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

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Abstract :

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

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

Highlights

► The Late Cretaceous India-Africa Transform plate boundary is identified at Chain Ridge. ► The Paleogene India-Africa transform plate boundary is identified at the Chain Fracture Zone and within the Owen Basin. ► The Masirah ophiolites emplaced along a transform boundary. ► The oceanic lithosphere subducting nowadays beneath Makran derives from the East Somali Basin instead of Neotethys.

Keywords : Transform boundaries, Arabian Sea, Masirah ophiolites

1. Introduction

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

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

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

2- Geological background & paleogeographic constraints

2-1- Opening of the Indian Ocean

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

Seafloor spreading rates at the Carlsberg Ridge peaked at 18 $cm.yr^{-1}$ at 52 Ma, before slowing down due to the onset of a global plate reorganization event, partly related to collision between India and the Kohistan-Ladakh arc (Burg, 2011; Cande and Stegman, 2011; Bouilhol *et al*., 2013; Jagoutz *et al.*, 2015; Cande and Patriat, 2015). However, the role of India-Eurasia collision over global plate dynamics is still highly debated due to uncertainties in its precise timing (see the various paleogeographic scenarios proposing ages of collision between 24 and 55 Ma in Patriat and Achache, 1984; Chaubey *et al*., 2002; Ali *et al.*, 2008*;* Molnar and Stock, 2009*;* van Hinsbergen *et al.*, 2012; Gibbons *et al*., 2015; Matthews *et al*., 2015; Buckman *et al*., 2018). Regardless of the precise timing of the India-Eurasia collision, the Indian Ocean's fabric documents a global plate reorganization event between 47 and 42 Ma, expressed by changes in spreading rates and trends, as well as a major ridge 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 Munschy, 2000*;* Calvès *et al.*, 2011*;* Gibbon*s 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 (Courtillot 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*
119 *al*., 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).

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

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

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

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

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

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

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

3- Materials and Methods

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

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

3-2- Seismic reflection

3-2-1. Sources of the datasets

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

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

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

3-2-2. Stratigraphy in the Owen Basin

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

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

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

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

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

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

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

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

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

Eastern Oman margin -Masirah :

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

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

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

Owen Basin:

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

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

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

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

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

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

5-3-Paleogeographic implications

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

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

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

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

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

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

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

- deactivation of the subduction at the origin of the Bela and Muslim-Bagh ophiolites and the Masirah Slab in tomography (Gaina *et al*., 2015);
- collision of the Woyla Arc (Wajzer *et al*., 1991; Gibbons *et al*., 2015) and Burma Block by the Late Maastrichtian (Socquet and Pubellier, 2005) or the Early Tertiary (Searle *et al*., 2007) with southeastern Eurasia.

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

6- Conclusions

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

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

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Figure captions:

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

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

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

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

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

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

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

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

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

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

Figure 10 : Seismic lines from the Owen-2 cruise (Rodriguez *et al*., 2016) crossing the Owen Basin. These seismic lines highlight the presence of pre-Maastrichtian fanning configurations lying above the basement of the western part of the Owen Basin, and their absence in its eastern part. The boundary of the pre-Maastrichtian fanning configurations roughly coincides with the expected location of the fossil Chain Fracture Zone (according to reconstructions by *Royer et al*., 2002).

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 Ophiolites. See fig. 3 for location.

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

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

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

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Figure

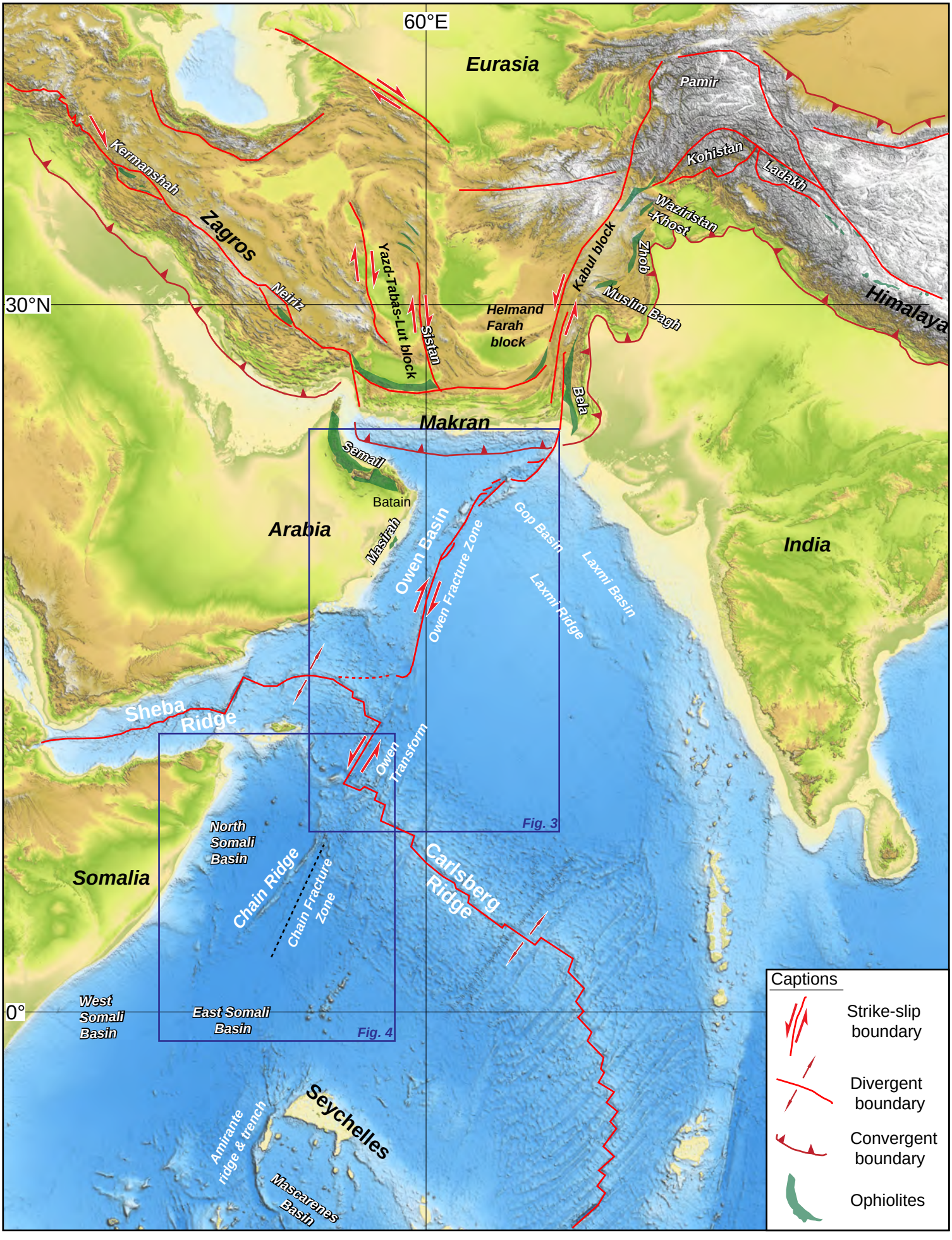
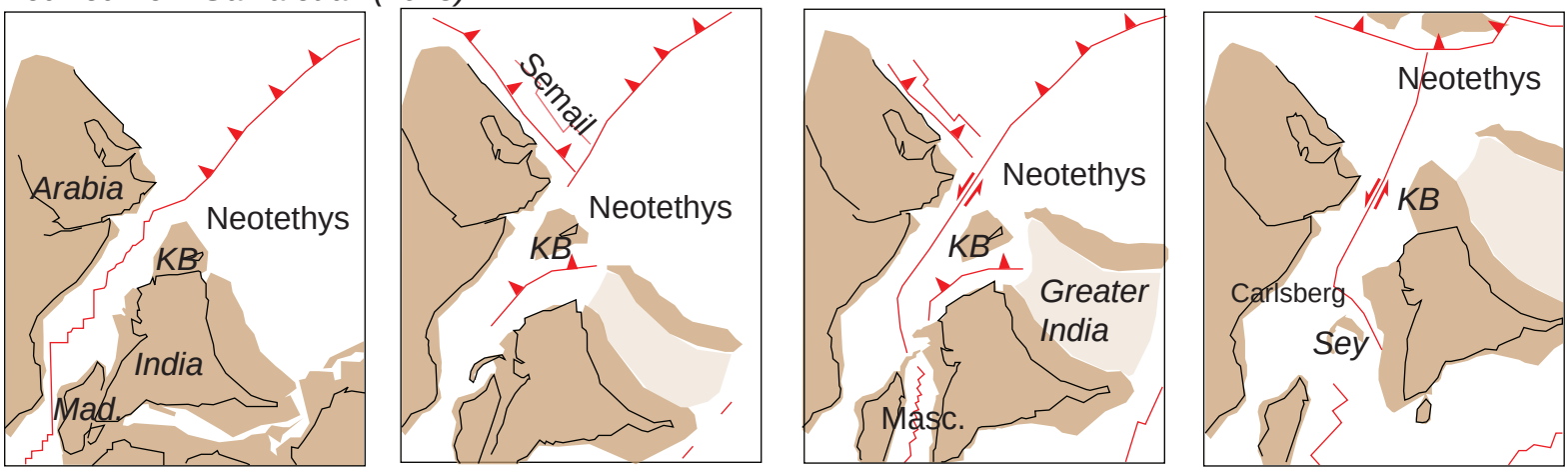
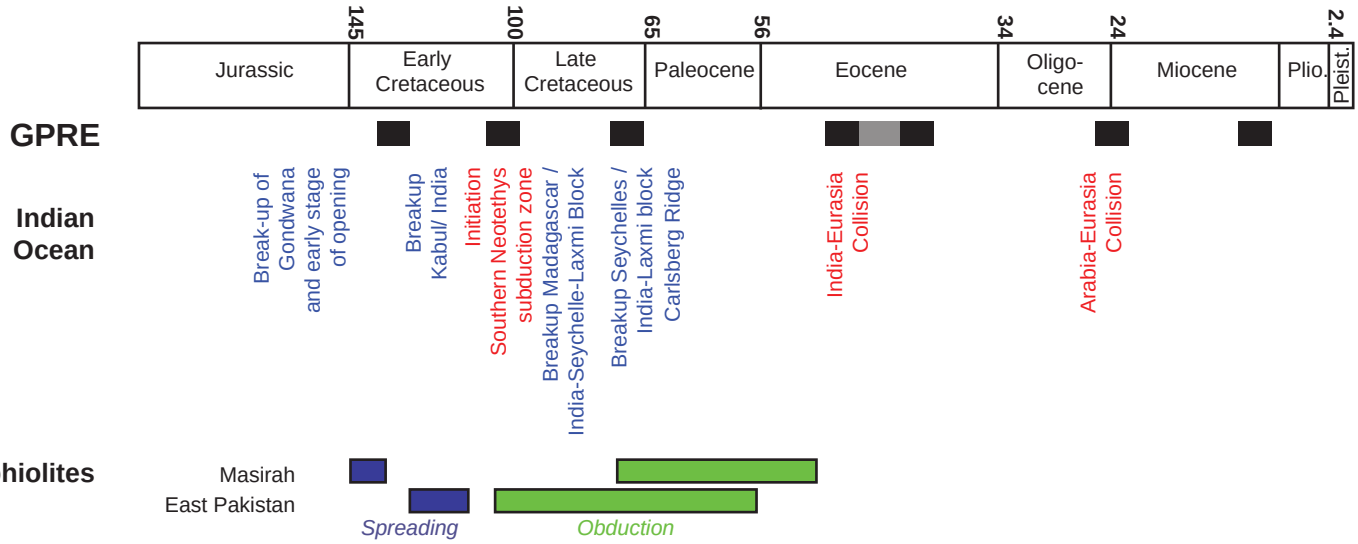

60°E
30°N
0°
Eurasia
Pamir
Kohistan
Ladakh
Waziristan
-Khost
Zhob
Muslim Bagh
Himalaya
Kermanshah
Zagros
Neiriz
Yazd-Tabas-Lut block
Sistan
Helmand
Farah
block
Kabul block
Bala
Makran
Semail
Batain
Masirah
Arabia
India
Owen Basin
Owen Fracture Zone
Gop Basin
Laxmi Basin
Laxmi Ridge
Sheba
Ridge
Owen
Transform
Fig. 3
North
Somali
Basin
Somalia
Chain Ridge
Chain Fracture
Zone
Carlsberg
Ridge
West
Somali
Basin
East Somali
Basin
Fig. 4
Seychelles
Amirante
ridge & trench
Mascarenes
Basin
Captions
Strike-slip
boundary
Divergent
boundary
Convergent
boundary
Ophiolites

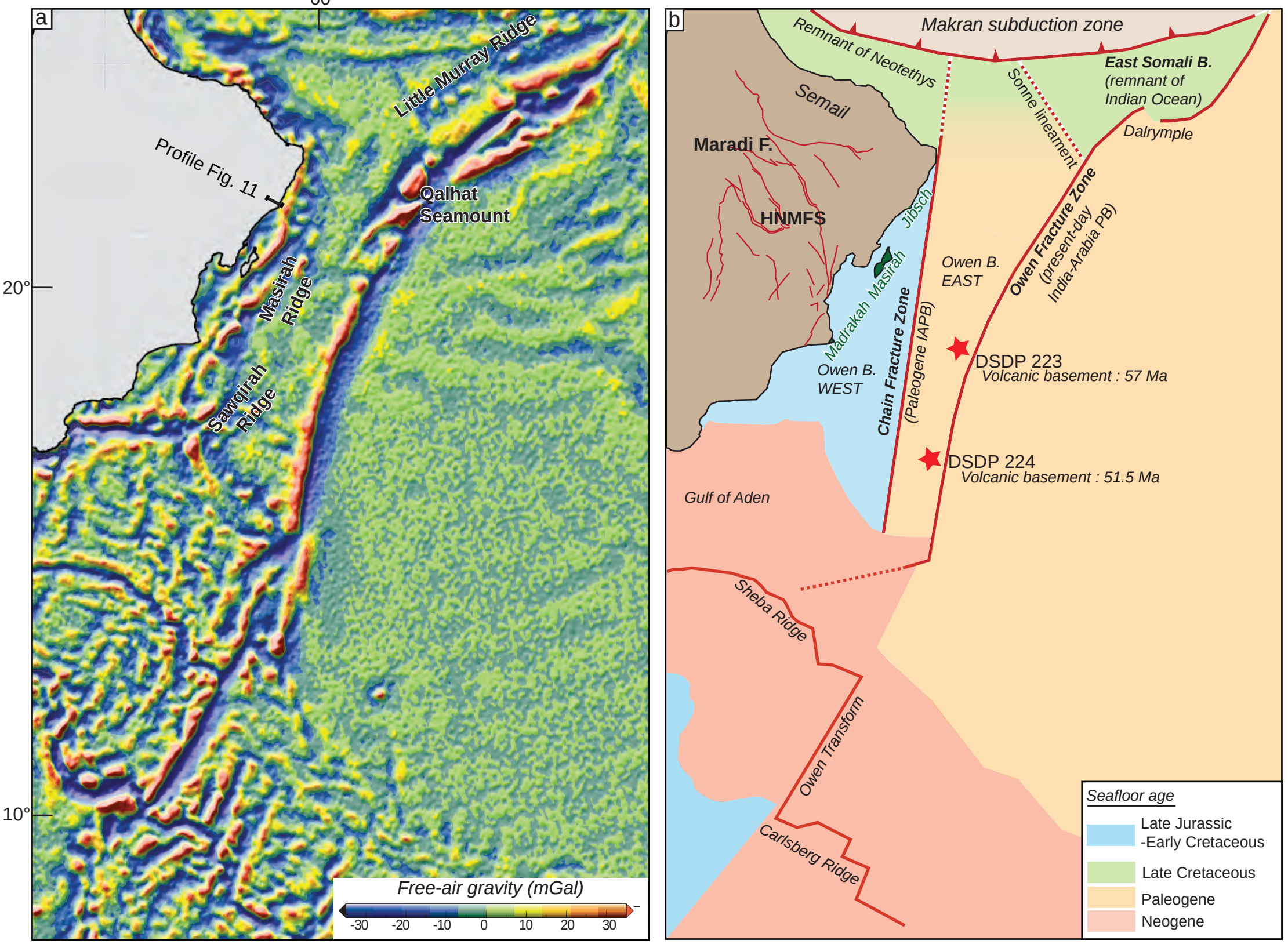
Figure *Modified from Gaina et al. (2015)*



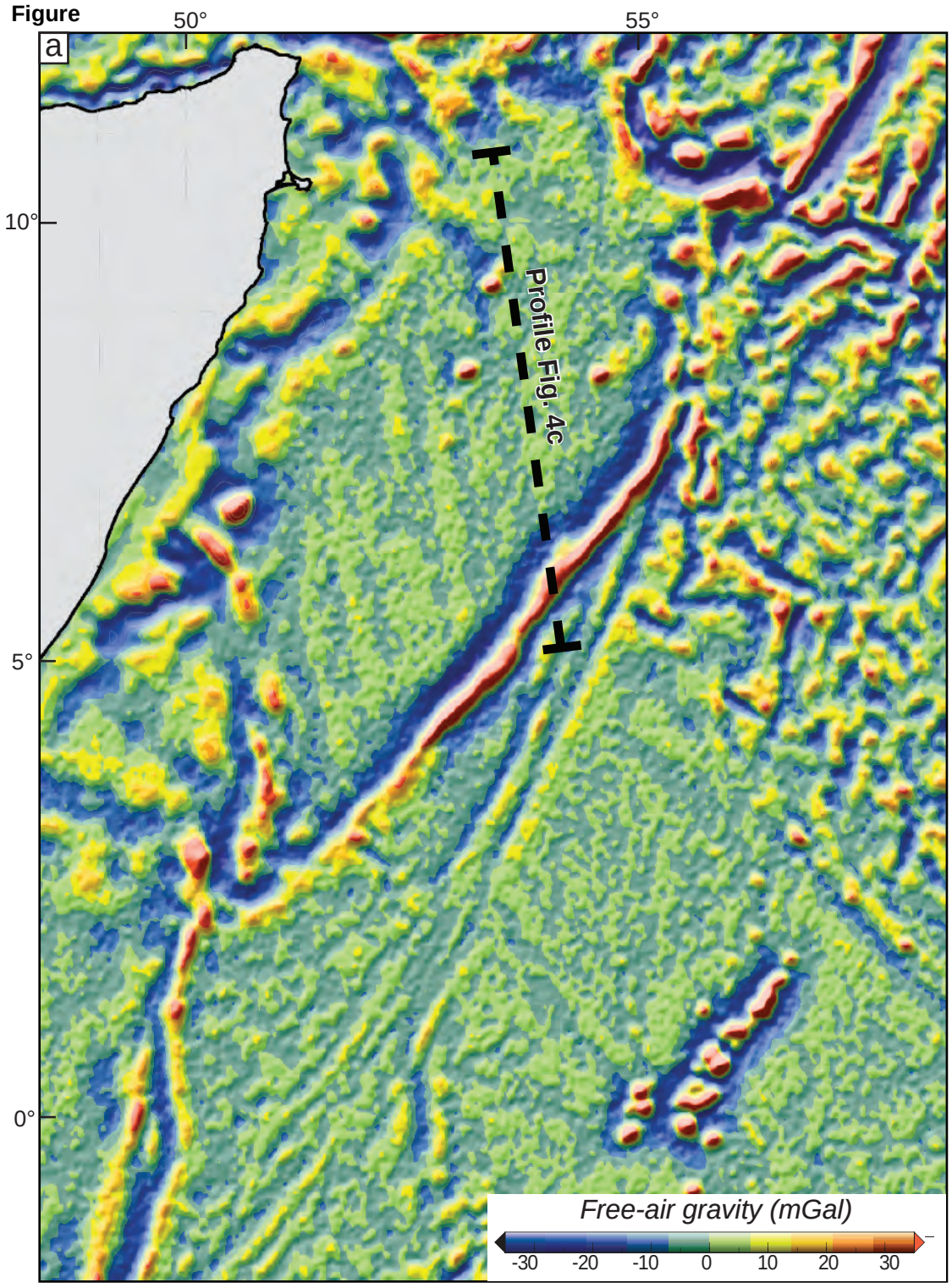
~130 Ma ~87 Ma ~75 Ma ~60 Ma

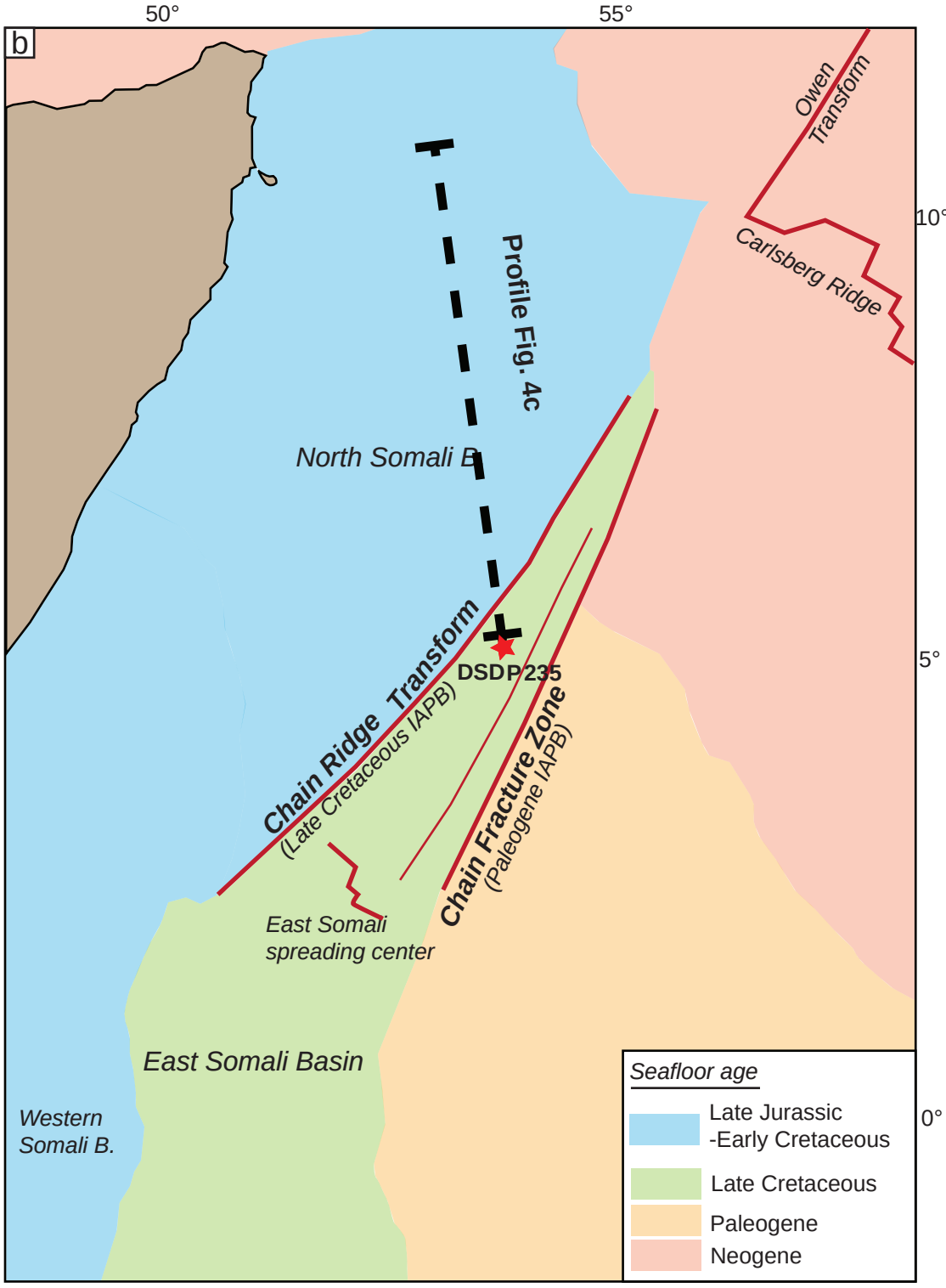


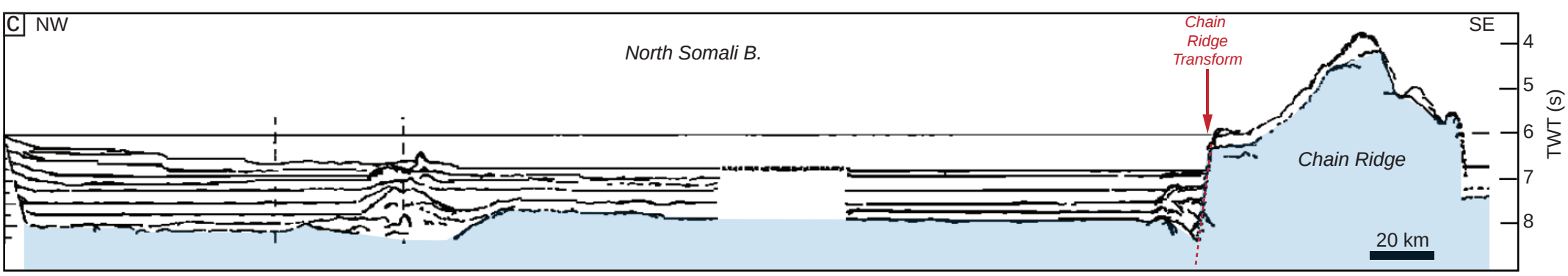
Figure


a
60°
20°
10°
Little Murray Ridge
Profile Fig. 11
Qalhat
Seamount
Masirah
Ridge
Sawqirah
Ridge
Free-air gravity (mGal)
-30
-20
-10
0
10
20
30
b
Makran subduction zone
Remnant of Neotethys
Semail
Maradi F.
HNMFS
Sonne lineament
East Somali B.
(remnant of
Indian Ocean)
Dalrymple
Jibsch
Owen Fracture Zone
(present-day
India-Arabia PB)
Owen B.
EAST
Madrakah
Masirah
Owen B.
WEST
Chain Fracture Zone
(Paleogene IAPB)
DSDP 223
Volcanic basement : 57 Ma
DSDP 224
Volcanic basement : 51.5 Ma
Gulf of Aden
Sheba Ridge
Owen Transform
Carlsberg Ridge
Seafloor age
Late Jurassic
-Early Cretaceous
Late Cretaceous
Paleogene
Neogene

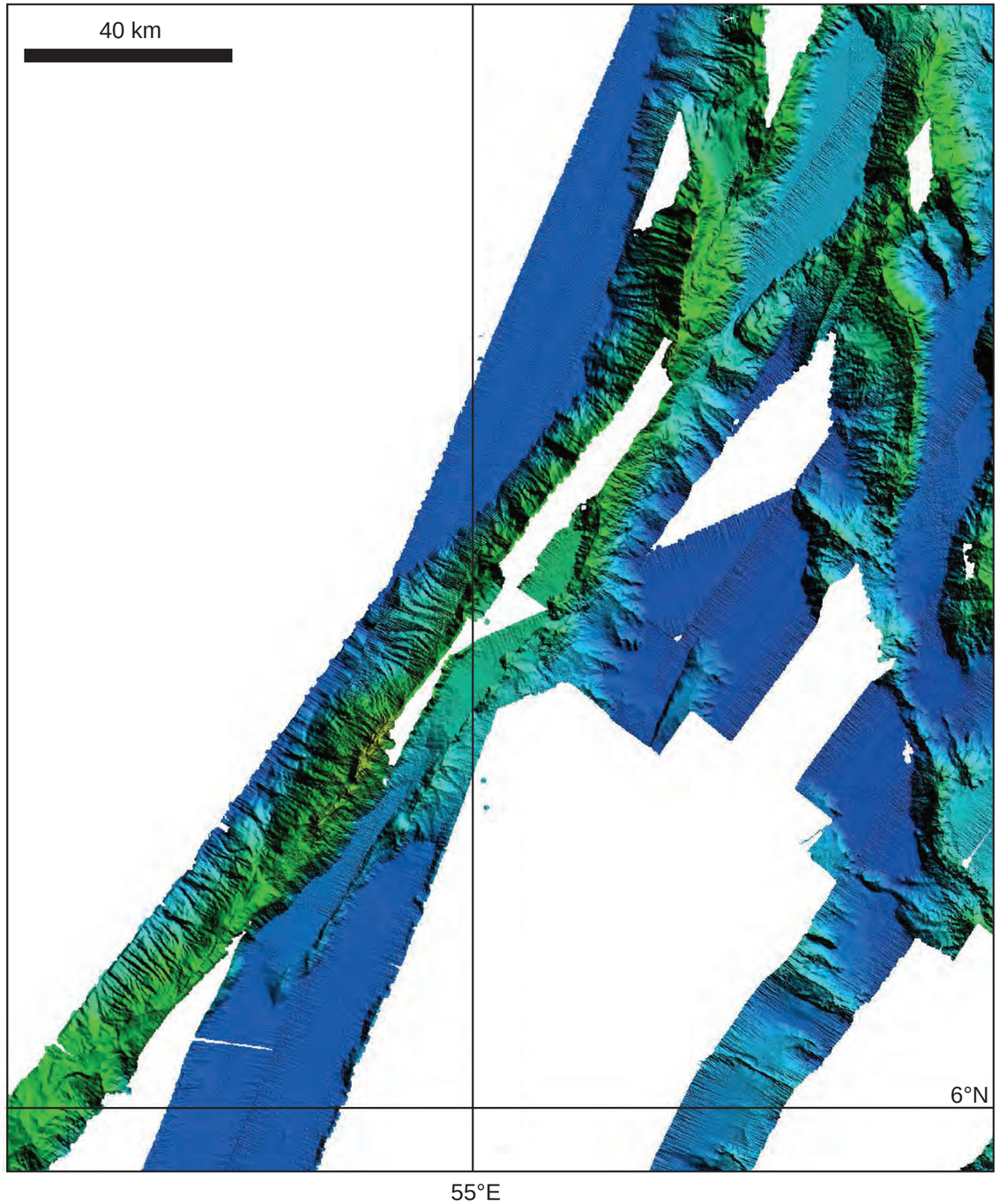
Figure

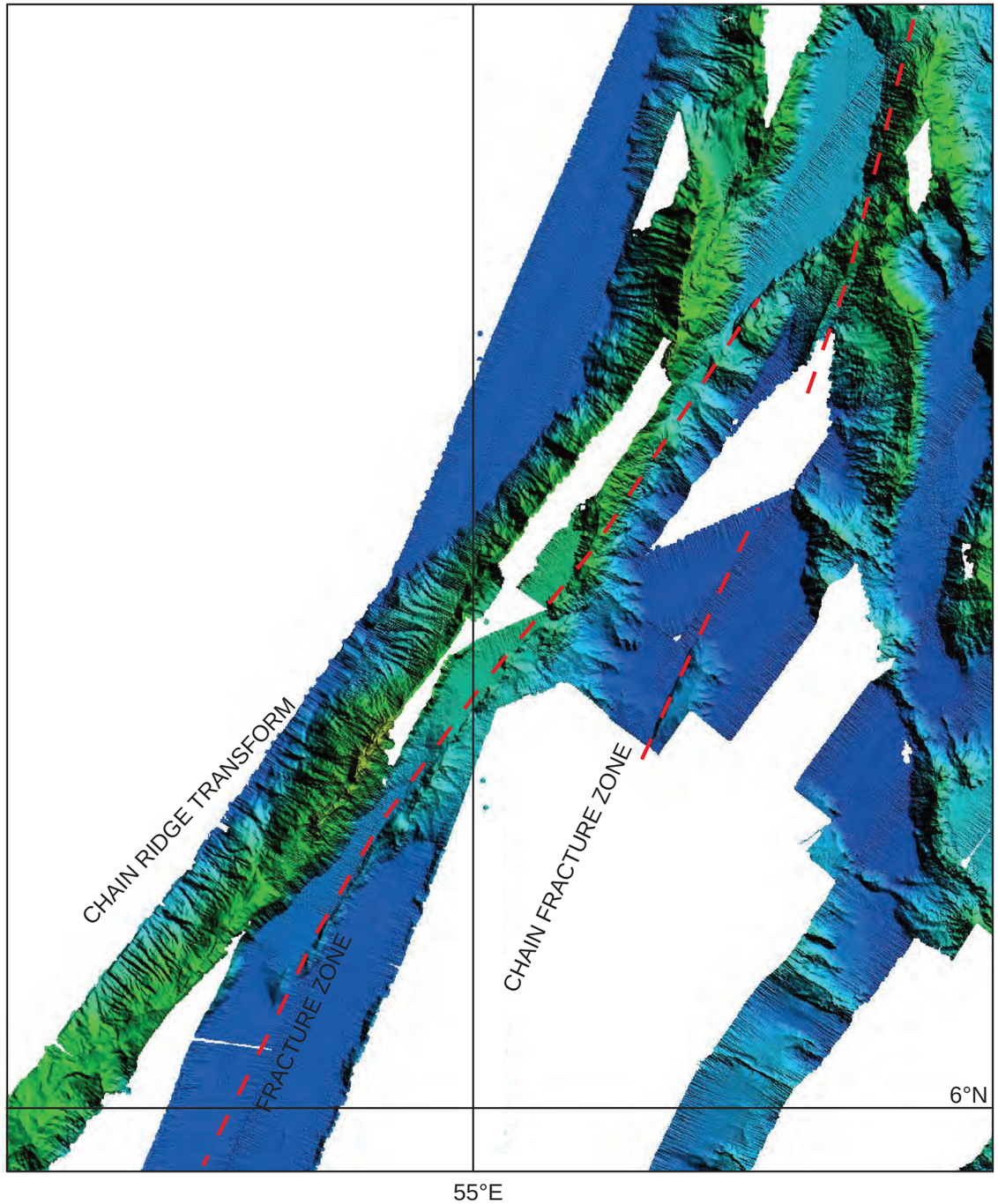

a
50°
55°
10°
5°
0°
Profile Fig. 4c
Free-air gravity (mGal)
-30
-20
-10
0
10
20
30


b
50°
55°
10°
5°
0°
Owen Transform
Carlsberg Ridge
Profile Fig. 4c
North Somali B.
Chain Ridge Transform
(Late Cretaceous IAPB)
DSDP 235
Chain Fracture Zone
(Paleogene IAPB)
East Somali
spreading center
East Somali Basin
Western
Somali B.
Seafloor age
Late Jurassic
-Early Cretaceous
Late Cretaceous
Paleogene
Neogene

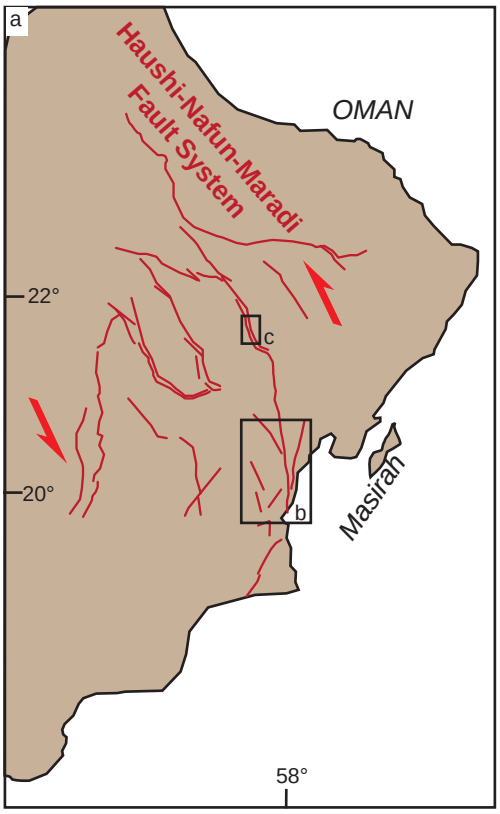

C
NW
SE
North Somali B.
Chain
Ridge
Transform
Chain Ridge
20 km
4
5
6
7
8
TWT (s)

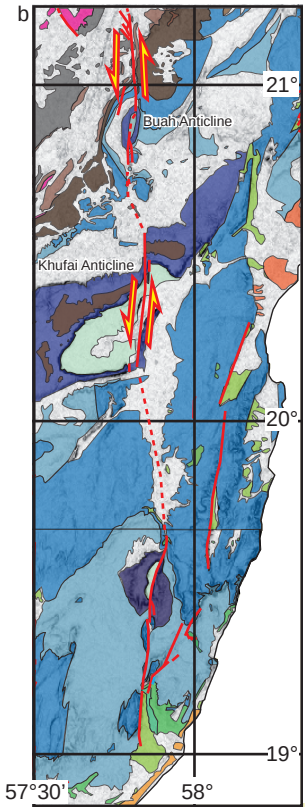
Figure


40 km
6°N
55°E

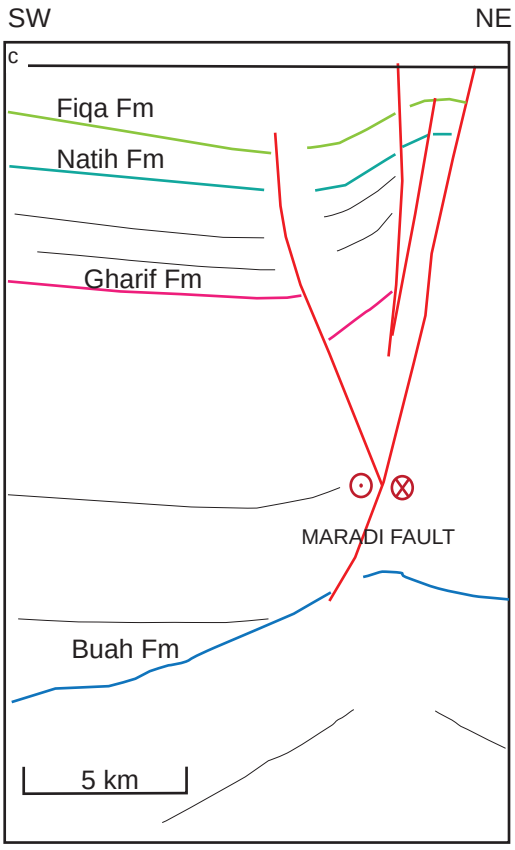

CHAIN RIDGE TRANSFORM
FRACTURE ZONE
CHAIN FRACTURE ZONE
6°N
55°E

Figure





Modified from Platel et al., 1992



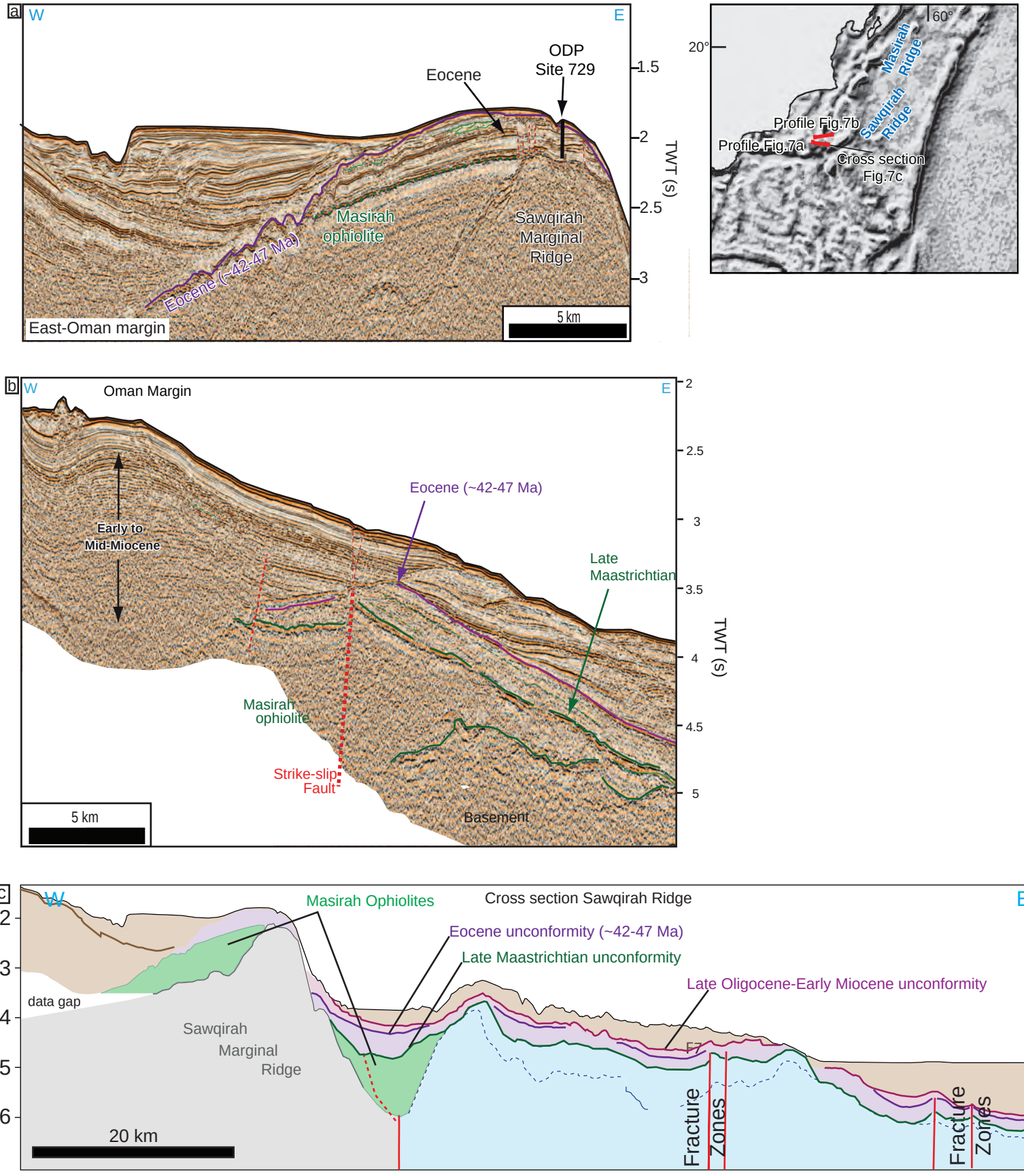
Modified from Filbrandt et al., 2006

TERTIARY
Hadramaut Group

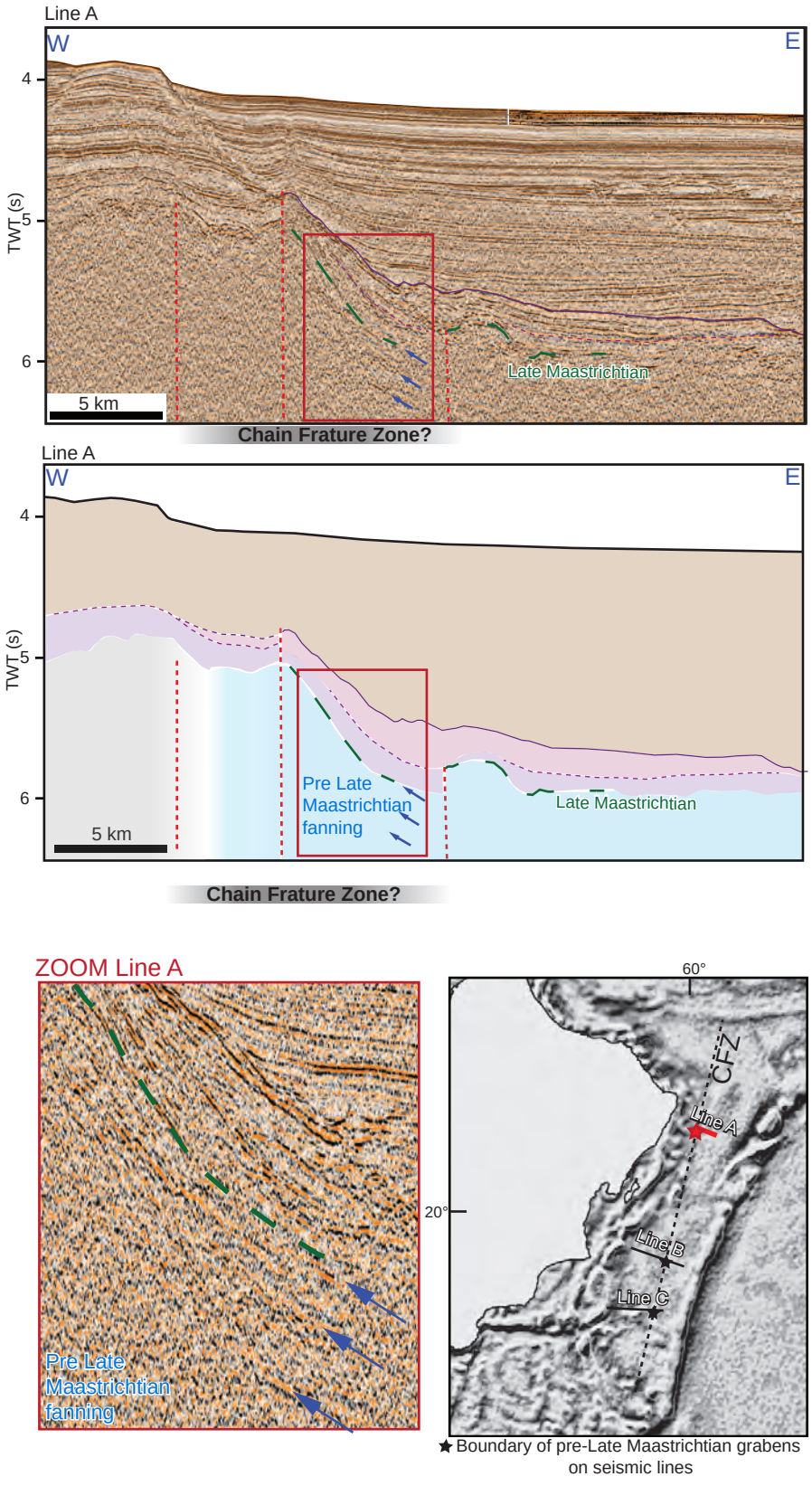
MESOZOIC
Samhan and Fiqa Fm
Natih and Nahr Fm
Qishn & Jurf Fm
Mafraq & Dhruma Fm

PRE-PERMIAN
Gharif & Khuff Fm
Al Khlata & Saiwan Fm
Amin & Andam Fm
Thumaylah Fm
Abu Mahara Fm
Khufai Fm
Shuram Fm
Buah Fm

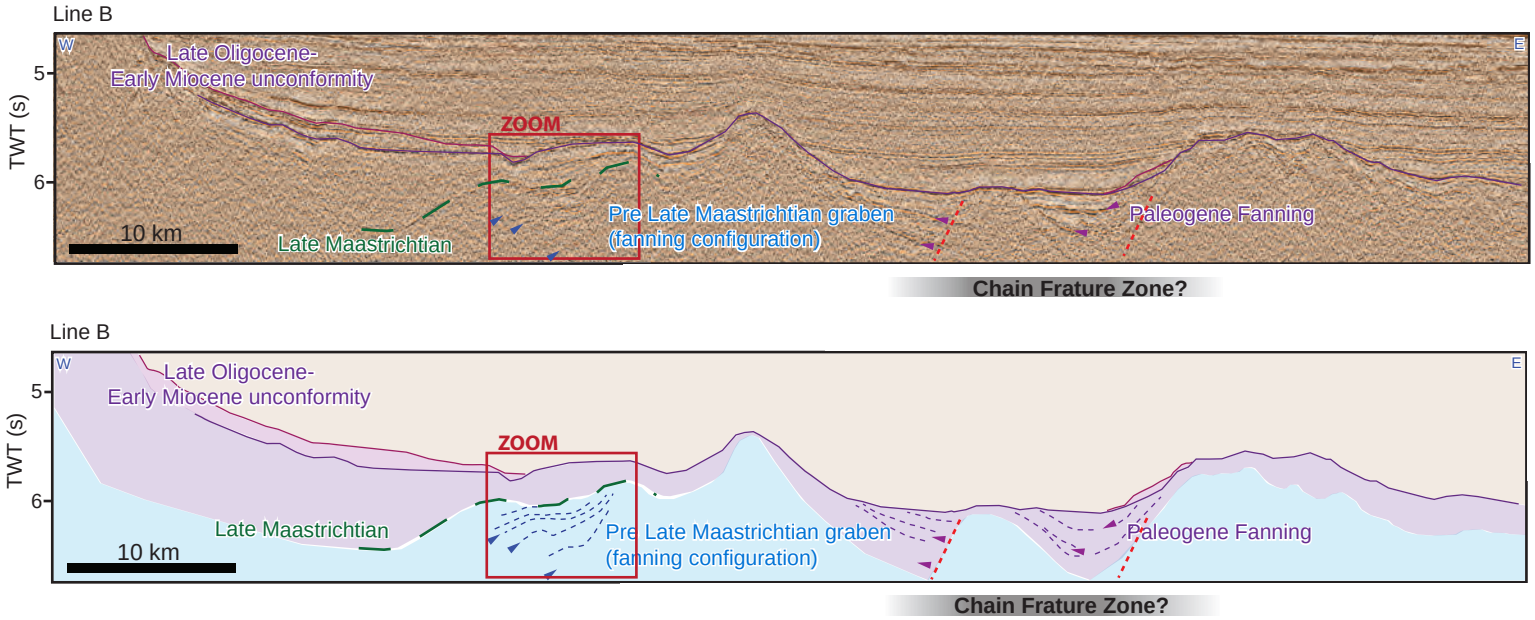
Figure

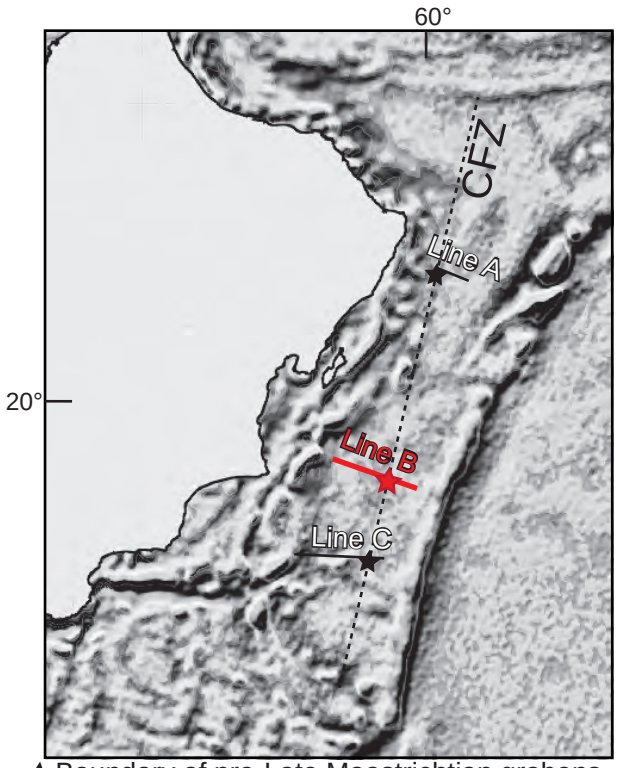

a
W
E
ODP
Site 729
Eocene
1.5
2
2.5
3
TWT (s)
Masirah
ophiolite
Sawqirah
Marginal
Ridge
Eocene (~42-47 Ma)
East-Oman margin
5 km
60°
20°
Masirah
Ridge
Sawqirah
Ridge
Profile Fig.7b
Profile Fig.7a
Cross section
Fig.7c
b
W
Oman Margin
E
2
2.5
3
3.5
4
4.5
5
TWT (s)
Eocene (~42-47 Ma)
Early to
Mid-Miocene
Late
Maastrichtian
Masirah
ophiolite
Strike-slip
Fault
5 km
Basement
c
W
Masirah Ophiolites
Cross section Sawqirah Ridge
E
Eocene unconformity (~42-47 Ma)
Late Maastrichtian unconformity
Late Oligocene-Early Miocene unconformity
2
3
4
5
6
TWT (s)
data gap
Sawqirah
Marginal
Ridge
F7
Fracture
Zones
Fracture
Zones
20 km

Figure

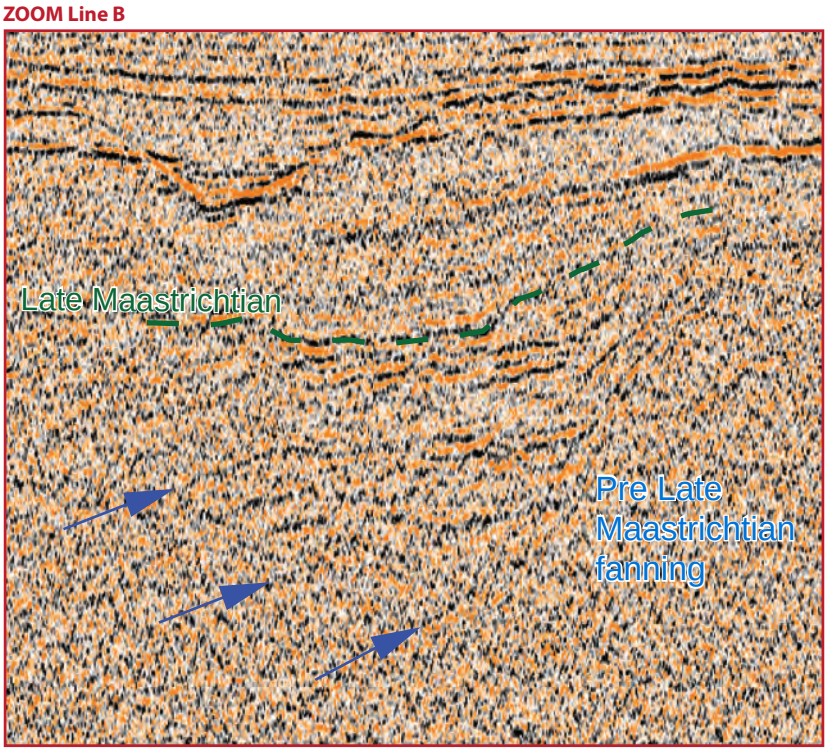

Line A
W
E
4
5
6
TWT (s)
Late Maastrichtian
5 km
Chain Frature Zone?
Line A
W
E
4
5
6
TWT (s)
Pre Late
Maastrichtian
fanning
Late Maastrichtian
5 km
Chain Frature Zone?
ZOOM Line A
Pre Late
Maastrichtian
fanning
60°
20°
CFZ
Line A
Line B
Line C
★Boundary of pre-Late Maastrichtian grabens
on seismic lines

Figure

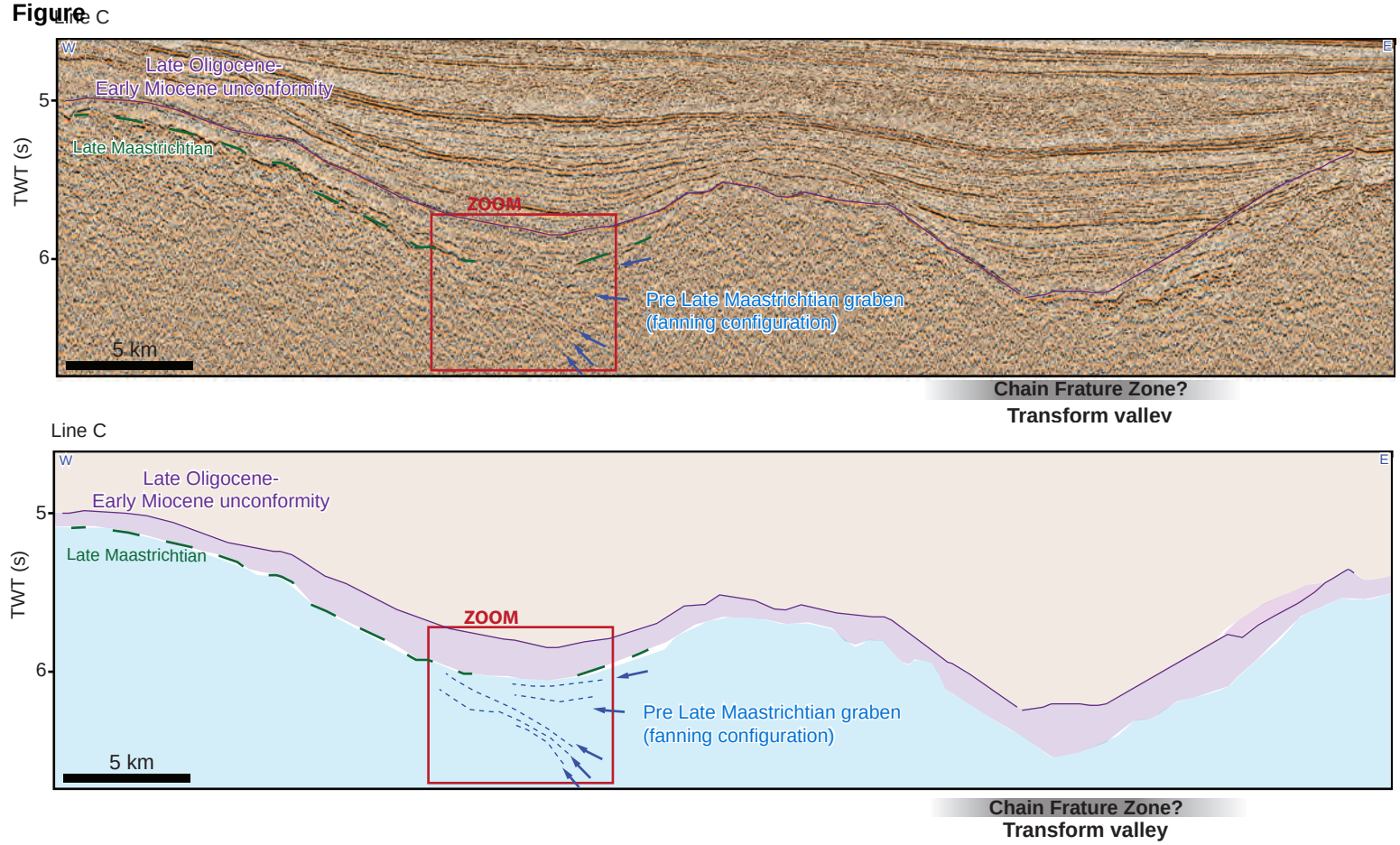


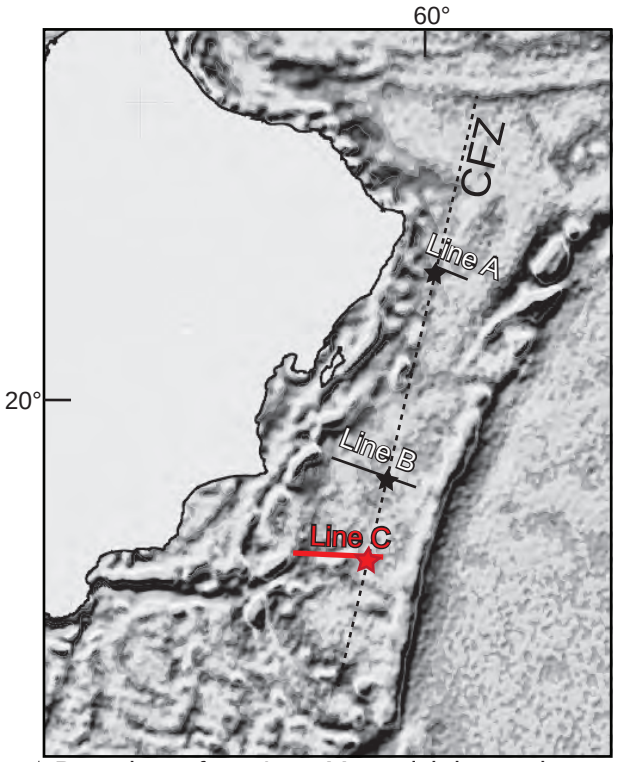


★ Boundary of pre-Late Maastrichtian grabens on seismic lines

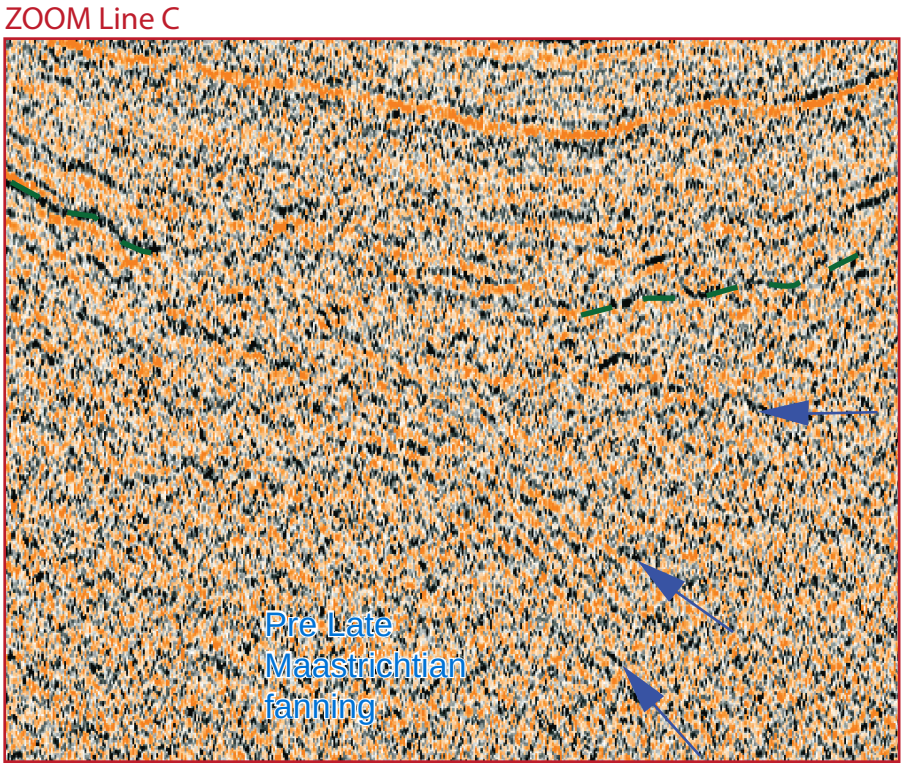


Figure

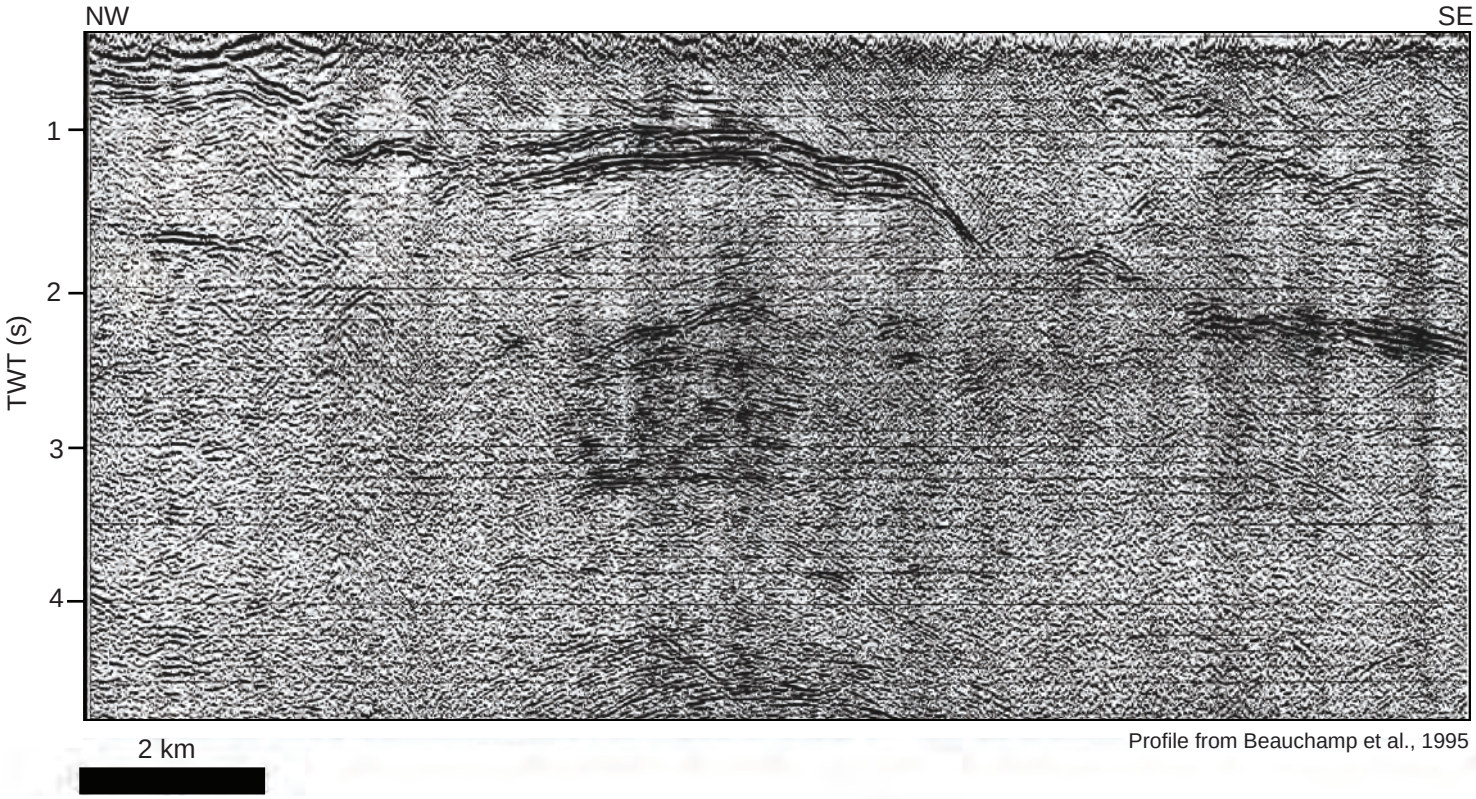




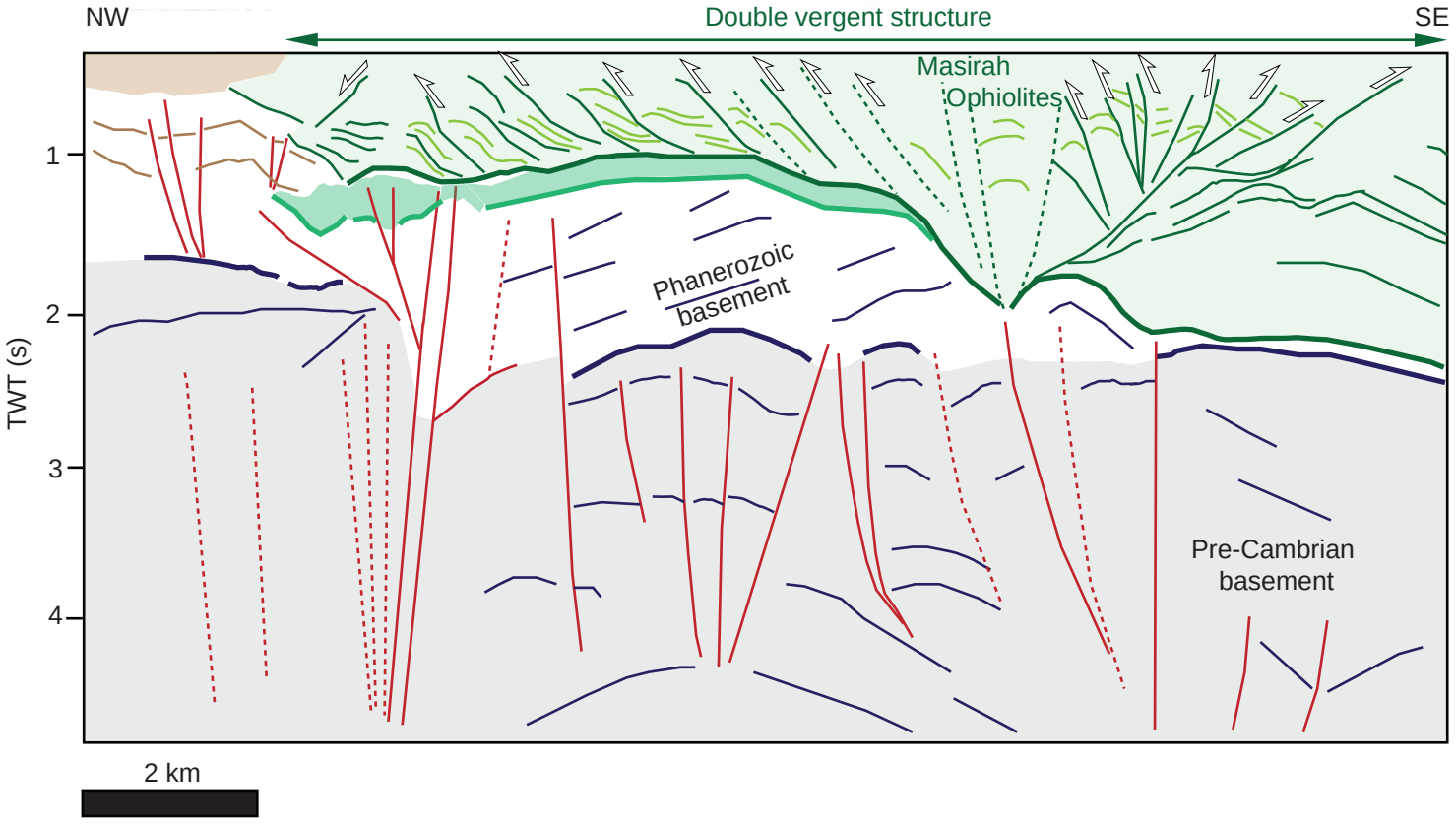
★ Boundary of pre-Late Maastrichtian grabens on seismic lines



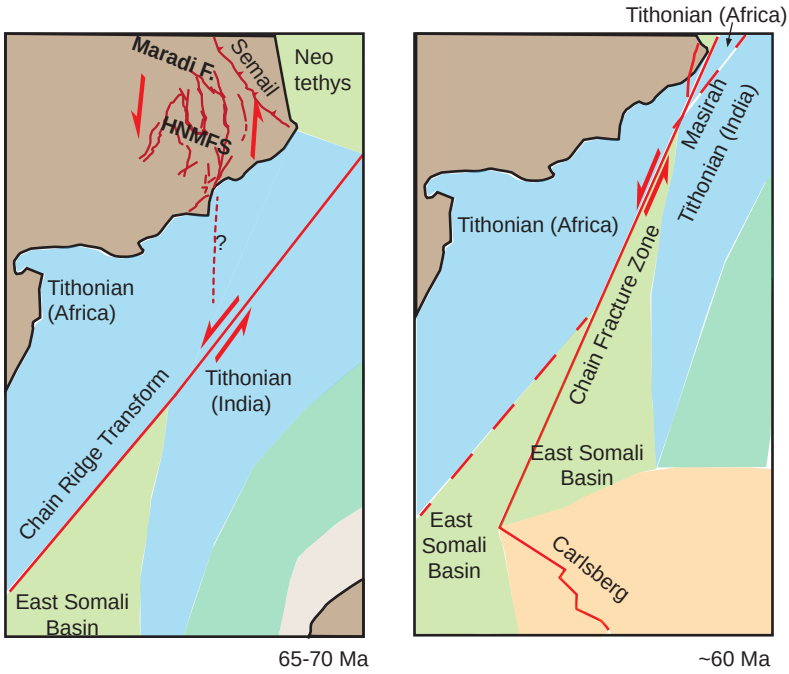
Figure



Profile from Beauchamp et al., 1995

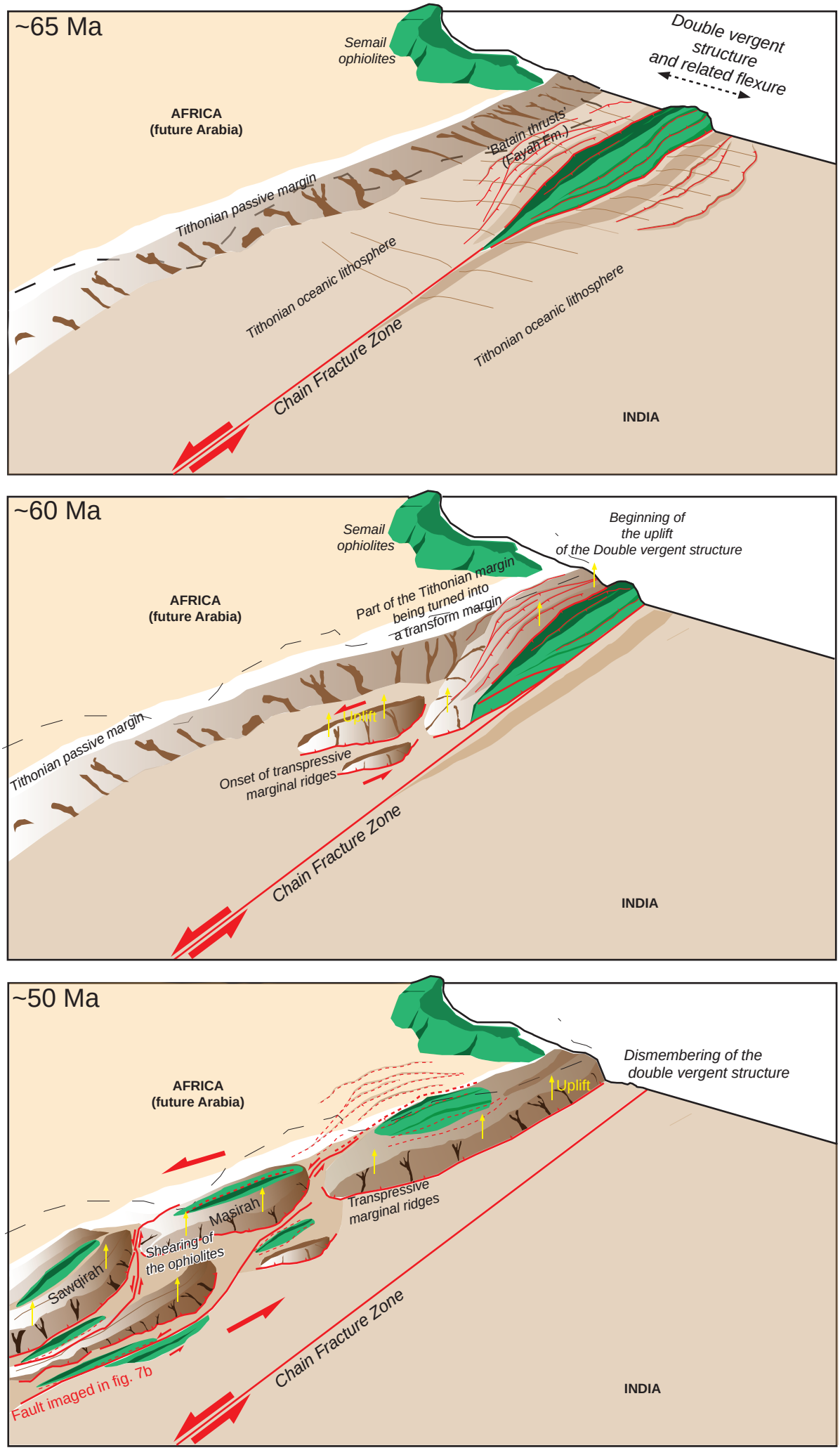


Figure

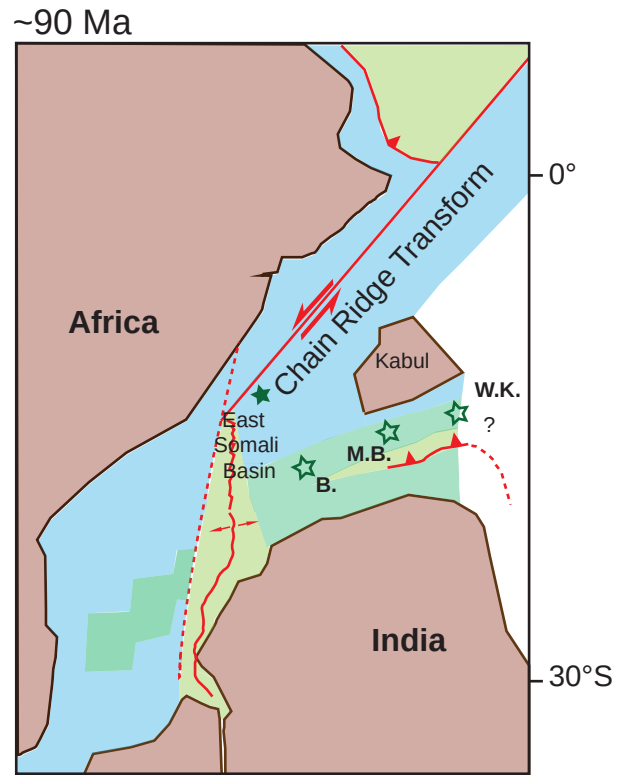

Maradi F.
Semail
Neo
tethys
HNMFs
?
Tithonian
(Africa)
Chain Ridge Transform
Tithonian
(India)
East Somali
Basin
65-70 Ma
Tithonian (Africa)
Masirah
Tithonian (India)
Tithonian (Africa)
Chain Fracture Zone
East Somali
Basin
East
Somali
Basin
Carlsberg
~60 Ma

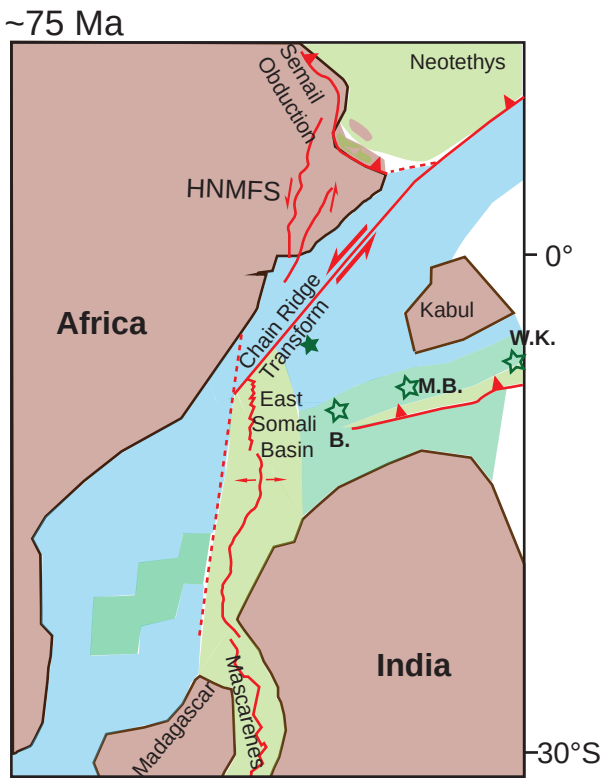
F12

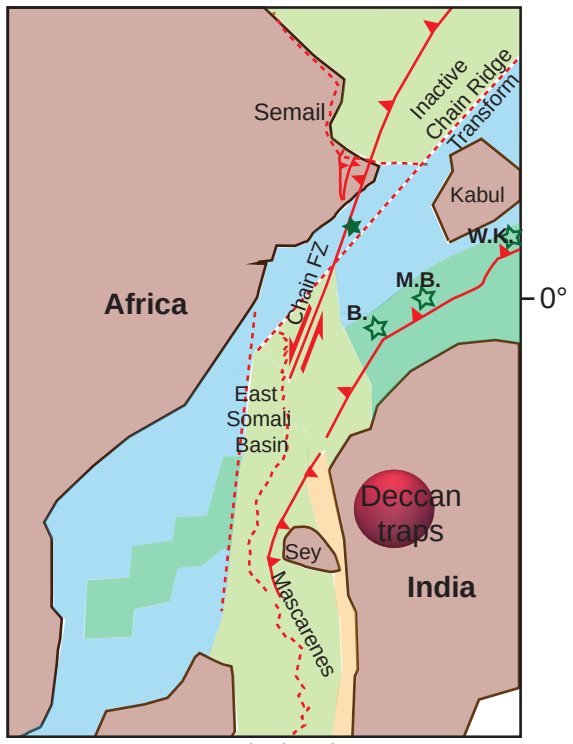
Figure


~65 Ma
Semail ophiolites
Double vergent structure and related flexure
AFRICA (future Arabia)
'Batain thrusts' (Fayah Fm.)
Tithonian passive margin
Tithonian oceanic lithosphere
Chain Fracture Zone
Tithonian oceanic lithosphere
INDIA
~60 Ma
Semail ophiolites
Beginning of the uplift of the Double vergent structure
AFRICA (future Arabia)
Part of the Tithonian margin being turned into a transform margin
Tithonian passive margin
Uplift
Onset of transpressive marginal ridges
Chain Fracture Zone
INDIA
~50 Ma
Dismembering of the double vergent structure
AFRICA (future Arabia)
Uplift
Masirah
Transpressive marginal ridges
Shearing of the ophiolites
Sawqirah
Fault imaged in fig. 7b
Chain Fracture Zone
INDIA

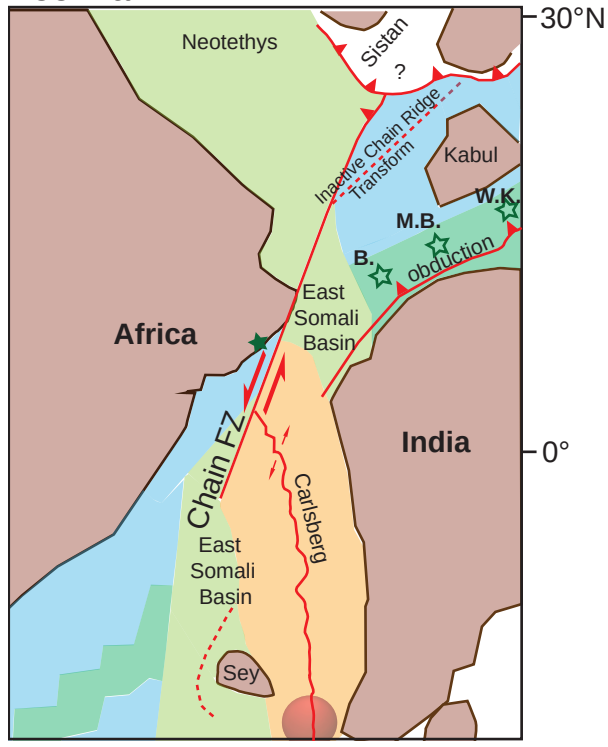
Figure

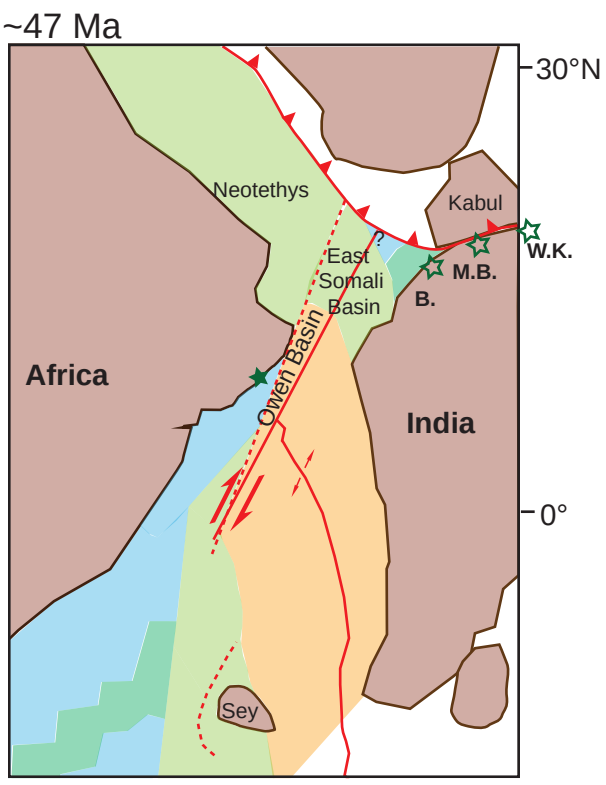


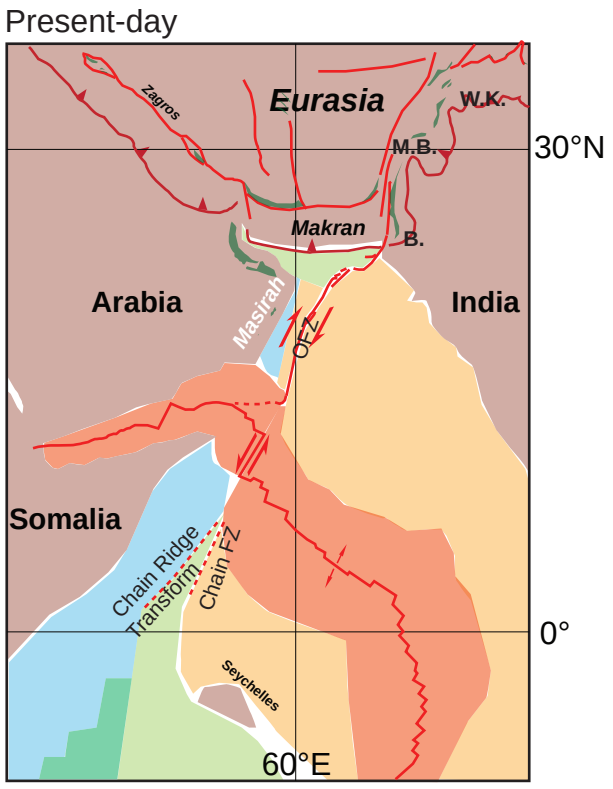




Deactivation of
Mascarenes-East Somali
spreading center







Seafloor age

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

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