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1 **Successive shifts of the India-Africa transform plate boundary**
2 **during the Late Cretaceous-Paleogene interval:**
3 **implications for ophiolite emplacement along transforms**

4
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18
19

20 **Abstract**

21 **The Arabian Sea in the NW Indian Ocean is a place where two major transform boundaries are**
22 **currently active : the Owen Fracture Zone between India and Arabia and the Owen Transform**
23 **between India and Somalia. These transform systems result from the fragmentation of the India-**
24 **Africa Transform boundary, which initiated about 90 Myrs ago, when the India-Seychelles**
25 **block separated from Madagascar to move towards Eurasia. Therefore, the geological record of**
26 **the Arabian Sea makes it possible to investigate the sensitivity of a transform system to several**
27 **major geodynamic changes.**

28 **Here we focus on the evolution of the India-Africa transform system during the ~47-90 Ma**
29 **interval. We identify the Late Cretaceous (~90-65 Ma) transform plate boundary along Chain**
30 **Ridge, in the North Somali Basin. From 65 to ~42-47 Ma, the India-Africa transform is**
31 **identified at the Chain Fracture Zone, which crossed both the Owen Basin and the North East**
32 **Oman margin. Finally, the transform system jumped to its present-day location in the vicinity of**
33 **the Owen Ridge. These shifts of the India-Africa boundary with time provide a consistent**
34 **paleogeographic framework for the emplacement of the Masirah Ophiolitic Belt, which**
35 **constitutes a case of ophiolite emplaced along a transform boundary. The successive locations of**
36 **the India-Africa boundary further highlight the origin of the Owen Basin lithosphere incoming**
37 **into the Makran subduction zone.**

38

39 **1. Introduction**

40 Transform plate boundaries experience episodes of structural reorganization and migration related to
41 geodynamic changes (e.g., the San Andreas and Queen Charlotte Faults: DeMets and Merkouriev,
42 2016; the Levant Fault: Smit *et al.*, 2010; the North Anatolian Fault: Hubert-Ferrari *et al.*, 2009;
43 LePichon *et al.*, 2016; the Saint Paul transform: Maia *et al.*, 2016). In the oceanic domain, several
44 transform systems have been active over more than 100 Myrs (Bonatti and Crane, 1982; Ligi *et al.*,
45 2002; Maia *et al.*, 2016; Maia, 2018), which allows us to investigate their behavior in the wake of
46 major geodynamic changes.

47 Transform motion between India and Africa started around 90 Ma, when rifting began between
48 Madagascar and the India-Seychelles block (Bernard and Munsch, 2000; Shuhail *et al.*, 2018). Since
49 then, Africa has been split into different plates, including Arabia and Somalia, which still have active
50 transform boundaries with India at the Owen Fracture Zone and the Owen transform, respectively
51 (Fig. 1; Fournier *et al.*, 2008a, b; 2011; Rodriguez *et al.*, 2011). The India-Africa transform plate
52 boundary therefore constitutes a good case-study to investigate the response of an oceanic transform
53 system to geodynamic changes on the 100-Myr scale. The sensitivity of the India-Africa transform
54 system since the Late Paleogene (~24 Ma) is described in Rodriguez *et al.* (2011; 2013; 2014a,b;
55 2016; 2018). However, the geological description of this transform fault is largely incomplete for the
56 Late Cretaceous-Paleogene, a period marked by two major global plate reorganization events at 63-73
57 Ma (Cande and Patriat, 2015) and 42-47 Ma (Matthews *et al.*, 2016).

58 The aim of the present study is to identify the successive locations and configurations of the India-
59 Africa transform boundary during this time interval, based on geological and free-air gravity maps, as
60 well as seismic profiles crossing the Owen and the North Somali Basins. The successive shifts of the
61 India-Africa transform boundary shed light onto 1) the mode of emplacement of the Masirah
62 Ophiolite, and of the Bela, Muslim Bagh, Zhob, and Waziristan-Khost ophiolites in Pakistan and
63 Afghanistan (Fig. 1), and on 2) the origin of the oceanic lithosphere presently subducting under
64 eastern Makran (Pakistan).

65

66 **2- Geological background & paleogeographic constraints**

67 ***2-1- Opening of the Indian Ocean***

68 From the Jurassic to the Cenomanian, two subduction zones drove the fragmentation of
69 Gondwanaland and the subsequent opening of the Indian Ocean (Norton and Selater, 1979; Besse and
70 Courtillot, 1988; Seton *et al.*, 2012; Matthews *et al.*, 2012): the Northern Neotethys Subduction
71 (nowadays recorded along the Indus-Yarlong-Tsangpo suture zone) and the East Gondwana
72 Subduction (which was located to the East of Australia and Antarctica Plates). A global plate
73 reorganization event at 100-105 Ma corresponds to the initiation of a new subduction in the Southern
74 Neotethys Ocean, while the East Gondwana subduction deactivated (Matthews *et al.*, 2012; Jolivet *et*
75 *al.*, 2016). A late consequence of the 100-105 Ma plate reorganization event is the onset of the
76 northwards migration of India in the Late Cretaceous (84-87 Ma; Fig. 2; Bernard and Munsch, 2000;
77 Calvès *et al.*, 2011; Matthews *et al.*, 2012; Gibbons *et al.*, 2013; Battacharya and Yateesh, 2015).
78 India's northwards drift is disturbed in the Late Maastrichtian, resulting in major changes in
79 configuration of Indian Ocean's spreading centers. This change is recorded by the bending of fracture
80 zones since chron 33 (74 Ma) at the SW Indian Ridge (Cande and Patriat, 2015) and a series of ridge
81 jumps from the Mascarenes spreading centers to the Gop basin and eventually, the Carlsberg Ridge
82 since 63 Ma (Royer *et al.*, 2002).

83 Seafloor spreading rates at the Carlsberg Ridge peaked at 18 cm.yr^{-1} at 52 Ma, before slowing down
84 due to the onset of a global plate reorganization event, partly related to collision between India and the
85 Kohistan-Ladakh arc (Burg, 2011; Cande and Stegman, 2011; Bouilhol *et al.*, 2013; Jagoutz *et al.*,
86 2015; Cande and Patriat, 2015). However, the role of India-Eurasia collision over global plate
87 dynamics is still highly debated due to uncertainties in its precise timing (see the various
88 paleogeographic scenarios proposing ages of collision between 24 and 55 Ma in Patriat and Achache,
89 1984; Chaubey *et al.*, 2002; Ali *et al.*, 2008; Molnar and Stock, 2009; van Hinsbergen *et al.*, 2012;
90 Gibbons *et al.*, 2015; Matthews *et al.*, 2015; Buckman *et al.*, 2018). Regardless of the precise timing
91 of the India-Eurasia collision, the Indian Ocean's fabric documents a global plate reorganization event
92 between 47 and 42 Ma, expressed by changes in spreading rates and trends, as well as a major ridge
93 jump from the Wharton Basin to the South East Indian Ridge (Coffin *et al.*, 2002).

95 **2-2. The fragmentation of the India-Seychelles-Madagascar block**

96 The series of global plate reorganization events that shaped the Indian Ocean induced several episodes
97 of breakup within the India-Madagascar block initially separated from Africa and Australia in the Late
98 Jurassic (Gibbons *et al.*, 2013).

99 First, a mid-oceanic ridge active during Albian-Senonian isolated the Kabul Block continental sliver
100 from India (Fig. 2; Tapponnier *et al.*, 1981; Gnos and Perrin, 1997; Gaina *et al.*, 2015).

101 Second, a Late Cretaceous break-up between Madagascar and the India-Laxmi-Seychelles continental
102 blocks (Fig. 1) led to the opening of the Mascarene and the East Somali Basins (Fig. 2; Schlich, 1982;
103 Bernard and Munsch, 2000; Calvès *et al.*, 2011; Gibbons *et al.*, 2013; Gibbons *et al.*, 2015;
104 Battacharya and Yateesh, 2015; Shuhail *et al.*, 2018).

105 Third, the break-up between the Seychelles-Laxmi block and India formed the Gop Basin (between
106 magnetic chrons 31 (68 Ma) and 30 (67 Ma; Minshull *et al.*, 2008; Yateesh *et al.*, 2009; Eagles and
107 Hoang, 2014). Following the culmination of the Deccan trap volcanism at ~65.5 Ma (Courtilot and
108 Renne, 2003; Hooper *et al.*, 2010), the onset of the Carlsberg Ridge at chron 28 (63 Ma) marks the full
109 Laxmi-Seychelles break-up (Dyment, 1998; Royer *et al.*, 2002).

110

111 **2-3- Late Cretaceous-Early Paleocene ophiolites in the NW Indian Ocean**

112 Ophiolites are remnants of oceanic lithosphere emplaced over continental lithosphere that are mainly
113 encountered in fossil convergence zones, but also in contexts such as transform boundaries (Dilek and
114 Furnes, 2014). To avoid any confusion, we use the term of '*obduction*' where the ophiolites can be
115 related to a subduction zone, and the term of '*ophiolite emplacement*' where the ophiolite cannot be
116 unambiguously tied to a subduction zone.

117 The initiation of an intra-oceanic subduction ~100-105 Ma in the southern part of the Neotethys
118 Ocean led to obduction north of Arabia and India during the Campanian (Hacker *et al.*, 1996; Agard *et al.*,
119 2007, 2011; Hébert *et al.*, 2012; Morris *et al.*, 2017; Nicolas and Boudier, 2017; Guilmette *et al.*,
120 2018). In the surroundings of the Arabian Sea, the related ophiolites are the Semail in Oman (Searle
121 and Cox, 1999; Breton *et al.*, 2004) and Zhob-Waziristan-Khost ophiolites in NE Pakistan
122 (Cassaigneau, 1979; Badshah *et al.*, 2000; Sarwar, 1992; Khan *et al.*, 2007).

123 In south east Pakistan, the Bela and Muslim Bagh ophiolites record a different timing of subduction
124 initiation, ranging between 65-70 Ma from the dating of metamorphic soles (Allemann, 1979;
125 Mahmood *et al.*, 1995; Gnos *et al.*, 1998; Khan *et al.*, 2007), and 80 Ma from dating of Supra-
126 Subduction Zone lavas (Kakar *et al.*, 2014). These ophiolites are derived from the basin extending
127 between India and the Kabul Block.

128 The Masirah Ophiolite running along eastern Oman (Fig. 1) has a different paleogeographic origin.
129 The oceanic crust exposed in the Masirah Ophiolite was formed at a latitude of ~30-50°S (Gnos and
130 Perrin, 1997) in Tithonian-Berriasian times (~140-145 Ma; Peters and Mercolli, 1998). These
131 ophiolites are therefore remnants of the Indian Ocean formed during the early stages of Gondwanaland
132 break-up. The oldest Arabia-derived sediments (detrital Fayah formation) date back to Coniacian at
133 Masirah (Immenhauser, 1996), indicating that the Masirah ophiolite was a part of India's lithosphere
134 prior to its obduction (Gnos *et al.*, 1997). A particularity of the Masirah Ophiolite is the lack of
135 metamorphic sole and hence, possibly no relationship to subduction (Wakabayashi and Dilek, 2003;
136 Agard *et al.*, 2016). The age of emplacement is defined from stratigraphic and structural constraints
137 (Immenhauser, 1996; Schreurs and Immenhauser, 1999; Immenhauser *et al.*, 2000). Late
138 Maastrichtian folds affecting deep-sea sediments in the Batain plain record the first step of
139 emplacement, whereas unconformable, Priabonian shallow water carbonates seal the ophiolite.

140

141 ***2-4- The Oman abyssal plain and the Owen Basin***

142 The oceanic lithosphere incoming into the present-day Makran Subduction Zone is 70 to 100 Myrs-old
143 according to heat flow measurements (Hutchison *et al.*, 1981), similar to ophiolites exposed at Semail.
144 As a result, the lithosphere of the Oman abyssal plain is generally considered as a remnant of the
145 Neotethys Ocean (McCall, 1997; Ravaut *et al.*, 1997; 1998; Ellouz-Zimmerman *et al.*, 2007; Barrier
146 and Vrielynck, 2008; Frizon de Lamotte *et al.*, 2011; Burg, 2018).

147 However, offshore eastern Oman, most of the Owen basin basement is of Paleogene age (Fig. 3;
148 Mountain and Prell, 1990; Rodriguez *et al.*, 2016). Considering a Neotethys origin for the entire Oman
149 abyssal plain would imply that the Indian Ocean Tithonian lithosphere facing Arabia during the Late
150 Maastrichtian emplacement of the Masirah ophiolites (Peters and Mercolli, 1998) must have been

151 subducted between the Owen Basin and the Oman abyssal plain. Such a subduction zone is not
152 documented, however, questioning the fate of the Tithonian lithosphere now represented by the
153 Masirah ophiolite, and the origin of the Late Cretaceous lithosphere in the eastern part of the Oman
154 abyssal plain (Rodriguez *et al.*, 2016).

155 In addition, several features of the Oman abyssal plain remain enigmatic, including the Sonne
156 lineament and the Qalhat Seamount-Little Murray Ridge (Fig. 3). Although the NW-SE trending
157 Sonne lineament imaged on the free-air gravity map (Fig. 3) has been first interpreted as a still active
158 strike-slip fault (Kukowski *et al.*, 2001), no trace of activity has been observed on seismic lines
159 acquired since (Mouchot, 2009). The Qalhat Seamount and Little Murray Ridge constitute a chain of
160 submarine volcanoes of Late Cretaceous age (Edwards *et al.*, 2000; Mouchot, 2009) whose
161 paleogeographic origin remains unclear.

162

163 **3- Materials and Methods**

164 ***3-1- Geological, free-air gravity maps and plate reconstructions***

165 The free-air gravity maps (Figs. 3, 4) have been designed using the DTU 13 database filtered for short
166 wavelengths (Andersen *et al.*, 2013). Offshore, a few multibeam tracks have been acquired in the area
167 of the Chain Ridge (Fig. 5) during transits of the AOC and VARUNA-CARLMAG cruises onboard
168 the BHO Beautemps-Beaupré operated by the French navy in 2006 and 2019. The structure of the
169 strike-slip fault system crossing the Huqf desert in Oman (Fig. 6) is mapped after geological maps of
170 Oman at 1: 250 000 (sheets of Duqm, Madreka, Khalouf by Platel *et al.*, 1992) and maps built from
171 seismic data (Filbrandt *et al.*, 2006). The paleogeographic reconstructions of India and Africa
172 continents are drawn after the Gplates files provided in Matthews *et al.* (2016). The successive
173 locations of the India-Africa plate boundary identified hereafter complete these reconstructions.

174

175 ***3-2- Seismic reflection***

176 ***3-2-1. Sources of the datasets***

177 For the Owen Basin, we use the seismic dataset from the OWEN 2 survey (Figs. 7 to 10; Rodriguez *et*
178 *al.*, 2016), acquired in 2012 onboard the R/V Beautemps-Beaupré using a high-speed (10 knots)

179 seismic device. The source consists in two GI air-guns (one 105/105 c.i. and one 45/45 c.i.) fired every
180 10 seconds at 160 bars in harmonic mode, resulting in frequencies ranging from 15 to 120 Hz. The
181 receiver is a 24-channel, 300-m-long seismic streamer, allowing a common mid-point spacing of 6.25
182 m and a sub-surface penetration of about 2 s two-way travel time. The standard processing consisted
183 of geometry setting, water-velocity normal move-out, stacking, water-velocity f-k domain post-stack
184 time migration, bandpass filtering and automatic gain control.

185 New interpretations for seismic lines crossing the North Somali Basin (Fig. 4) and the Batain plain in
186 NE Oman (Fig. 11) are based on the dataset published in Bunce and Molnar (1977) and Beauchamp et
187 al. (1995), respectively.

188

189 *3-2-2. Stratigraphy in the Owen Basin*

190 Seismic profiles have been tied to drilling sites available in the Arabian Sea from DSDP and ODP legs
191 (Shipboard Scientific Party, 1974a, 1974b, 1989) and stratigraphic details can be found in Rodriguez
192 *et al.* (2016). Two key seismic horizons have been identified on the seismic lines (Figs. 7 to 10). The
193 cross-section of the Oman margin provided in Figure 7 summarizes the stratigraphic framework of the
194 area. A first key reflector corresponds to an angular unconformity recording the end of the uplift of
195 marginal ridges along the Oman margin in the Late Eocene. This unconformity is only recognized in
196 the western part of the Owen Basin, and becomes concordant to the east. A second Late Oligocene-
197 Early Miocene unconformity is observed across the entire Owen Basin, and reflects the diachronous
198 flooding of the Owen Basin by the Indus turbiditic system (Rodriguez *et al.*, 2016). Finally, the top of
199 the Masirah Ophiolites, expressed by a chaotic and highly reflective body on seismic lines (Fig. 7, 11),
200 is considered as Late Maastrichtian, in agreement with onland studies (Immenhauser *et al.*, 1996;
201 Immenhauser *et al.*, 2000).

202

203 **4- Configurations of the India-Africa plate boundary during the Late Cretaceous-** 204 **Eocene**

205 *4-1- Configuration of the Late Cretaceous India-Africa plate boundary*

206 In the northern Somali Basin, on the western edge of the NE-SW trending Chain Ridge, a large sub-
207 vertical fault (offset over ~ 2 s TWT) is imaged on the seismic profile (Fig. 4; Bunce and Molnar,
208 1977). The fault lineament is well-expressed on the free-air gravity field, and partly mapped on the
209 multibeam coverage of Chain Ridge (Fig. 5). This fault juxtaposes two different oceanic lithospheres.
210 On the eastern flank of Chain Ridge, gabbros dredged at DSDP Site 235 indicate a 90 Myrs-old
211 seafloor (Shipboard Scientific Party, 1974a), i.e., a piece of the East Somali Basin. For the seafloor
212 west of Chain Ridge, magnetic anomalies document a Late Jurassic to Early Cretaceous age (160 to
213 130 Ma; Cochran, 1988; Gaina *et al.*, 2015). The western part of the northern Somali Basin is
214 therefore a remnant of the first stage of opening of the Indian Ocean. The juxtaposition of oceanic
215 lithospheres of different ages is explained by considering the fault observed west of Chain Ridge as
216 the fossil Late Cretaceous India-Africa transform plate boundary (Chain Ridge Transform, Fig. 4).

217 Evidence for Late Cretaceous (Santonian-Campanian) left-lateral strike-slip tectonics is further
218 identified in Oman (Fig. 6). Three-dimensional seismic reflection data document a distributed system
219 of conjugate strike-slip faults, which display typical flower structures, previously mapped by Filbrandt
220 *et al.* (2006). Left-lateral faults are also widely observed in the Huqf desert (Oman), cutting through
221 outcrops of Neoproterozoic remnants of the Pan-African orogeny, at the Khufai, Buah, Shuram,
222 Mukhaibah and Haushi anticlines (Fig. 6; Shackleton and Ries, 1990; Allen, 2007). This set of
223 observations defines the NW-SE trending transtensive Haushi-Nafun-Maradi Fault System (HNMFS
224 hereafter), mapped in Figs. 3 and 6. The HNMFS was active only during the deposition of the Fiqra
225 formation in Early Maastrichtian (Filbrandt *et al.*, 2006) and also locally accompanied by volcanic
226 activity (Glennie *et al.*, 1974; Wyns *et al.*, 1992).

227 Despite a poor sedimentary record due to low sedimentation rates during Late Maastrichtian-Early
228 Paleogene, the seismic lines crossing the western part of the Owen Basin at various latitudes document
229 some sedimentary layers beneath the Late Maastrichtian horizon sealing the Masirah ophiolites (Figs.
230 8-10). These Late Maastrichtian-Early Paleocene layers are trapped in half-graben structures and
231 display a fanning configuration (Figs. 8-10), which reflects tectonic activity. The low density of
232 available seismic lines does not allow us to map accurately these grabens and their precise relationship

233 with the HNMFS, but they are likely coeval with the tectonic deformation observed along the
234 HNMFS.

235

236 ***4-2- Configuration of the Paleocene-Eocene India-Africa plate boundary***

237 In the North Somali Basin, the Paleocene-Eocene India Africa plate boundary is expressed as the
238 Chain Fracture Zone (Figs. 1, 4), which bounds the seafloor accreted at the Carlsberg Ridge since 63
239 Ma (Royer et al., 2002; Chaubey et al., 2002). However, the trace of the India-Africa transform
240 boundary has not been clearly identified offshore Arabia in the Owen Basin, due to the complex
241 history of the area related to various episodes of margin reactivation (*Rodriguez et al.*, 2014, 2016). In
242 this section we explore the remnants of the Paleocene-Eocene India Africa plate boundary preserved
243 along the East Oman Margin and the Owen Basin.

244 *Eastern Oman margin -Masirah :*

245 The free-air gravity map of the Oman margin (Fig. 3) documents a series of en-échelon marginal
246 ridges within a ~90-km-wide, N30°E-trending corridor running from Sawqirah to Ras Al Hadd (over
247 ~600 km). The seismic line displayed in Fig. 11 (from *Beauchamp et al.*, 1995) crosses the Masirah
248 Ophiolite onshore, in one of the few places where the initial structure of the ophiolite is still preserved.
249 There, the Masirah Ophiolites display a double vergent thrust stack of numerous ophiolite sheets,
250 according to our revised interpretation (Fig. 11; *Beauchamp et al.*, 1995). The cross section and the
251 profiles displayed in Fig 7 show that elsewhere along the en-échelon marginal ridge system, the
252 offshore segments of the Masirah Ophiolites are scattered. Vertical fault offsets (Fig. 7) indicate that
253 the initial Masirah Ophiolite has been highly dismembered during the formation (i.e., uplift and
254 shearing) of the en-échelon marginal ridge system (Fig. 3).

255 The stratigraphy of the eastern Oman margin documents the period of formation of this system of en-
256 échelon marginal ridges. Onland, the Masirah ophiolite overlies a Late Maastrichtian, deep-sea detrital
257 formation (Fayah Fm; Immenhauser, 1996), indicating that the marginal ridges did not exist at that
258 time. On the other hand, the Priabonian shallow-water carbonates of the Aydim formation and laterites

259 cover both the ophiolites and the marginal ridges (Immenhauser, 1996; Shipboard Scientific Party,
260 1989). The Aydim formation is coeval with a major angular unconformity along the edges of the
261 marginal ridges in the Owen Basin, marking the end of the marginal ridge uplift (Figure 3, 7;
262 Rodriguez *et al.*, 2016). The uplift of the en-échelon system of marginal ridges therefore lasted over
263 more than 25 Myrs, from 65-70 Ma up to ~40 Ma. This period is coeval with numerous geological
264 events identified along the east Oman margin, including alkaline volcanism in the Batain and Haushi-
265 Huqf areas (Gnos and Peters, 2003), and a reorganization of detrital sedimentary systems in SE Oman
266 consistent with surface uplift (Filbrandt *et al.*, 2006; Robinet *et al.*, 2013).

267 *Owen Basin:*

268 The seismic lines displayed in Figs. 8 to 10 document the structural expression of the Paleogene India-
269 Africa plate boundary within the Owen Basin, at various latitudes. In all these lines, we map the area
270 where the indicators of pre-Late Maastrichtian tectonics vanish within the Owen Basin (Figs. 8-10).
271 The area bounding the Late Maastrichtian basins displays a V-shape typical of transform valleys, with
272 flanks characterized by a ~30° slope, shaped by erosion due to bottom current and mass wasting
273 (frequently observed on figs. 8-10). Due to the low sedimentation rates during the Paleogene, the
274 preservation of this extinct transform structure in the geological record is poor.

275 The location of the Chain Fracture Zone according to reconstructions by Royer *et al.* (2002) coincides
276 with the eastern boundary of the pre-Maastrichtian basins identified on the seismic lines (Figs. 8-10).
277 In reconstructions, the Chain Fracture Zone follows the trend of the northeast Oman margin north of
278 20°N (Fig. 3), where its steepness is compatible with a transform margin. The eastern part of the Owen
279 Basin is Paleogene in age, consistent with basement ages obtained at ODP drilling sites along the
280 Owen Ridge (Shipboard Scientific Party, 1974b, 1989). The composite age of the basement may
281 therefore be explained by a major transform boundary crossing the Owen Basin (Fig. 3, Rodriguez *et*
282 *al.*, 2016).

283

284 **5- Discussion**

285 Identification or reappraisal of these structural relationships highlight a major change in the
286 configuration of the India-Africa boundary around ~65-70 Ma (i.e., coeval with the global plate
287 reorganization event; Cande and Patriat, 2015). Data indicate that the India-Africa plate boundary
288 migrated from the Chain Ridge Transform to the Chain Fracture Zone (Fig. 12). Here we address
289 critical points of the structural evolution of the India-Africa plate boundary raised by the
290 reconstruction of figure 12, as well as the paleogeographic implications of the transform plate
291 boundary migration.

292 ***5-1-Structural evolution of the India-Africa plate boundary during the Late Cretaceous-Eocene***

293 For the Late Cretaceous India-Africa plate boundary, our reconstruction highlights a lack of direct
294 connection between the Chain Ridge transform offshore Somalia and the HNMFS in Oman (Fig. 12).
295 While the HNMFS could be a distributed strike-slip system related to the partitioning of India-Africa
296 motion along the offshore Chain Ridge Transform (Filbrandt *et al.*, 2006), its trend may reflect older
297 Neoproterozoic structures (Allen, 2007) reactivated in response to the complex Late Cretaceous stress
298 field, influenced by both the obduction of the Semail to the north and transform tectonics to the east.

299 For the Paleocene-Middle Eocene India-Africa plate boundary, the development of the en-échelon
300 system of marginal ridges constitutes the clearest record of transform fault activity. The en-échelon
301 system of marginal ridges may be interpreted as the result of a sheared transform margin (Fig. 13), in a
302 transpressive, partitioned left-lateral strike-slip system of deformation related to the Chain Fracture
303 Zone between ~65-70 Ma and ~40-45 Ma. Strain partitioning may explain the development of the
304 marginal ridges along the southern part of the Oman margin, which was located more than 100 km
305 away from the Chain Fracture Zone. In this framework, the en-échelon system of marginal ridges
306 results from the reactivation of Tithonian passive margin structures, and probably structures
307 reactivated during the activity of the HNMFS (Fig. 13; see below).

308 Trehu *et al.* (2015) demonstrated for a similar marginal ridge at the Queen Charlotte Transform
309 (Carlson *et al.*, 1988; Barrie *et al.*, 2013; Rhor 2015) that such a configuration is typical of a slight
310 (<15°) component of oblique convergence inducing transpression.

311

312 ***5-2- Emplacement of the Masirah Ophiolite along the east Oman transform margin***

313 These results allow to reappraise the emplacement of the Masirah ophiolite of Jurassic age (Fig. 13).
314 The story begins during the Late Maastrichtian, coeval with the migration of the India-Africa plate
315 boundary at ~65-70 Ma from Chain Ridge to the Chain Fracture Zone. Paleogeographic
316 reconstructions show that the Chain Fracture Zone must have crossed the Owen basin and the
317 northeastern Oman margin in the area of the Batain plain (Royer *et al.*, 2002; Fournier *et al.*, 2010;
318 Rodriguez *et al.*, 2016). There, the Masirah Ophiolite was a double vergent structure (Fig. 11) formed
319 along a transpressive segment of the Chain Fracture Zone, or a remnant of Chain Ridge passing by the
320 Chain Fracture Zone. The Masirah Ophiolite is uplifted during the Paleogene, when the en-échelon
321 marginal ridges of the Oman transform margin developed (Fig. 10). During the Paleocene-Eocene,
322 distributed left-lateral shear and uplift of the marginal ridges promoted the dismembering of the
323 ophiolite fragments initially located in the Batain plain (Fig. 13). Dismembering of the ophiolites
324 within the shear zone would explain why the double vergent structure identified at the Batain, as well
325 as the fold system in front of the ophiolites (Schreurs and Immenhauser, 1999), are no longer observed
326 to the south at Sawqirah or Masirah.

327 The initial double-vergent structure proposed for the Masirah ophiolites along the Chain Fracture Zone
328 is very similar to many transverse ridges observed worldwide, such as the Davie Ridge offshore
329 Mozambique (Mahanjane, 2014), the St Paul transverse ridge in the Atlantic (Maia *et al.*, 2016) or the
330 MacQuarie Ridge at the Australia-Pacific plate boundary (Meckel *et al.*, 2003). The fact that double
331 vergent structures may be a favorable setting for the initiation of ophiolite emplacement has already
332 been proposed for the Meratus ophiolite in SE Borneo (Pubellier *et al.*, 1999) along an oblique
333 convergent plate boundary.

334 ***5-3-Paleogeographic implications***

335 Figure 14 presents paleogeographic reconstructions, which emphasize the successive locations of the
336 India-Africa boundary and the related transfer of fragments of oceanic lithosphere from one plate to
337 another. The migration of the India-Africa plate boundary from the Chain Ridge to the Chain Fracture
338 Zone around 65-70 Ma induced a transfer of a sliver of Late Cretaceous oceanic lithosphere from the

339 East Somali Basin to Africa, explaining the age contrast with the western part of the North Somali
340 Basin (Fig. 14c). The Late Cretaceous lithosphere from the East Somali Basin was displaced
341 northwards along the Chain Fracture Zone, while seafloor was formed at Carlsberg Ridge (Fig. 14d).
342 The plate boundary then jumped to its present-day location along the Owen Ridge, during the Late
343 Eocene-Oligocene (Rodriguez *et al.*, 2016), probably as a consequence of India-Eurasia collision and
344 the global plate reorganization event recorded around 47 Ma (Müller *et al.*, 2016). This migration of
345 the India-Africa plate boundary lead to another episode of transfer to Africa of a piece of the oceanic
346 lithosphere accreted at the Carlsberg Ridge (Fig. 14e; Rodriguez *et al.*, 2016). In this reconstruction,
347 the composite origin of the Owen Basin is explained by the juxtaposition of remnants of a Tithonian
348 passive margin to the west, slices of a Tithonian proto-Indian Ocean lithosphere preserved along the
349 Masirah ophiolite, and Paleogene lithosphere formed at the Carlsberg Ridge to the east (Fig. 14).
350 Therefore, the Late Cretaceous lithosphere subducting in front of the Makran has two different
351 paleogeographic origins (Fig. 14): the Neotethys west of the Chain Fracture Zone and the East Somali
352 Basin to the east (east of ~61°E).

353 This scenario also provides an explanation for the paleogeography of the Tithonian lithosphere at the
354 origin of the Masirah ophiolite, that does not require a subduction zone between the Owen Basin and
355 the Oman abyssal plain (Fig. 14). The East Somali Basin spreading center formed within the Tithonian
356 oceanic lithosphere at the origin of the ophiolites, or at the tip of the Lower Cretaceous basin located
357 between India and the Kabul block (Fig. 14). During the Late Cretaceous, the Tithonian lithosphere
358 was progressively displaced to the north along the Chain Ridge Transform, while the East Somali and
359 Mascarenes Basins opened to the south (the spreading center being at the tip of the Chain Ridge
360 Transform). In the Late Maastrichtian, when the Masirah ophiolite emplacement started (unrelated to
361 any subduction), the Tithonian lithosphere had reached the latitude of Oman (Fig. 12,14). After the
362 Masirah obduction, the remaining Tithonian lithosphere located east of the Chain Fracture Zone was
363 subducted beneath eastern Makran (Figs. 14c,d). In detail, this reconstruction suggests that the Sonne
364 lineament, Qalhat seamount and Little Murray Ridge (Fig. 3) are parts of the fossil ocean-ocean
365 transition between the East Somali Basin and the Carlsberg seafloor, when the Carlsberg Ridge
366 formed in the wake of the Deccan plume (Dyment, 1998).

367 With regards to the eastern Pakistan ophiolites, the India-Africa plate boundary was located west of
368 the Kabul block in the Late Maastrichtian according to our reconstruction (Fig. 14), making it difficult
369 to consider these ophiolite sequences as remnants of an India-Africa transform, unless a complex
370 stepover is involved. Instead, during the Paleogene-Early Eocene, the trend of the Chain Fracture Zone
371 allows a connection with the Sistan Ocean (Fig. 14; Treolar and Izatt, 1993; McCall, 1997). More
372 constraints from the surroundings of the Kabul block are needed to further document this episode of
373 transform tectonics.

374

375 ***5-4- Migration of the India-Africa plate boundary at ~74-63 Ma as part of a global plate***
376 ***reorganization event?***

377 The reorganization of the India-Africa plate boundary identified around 74-63 Ma may result from a
378 major geodynamic reorganization event affecting the entire Indian Ocean. The driver of this plate
379 reorganization event is a matter of debate. The Indonesian Slab reached the Lower Mantle during this
380 period, which affects the slab pull force (Faccenna *et al.*, 2013). The volcanic activity of the Deccan-
381 Réunion Plume peaked at 65 Ma, but earliest traces of Deccan type volcanism are encountered around
382 110-120 Ma (Mahoney *et al.*, 2002). Both slab penetration into the lower mantle and plume-push may
383 affect oceanic spreading patterns at mid-oceanic ridges and global plate dynamics (Cande *et al.*, 2011;
384 van Hinsbergen *et al.*, 2011; Faccenna *et al.*, 2013), even if the relative contribution of each process to
385 force balance remains a matter of debate (Anderson, 2001; Bercovici, 2003; Cande and Stegman,
386 2011). However, these processes do not explain the abrupt change in plate boundary configuration.

387 Two punctual geological events (duration <5 myrs) may have contributed to the plate boundary
388 reorganization event by affecting subduction dynamics (boundary forces):

389 - deactivation of the subduction at the origin of the Bela and Muslim-Bagh ophiolites and the Masirah
390 Slab in tomography (Gaina *et al.*, 2015);

391 - collision of the Woyla Arc (Wajzer *et al.*, 1991; Gibbons *et al.*, 2015) and Burma Block by the Late
392 Maastrichtian (Socquet and Pubellier, 2005) or the Early Tertiary (Searle *et al.*, 2007) with
393 southeastern Eurasia.

394 While collision of continental terranes and subduction deactivation events are common phenomenon
395 in plate tectonics, their relationship to transform boundary migration events is yet unclear (Maia,
396 2018). Our reconstructions nevertheless provide first order constraints on the context in which the
397 migration of the India-Africa transform boundary occurred and a way to test the sensitivity of
398 transform boundary to geodynamic changes. At ~70 Ma, spreading and convergence rates were high
399 ($>10 \text{ cm.yr}^{-1}$), the age contrast between the adjacent oceanic lithospheres at the Chain Ridge transform
400 was $> 30 \text{ Myrs}$, and the Chain Ridge transform offset was at least of 500-km (Figs. 12, 14). We
401 propose that the integrated strength of the Chain Ridge transform may have been too high at the time
402 of this plate reorganization to further accommodate the relative motion of India-Africa, hence resulting
403 in the relocation of the transform boundary in a weaker area, at the Chain Fracture Zone.

404

405 **6- Conclusions**

406

407 Our reconstructions show that during the Late Cretaceous-Late Eocene interval, the India-Africa
408 transform boundary migrated in response to broader geodynamic events. The Late Maastrichtian
409 migration from the Chain Ridge Transform to the Chain Fracture Zone records the plate reorganization
410 event at 74-63 Ma (Cande and Stegman, 2011). The Late Eocene migration from the Chain Fracture to
411 the present-day location along the Owen Ridge records the well-defined global plate reorganization
412 event at ~42-47 Ma (Muller *et al.*, 2016). The successive episodes of migration of the India-Africa
413 plate boundary since the Late Cretaceous contributed to the transfer of oceanic slivers between both
414 plates. Our updated paleogeographic framework suggests that the lithosphere presently subducting
415 beneath eastern Makran originates from the East Somali Basin in the Indian Ocean, instead of the
416 Neotethys as previously proposed.

417 This study also highlights how ophiolites may be emplaced along a transform boundary as a
418 consequence of a transform migration event. Although the proposed scenario fits with all available
419 geological constraints, a denser grid of seismic reflection profiles along the east Oman margin is
420 needed to confirm and describe more precisely the mode of development of the en-échelon marginal
421 ridges, and the related uplift and dismembering of the Masirah Ophiolitic Belt.

422

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427

428

429 **Figure captions:**

430 **Figure 1:** Structural map of the north western Indian Ocean, showing the currently active plate
431 boundaries, the distribution of the oceanic basins, as well as the distribution of the main ophiolites.

432 **Figure 2:** General paleogeographic reconstructions of the Indian Ocean from Early Cretaceous to
433 Early Tertiary, proposed by Gaina *et al.* (2015), and main geological events during the history of the
434 Indian Ocean. KB: Kabul Block; Masc. : Mascarenes; Sey: Seychelles; GPRE : Global Plate
435 Reorganization Events.

436 **Figure 3:** a) Free air gravity map of the Owen Basin offshore Oman and the Arabian Sea (filtered for
437 short wavelengths from DTU 13 database; Andersen *et al.*, 2013) and b) its interpretation,
438 with an emphasis on the composite age of the basement of the Owen Basin. HNMFS: Haushi-
439 Nafun-Maradi Fault System.

440 **Figure 4:** a) Free air gravity map of the North Somali Basin (filtered for short wavelengths from DTU
441 13 database; Andersen *et al.*, 2013) and b) its interpretation, with an emphasis on the composite age of
442 the basement of the North Somali Basin. c) New interpretation of a vintage seismic line from Bunce
443 and Molnar (1977) highlighting a major fossil transform fault at the western edge of Chain Ridge,
444 interpreted as a remnant of the Late Cretaceous India-Africa plate boundary.

445 **Figure 5 :** Multibeam map of the northern termination of the Chain Ridge and Chain Fracture Zone

446 **Figure 6:** a) Map of the Haushi Nafun Maradi Fault system; b) Simplified geological sketchmap of the
447 Huqf desert highlighting strike-slip offsets related to the Haushi-Nafun fault, after Platel *et al.*, 1992;
448 c) line drawing of a seismic profile crossing the Maradi fault, highlighting a negative flower structure,
449 redrawn from Filbrandt *et al.*, 2006.

450 **Figure 7:** a) Seismic line from the OWEN 2 cruise (Rodriguez *et al.*, 2016) crossing the western side
451 of the Sawqirah Ridge, where the Masirah ophiolites are tilted westwards, in direction of the Oman
452 platform; b) Seismic line from the OWEN 2 cruise (Rodriguez *et al.*, 2016) crossing the eastern edge
453 of the Sawqirah Ridge, showing a piece of the Masirah Ophiolite lying in the Owen Basin, and the
454 unconformity corresponding to the end of the formation of the marginal ridges. c) Cross section of the

455 Oman margin at the latitude of the Sawqirah Ridge (modified from Rodriguez *et al.*, 2016). Three
456 main angular unconformities can be tracked across the Owen Basin.

457

458 **Figure 8:** Seismic lines from the Owen-2 cruise (Rodriguez *et al.*, 2016) crossing the Owen Basin.

459 **Figure 9 :** Seismic lines from the Owen-2 cruise (Rodriguez *et al.*, 2016) crossing the Owen Basin.

460 **Figure 10 :** Seismic lines from the Owen-2 cruise (Rodriguez *et al.*, 2016) crossing the Owen Basin.

461 These seismic lines highlight the presence of pre-Maastrichtian fanning configurations lying above the
462 basement of the western part of the Owen Basin, and their absence in its eastern part. The boundary of
463 the pre-Maastrichtian fanning configurations roughly coincides with the expected location of the fossil
464 Chain Fracture Zone (according to reconstructions by Royer *et al.*, 2002).

465 **Figure 11:** a) Seismic profile crossing the Masirah ophiolite in the Batain plain (from Beauchamp *et al.*, 1995) and b) its revised interpretation, highlighting the positive flower structure of the Masirah
466 Ophiolites. See fig. 3 for location.

468 **Figure 12:** Reconstruction of the configuration of the India-Africa plate Boundary at 65-70 Ma and 60
469 Ma, highlighting the major migration of the transform system occurring at that time.

470 **Figure 13:** Simplified reconstruction of the mode of emplacement of the Masirah ophiolites along
471 with the development of the en-échelon marginal ridge system offshore Oman. Note that the
472 emplacement of the ophiolites last over more than 25 Myrs and does not imply any subduction zone.

473 **Figure 14:** Revised paleogeographic reconstructions of the northwestern Indian Ocean, from 90 Ma to
474 present-day, modified after Matthews *et al.* (2016). These reconstructions highlight the successive
475 locations of the India-Africa plate boundary: the Chain Ridge Transform from 90 to 65 Ma, the Chain
476 Fracture Zone from 65 to 47 Ma, in the vicinity of the Owen Ridge since the Oligocene. The main
477 paleogeographic implications are the East Somali Basin origin of the lithosphere subducting beneath
478 the eastern Makran, and the disconnection between the India-Africa transform boundary and the
479 eastern Pakistan ophiolites.

480

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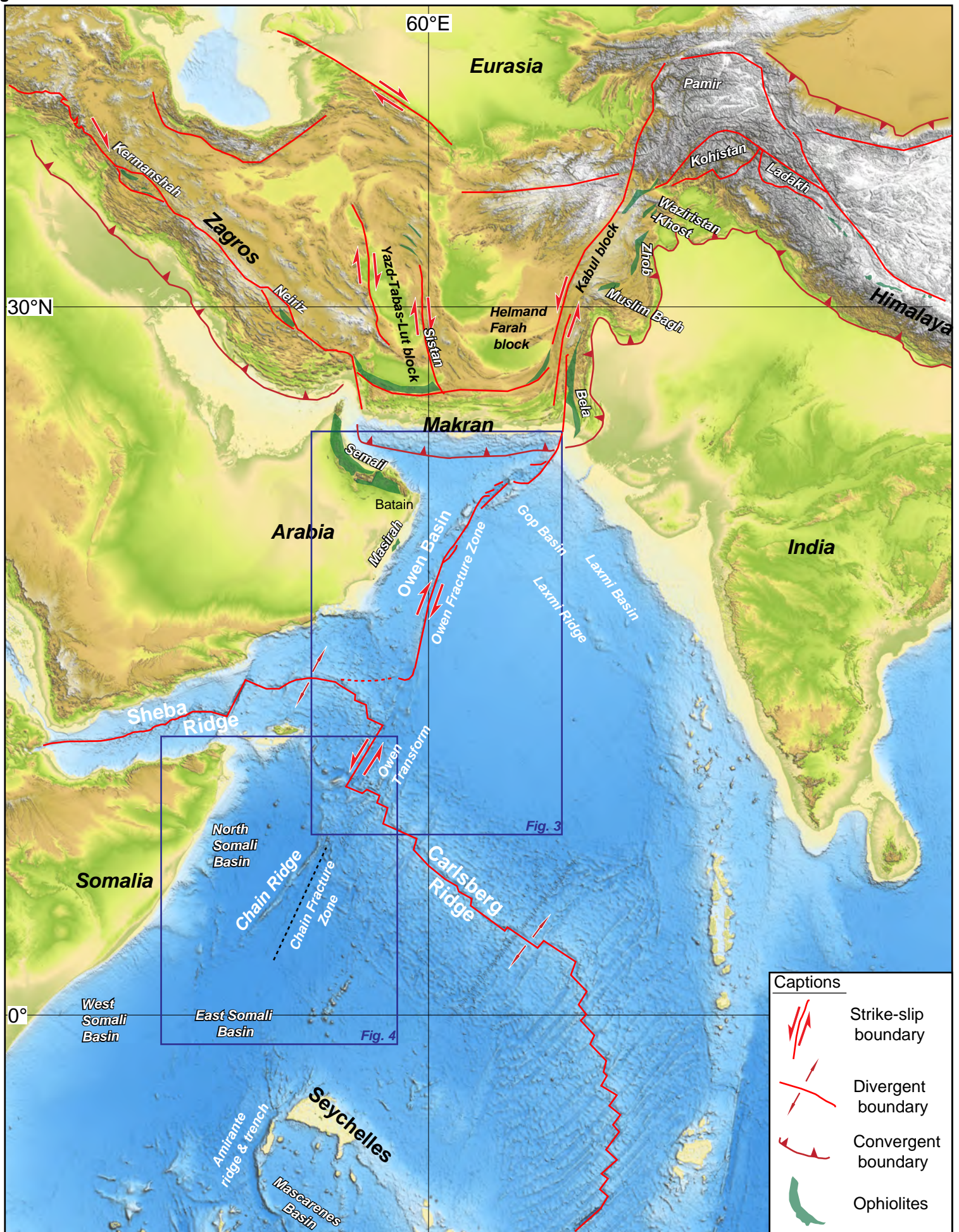
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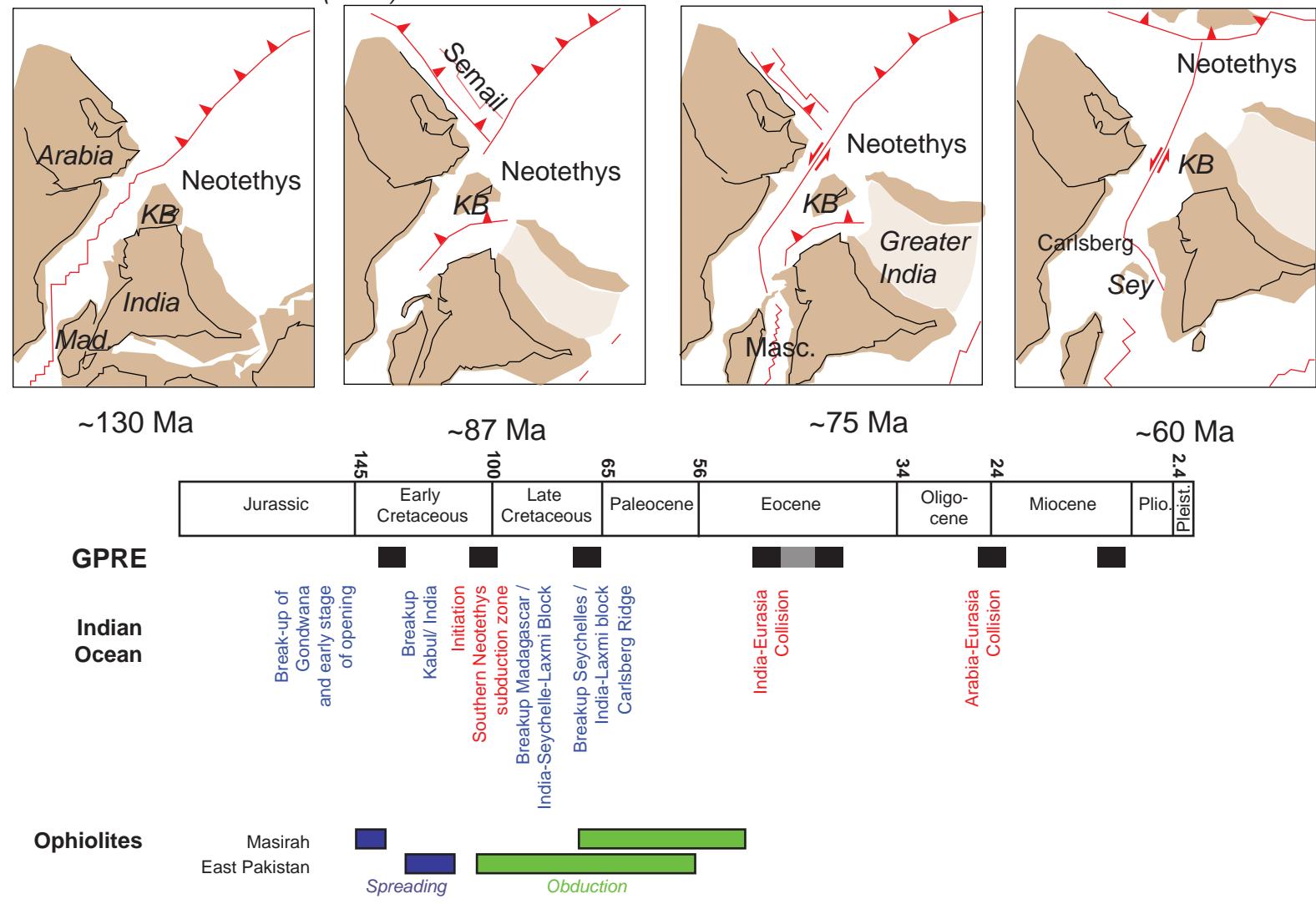
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Figure

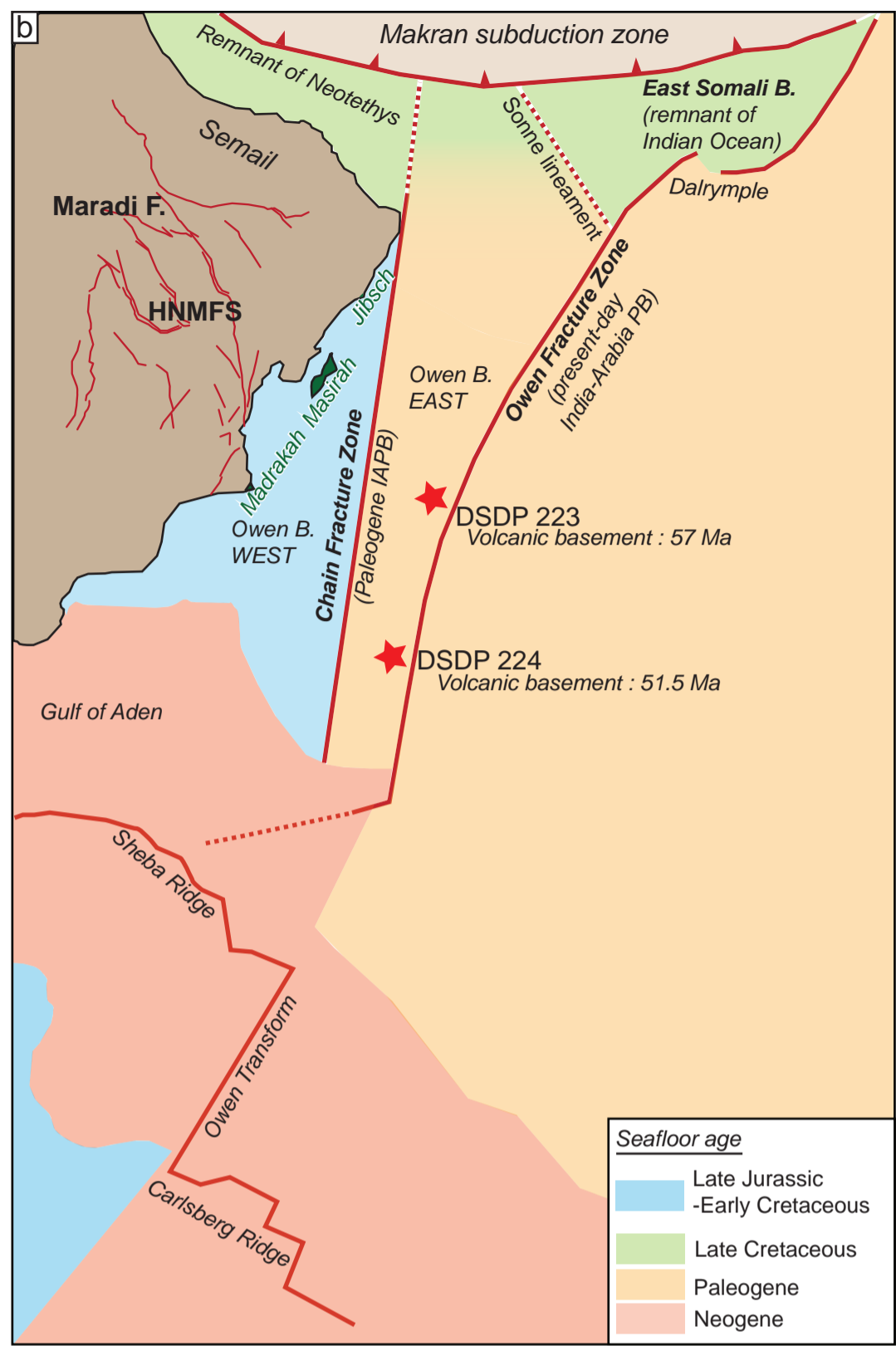
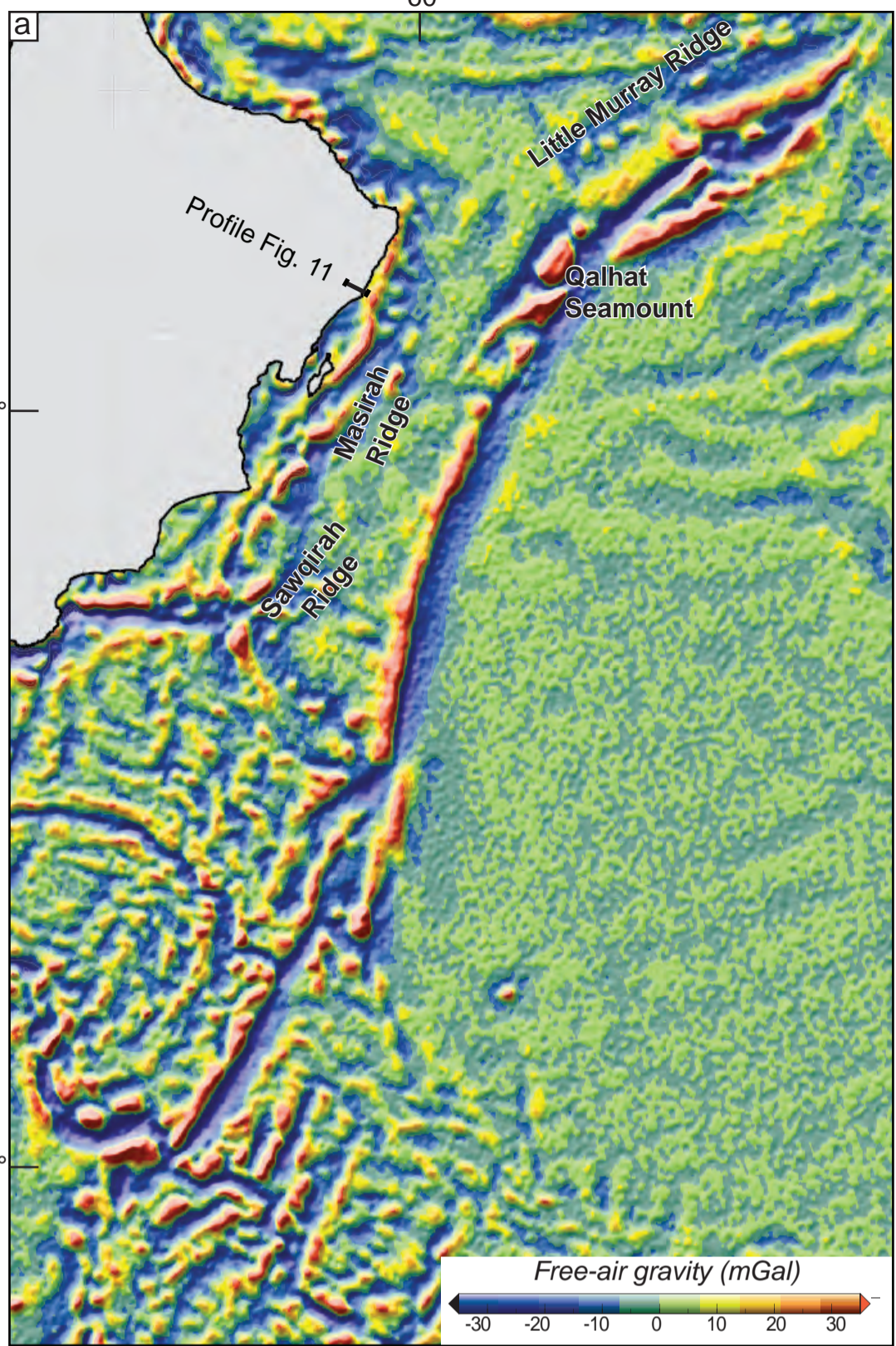


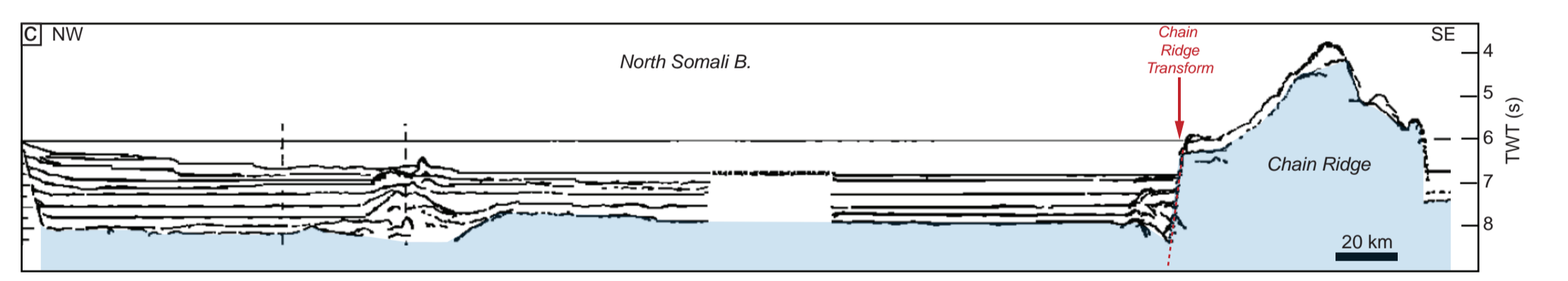
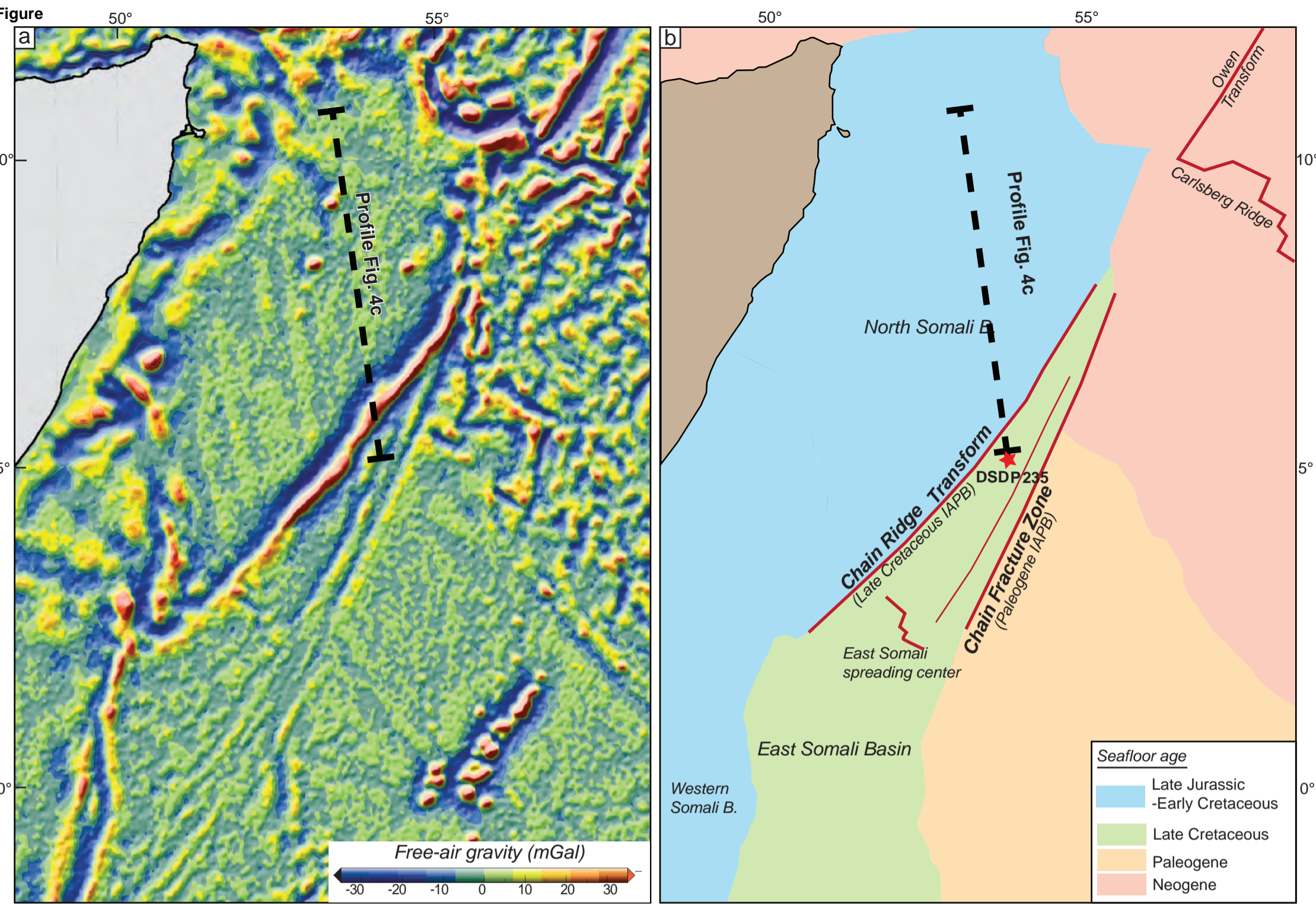
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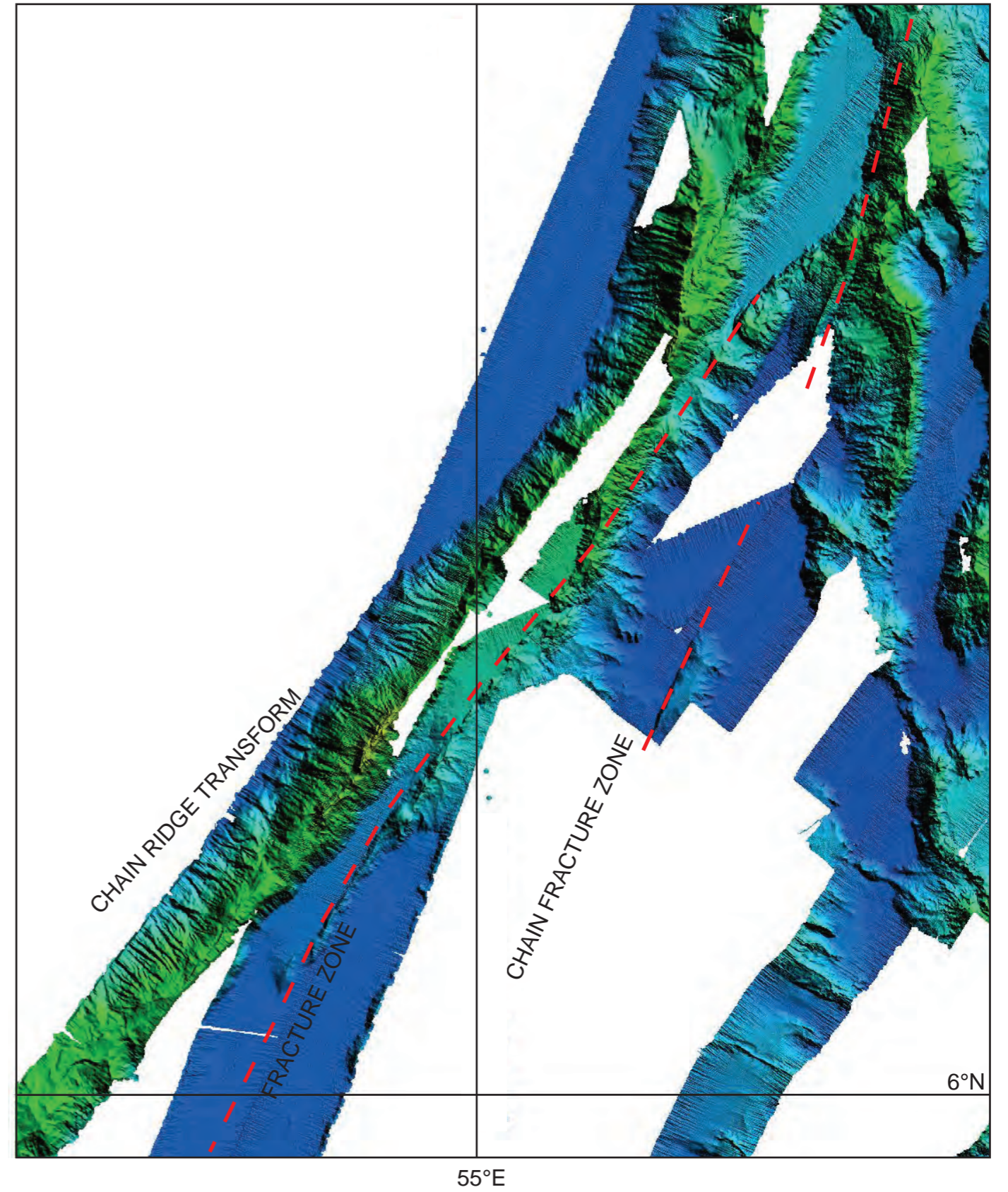
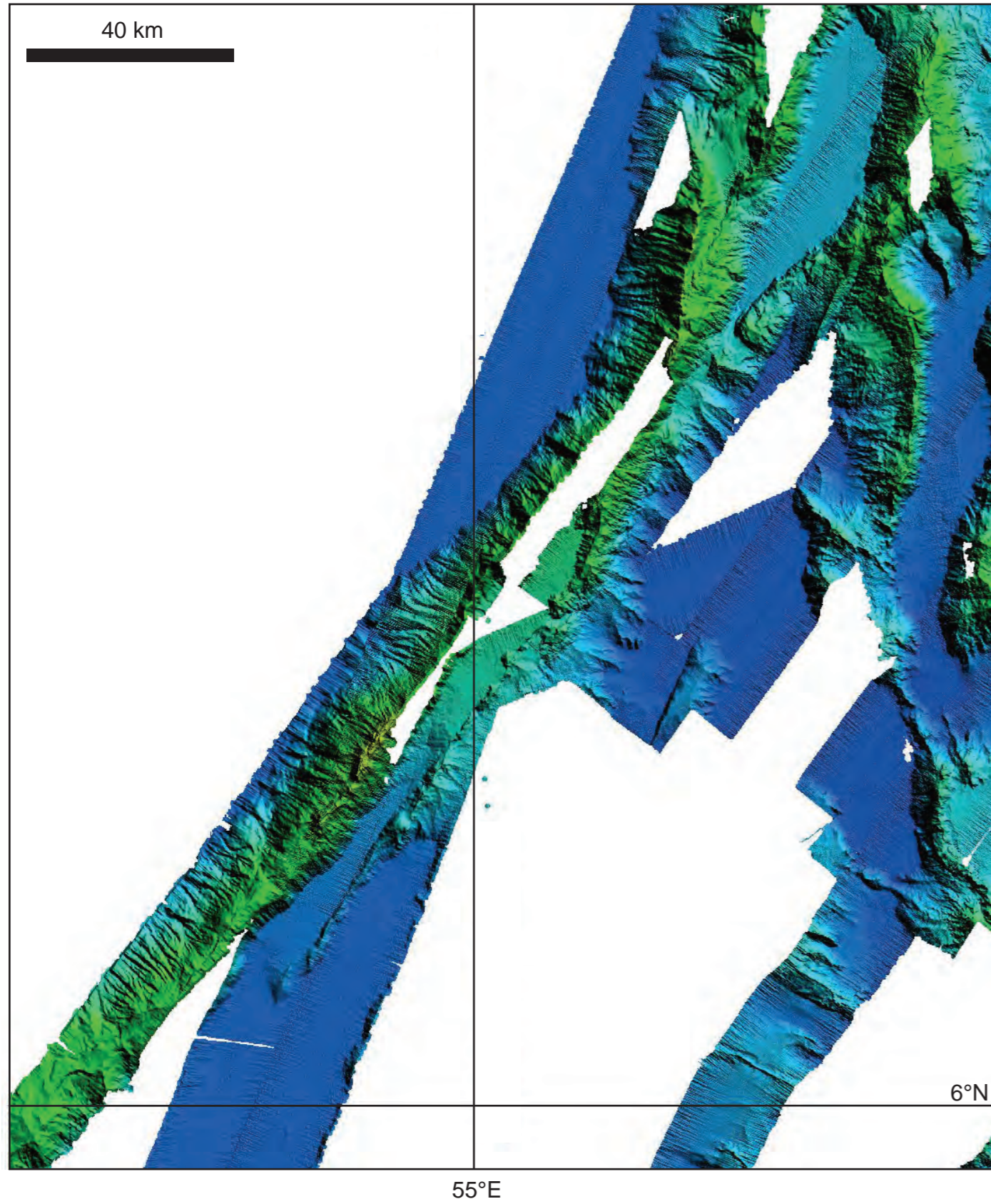


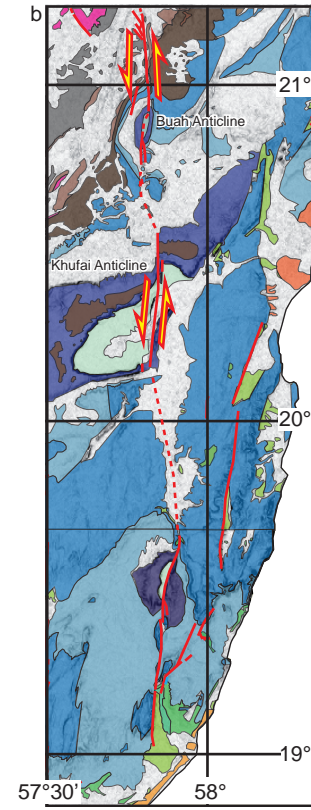
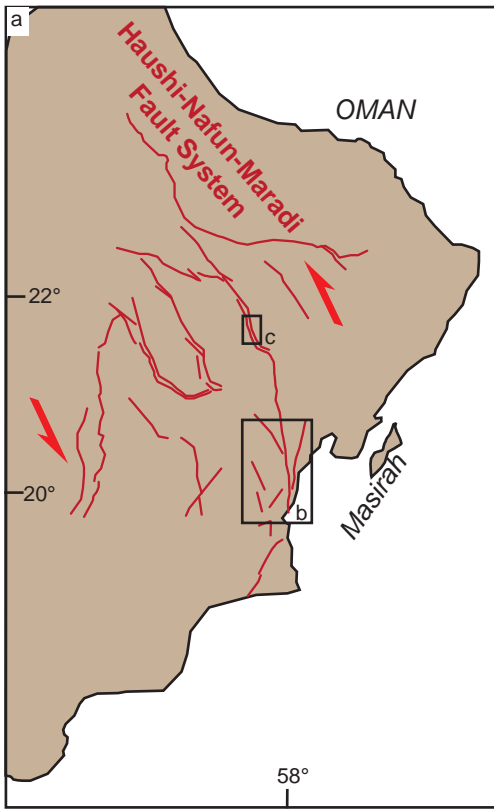
Figure

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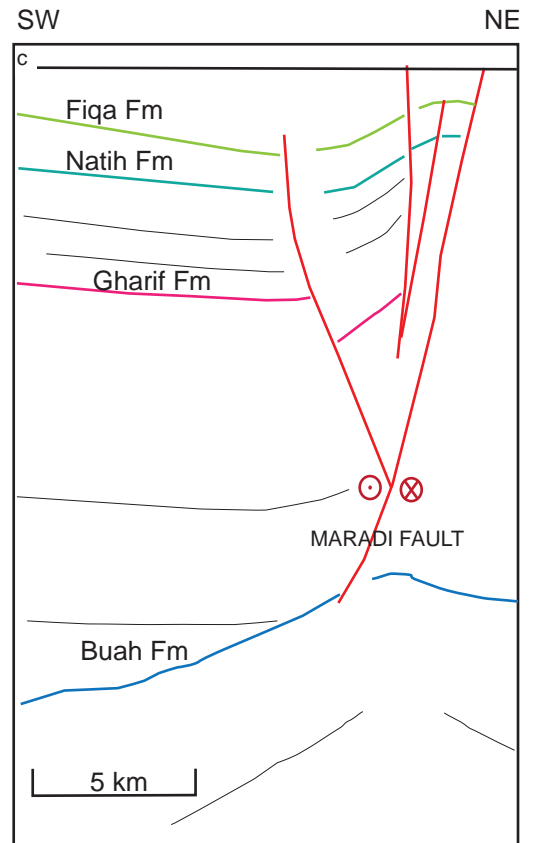




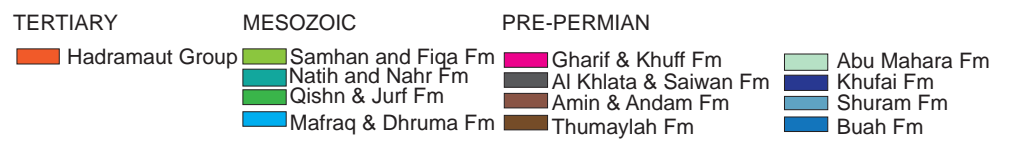




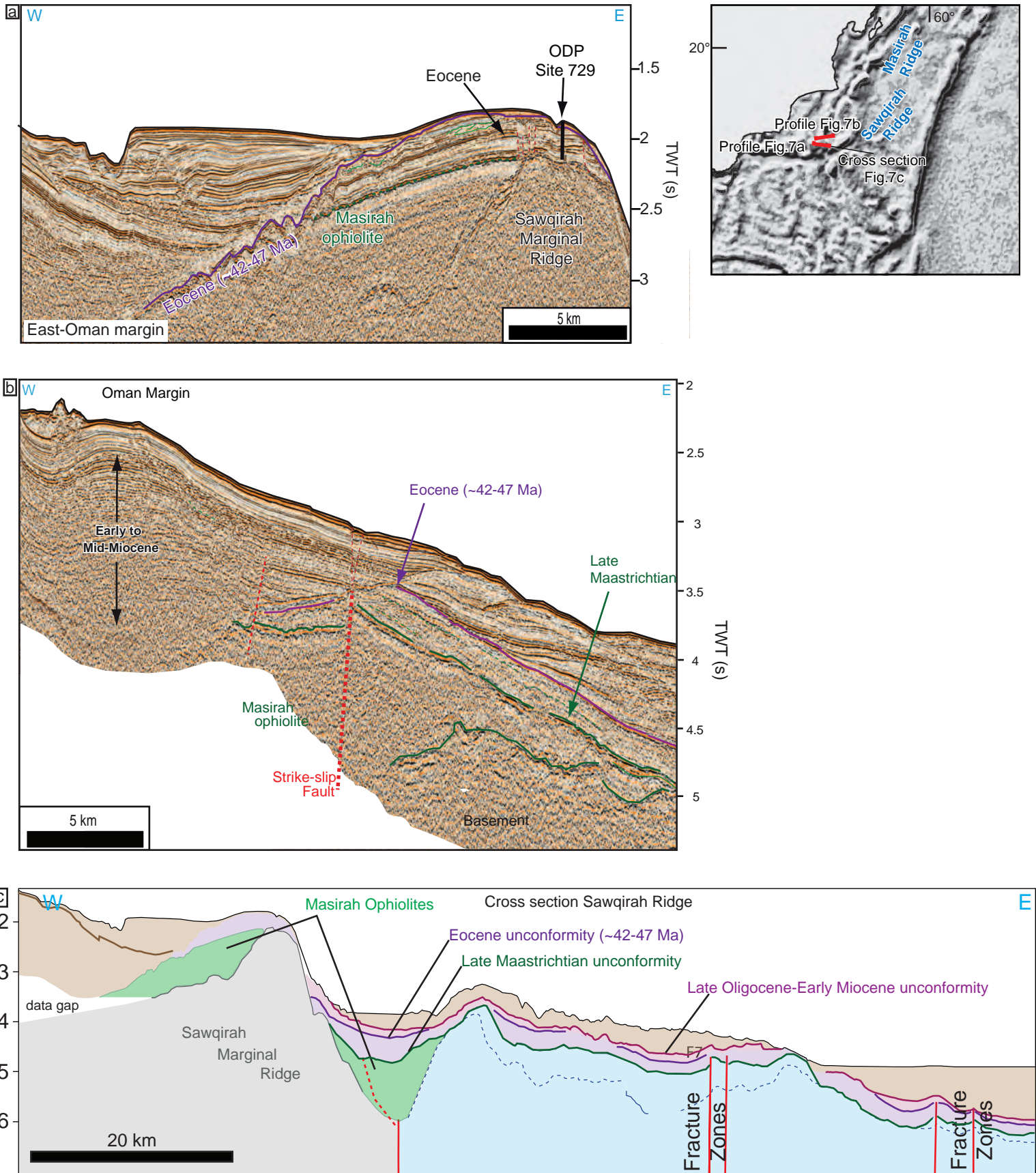
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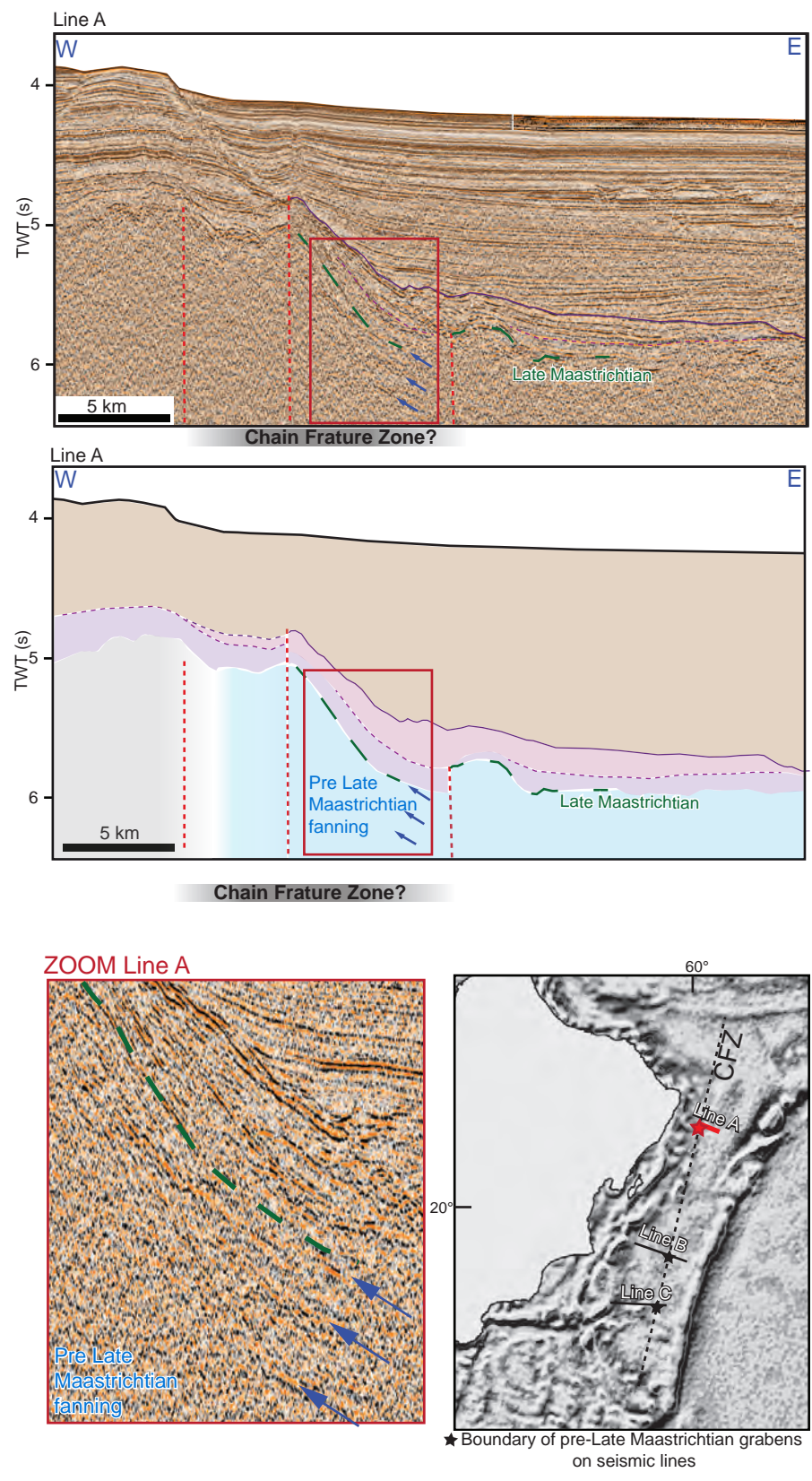


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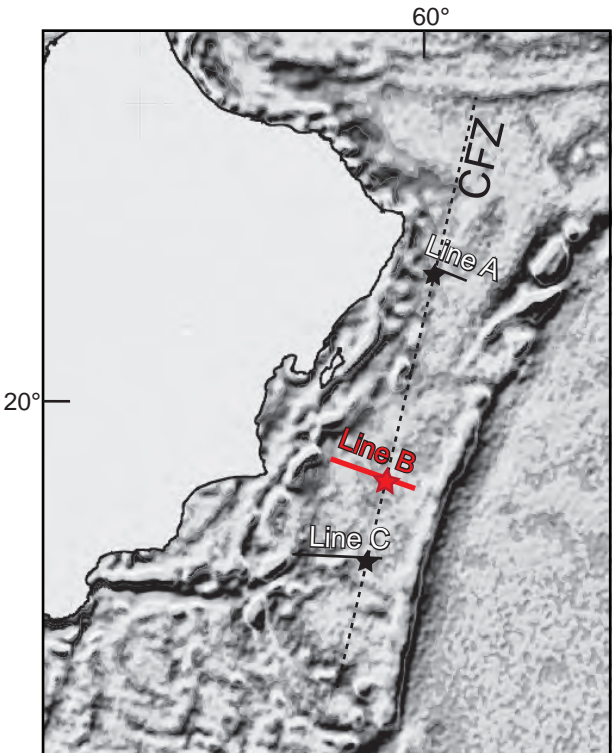
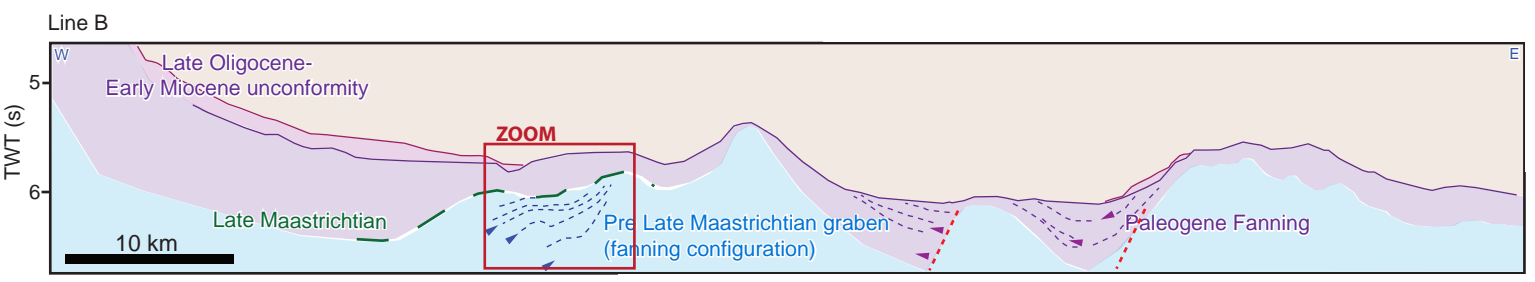
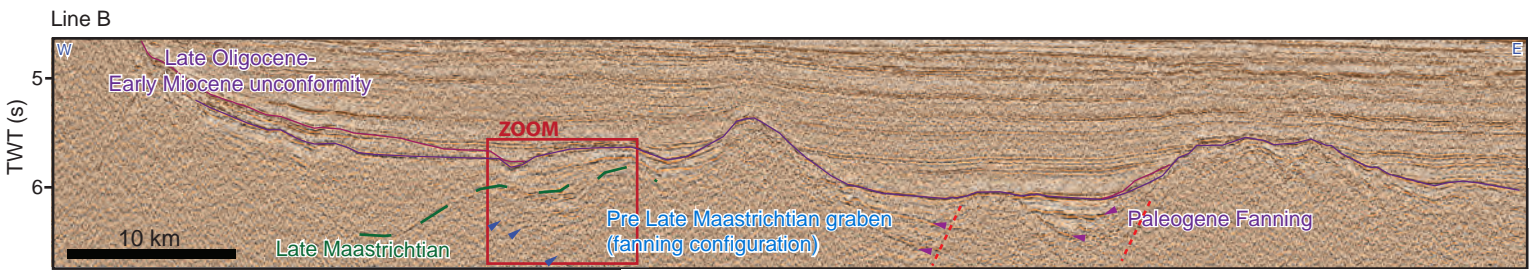


Figure





Figure



★ Boundary of pre-Late Maastrichtian grabens on seismic lines

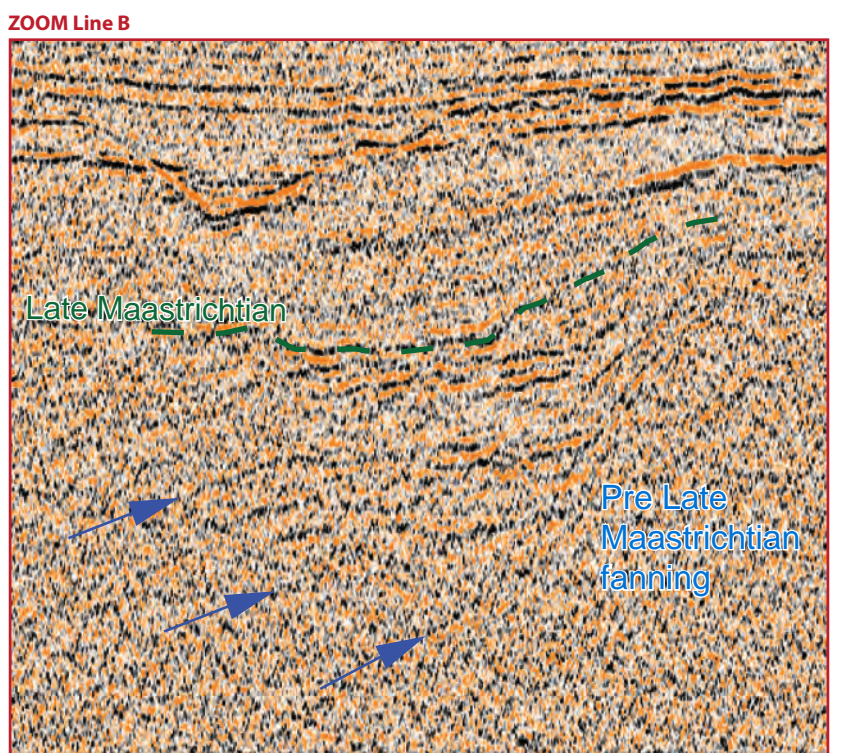
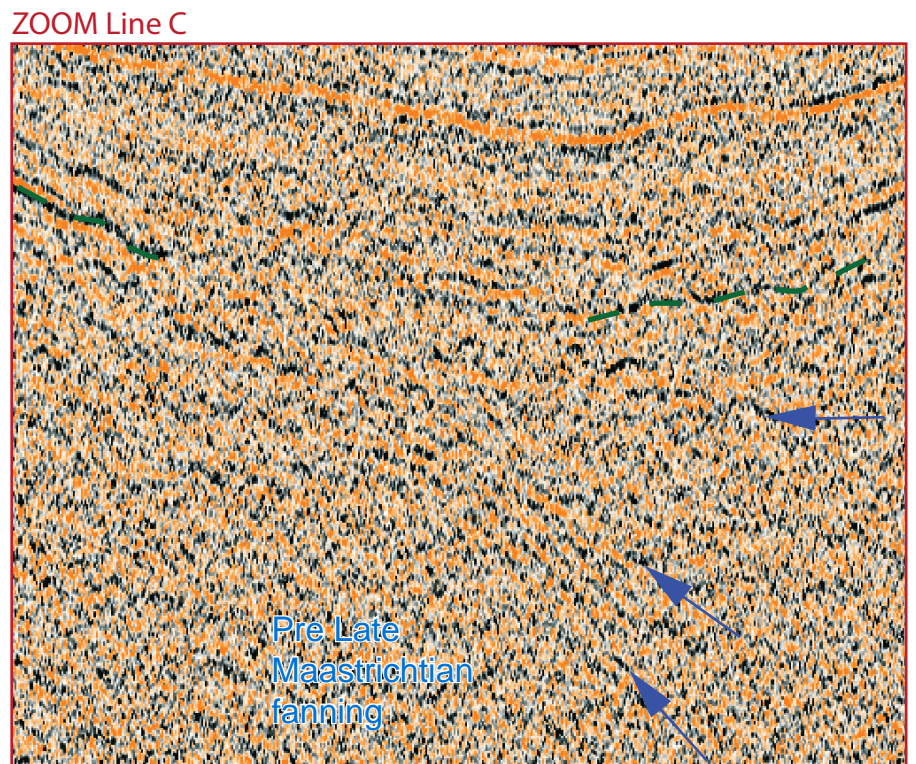
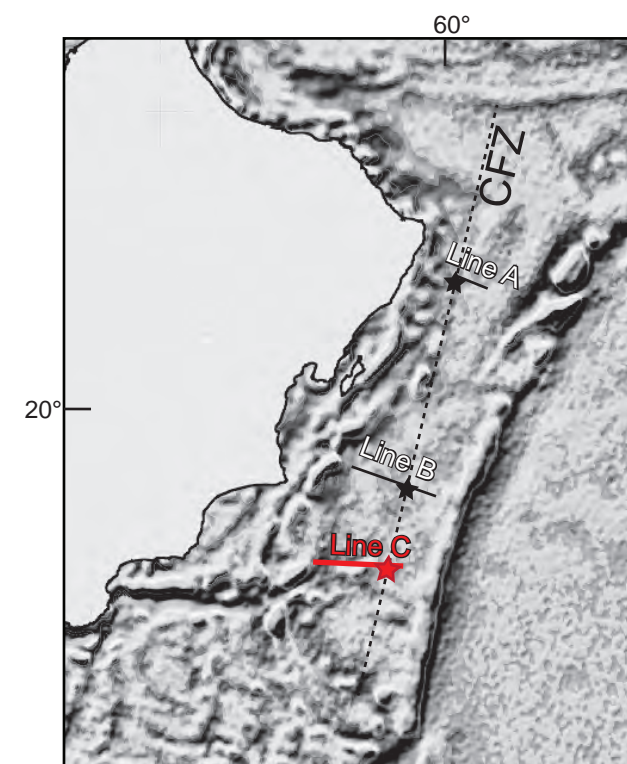
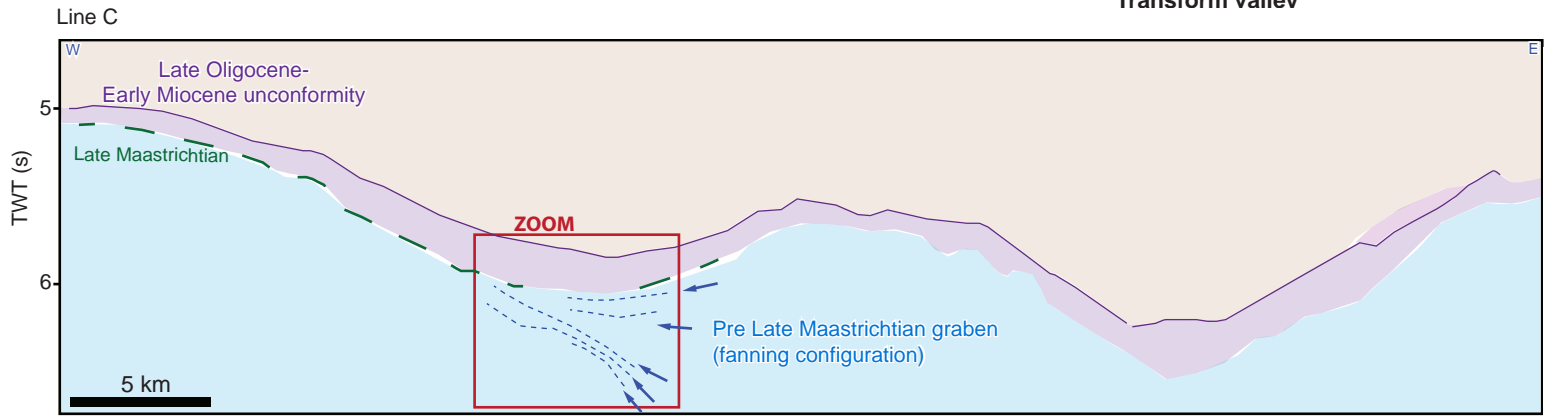
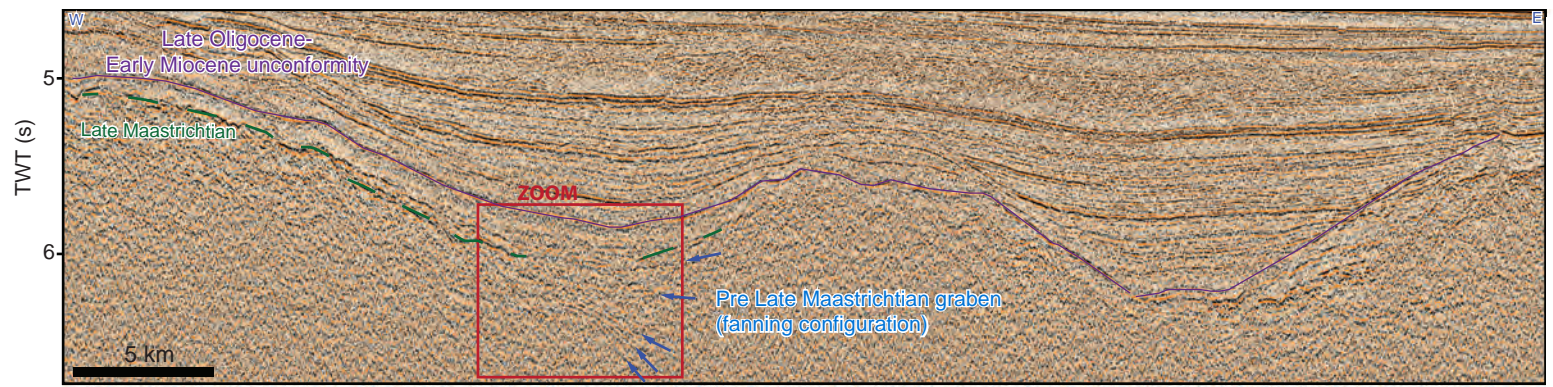
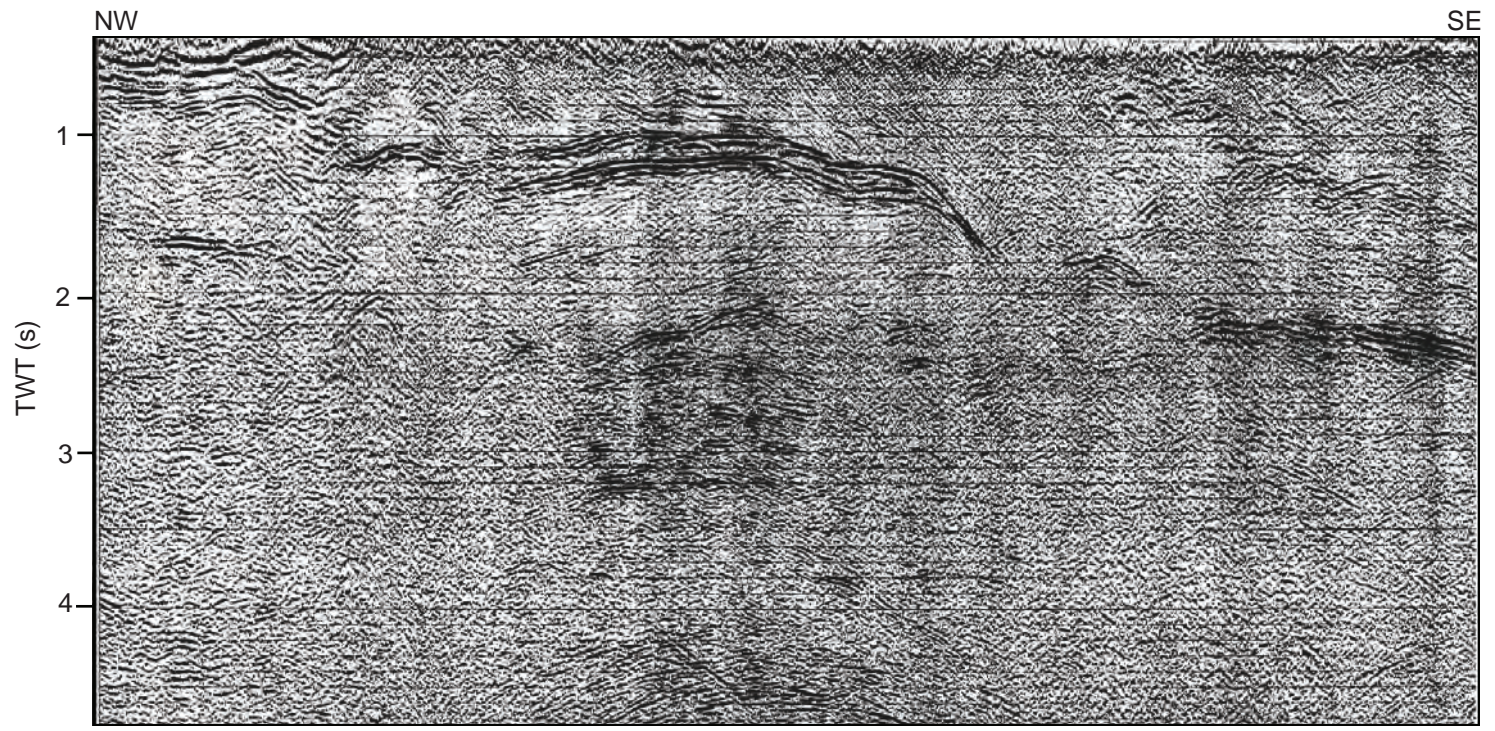


Figure C

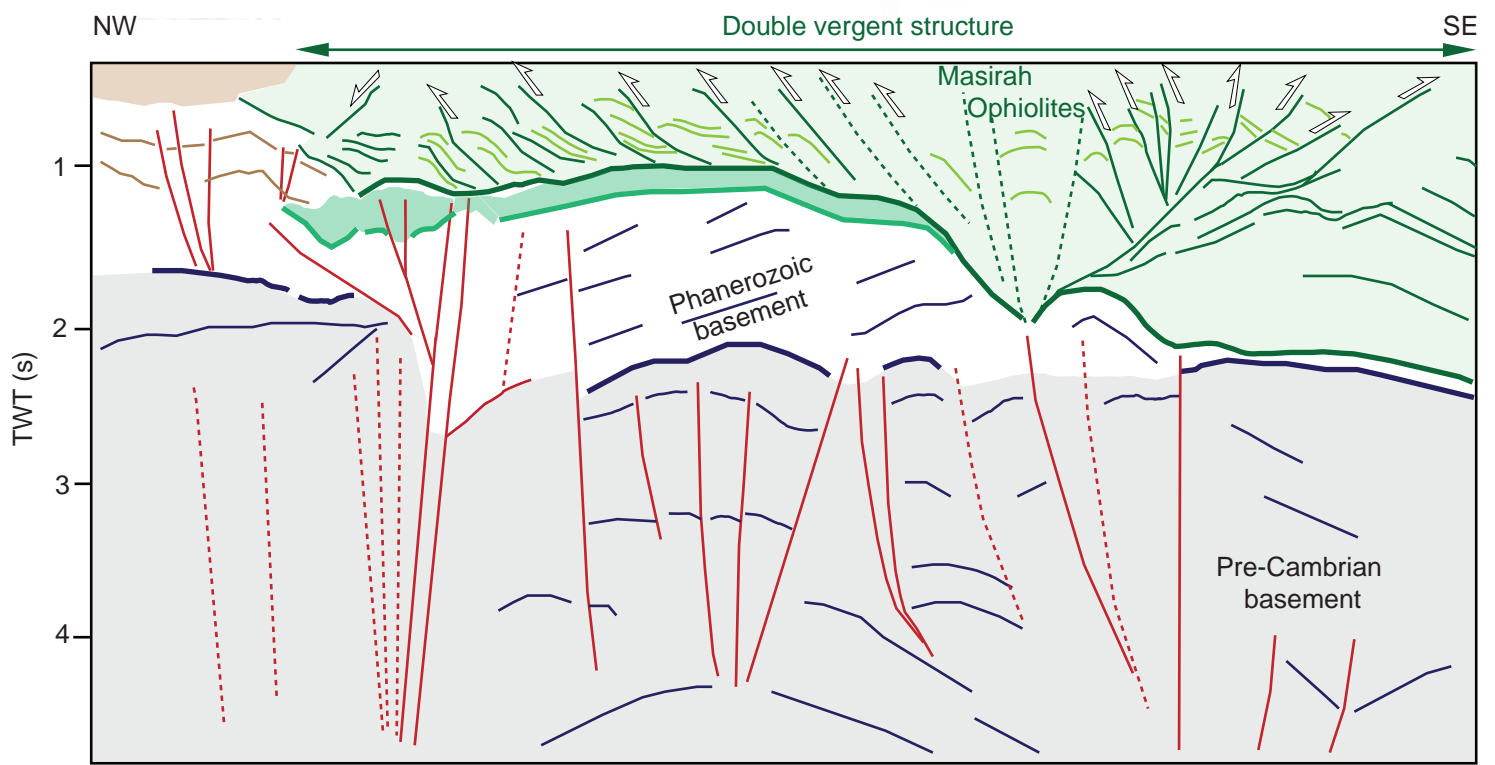


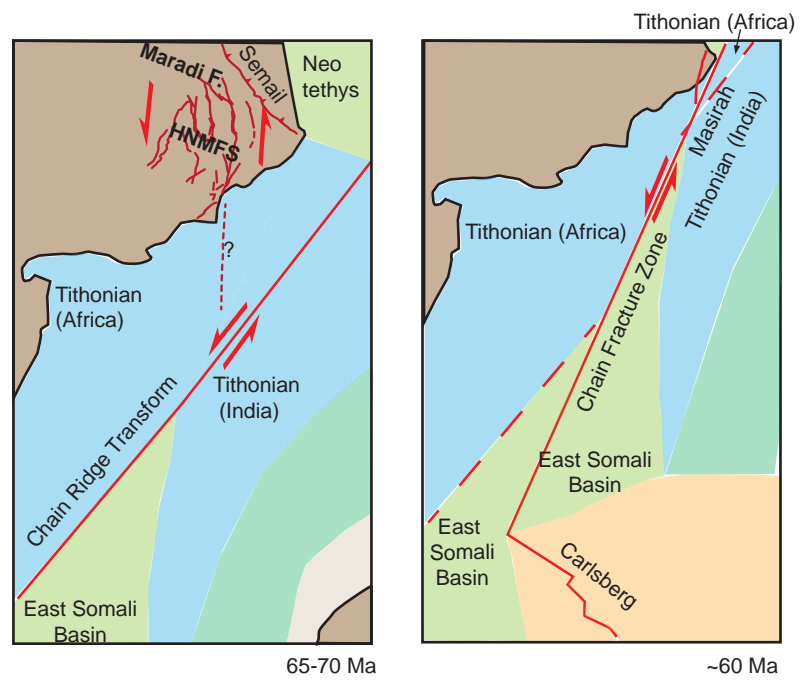
★ Boundary of pre-Late Maastrichtian grabens on seismic lines

Figure

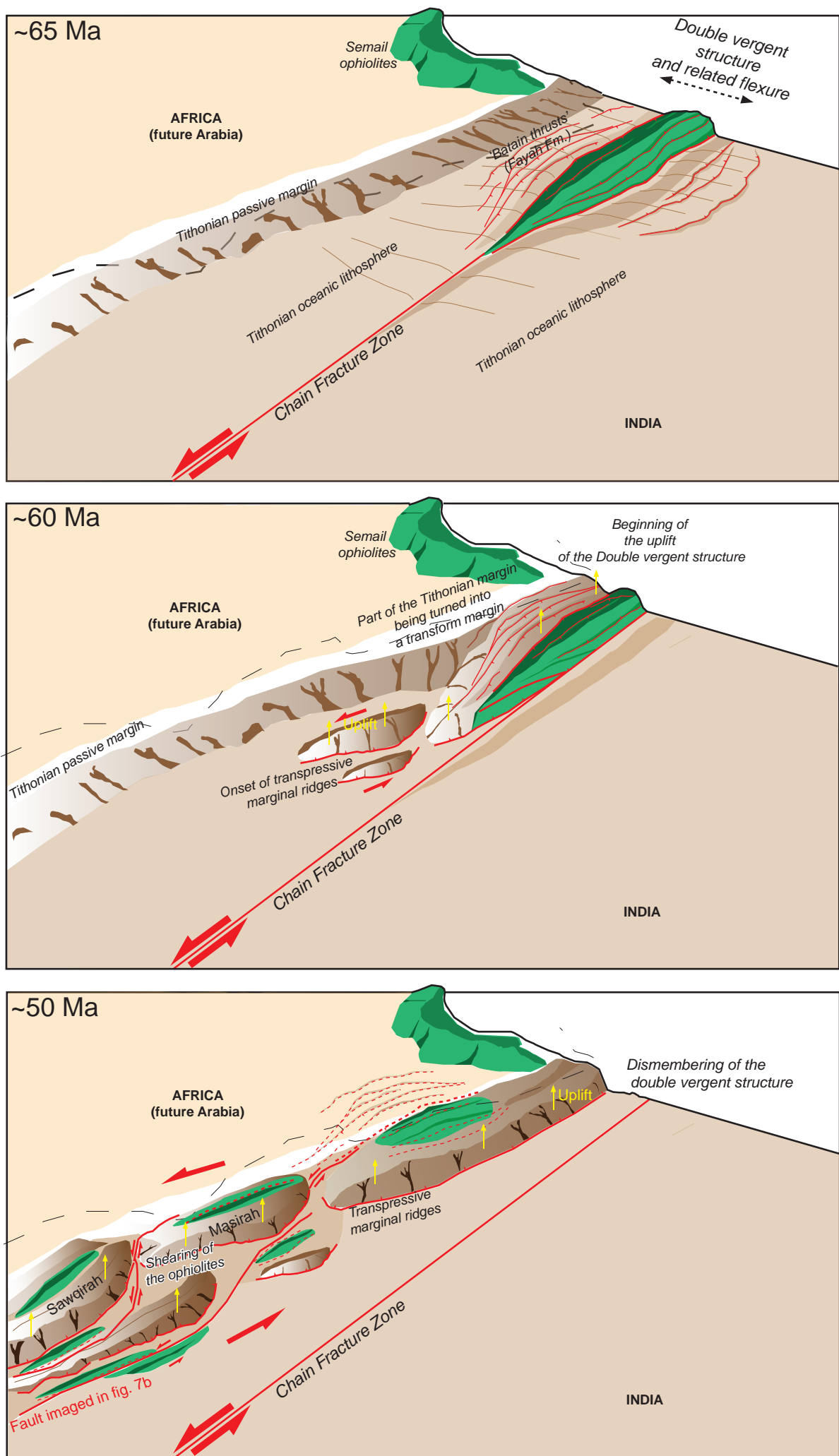


Profile from Beauchamp et al., 1995

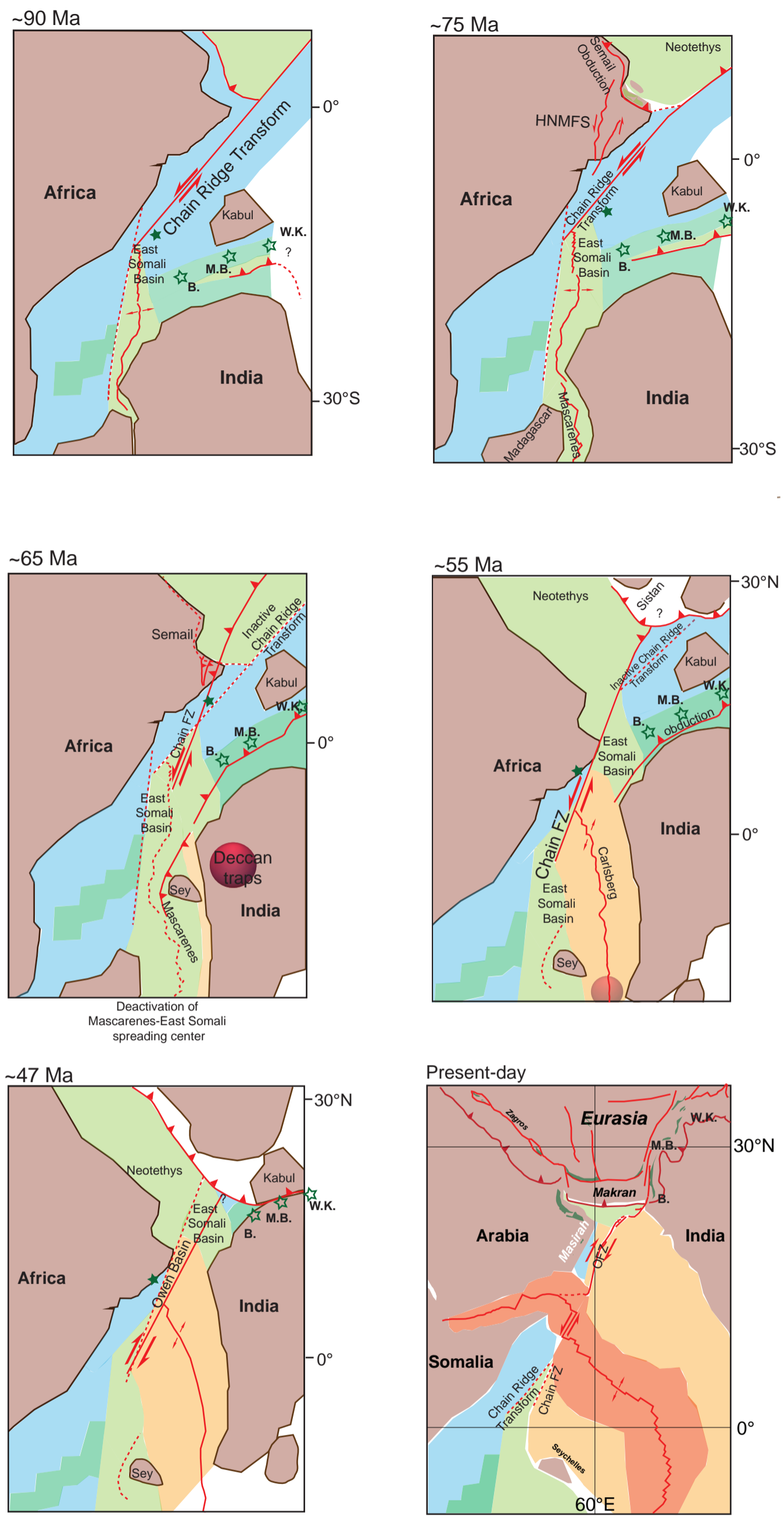




Figure



Figure



Seafloor age

- Late Jurassic - Early Cretaceous
- Early-Middle Cretaceous
- Late Cretaceous
- Paleogene
- Neogene

- Masirah oceanic lithosphere
- B. : Bela
- M.B.: Muslim Bagh
- W.K.: Waziristan Khost
- } oceanic lithosphere
- Strike-slip boundary
- Divergent boundary
- Convergent boundary