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The Minorca Basin: a buffer zone between the Valencia and Liguro-Provençal Basins (NW Mediterranean Sea)

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Abstract :

Detailed analyses of seismic profiles and boreholes in the Valencia Basin (VB) reveal a differentiated basin, the Minorca Basin (MB), lying between the old Mesozoic Valencia Basin sensu stricto (VBs) and the young Oligocene Liguro-Provençal Basin (LPB). The relationship between these basins is shown through the correlation of four Miocene-to-present-day megasequences. The Central and North Balearic Fracture Zones (CFZ and NBFZ) that border the MB represent two morphological and geodynamical thresholds that created an accommodation in steps between the three domains. Little to no horizontal Neogene movements are found for the Ibiza and Majorca Islands. In contrast, the counterclockwise movement of the Corso-Sardinian blocks induced a counterclockwise movement of the Minorca block towards the SE along the CFZ and NBFZ, during the exhumation of lower continental crust in the LPB. This new understanding implies pure Neogene vertical subsidence in the VBs and places the AlKaPeCa northeastward of the present-day Alboran Area.

13

14 **General Setting**

15 Although the Valencia Basin (VB) is recognized as a former Mesozoic basin
16 (Maillard, 1992; Roca, 1992, 2001; Ayala *et al.*, 2015), it is generally considered to be an
17 aborted Miocene back-arc basin in the southwestward continuation of the Liguro-Provençal
18 Basin (LPB). Two main types of models are normally proposed for its evolution during the
19 Neogene: 1) a continuity from the LPB to the Alboran domain going through the VB (e.g.
20 Doglioni *et al.*, 1997, 1999; Lonergan & White, 1997; Gueguen *et al.*, 1998; Faccenna *et al.*,
21 2004; Jolivet *et al.*, 2006) or 2) a segmented and multi-phased response between the LPB and
22 VB (e.g. Rehault *et al.*, 1984; Sanz de Galdeano 1990; Maillard & Mauffret, 1999; Maerten &
23 Seranne 1995; Roca, 2001). In both cases, the North Balearic Fracture Zone (NBFZ) played a
24 key role in this opening “swinging door” movement (as described by Martin, 2006), leading
25 to the counterclockwise rotation of the Corsica-Sardinia microplate and a clockwise rotation
26 of the Balearic promontory during the Oligocene-Early Miocene (e.g. Auzende *et al.*, 1973;
27 Dewey *et al.*, 1973; Mauffret *et al.*, 1995; Olivet, 1996; Maillard & Mauffret, 1999; Gueguen
28 *et al.*, 1998; Gattacceca *et al.*, 2007; Carminati *et al.*, 2012). Southwest of the NBFZ, two
29 secondary transfer zones are also suggested, the Central Fracture Zone (CFZ) between
30 Minorca-Mallorca islands, and the Ibiza Fracture Zone (IFZ) between Mallorca-Ibiza islands.
31 The initial rifting phase during the Neogene (Chattian / Early Burdigalian) is recorded in the
32 sedimentary strata of the Gulf of Lion (GOL) (Edel, 1980; Gorini *et al.*, 1993; Ferrandini *et*
33 *al.*, 2003; Gattacceca *et al.*, 2007) and similar deltaic to shallow marine environments are
34 recorded on the Catalan margin in the northwestern part of the VB (Roca *et al.*, 1999; Roca,
35 2001). On the Ebro margin (Tarragona trough) and on land (Valles-Penedes graben), the
36 synrift deposits are described as Burdigalian to Langhian/Early Serravallian (Clavell &

37 [Berastegui, 1991](#); [Bartrina et al. 1992](#); [Alvarez de Buergo & Melendez-Hevia 1994](#); [Cabrera](#)
38 [and Calvet, 1996](#); [Martinez Del Olmo, 1996](#); [Rodriguez-Murillas et al., 2013](#)).

39 In this study, based on a large set of seismic data and boreholes, we detail the
40 sedimentary architecture, the nature of the base of the Tertiary series, the segmentation of the
41 VB, and also highlight the role of tectonic heritage in the subsidence history of each segment.

42 **Correlation along the study area**

43 Our study is based on a large set of seismic and borehole data gathered during the extensive
44 French academia-industry programs (Actions-Marges, GRI Téthys Sud), in close
45 collaboration with the Total and Schlumberger groups (Figure 1). Due to this dense set of
46 profiles, seismic reflectors were identified and successfully correlated to previous detailed
47 studies in the LPB ([Rabineau, 2001](#); [Bache, 2008](#); [Leroux, 2012](#)). Ages of paleomarkers were
48 defined using biostratigraphic data from thirty-eight boreholes in the VB and seven boreholes
49 in the GOL.

50 The evolution and appearance of these seismic markers highlights the subdivision of
51 the area into three domains: (1) the Valencia Basin *sensu stricto* (VBss), limited to the NE by
52 the CFZ, (2) the Minorca Basin (MB) bounded by the CFZ and the NBFZ, and (3) the LPB.
53 Four megasequences are described along the VB and LPB (Figure 2):

54 (1) The Late Oligocene to Early Miocene megasequence, not visible on Figure 2, is
55 essentially limited to the Catalan and GOL graben (e.g. [Roca, 2001](#)).

56 (2) The Miocene megasequence defined in the basin lies between the Tertiary
57 basement and M30 (Figure 2). Several reflectors were correlated through the VB
58 and LPB. M03 is a high-amplitude, continuous reflector dated to the top of the
59 Burdigalian from correlation to Catalan margin boreholes (e.g. Barcelona Marino

60 B1 and C1). Its extent is limited to the MB and LPB. M06 and M08 are
61 respectively estimated to be Langhian and Latest Serravallian to Early Tortonian
62 (Benicarlo C1 and Tarragona trough boreholes). In the VBss, sediments below
63 M06 include distal and pelagic Late Burdigalian to Langhian deposits. The
64 continuity of M08 toward the MB and LPB is clearly conceivable, but a direct
65 correlation was impossible due to unfavorable morphologies. The M11, dated as
66 Late Tortonian to Early Messinian (borehole Benicarlo C1), is mainly an erosive
67 surface in the VBss, which evolves into a conformable surface in the MB (M20b).

68 (3) The Messinian megasequence comprises the Lower Unit, Mobile Unit, Upper Unit
69 (e.g. Lofi et al., 2011; Gorini et al., 2015), comprised between M30 and M30
70 surfaces. In the VBss, the base of the Upper Unit corresponds to the M30 surface,
71 which is erosive or conformable and can be correlated in the upper margin with the
72 Messinian Margin erosional surface (MES).

73 (4) The Pliocene to Quaternary megasequence covers most of the major structural
74 highs. Large prograding and pro-aggrading clinoforms characterize the shelf due to
75 high sediment supply and glacio-eustatic variations (e.g. Lofi et al., 2003;
76 Kertznus and Kneller, 2009). Two prominent surfaces, P60 and P50, were
77 correlated to Q10 and P11, dated at 0.9 Ma and 2.6 Ma, respectively (e.g.
78 Rabineau et al., 2014; Leroux et al., 2014).

79 **Segmentation and Individualization of the Minorca basin**

80 Figures 3A, 3B, 4A, and 4B emphasize the evolution of these seismic markers along 6
81 NE-SW and 3 NW-SE profiles crossing the three basins. The Oligocene-Aquitania
82 megasequence is restricted to the GOL and Catalan margins. The Miocene and Messinian
83 megasequences show a gradual thickening from the VBss towards the LPB. The thickness of

84 the Miocene megasequence increases from 0-0.9 second two-way time (stwt) (VBss) to 1.1+/-
85 0.3 stwt (MB), and is fully developed in the LPB (1.4+/- 0.4 stwt) (Figure 3B). A new seismic-
86 stratigraphic unit is also identified in the MB (green unit in Figure 3B), which increases in
87 thickness towards the LPB. Continuous reflectors with medium-amplitude clinoforms that
88 prograde toward the NE characterize this unit (Figures 2, 3B). The base of this Upper
89 Miocene prograding sequence changes rapidly, from a truncation surface (VBss) to a
90 correlative conformity (MB), and shows an increase in depth, from 3.3 s (VBss) to 4.5 s
91 (MB), and ultimately to 5.2 s (LPB). The thickness of the Messinian megasequence varies:
92 0.05 to 0.3 s in the VBss, 0.6 to 0.7 s in the MB, and > 1.26 s in the LPB. Furthermore, the
93 MB is characterized by the development of the Lower Unit and Mobile Unit (in the NE),
94 whereas the full development of the Lower and Mobile units is limited to the LPB. The base
95 of the Mobile Unit also evolves, from 4.5 s in the MB to ~5 s in the LPB. For Pliocene and
96 Quaternary deposits, the variation in thickness is mainly controlled by sedimentary transport
97 from the Ebro river (Nelson, 1990) and the Rhône river for the deep LPB (e.g. Leroux, 2012).

98 The segmentation into three domains appears in the Bouguer anomaly map and the
99 residual geoid anomaly map, which show a strong SW-NE segmentation between the LPB,
100 MB, and VBss (Ayala *et al.*, 2015), and also on the base of Tertiary map of the entire VBss-
101 MB-LPB area (Figure 5). The base of the Tertiary in the MB presents a mean depth of 4.6 +/-
102 0.5 (stwt), intermediate between the VBss (3.5 +/- 0.3 stwt) and the deeper LPB (6.5 +/- 0.2
103 stwt) (Figure 3B). This segmentation is clearly depicted by the CFZ to the southwest of the
104 MB and by the NBFZ to the northeast of the MB (Maillard & Mauffret, 1999). These
105 differences in depth imply a difference in Neogene subsidence in the three segments,
106 decreasing towards the SW. This is also observed in the first occurrences of marine
107 sediments, which started at the Oligocene in the LPB and the Catalan margin (MB), and only

108 at the Late Burdigalian-Langhian in the VBss (Figure 6). The Neogene subsidence in the
109 VBss started later than it did in the LPB and MB.

110 Alternatively, some authors suggest another segment in the VBss with the Ibiza
111 Fracture Zone (IFZ) (Maillard & Mauffret, 1999) explaining the suggested clockwise 93 km
112 southeastward movement of Mallorca block. However, the authors state that IFZ is “*not*
113 *documented as there is no or very little information in that region*”, its presence was only
114 presumed due to differences in crustal thicknesses (suggested to reach 13 km in the
115 southwestern part). However, modern high-quality data presented by Alaya *et al.* (2015)
116 falsifies this view and shows instead a thickness of 5 to 6 km in the SW part. Previous studies
117 identified a Mesozoic basin in the whole VBss (e.g. Roca, 1992; Maillard, 1993), with a
118 maximum thickness reaching more than 3 km. Toward the Balearic promontory the Estudio
119 Sismico de la Corteza Ibérica (ESCI) profiles show a continuation of this Mesozoic basin
120 (Roca *et al.*, in Cavazza *et al.*, 2004) and we infer that the VBss extends between the Ibiza
121 and Mallorca Islands and the Ebro-Tarragona margin. In contrast, in the MB and LPB, the
122 substratum is characterized by chaotic, hyperbolic, and medium-amplitude reflectors (Figures
123 2b and 2c). In the MB, mean velocities from the ESP60 profile (Figure 3B, cross section 3)
124 were 4.2 to 6.1 km/s in the upper part of the Tertiary basement and were interpreted as
125 Neogene volcanic layers (Mauffret *et al.*, 1995) (Figures 2, 3B, 4B). In the LPB, the domain
126 limited between hinge line 3 and the proto-oceanic crust limit (Figure 5) has recently been
127 identified as a thin layer of lower continental crust (C.C.) (Moulin *et al.*, 2015), exhumed
128 along a landward deep detachment (Séranne, 1999) and overlying an heterogeneous, intruded
129 layer (gabbros or granulites), with velocities of 6.0 and 6.4 km/s for the upper layer and 6.6 to
130 7.5 km/s for the lower layer (Moulin *et al.*, 2015).

131 **The Minorca Basin, a buffer segment**

132 As previously shown by Roca (1992) and Ayala *et al.* (2015), there is little to no
133 evidence of Neogene horizontal movement (no extension, very few faults observable on
134 seismic data) in the offshore Mesozoic sedimentary sequences of the VBss. The neogene syn-
135 rift deposits are localized either on land or on the MB borders (Figure 4, zoom A).
136 Paleomagnetic data on the Balearic Islands describes two phases of Miocene rotation and is
137 usually used for geodynamic reconstruction. However, these two phases of rotation are linked
138 to the Betics compressive phase and should not be connected with the kinematic rotation of
139 the islands (Parès *et al.*, 1992). If a rift had propagated into the VBss, the Mesozoic
140 sedimentary sequences should also have been affected by the extension. On the contrary, the
141 Neogene sedimentary layers in the central part of the VBss are horizontal and parallel (Figure
142 4, zooms B and C), which implies a vertical subsidence during this period, as has been
143 described in sag basins where no extensive movements are depicted (Moulin *et al.*, 2005;
144 Aslanian *et al.*, 2009). The significant thickness of Mesozoic deposits associated with
145 thinning of the crust have led Roca and Guimera (1992) to propose a Mesozoic thinning that
146 would account for at least half of the entire thinning, implying a huge tectonic heritage in the
147 VBss. It is beyond the scope of this paper to discuss the genesis of the Mesozoic basin, but for
148 the Neogene phase, movement of the Ibiza-Mallorca blocks toward the southeast in the VBss
149 would imply major extensive deformations in the Mesozoic deposits, which are not observed
150 on seismic data (Roca, 1992; Ayala *et al.*, 2015).

151 Following what was suggested by previous authors (e.g. Tassone *et al.*, 1996; Roca *et*
152 *al.*, 1999), our results show that the MB and LPB exhibit the same Oligo-Miocene
153 synchronous syn-rift sedimentary sequence, which does not support the hypothesis of rift
154 propagation that should have produced diachronous sequences. The continuity between the
155 two basins is further substantiated by the first occurrences of marine sediment at Oligocene
156 times in the LPB and the Catalan margin (MB) (Figure 6).

157 The position of the almost rigid Corso-Sardinian block (Arthaud and Matte, 1977)
158 before the Miocene rift phase implies that the Minorca block was about 100 km closer to the
159 Catalan margin (Figures 6 and 8) at that time (e.g. Le Cann, 1987; Olivet, 1996). The NBFZ,
160 which was, during the Pyrenean compressive phase, a dextral N-S transfer zone between the
161 Iberian and Corso-Sardinian microplates (e.g. Olivet, 1996), was reactivated during the Oligo-
162 Miocene extension phase, leading to the counterclockwise movement of the Corso-Sardinian
163 block, which is accompanied by the counterclockwise movement of the Minorca block to the
164 SE along the CFZ (Le Cann, 1987; Gueguen, 1995; Olivet, 1996), contrary to what was
165 proposed based on scarce paleomagnetic data on the Balearic Island (Parès *et al.*, 1992). This
166 movement coincides with the exhumation of the 4 km-thick lower C.C. in the LPB (a
167 metamorphic core complex for Jolivet *et al.*, 2015). This movement stopped when the proto-
168 oceanic crust started (Moulin *et al.*, 2015). During the Early Miocene-Messinian times, the
169 two transfer zones, CFZ and NBFZ, accommodate the subsidence between the VBss (high
170 position) and the LPB (deep domain) (Figures 3A, 3B).

171 While both VBss and LPB segments, (Leroux *et al.*, 2015), exhibit pure vertical subsidence
172 (Figures 4B), the thinning process may not be the same, as VBss is a polyphased basin, and
173 the LPB thinning was only during the Neogene and due to the exhumation of the lower C.C..
174 In between the VBss and LPB, the Minorca Neogene movement may have involved an
175 exhumation, such as in the GOL, but the substratum may also comprise stretched and intruded
176 upper C.C.. This issue is still open and will need the acquisition of additional wide-angle
177 seismic data in the MB to be able to address the uncertainties.

178 The idea that the MB should be considered as a Neogene buffer zone between the young
179 Oligocene-to-Miocene LPB and the old Mesozoic VBss, modifies the general view of the
180 northern part of the Occidental Mediterranean Sea before opening (Figure 7). First, the
181 divergent movements of the Kabylia blocks on one side and Peloritain-Calabria blocks on

182 the other side appear at the southwards end of the buffer zone. Second, little to no Neogene
183 movements for the Ibiza and Majorca Islands place the AlKaPeCa group (Alboran, Kabyle,
184 Peloritain, and Calabrian blocks; e.g. [Mauffret *et al.*, 1995](#)) further to the southeast,
185 northeastward of what is at present-day the Alboran Area.

186

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198 **Competing financial interests**

199 The authors declare no competing financial interests.

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386 FIGURES

387 Figure 1: Location of the study area and dataset on the bathymetric and geological map of the
388 Valencia basin s.l. Red boxes indicate location of seismic profiles presented in Figure 2,
389 showing (from SW to NE) details of the Valencia basin s.s. (VBss), the Minorca basin
390 (MB), and the Liguro-Provençal basin (LPB). Green box indicate location of seismic
391 profiles zooms presented in Figure 4.

392 Figure 2: Correlation of stratigraphic markers from the SW (VBss) to the NE (MB and LPB).
393 Names of Liguro-Provençal markers are derived from previous study (Bache, 2008;
394 Leroux, 2012). Locations of seismic profiles are shown on Figure 1.

395 Figure 3A: Non-interpreted seismic profiles oriented SW-NE (location Figure 1) crossing the
396 three defined Valencia s.s., Menorca and Ligurian-Provençal basins. MEDS76 profiles
397 were provided courtesy of Schlumberger multicient.

398 Figure 3B: Interpreted seismic profiles oriented SW-NE (location on Figures 1), highlighting
399 the evolution of the Burdigalian-Messinian, Messinian trilogy and Pliocene-Quaternary
400 megasequences and showing the general characteristics of each basin (explanation in
401 the text).

402 Figure 4A: Non-interpreted seismic profiles oriented NW-SE (location on Figure 1) illustrating
403 the Valencia s.s., Menorca and Ligurian-Provençal basins. Three zooms illustrate the
404 various structural and subsidence style between the Catalan margin (MB) (zoom 1), the
405 Tarragona trough (VBss) (zoom 2) and VBss's central depression (zoom 3). MEDS76
406 and MSP74 profiles were provided courtesy of Schlumberger multicient.

407 Figure 4B: Interpreted seismic profiles oriented NW-SE (location on Figure 1) highlighting the
408 evolution of the Oligocene-Aquitainian, Burdigalian-Messinian, and Pliocene-
409 Quaternary megasequences and showing the general characteristics of each basin. On
410 the Catalan margin the major half-graben is formed by major normal faults which led to

411 the deposition of a sedimentary wedge during Oligocene to Aquitanian (zoom 1). On the
412 contrary VBss basin records sub-parallel, horizontal and isopach strata in the deepest
413 area during Langhian to Serravallian times (zoom 2 and 3). Sediments deformation are
414 only due to triassic salt diapir activity (zoom 2).

415 Figure 5: Tertiary basement map in two-way time (s) of the NW Mediterranean sea
416 highlighting the depth increase in steps from the VBss to the LPB. Two NW-SE
417 oriented thresholds individualize the Minorca basin (CFZ: Central Fracture Zone;
418 NBFZ: North Balearic Fracture Zone). Hinge Lines highlighted in the Liguro-Provençal
419 basin show the main boundaries in the crustal evolution and subsidence response (from
420 Leroux et al., 2015; Moulin et al., 2015). Cartography of the atypical oceanic crust
421 result from a compilation of gravimetric, magnetic and velocity response (e.g. from
422 Bache, 2008; Moulin *et al.*, 2015; Afilhado *et al.*, 2015).

423 Figure 6: Paleogeographic maps of the Valencia s.l. and Liguro-Provençal domains showing a
424 repartition of marine water during Oligocene, Burdigalian and Langhian time. Circles
425 represent facies observations from boreholes. Paleocoast positions are from
426 Meulenkamp & Sissingh, 2003; Jolivet *et al.*, 2006; Roca *et al.*, 1999 combined to our
427 seismic correlations.

428 Figure 7: Northwestern Mediterranean cinematic reconstruction before opening of Liguro-
429 Provençal, Minorca and Algerian domains. Two options concerning the initial position
430 of Ibiza and Majorca are shown. In red, Early Neogene situation of Corso-Sardinian,
431 Minorca and Ibiza-Mallorca blocks proposed in this study (also suggested in Le Cann,
432 1987, Olivet, 1996, Bache, 2008, Bache *et al.*, 2010) (option a-no movement for Ibiza
433 and Mallorca islands). In purple Early Neogene situation proposed by previous studies
434 e.g. Maillard and Mauffret (1999) (option b-large movement for the Ibiza-Mallorca
435 islands). The position of AlKaPeCa blocks are from Mauffret *et al.* (1995). Two options

436 concerning the initial situation of Alboran domain are also proposed following e.g.
437 Mauffret et al. (1995) (option 1) and e.g. Doglioni et al. (1997) (option 2). The hachured
438 area corresponds to the present day exhumed lower continental crust position as
439 interpreted by Moulin *et al.* (2015).
440

Figure 1

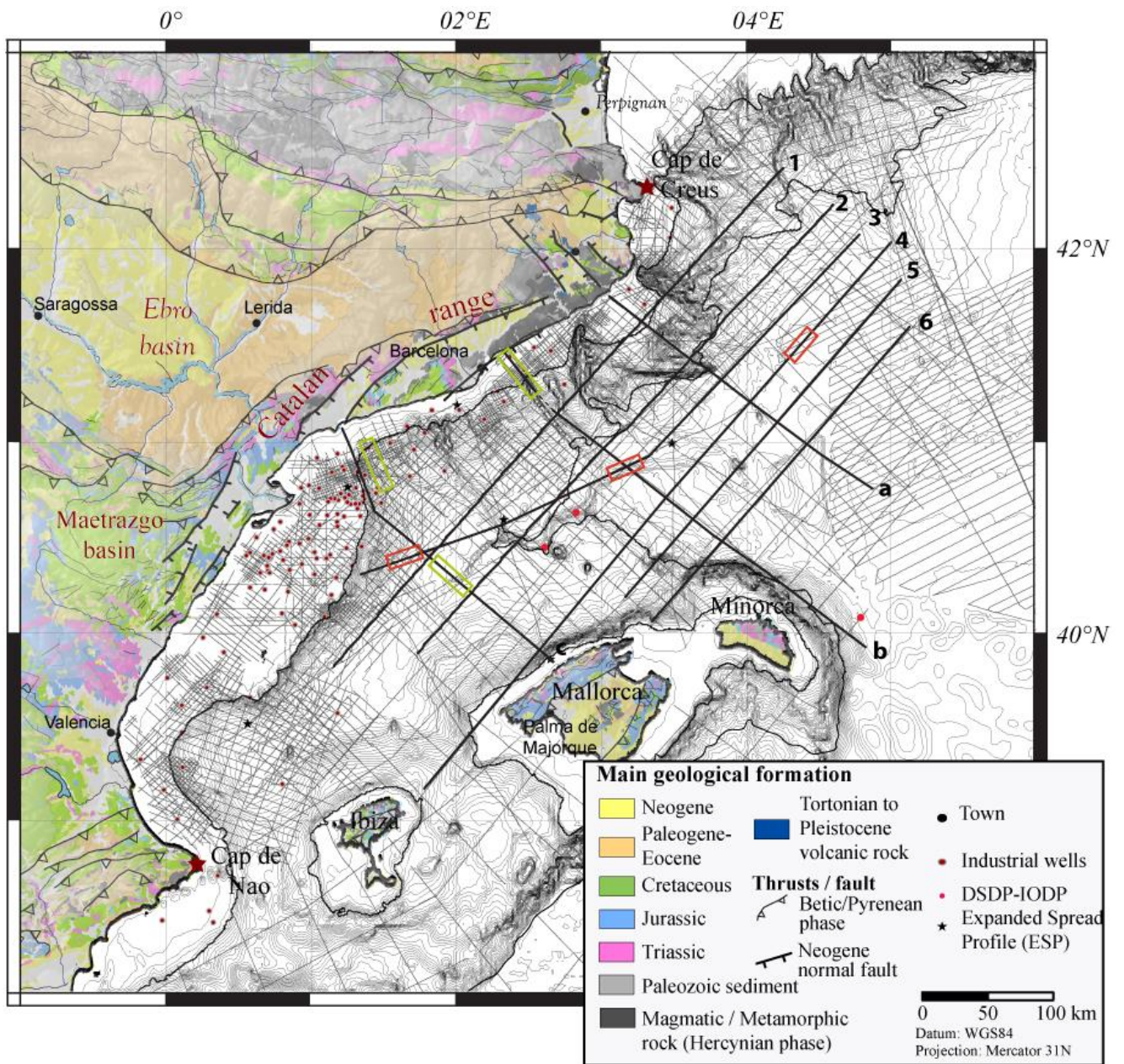
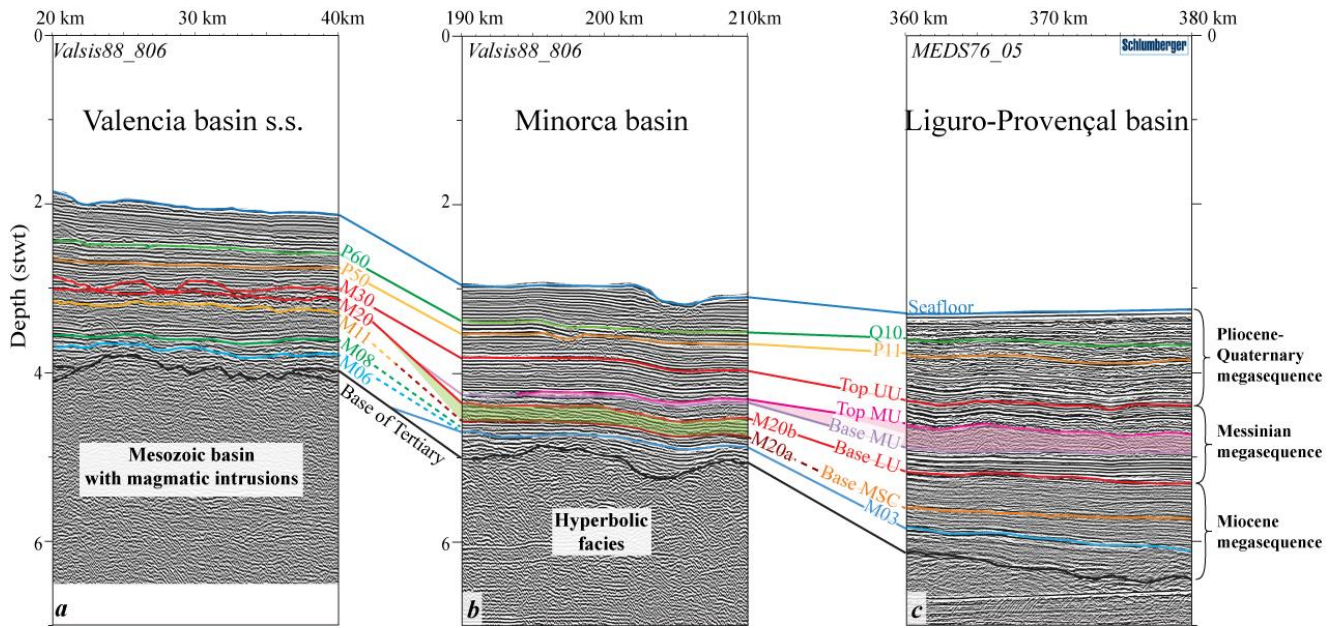


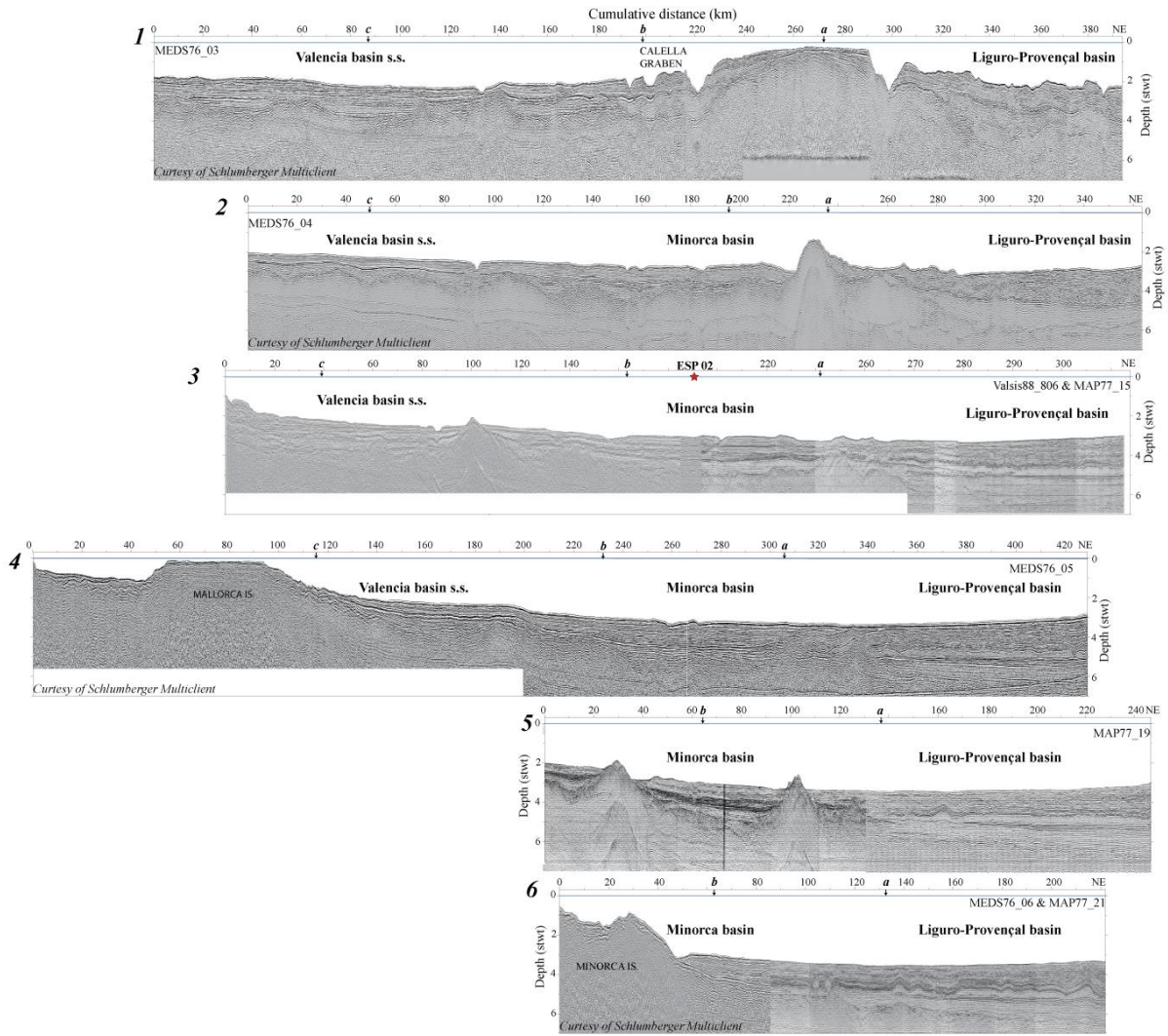
Figure 2

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442 **Figure 3A**

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Figure 3B

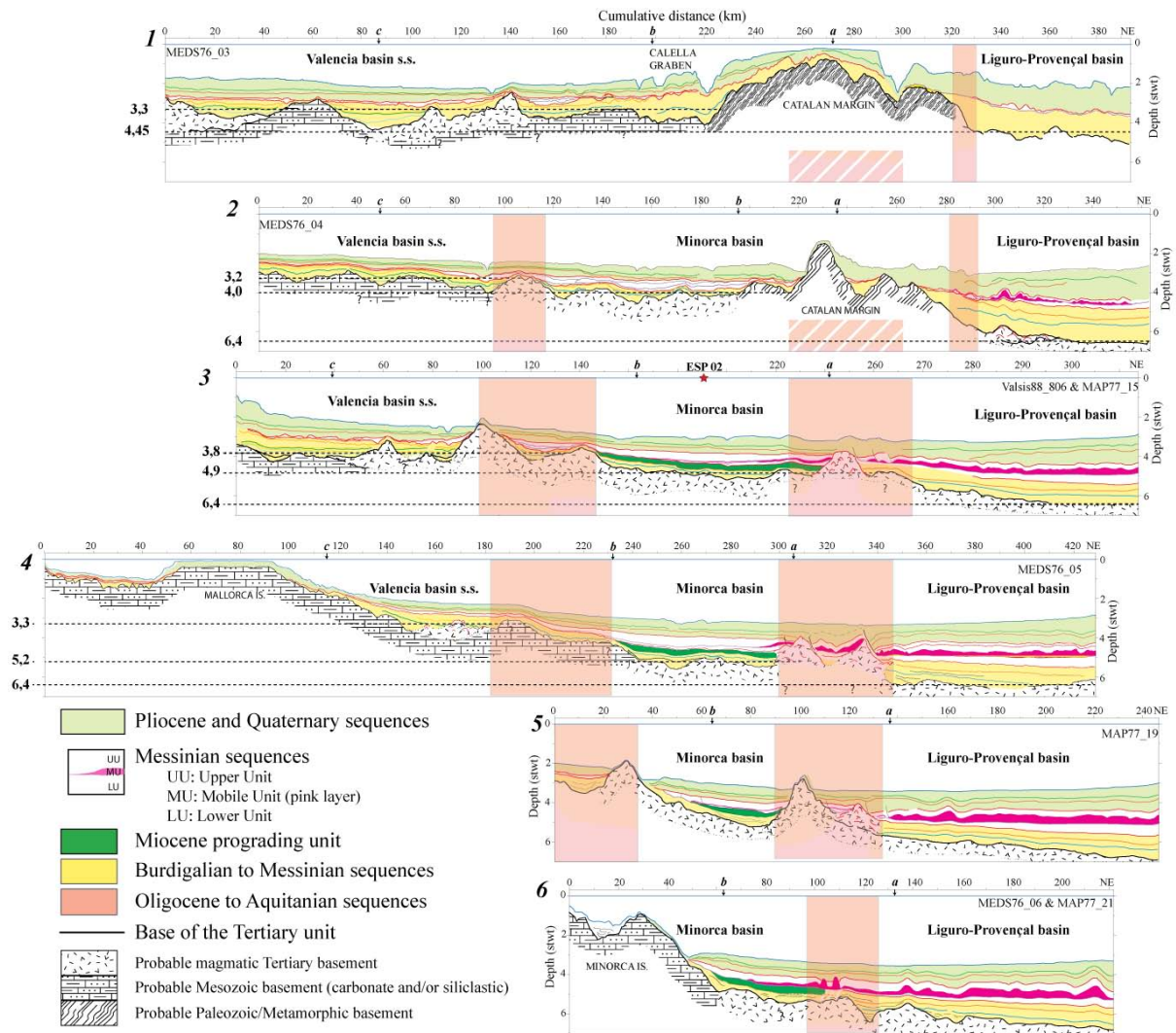


Figure 4A

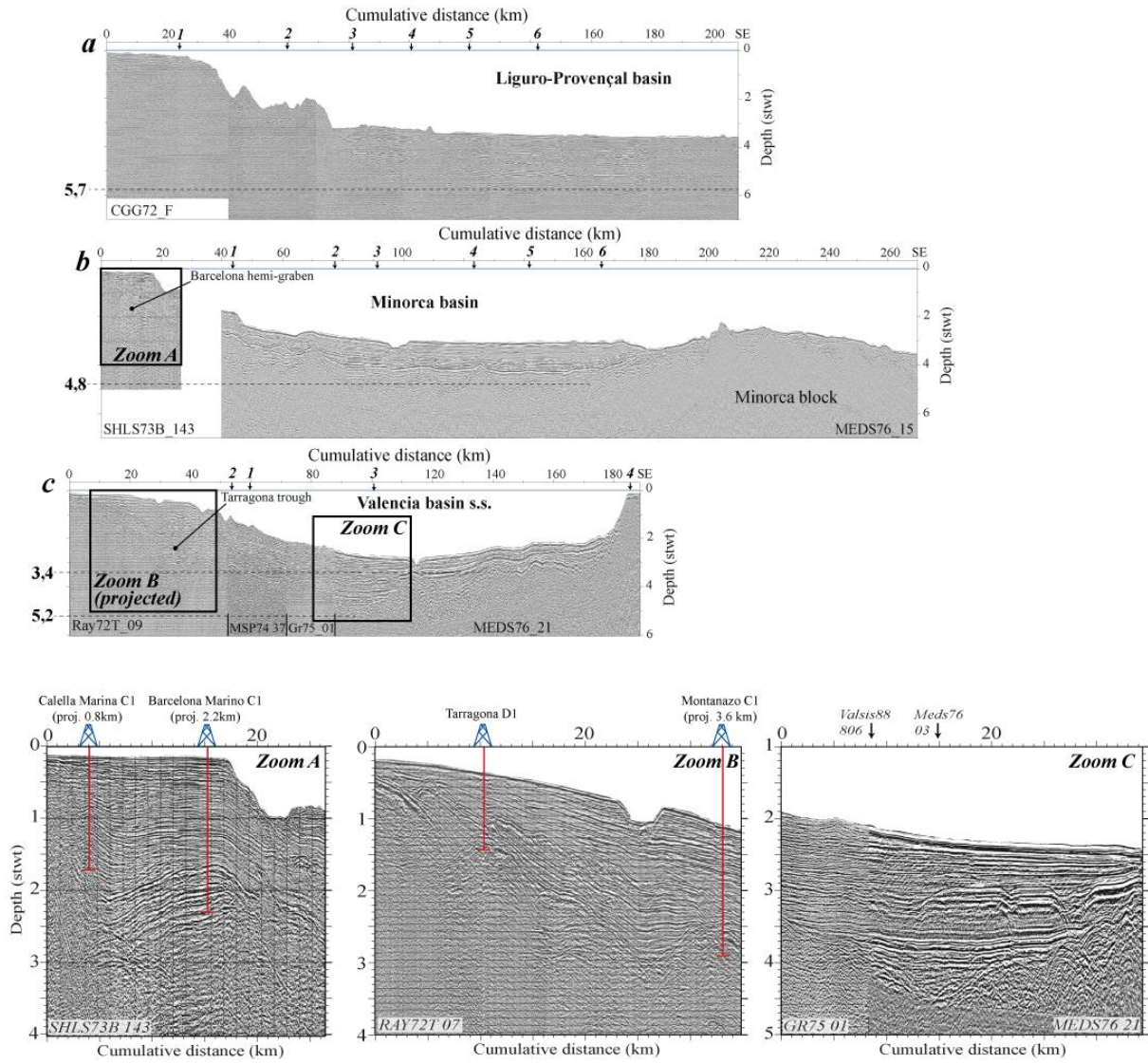
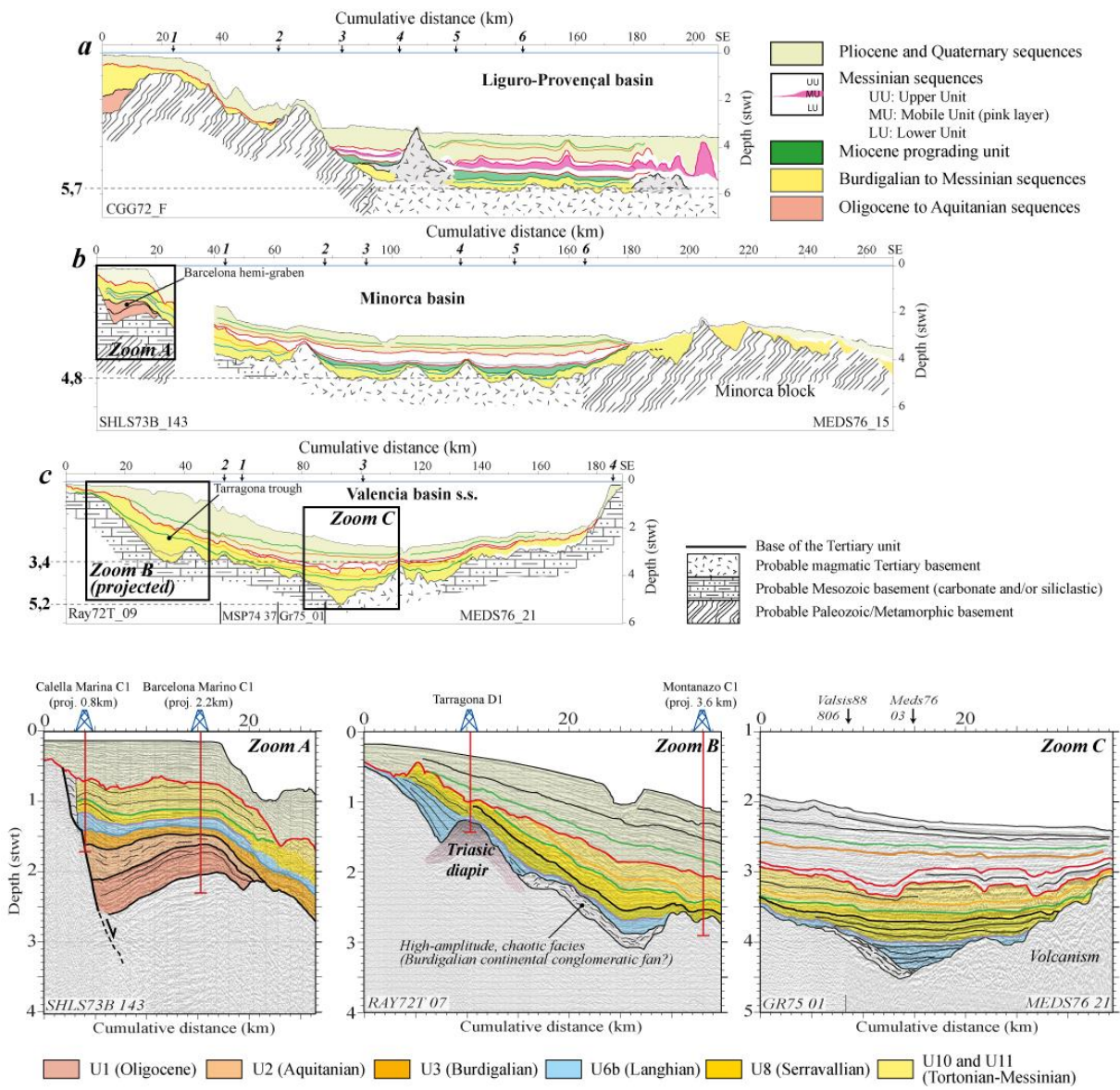
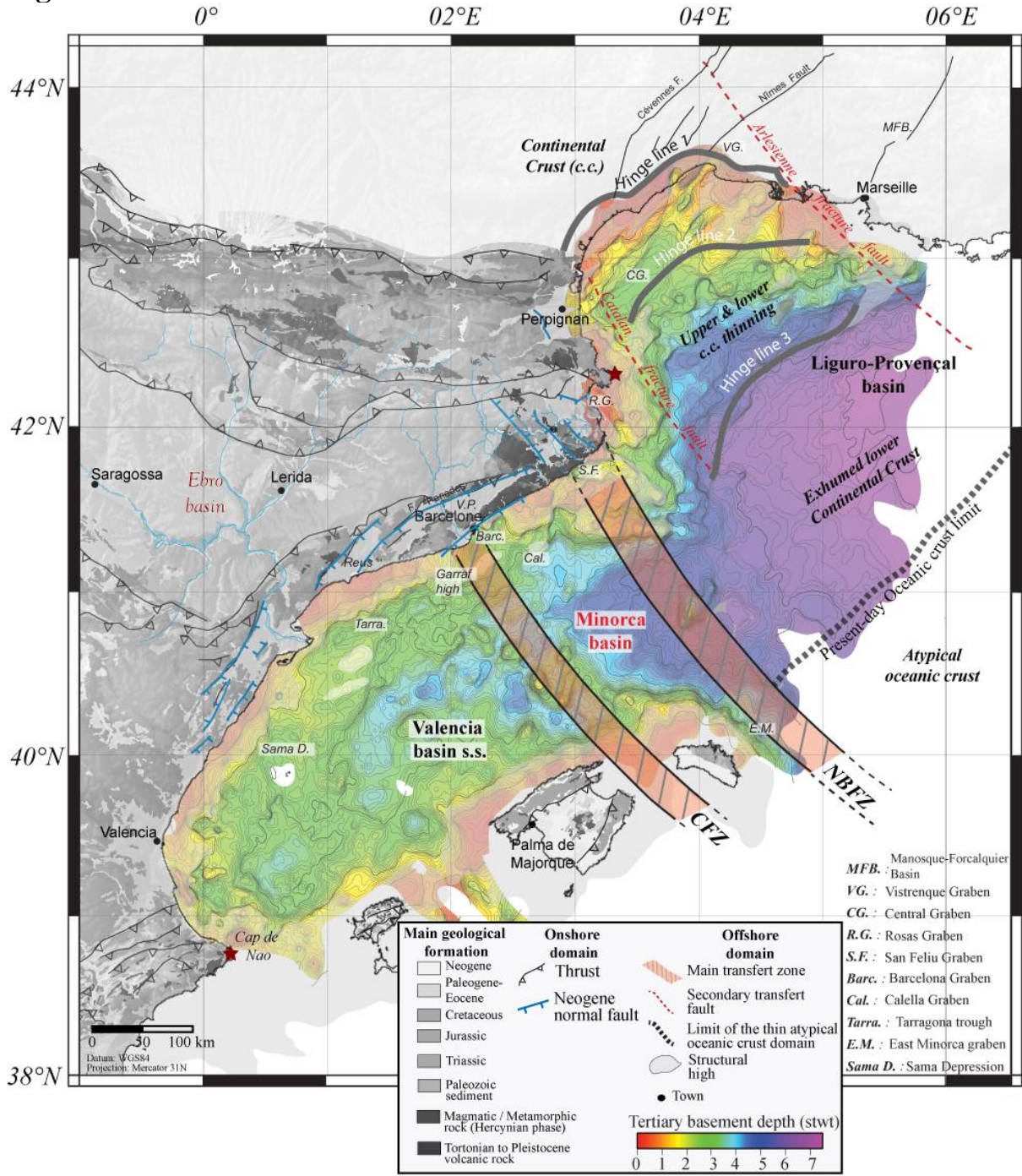


Figure 4B



447 **Figure 5**



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