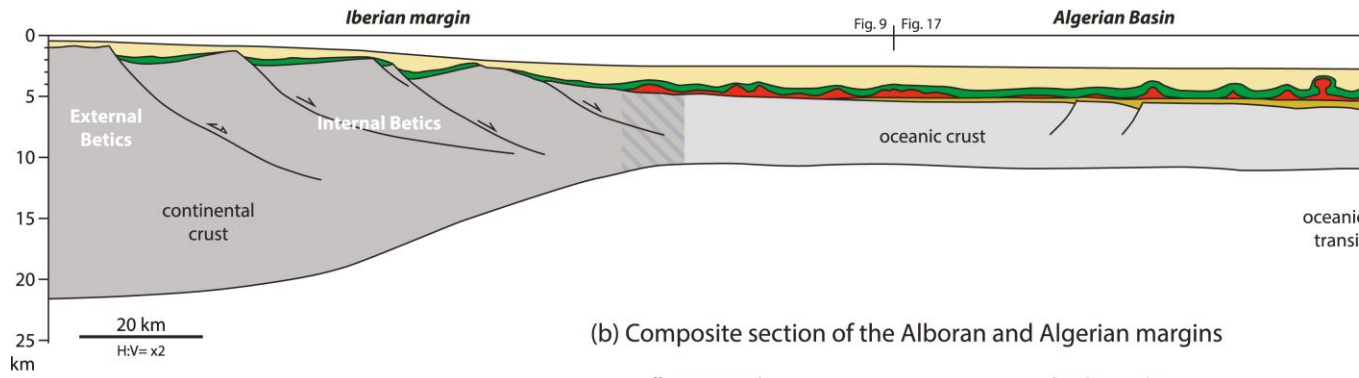
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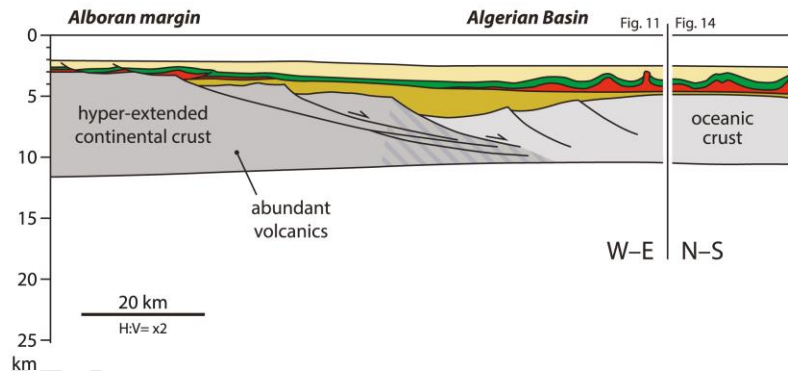
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(a) N-S section of the Algerian Basin margins

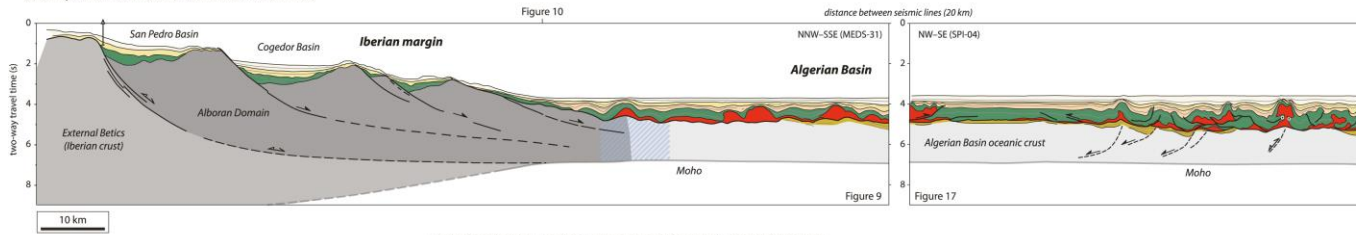


(b) Composite section of the Alboran and Algerian margins



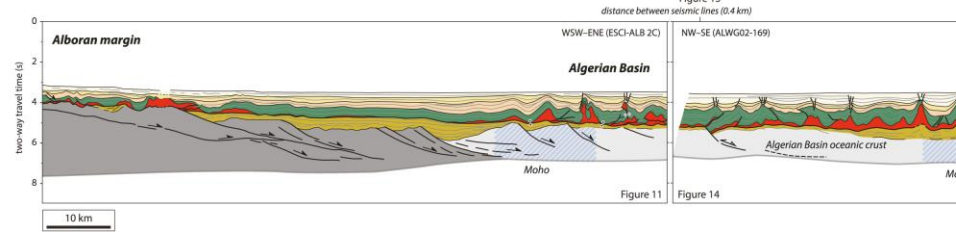
- inverted thrust as a normal fault
- Pliocene-Quaternary
- Messinian**
- UU unit
- salt
- presalt (Middle Miocene to Tortonian)

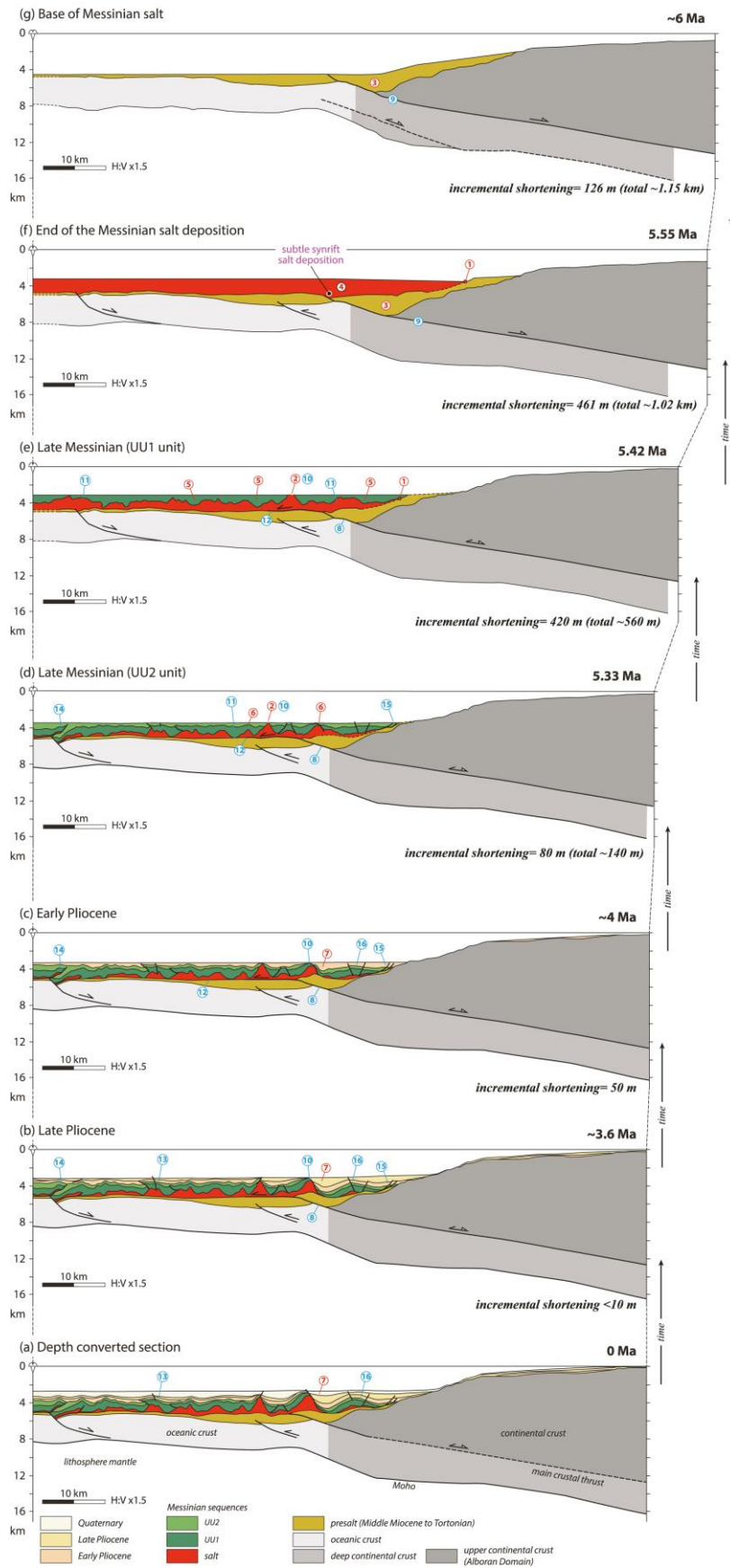
(a) Composite N-S transect (lines MEDS-31 and SPI-04)

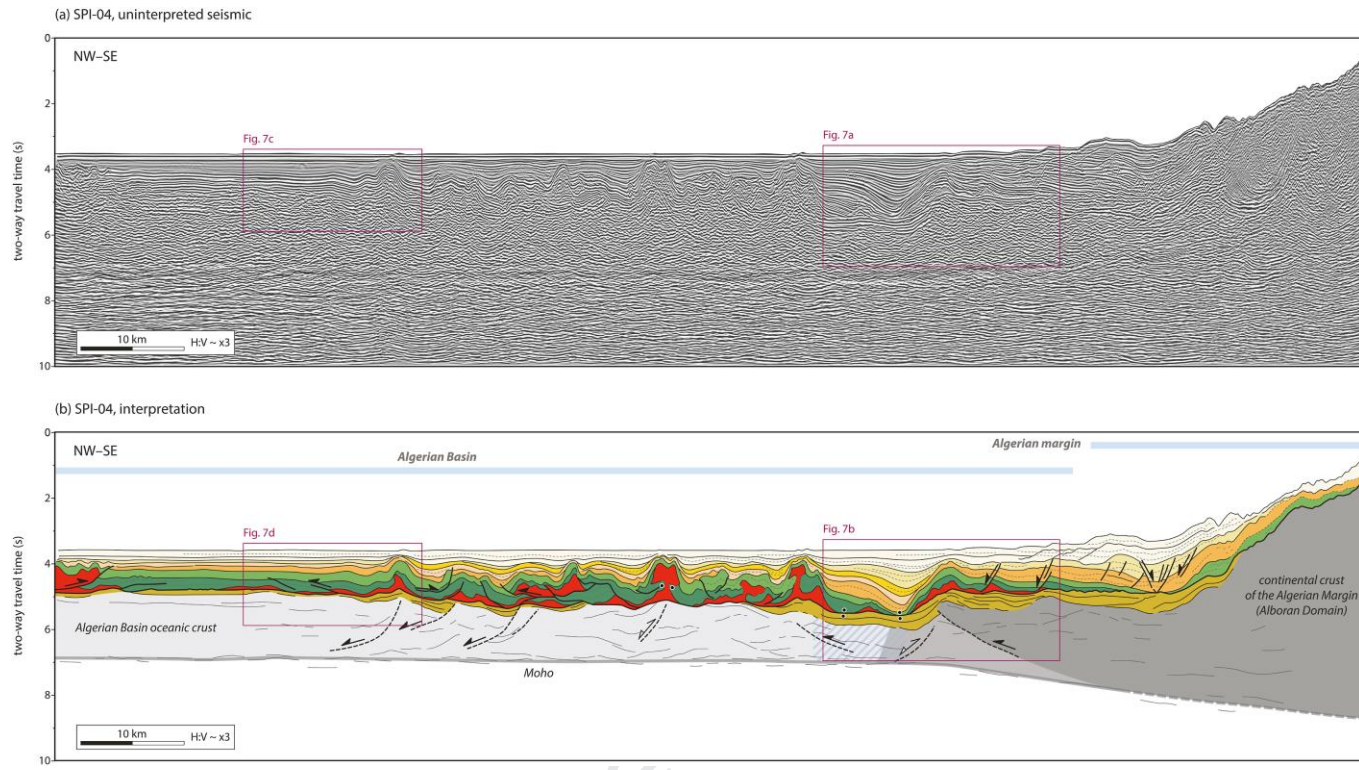


- Legend**
- Quaternary
 - Late Pliocene
 - Early Pliocene
 - Messinian sequences**
 - UU
 - salt
 - presalt (Middle Miocene to Tortonian)
 - oceanic crust
 - deep continental crust
 - continent-oceanic boundary (OCT)
 - continental crust of the Alboran Domain and African plate

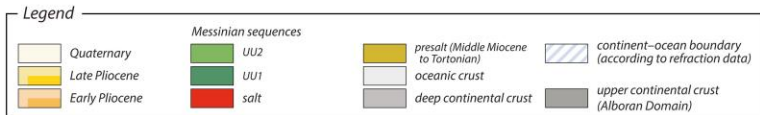
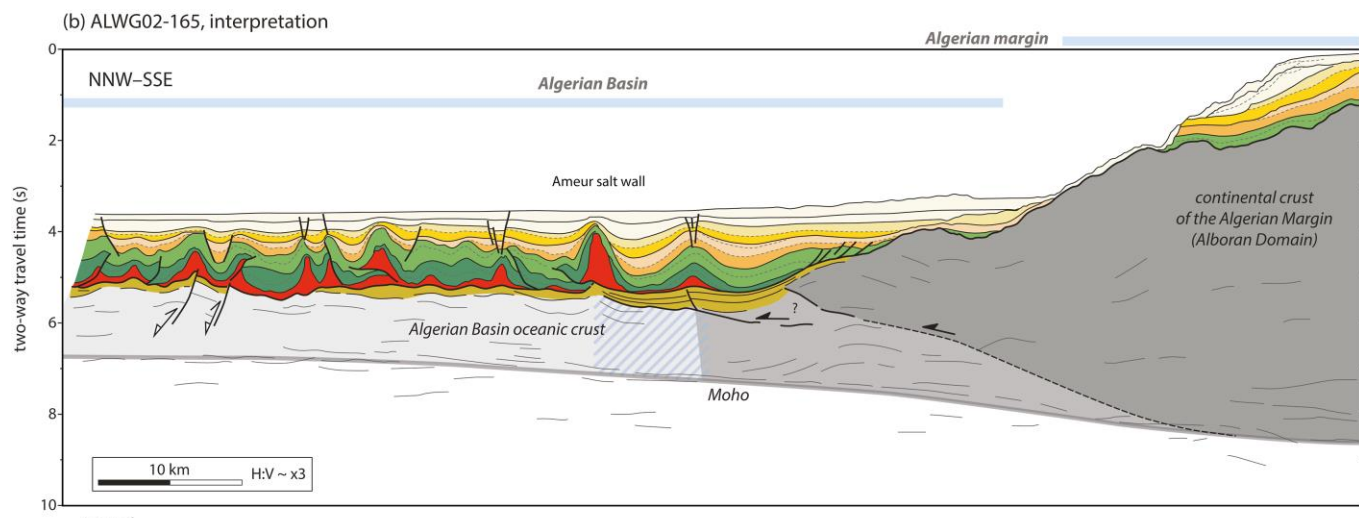
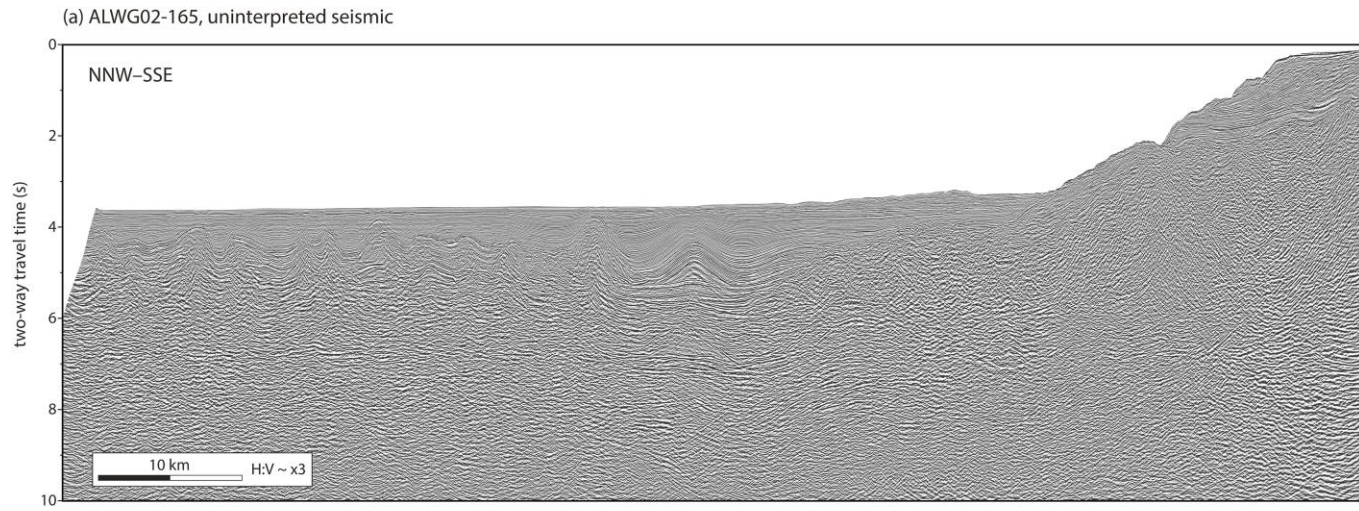
(b) Composite W-E and N-S transect (lines ESCI-ALB 2C and ALWG02-169)



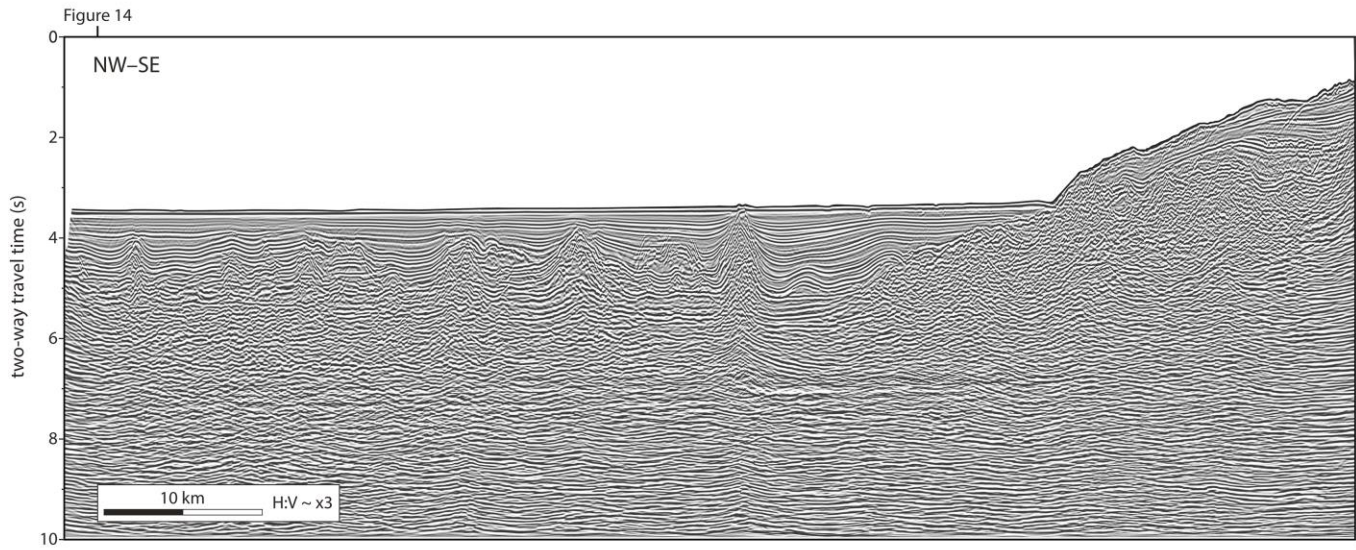




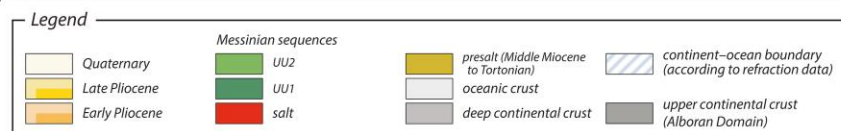
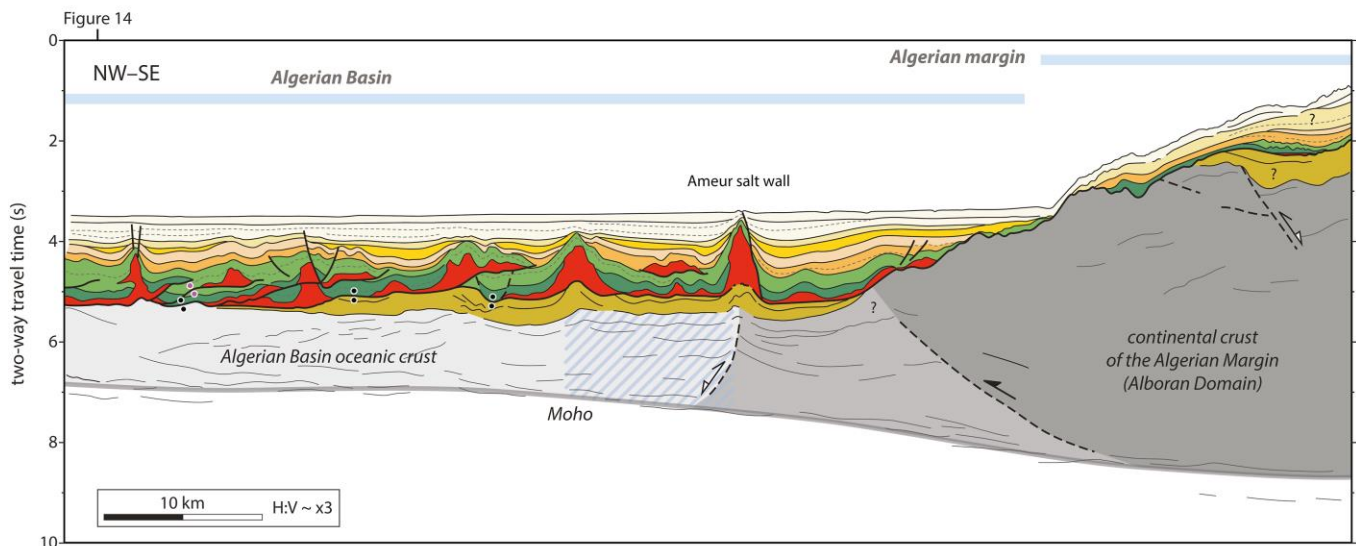
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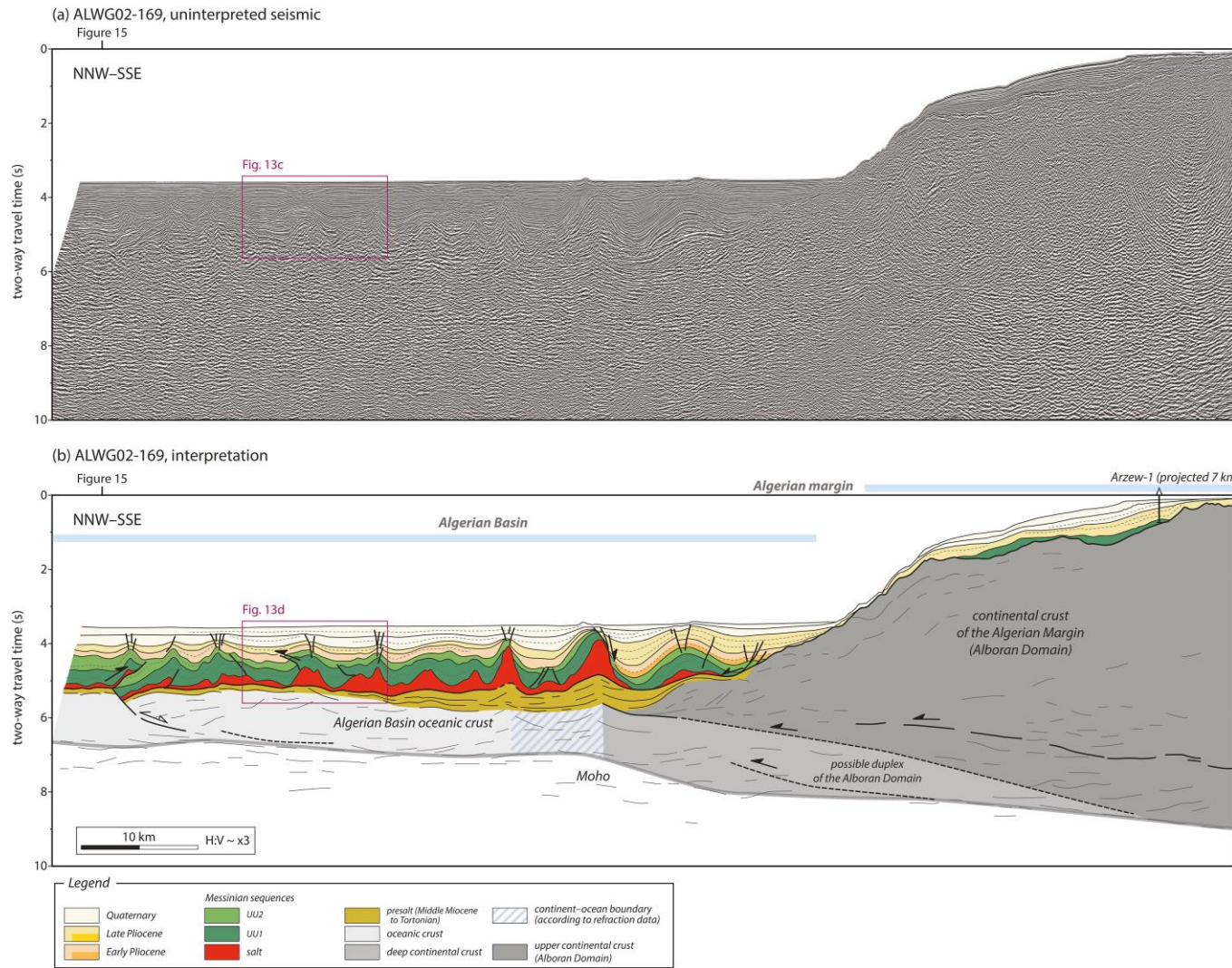


(a) SPI-02, uninterpreted seismic

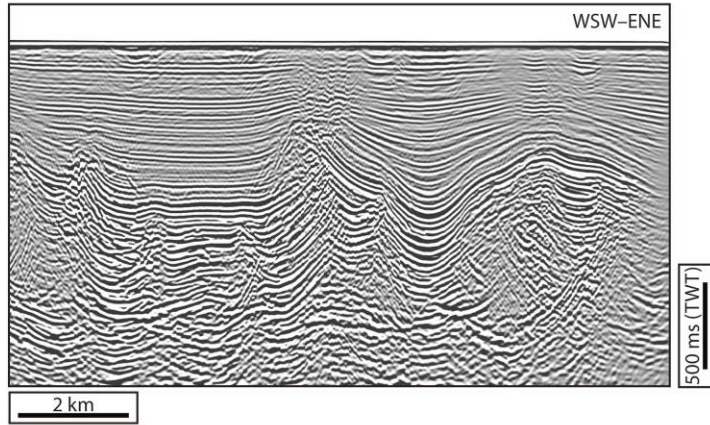


(b) SPI-02, interpretation

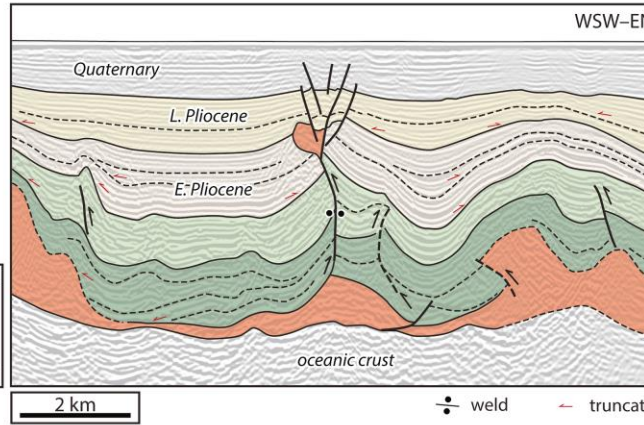




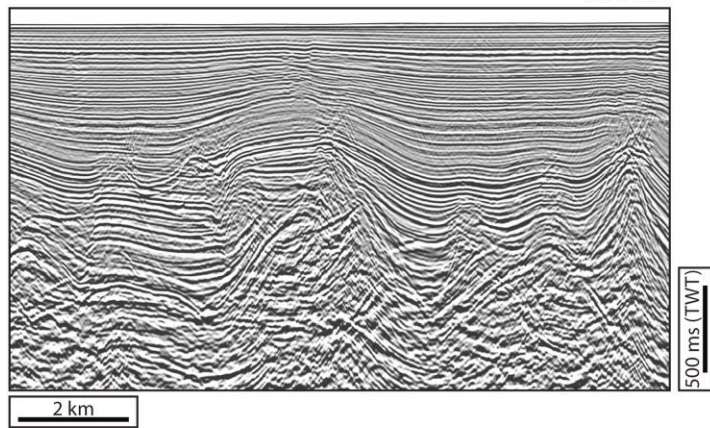
(a) Uninterpreted seismic (downdip domain, Alboran margin)



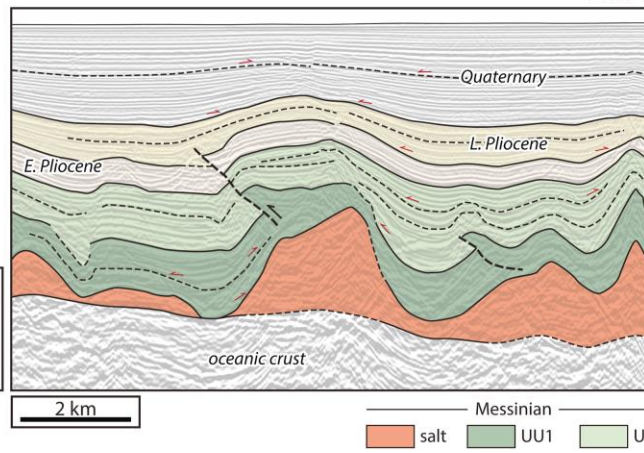
(b) Interpreted seismic (downdip domain, Alboran margin)



(c) Uninterpreted seismic (Algerian Basin)

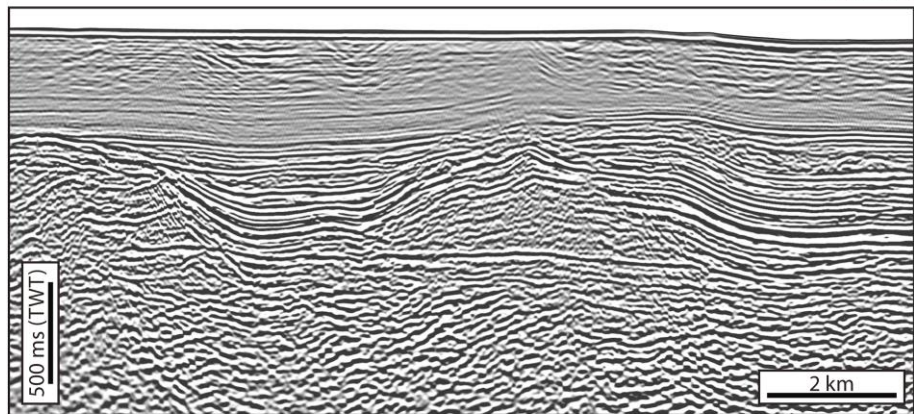


(d) Interpreted seismic (Algerian Basin)

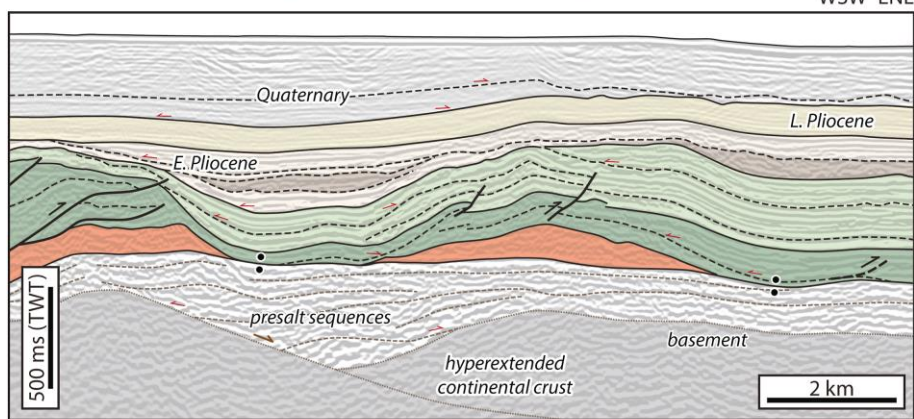


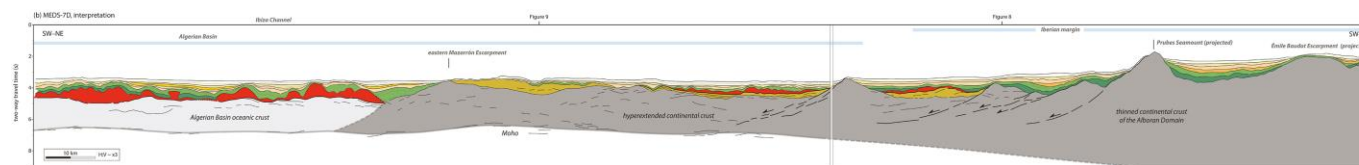
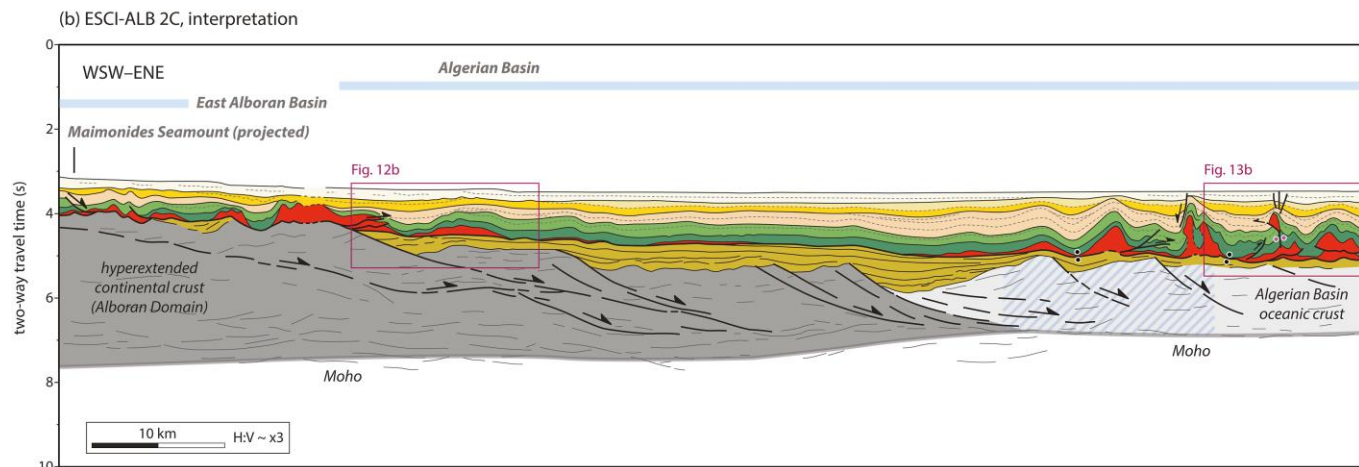
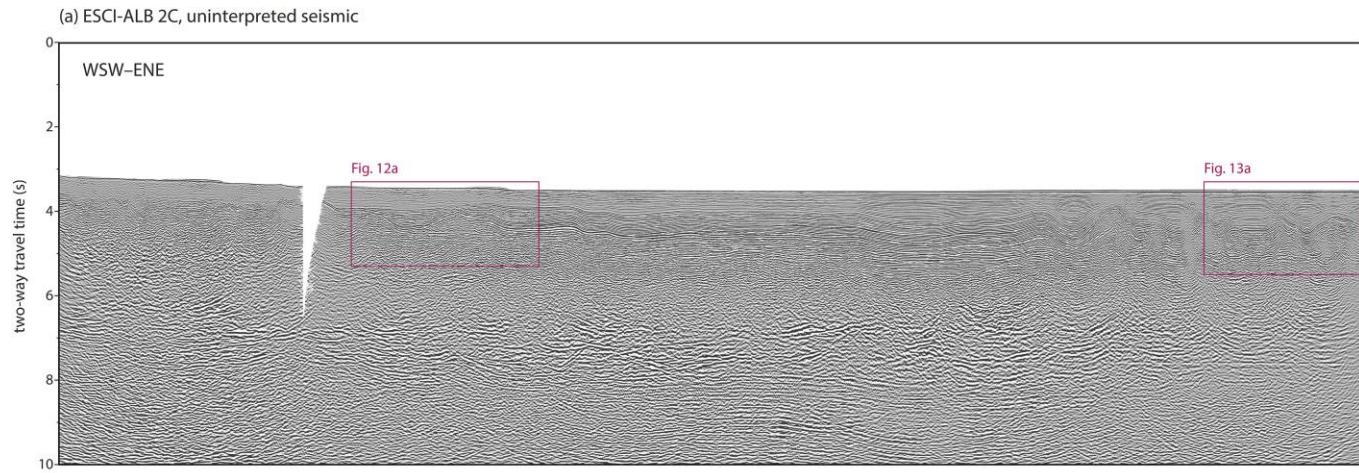
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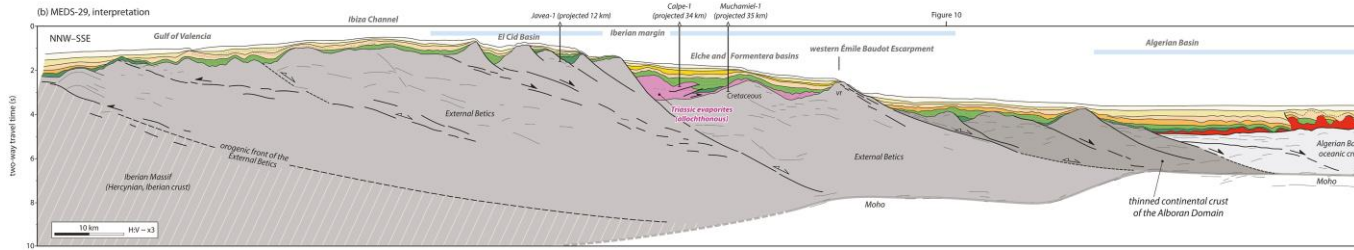
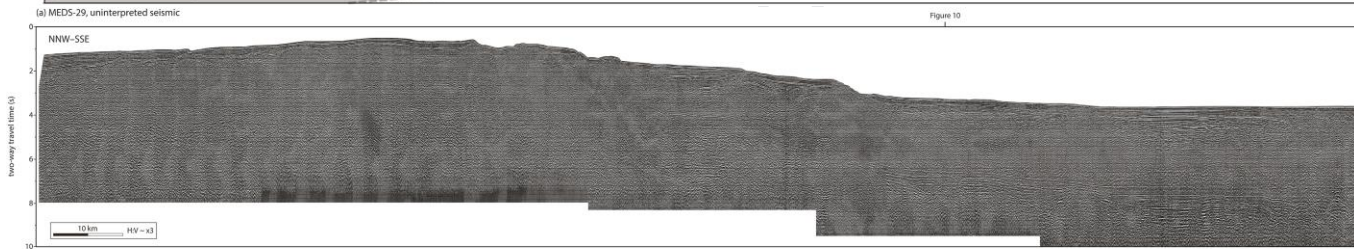
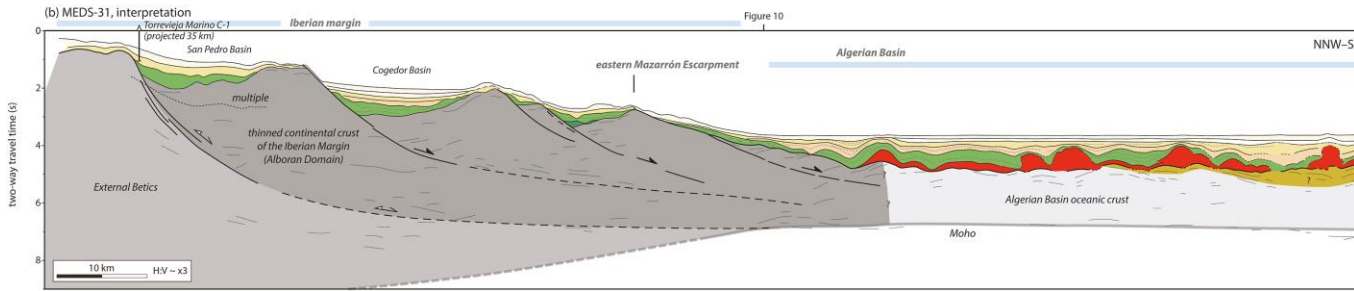
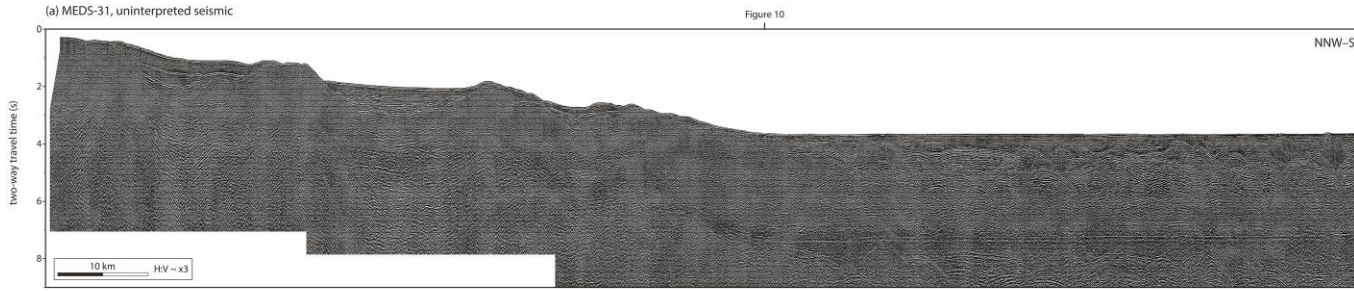
(a) Uninterpreted seismic (updip domain, Alboran margin)



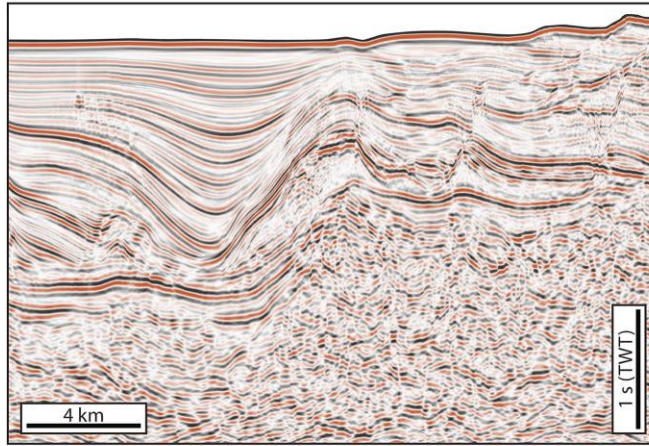
(b) Interpreted seismic (updip domain, Alboran margin)



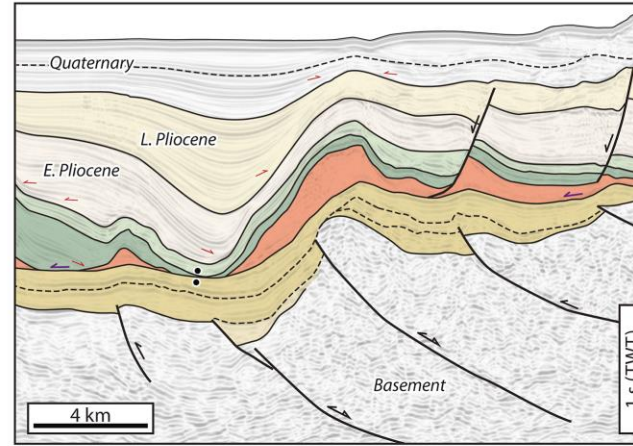




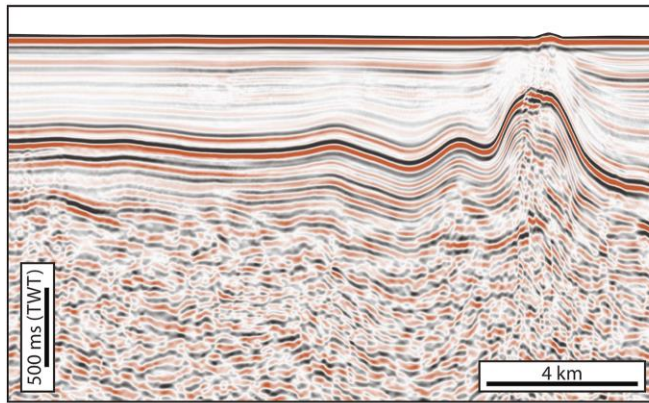
(a) Uninterpreted seismic (continental rise, Algerian margin)



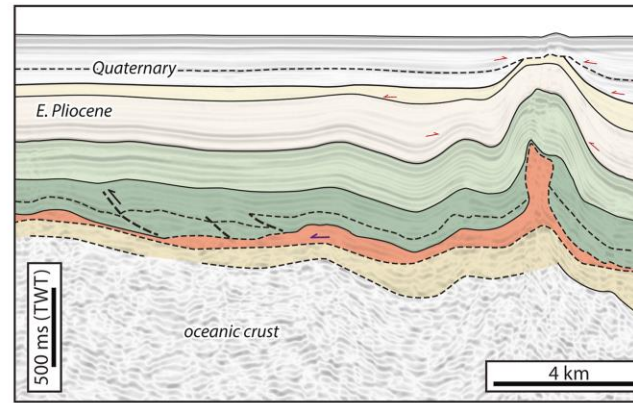
(b) Interpreted seismic (continental rise, Algerian margin)



(c) Uninterpreted seismic (oceanic floor of the Algerian Basin)

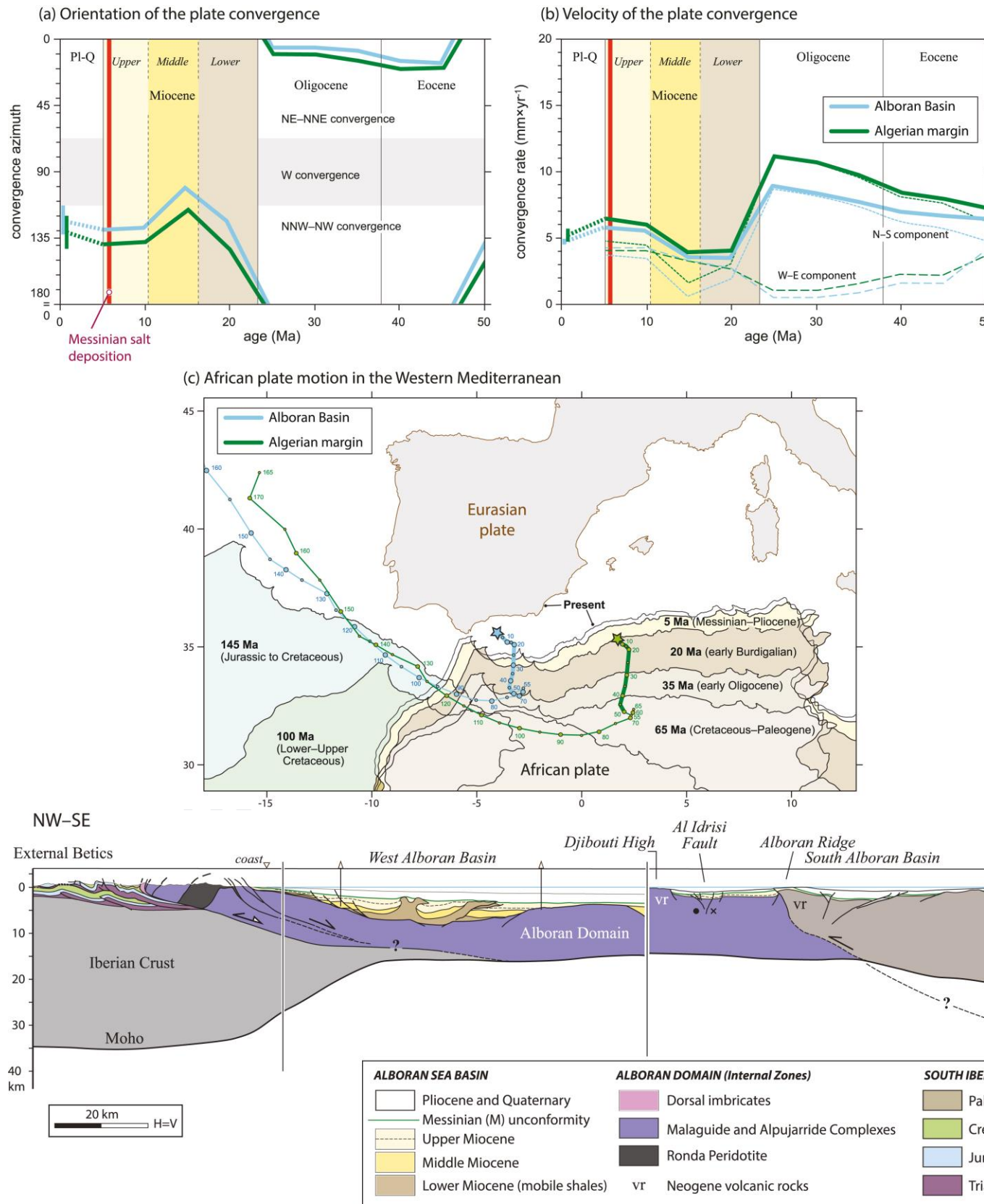


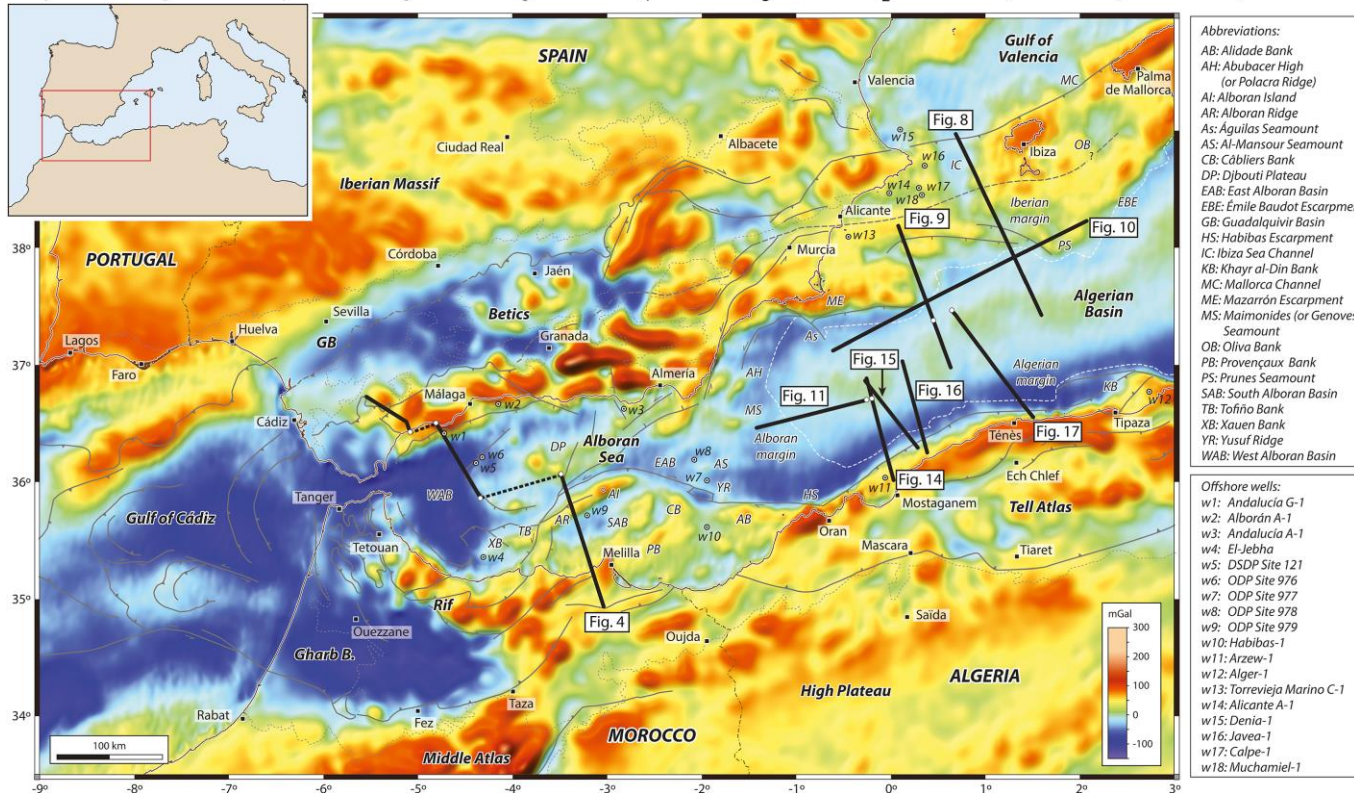
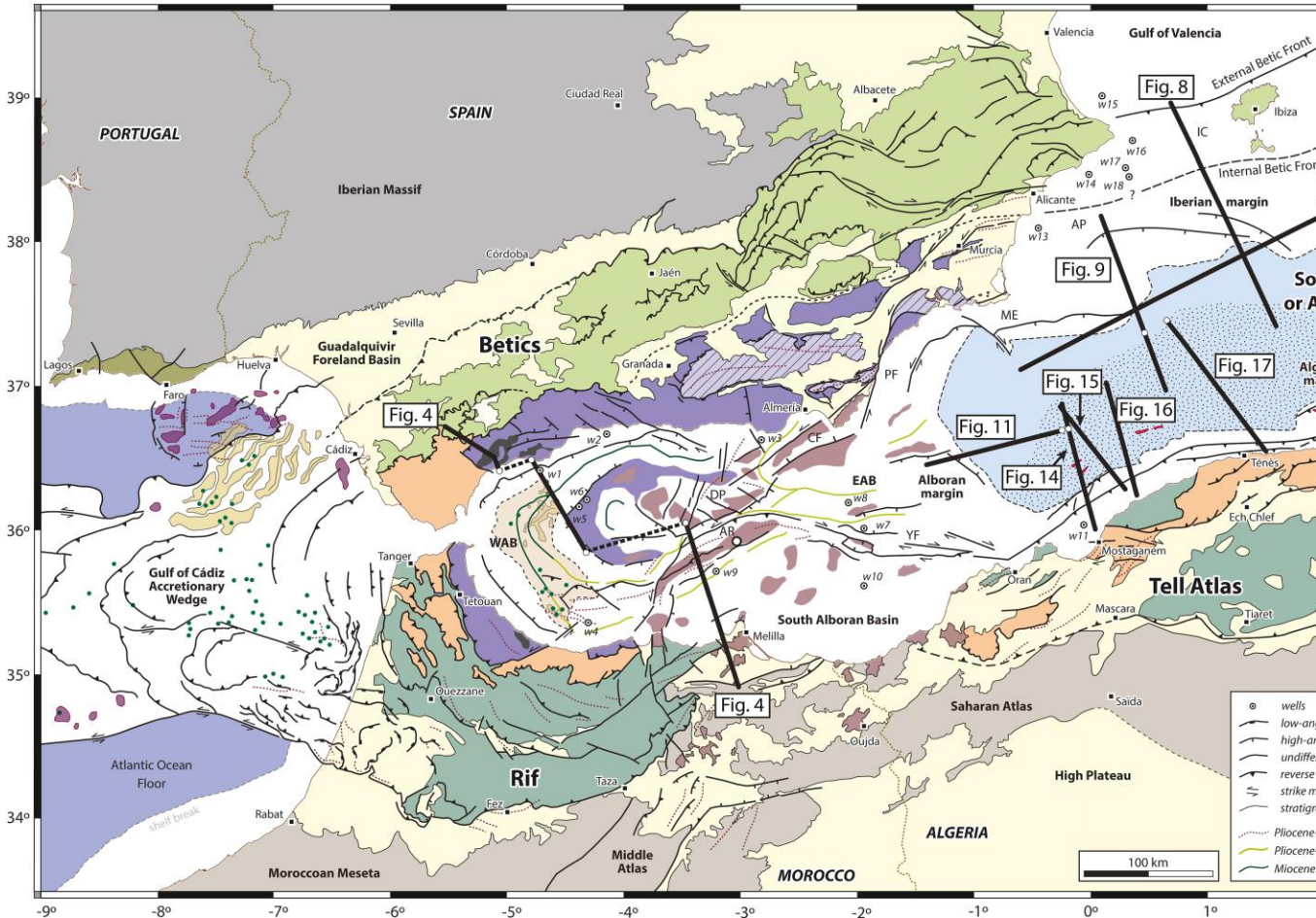
(d) Interpreted seismic (oceanic floor of the Algerian Basin)

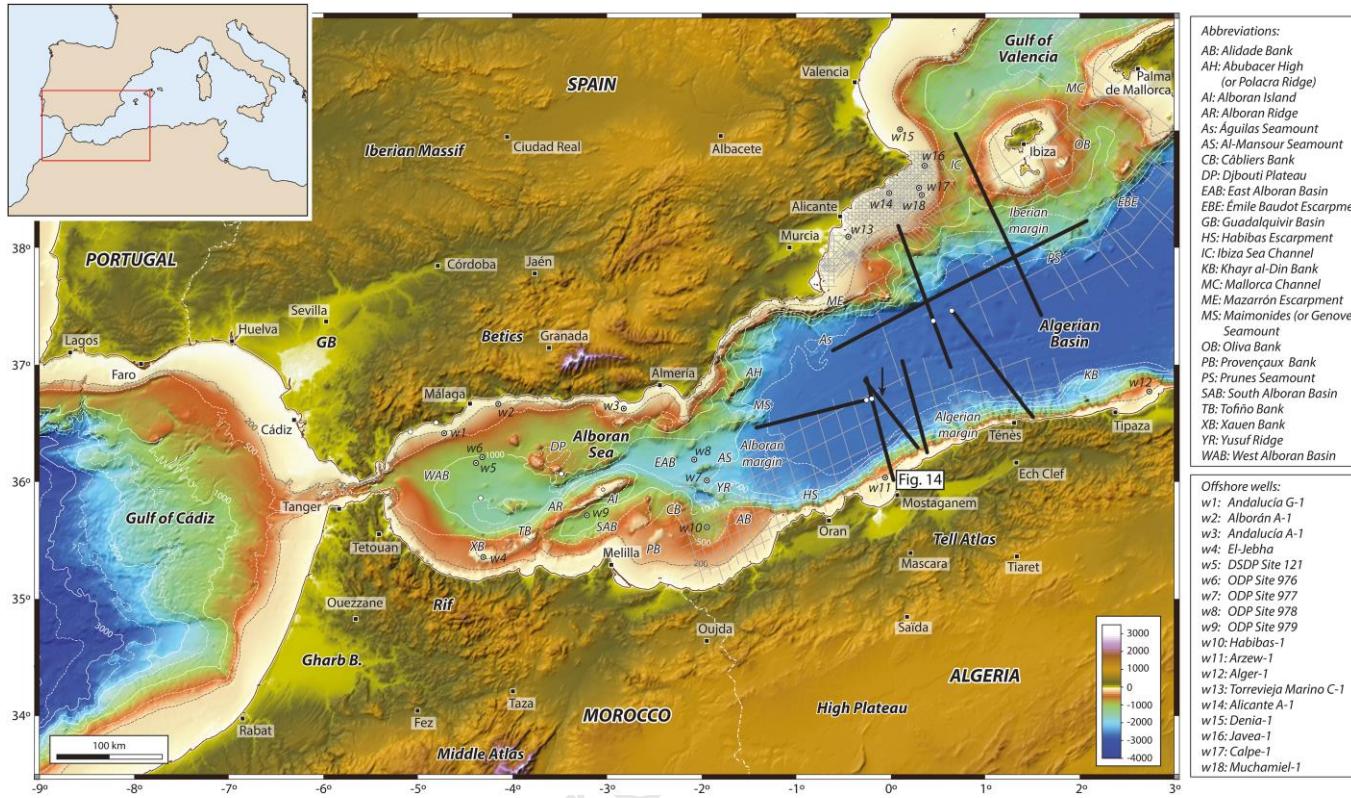


- | | | | |
|-----------------|-----------------------|-----------|-----------|
| salt detachment | truncation | uncertain | Messinian |
| weld | inverted normal fault | presalt | salt |
| | | | UU1 |

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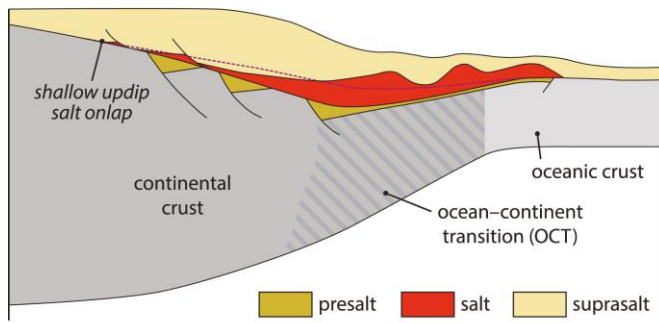




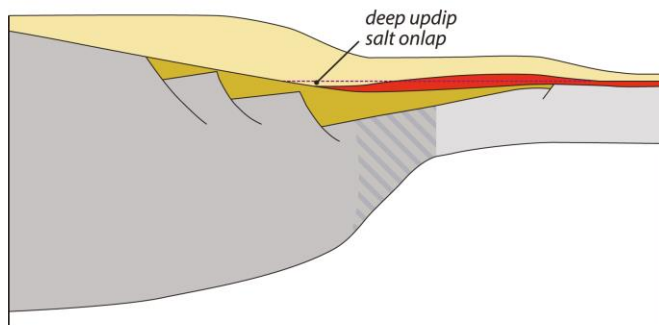


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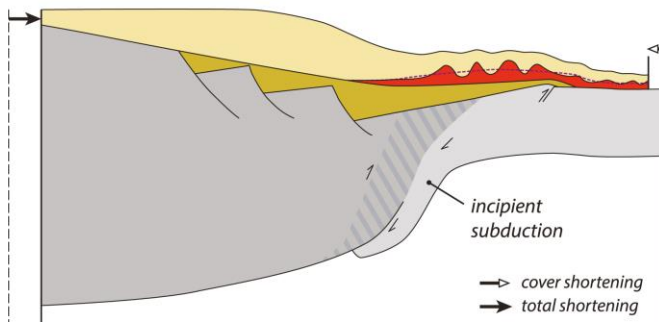
(a) Gently dipping salt sag basin



(b) Deep salt basin



(c) Inverted margin with a deep salt basin



Highlights:

- Crustal structure of the W Algerian Basin is reviewed by the first time
- Seismic interpretation to unravel the crustal structures of the basin and margins
- How the Messinian salt layer is deformed in the oceanic floor of the basin
- How the deformation occurring in the margins affected the deep-seated salt layer
- Restoration to evaluate timing, magnitude, and rate of post-6 Ma deformations

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Juan I. Soto reports financial support was provided by The University of Texas at Austin.

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