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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.

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 Krane, 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

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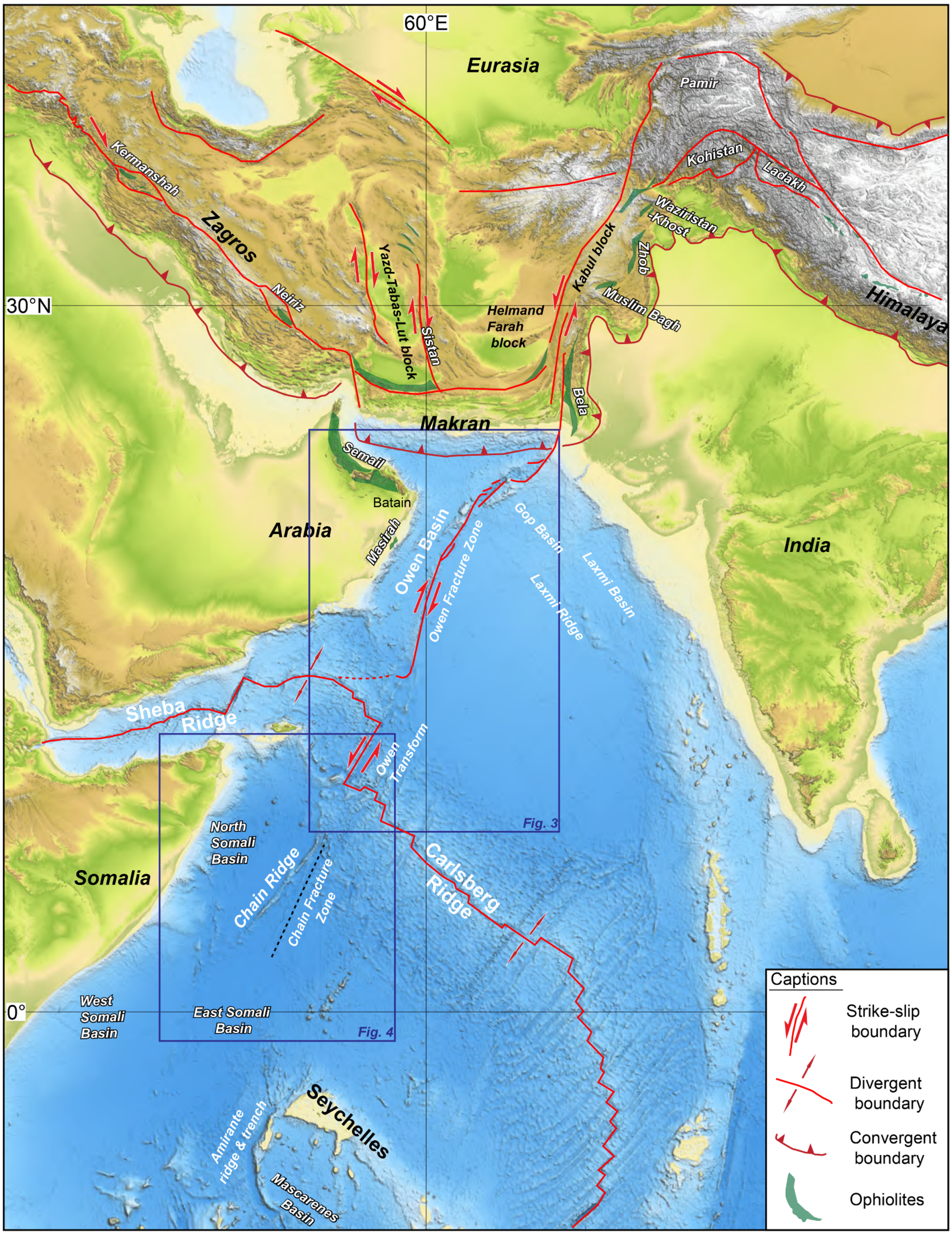

Fig. 1. Structural map of the north western Indian Ocean, showing the currently active plate boundaries, the distribution of the oceanic basins, as well as the distribution of the main ophiolites.

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

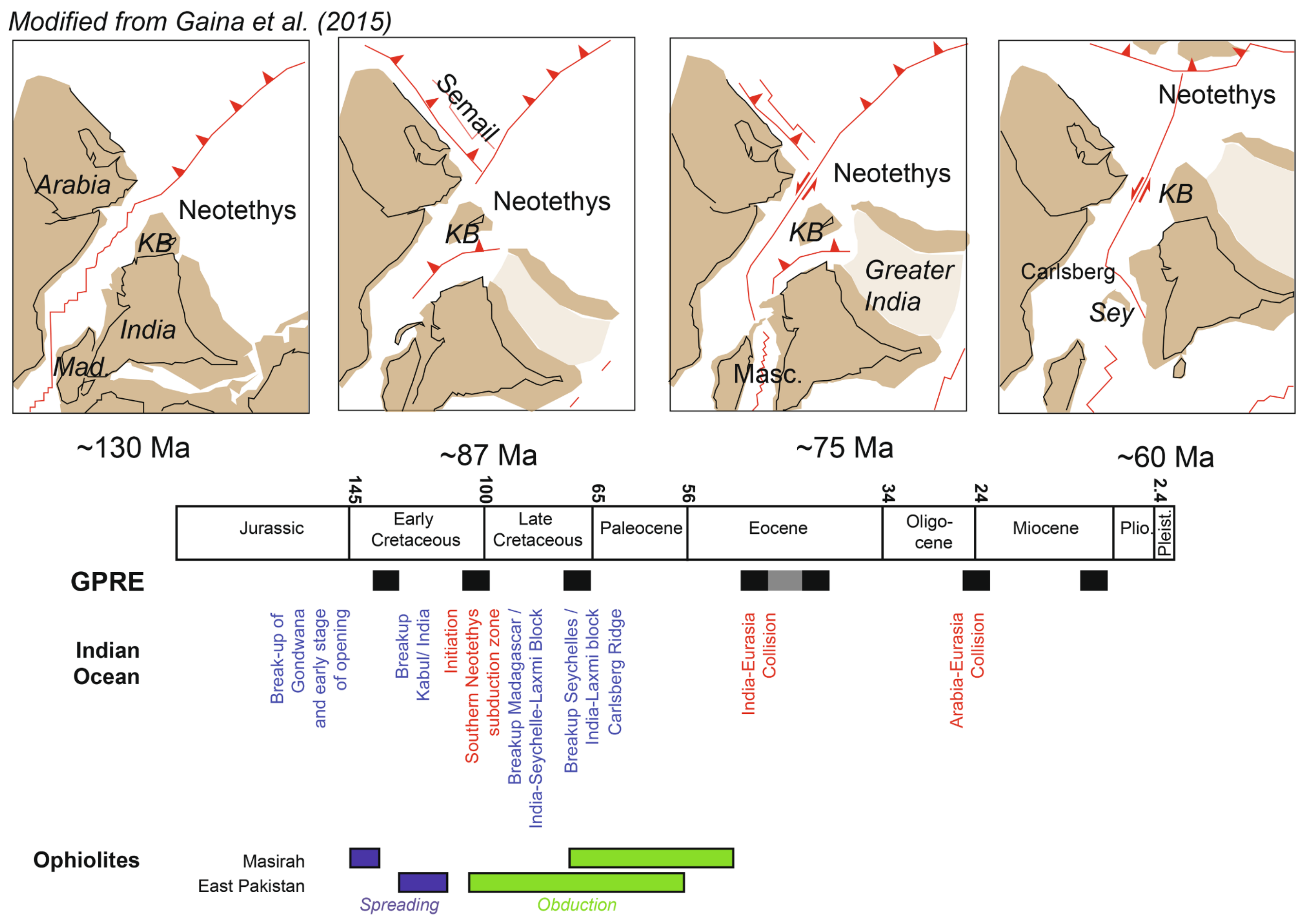

Fig. 2. General paleogeographic reconstructions of the Indian Ocean from Early Cretaceous to Early Tertiary, proposed by Gaina et al. (2015), and main geological events during the history of the Indian Ocean. KB: Kabul Block; Masc.: Mascarenes; Sey: Seychelles; GPRE: Global Plate Reorganization Events.

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).

2.2. The fragmentation of the India-Seychelles-Madagascar block

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

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

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

Third, the break-up between the Seychelles-Laxmi block and India

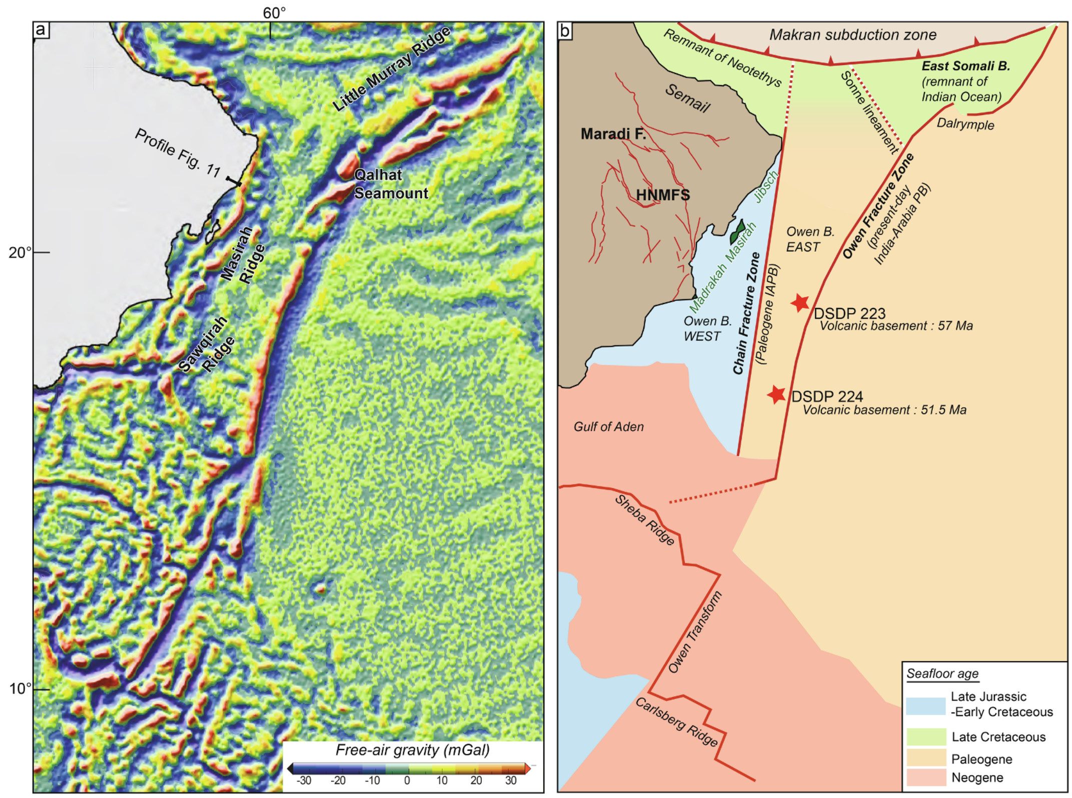

Fig. 3. (a) Free air gravity map of the Owen Basin offshore Oman and the Arabian Sea (filtered for short wavelengths from DTU 13 database; Andersen et al., 2013) and (b) its interpretation, with an emphasis on the composite age of the basement of the Owen Basin. HNMFS: Haushi-Nafun-Maradi Fault System.

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

2.3. Late Cretaceous-Early Paleocene ophiolites in the NW Indian Ocean

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

The initiation of an intra-oceanic subduction ~100–105 Ma in the southern part of the Neotethys Ocean led to obduction north of Arabia and India during the Campanian (Hacker et al., 1996; Agard et al., 2007, 2011; Hébert et al., 2012; Nicolas and Boudier, 2017; Guilmette et al., 2018). In the surroundings of the Arabian Sea, the related ophiolites are the Semail in Oman (Searle and Cox, 1999; Breton et al., 2004) and Zhob-Waziristan-Khost ophiolites in NE Pakistan (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 and 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 70–100 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

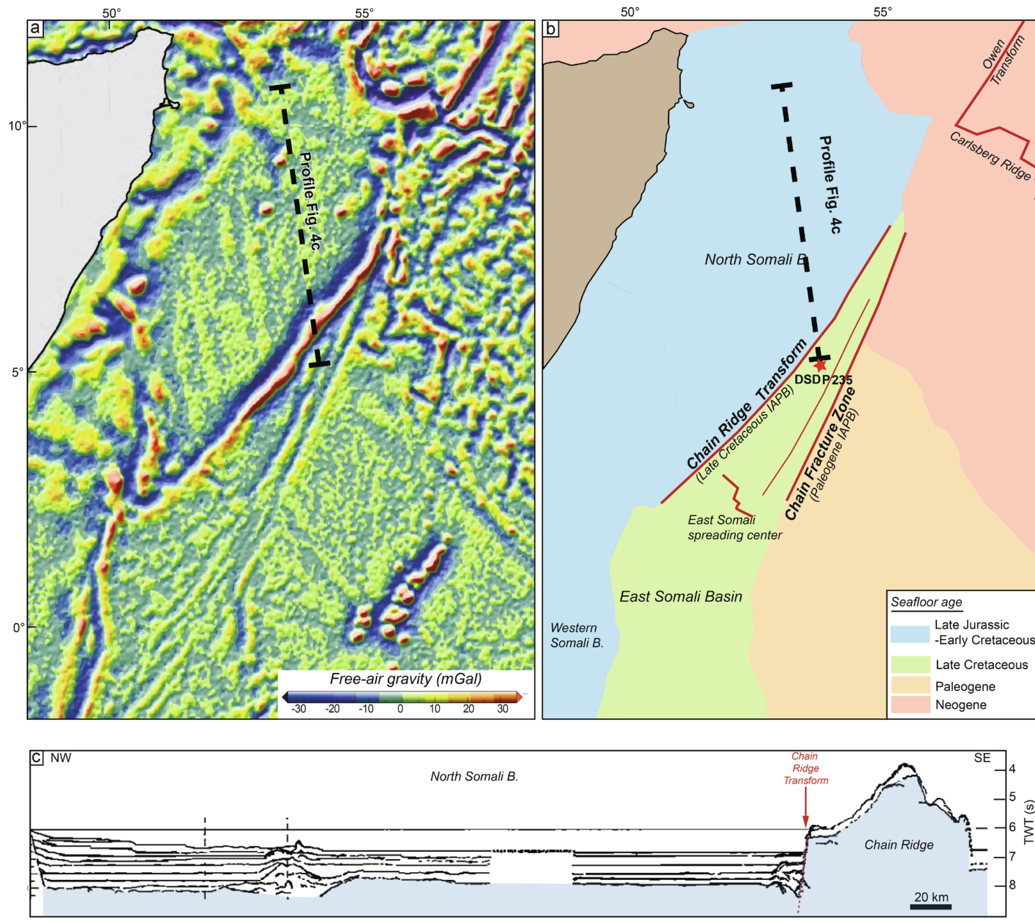

Fig. 4. (a) Free air gravity map of the North Somali Basin (filtered for short wavelengths from DTU 13 database; Andersen et al., 2013) and (b) its interpretation, with an emphasis on the composite age of the basement of the North Somali Basin. (c) New interpretation of a vintage seismic line from Bunce 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.

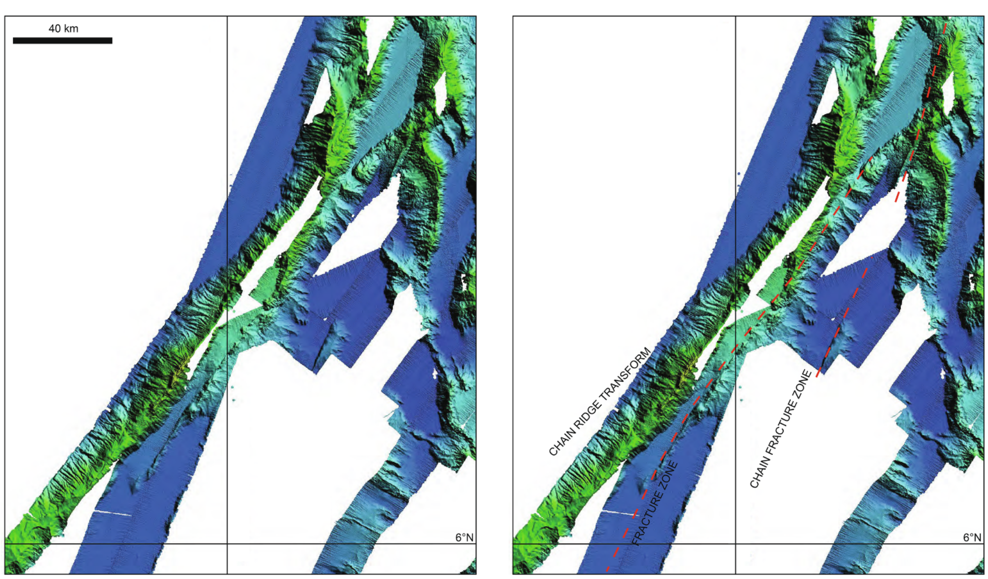

Fig. 5. Multibeam map of the northern termination of the Chain Ridge and Chain Fracture Zone.

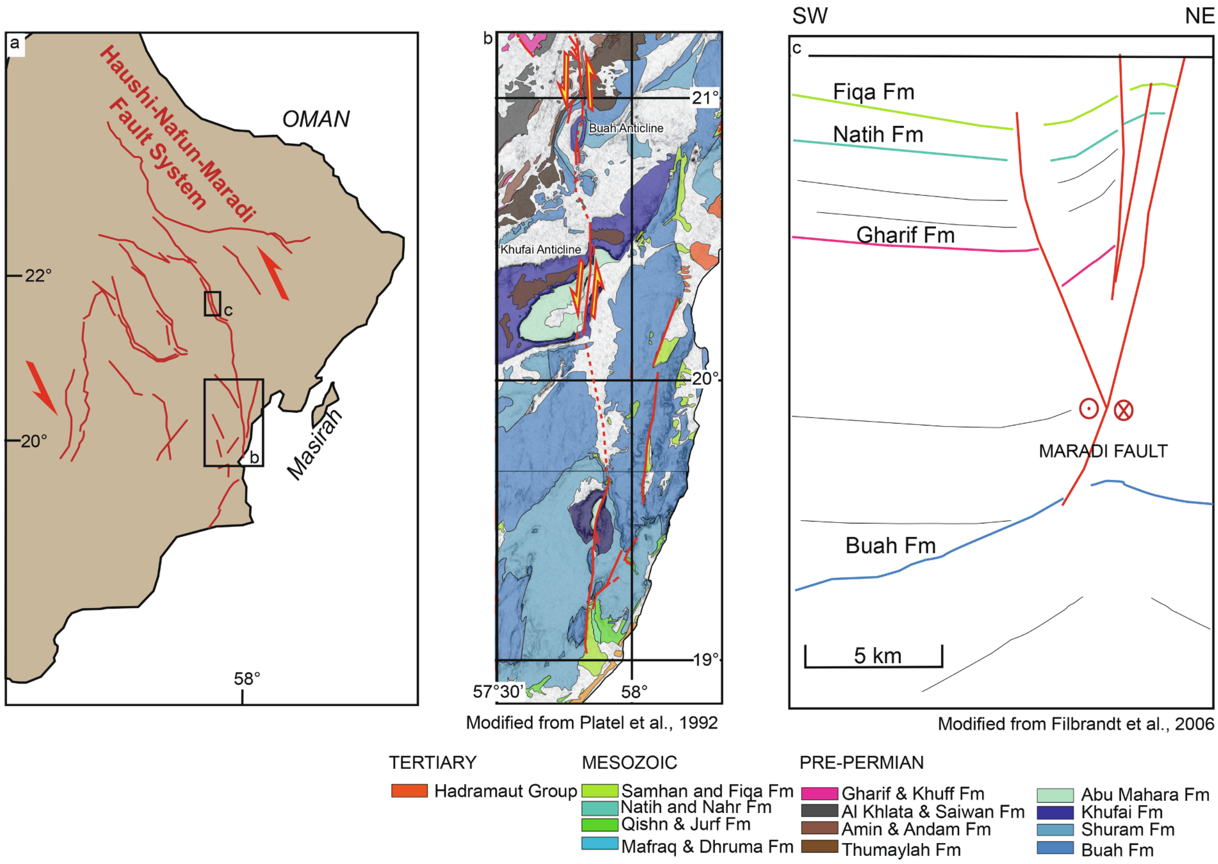

Fig. 6. (a) Map of the Haushi Nafun Maradi Fault system; (b) Simplified geological sketchmap of the Huqf desert highlighting strike-slip offsets related to the Haushi-Nafun fault, after Platel et al., 1992; (c) line drawing of a seismic profile crossing the Maradi fault, highlighting a negative flower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

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 and 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: 250000 (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. 7–10; 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 s 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.

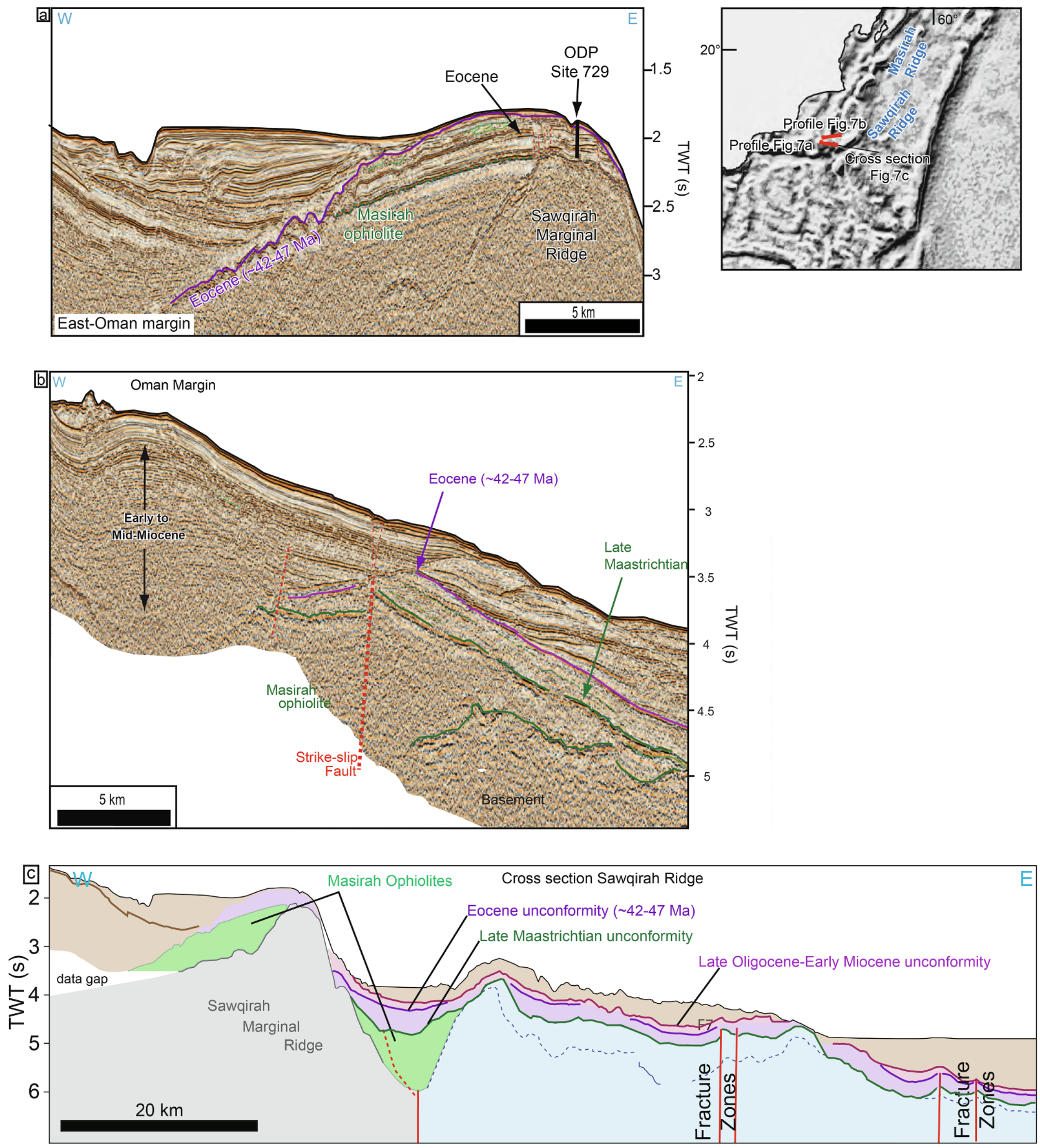

Fig. 7. (a) Seismic line from the OWEN 2 cruise (Rodriguez et al., 2016) crossing the western side of the Sawqirah Ridge, where the Masirah ophiolites are tilted westwards, in direction of the Oman platform; (b) Seismic line from the OWEN 2 cruise (Rodriguez et al., 2016) crossing the eastern edge of 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.

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. 7–10). The cross-section of the Oman margin provided in Fig. 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 (Figs. 7 and 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

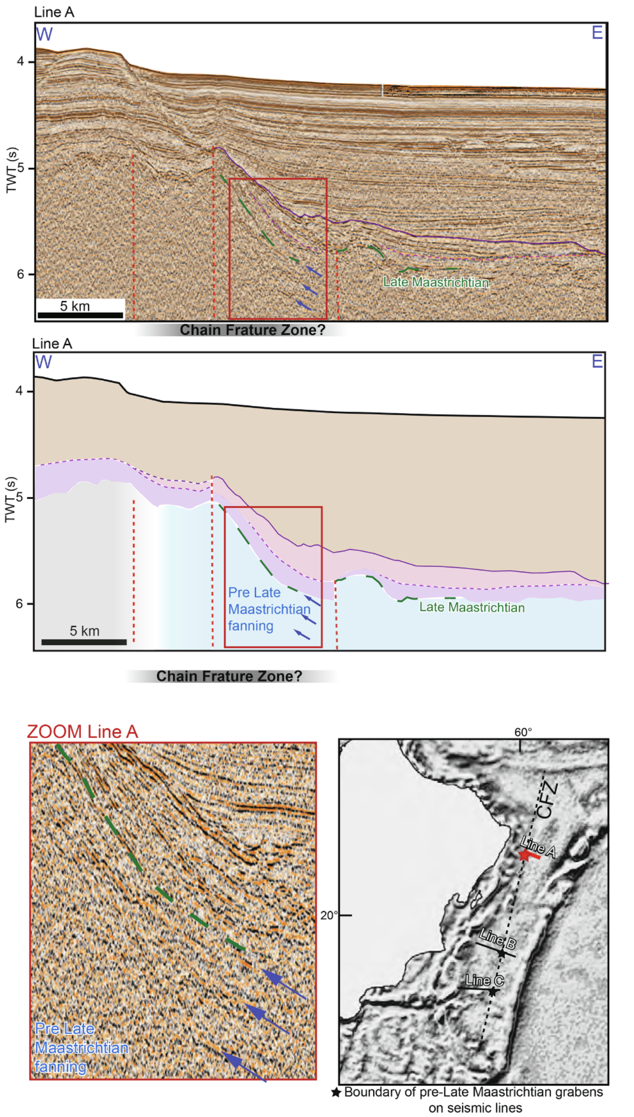

Fig. 8. Seismic lines from the Owen-2 cruise (Rodriguez et al., 2016) crossing the Owen Basin.

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 (160–130 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 and 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.

4.2.1. 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 laterites 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 (Figs. 3 and 7; Rodriguez et al., 2016). The uplift of the en-échelon system of

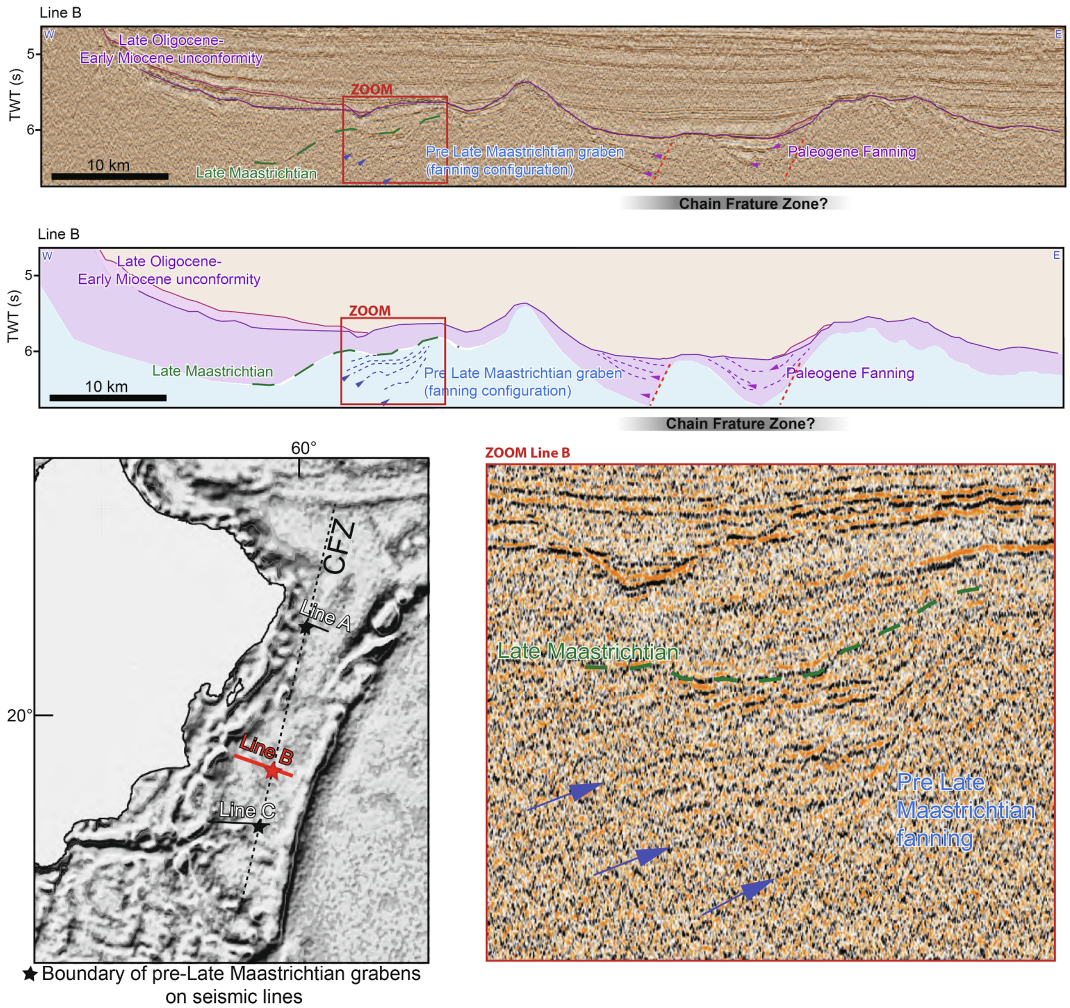

Fig. 9. Seismic lines from the Owen-2 cruise (Rodriguez et al., 2016) crossing the Owen Basin.

marginal ridges therefore lasted over more than 25 Myrs, from 65 to 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).

4.2.2. Owen Basin

The seismic lines displayed in Figs. 8–10 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

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

5.1. Structural evolution of the India-Africa plate boundary during the Late Cretaceous-Eocene

For the Late Cretaceous India-Africa plate boundary, our

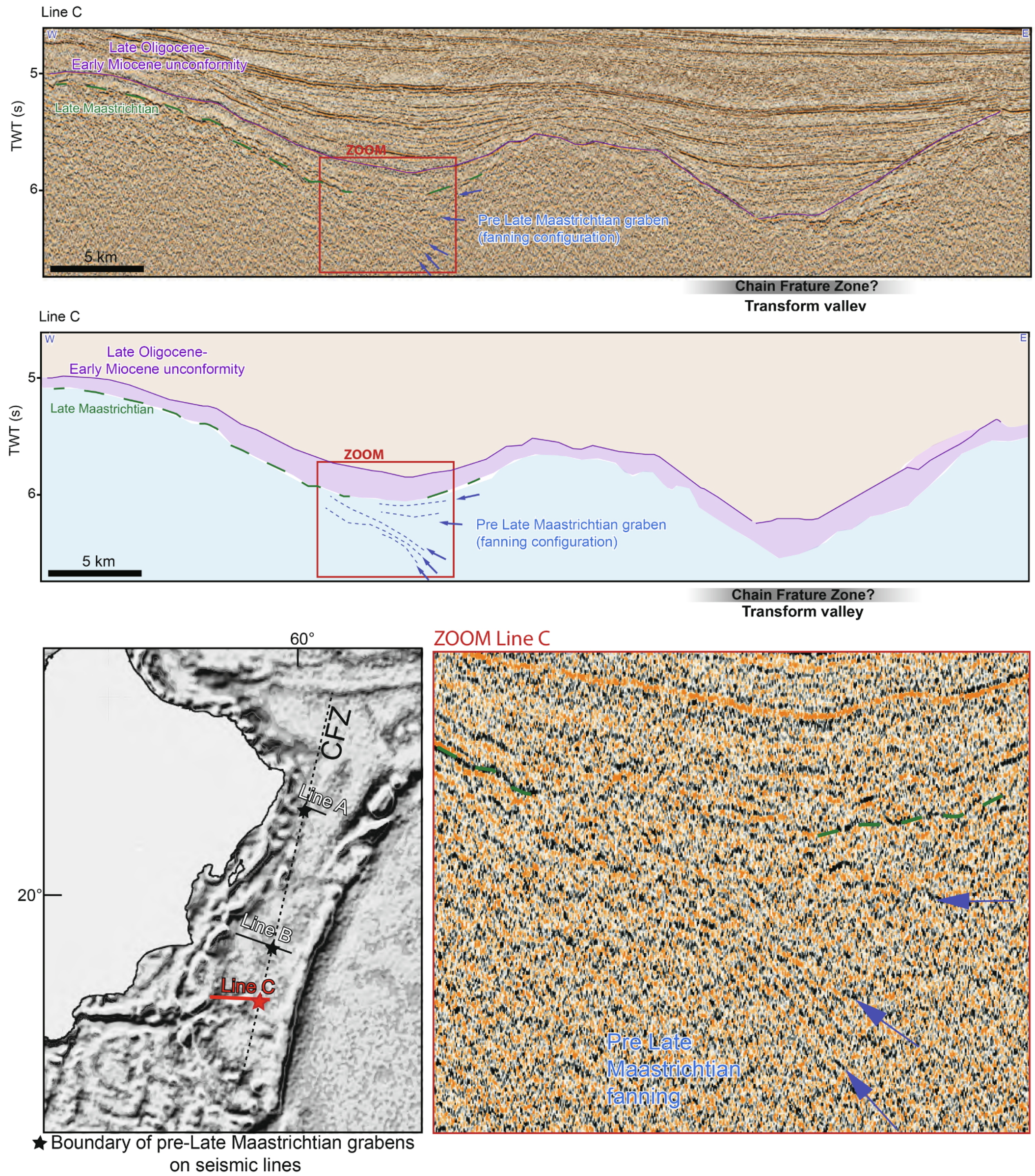

Fig. 10. Seismic lines from the Owen-2 cruise (Rodriguez et al., 2016) crossing the Owen Basin. These seismic lines highlight the presence of pre-Maastrichtian fanning configurations lying above the basement of the western part of the Owen Basin, and their absence in its eastern part. The boundary of 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).

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

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

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

5.2. Emplacement of the Masirah ophiolite along the east Oman transform margin

These results allow to reappraise the emplacement of the Masirah

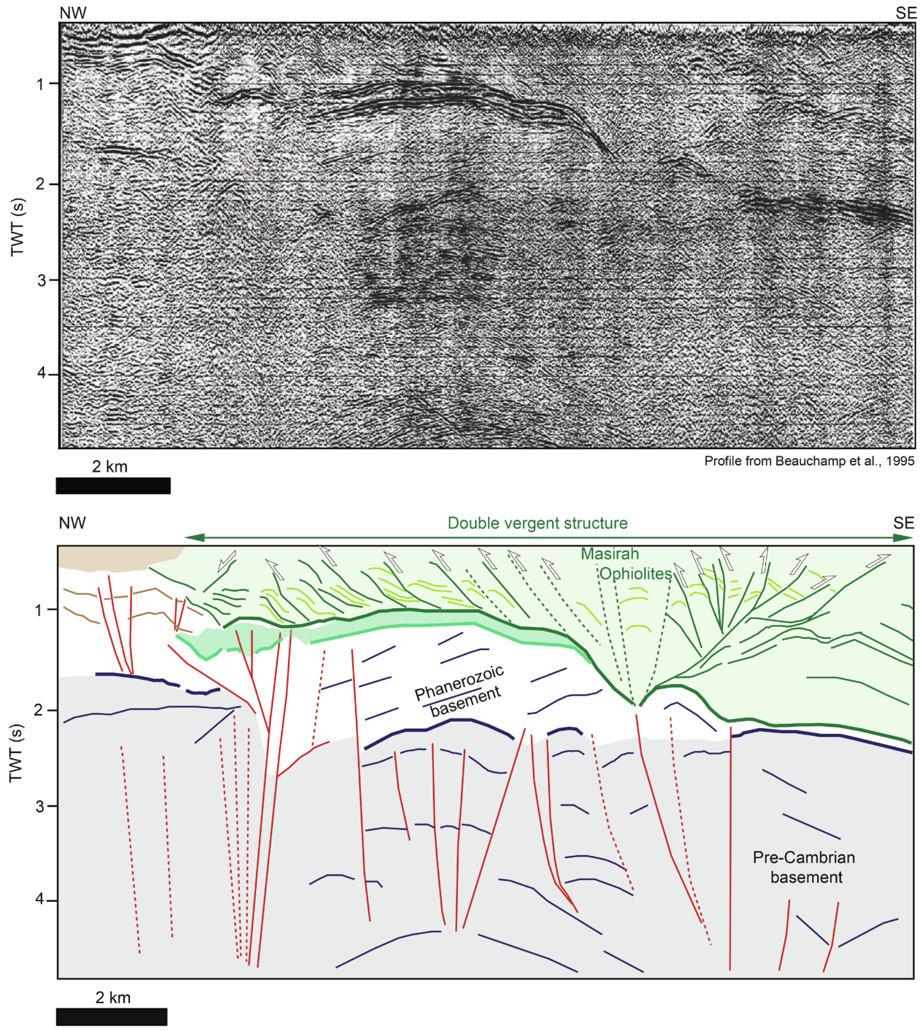

Fig. 11. (a) Seismic profile crossing the Masirah ophiolite in the Batain plain (from Beauchamp et al., 1995) and (b) its revised interpretation, highlighting the positive flower structure of the Masirah Ophiolites. See Fig. 3 for location.

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

Fig. 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,

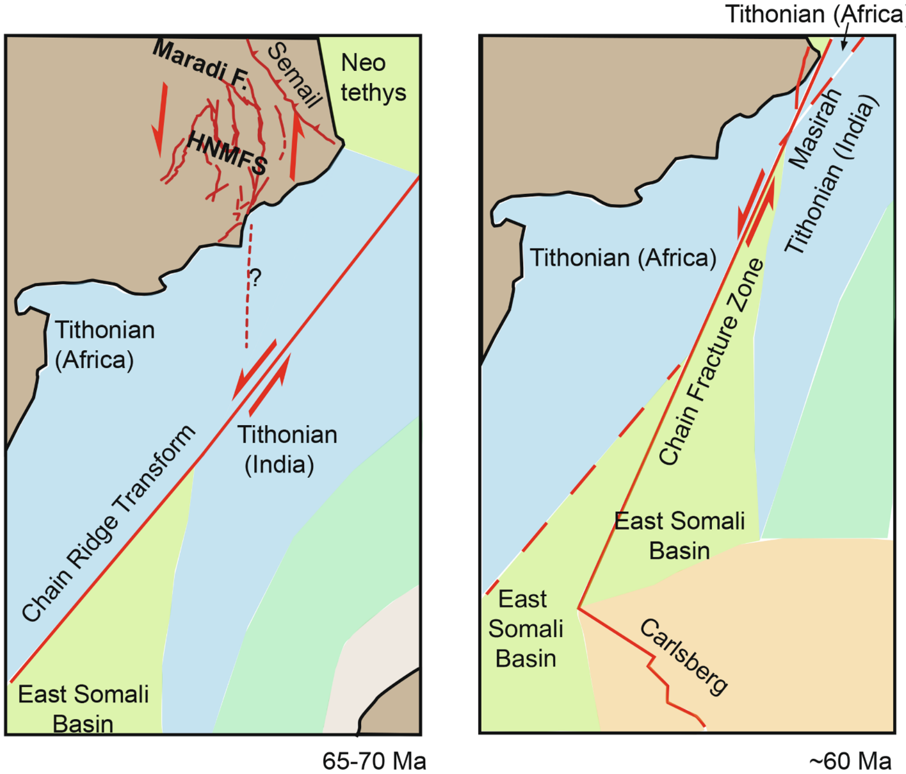

Fig. 12. Reconstruction of the configuration of the India-Africa plate Boundary at 65–70 Ma and 60 Ma, highlighting the major migration of the transform system occurring at that time.

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 (Figs. 12 and 14). After the Masirah obduction, the remaining Tithonian lithosphere located east of the Chain Fracture Zone was subducted beneath eastern Makran (Fig. 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

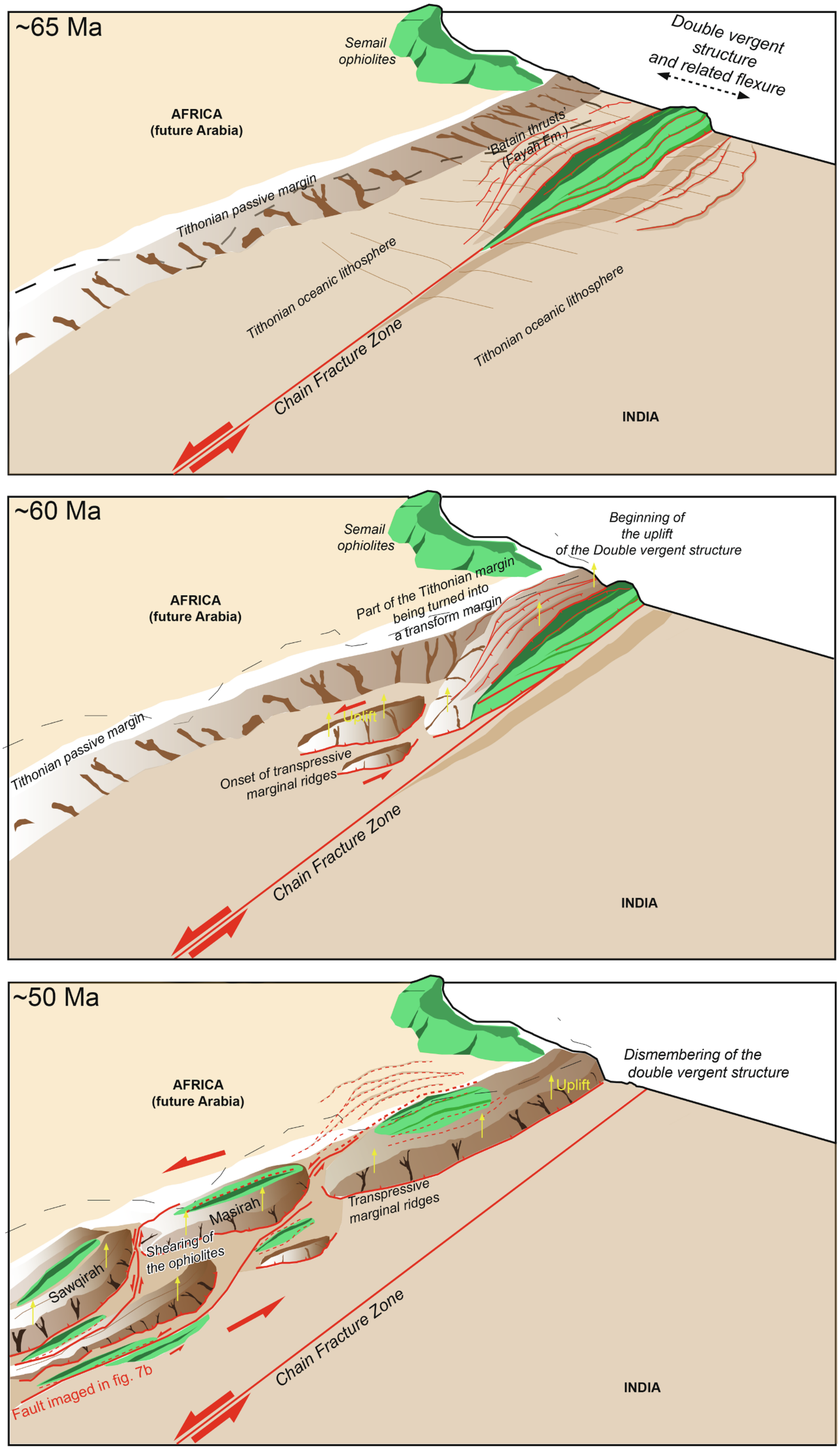

Fig. 13. Simplified reconstruction of the mode of emplacement of the Masirah ophiolites along with the development of the en-échelon marginal ridge system offshore Oman. Note that the emplacement of the ophiolites last over more than 25 Myrs and does not imply any subduction zone.

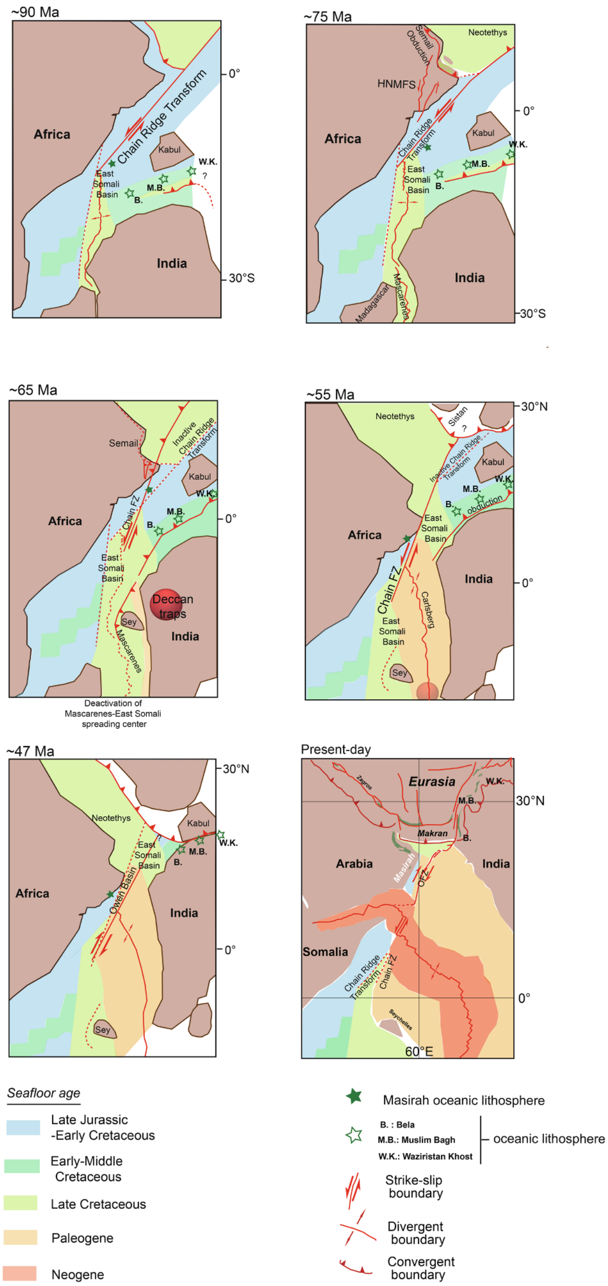

Fig. 14. Revised paleogeographic reconstructions of the northwestern Indian Ocean, from 90 Ma to present-day, modified after Matthews et al. (2016). These reconstructions highlight the successive locations of the India-Africa plate boundary: the Chain Ridge Transform from 90 to 65 Ma, the Chain Fracture 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.

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 and 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 (Müller 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.

7. Authors agreement

All the authors have read and approved the content of this paper. Part of the seismic profile dataset have already been published (Rodriguez et al., Marine Petroleum Geology) but we here focus on a different problematic and provide new and updated interpretations of these data. This study is not considered for publication elsewhere.

Declaration of Competing Interest

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

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jseaes.2019.104225.

References

Agard, P., Omrani, J., Jolivet, L., Whitechurch, H., Vrielynck, B., Spakman, W., Monié, P., Meyer, B., Wortel, R., 2011. Zagros orogeny: a subduction-dominated process, In: Lacombe, O., Grasemann, B., Simpson, G. (Eds.), Geodynamic Evolution of the Zagros. Geological Magazine, p. 692–725.

Agard, P., Jolivet, L., Vrielynck, B., Burov, E., Monié, P., 2007. Plate acceleration: the obduction trigger? Earth Planet. Sci. Lett. 258, 428–441.

Agard, P., Yamato, P., Soret, M., Prigent, C., Guillot, S., Plunder, A., Dubacq, B., Chauvet, A., Monié, P., 2016. Plate interface rheological switches during subduction infancy: control on slab penetration and metamorphic sole formation. Earth Planet. Sci. Lett. 451, 208–220.

Ali, J.R., Aitchison, J.C., 2008. Gondwana to Asia: Plate tectonics, paleogeography and

the biological connectivity of the Indian sub-continent from the Middle Jurassic through latest Eocene (166–35 Ma). Earth-Sci. Rev. 88, 145–166.
Allemann, F., 1979. Time of emplacement of the Zhob Valley ophiolites and Bela ophiolites, Baluchistan (preliminary report). In: Geodynamics of Pakistan, Geol. Surv. Pakistan, Spec. Mem. 215–242.
Allen, P.A., 2007. The Huqf supergroup of Oman: basin development and context for Neoproterozoic glaciation. Earth-Sci. Rev. 84, 139–185.
Andersen O., Knudsen, P., Kenyon, S., Factor, J., Holmes, S., 2013. The dtu13 global marine gravity field—first evaluation. Technical report, DTU Space – National Space Institute.
Anderson, D.L., 2001. Top-down tectonics? Science 293, 2016–2018.
Badshah, M.S., Gnos, E., Jan, M.Q., Afridi, M.I., 2000. Stratigraphic and tectonic evolution of the northwestern Indian plate and Kabul Block. In: Khan, M.A., Treloar, P.J., Searle, M.P., Jan, M. (Eds.), Tectonics of the Nanga Parbat Syntaxis and the Western Himalaya, Geological Society of London Special Publication, 170, 467–475.
Barrie, J.V., Conway, K.W., Harris, P.T., 2013. The Queen Charlotte Fault, British Columbia: seafloor anatomy of a transform fault and its influence on sediment processes. Geo-Mar. Lett. 33, 311–318.
Barrier, E., Vrielynck, B., 2008. Palaeotectonic maps of the Middle East. Tectono-sedimentary-palinspastic maps from Late Norian to Pliocene. 14 maps. Paris CGMW/CCGM.
Beauchamp, W.H., Ries, A.C., Coward, M.P., Miles, J.A., 1995. Masirah Graben, Oman: a hidden Cretaceous rift basin? Am. Assoc. Petrol. Geol. Bull. 79, 864–879.
Bercovici, D., 2003. The generation of plate tectonics from mantle convection. Earth Planet. Sci. Lett. 205, 107–121.
Bernard, A., Munschy, M., 2000. Le bassin des Mascareignes et le bassin de Laxmi (océan Indien occidental) se sont-ils formés à l'axe d'un même centre d'expansion ? Comptes Rendus de l' Académie des Sciences Paris 330, 777–783.
Besse, J., Courtillot, V., 1988. Paleogeographic maps of the continents bordering the Indian Ocean since the Early Jurassic. J. Geophys. Res. 93, 11791–11808.
Bhattacharya, G.C., Yatheesh, V., 2015. Plate-tectonic evolution of the deep ocean basins adjoining the western continental margin of India – a proposed model for the early opening scenario. In: Mukherjee, S. (Ed.), Petroleum Geoscience: Indian Contexts. Springer International Publishing, Switzerland, 1–61.
Bonatti, E., Krane, K., 1982. Oscillatory spreading explanation of anomalously old uplifted crust near oceanic transform. Nature 300, 343–345.
Bouilhol, P., Jagoutz, O., Hanchar, J.M., Dudas, F.O., 2013. Dating the India-Eurasia collision through arc magmatic records. Earth Planet. Sci. Lett. 366, 163–175.
Breton, J.-P., Béchennec, F., Le Métour, J., Moen-Maurel, L., Razin, P., 2004. Eoalpine (Cretaceous) evolution of the Oman Tethyan continental margin: insights from a structural field study in Jabal Akhdar (Oman Mountains). Geoarabia 9, 1–18.
Buckman, S., Aitchinson, J.C., Nutman, A.P., Bennett, V.C., Saktura, W.M., Walsh, J.M.J., Kachovich, S., Hidaka, H., 2018. The Spongtang Massif in Ladakh, NW Himalaya: an Early Cretaceous record of spontaneous, intra-oceanic subduction initiation in the Neotethys. Gondwana Res. 63, 226–249.
Bunce, E.T., Molnar, P., 1977. Seismic reflection profiling and basement topography in the Somali Basin: possible fracture zones between Madagascar and Africa. J. Geophys. Res. 82, 5305–5311.
Burg, J.P., 2018. Geology of the onshore Makran accretionary wedge: synthesis and tectonic interpretation. Earth-Sci. Rev. 185, 1210–1231.
Burg J.P., 2011. The Asia-Kohistan-India collision: review and discussion. D. Brown and P.D. Ryan (eds), Arc-Continent Collision, Frontiers in Earth Sciences, 279–309, 10.1007/978-3-540-88558-0_10.
Calvès, G., Schwab, A.M., Huuse, M., Clift, P.D., Gaina, C., Jolley, D., Tabrez, A.R., Inam, A., 2011. Seismic volcanostratigraphy of the western Indian rifted margin: the pre-Deccan igneous province. J. Geophys. Res. 116, B01101. https://doi.org/10.1029/2010JB000862.
Cande, S., Patriat, C.P., 2015. The anticorrelated velocities of Africa and India in the Late Cretaceous and early Cenozoic. Geophys. J. Int. 200, 227–243.
Cande, S.C., Stegman, D.R., 2011. Indian and African plate motions driven by the push force of the Réunion plume head. Nature 475, 47–52.
Carlson, P.R., Bruns, T.R., Plafker, G., 1988. Late Cenozoic offsets on the offshore connection between the Fairweather and Queen Charlotte faults off southeast Alaska. Mar. Geol. 85, 89–97.
Cassaigneau, C., 1979, Contribution à l'étude des structures Inde-Eurasie. La zone de suture de Khost dans le Sud-Est de l'Afghanistan, l'obduction Paléocène et la tectonique Tertiaire, PhD-thesis, 124: Université des Sciences et Techniques du Languedoc, Montpellier.
Chaubey, A.K., Dyment, J., Bhattacharya, G.C., Royer, J.Y., Srinivas, K., Yatheesh, V., 2002. Paleogene magnetic isochrons and palaeo-propagators in the Arabian and Eastern Somali basins, NW Indian Ocean. In: Clift, P.D., Croon, D., Gaedicke, C., Craig, J. (Eds.), The Tectonic and Climatic Evolution of the Arabian Sea Region. Geological Society, London, Special Publication 195, 71–85.
Cochran, J.R., 1988. Somali Basin, Chain Ridge, and origin of the northern Somali Basin gravity and geoid low. J. Geophys. Res. 93, 11985–12008.
Coffin, M.F., Pringle, M.S., Duncan, R.A., Gladczenko, T.P., Storey, M., Müller, R.D., Gahagan, L.A., 2002. Kerguelen Hotspot magma output since 130 Ma. J. Petrol. 43, 1121–1139.
Courtillot, V.E., Renne, P.R., 2003. On the ages of flood basalt events. Comptes Rendus Géoscience 335, 113–140.
DeMets, C., Merkouriev, S., 2016. High-resolution estimates of Nubia-Somalia plate motion since 20 Ma from reconstructions of the Southwest Indian Ridge, Red Sea and Gulf of Aden. Geophys. J. Int. 207, 317–322. https://doi.org/10.1093/gji/ggw276.
Dilek, Y., Furnes, H., 2014. Ophiolites and their origins. Elements 10, 93–100.
Dyment, J., 1998. Evolution of the Carlsberg Ridge between 60 and 45 Ma: Ridge propagation, spreading asymmetry, and the Deccan-Reunion hotspot. J. Geophys. Res. 103, 24067–24084. https://doi.org/10.1029/98JB01759.
Eagles, G., Hoang, H.H., 2014. Cretaceous to present kinematics of the Indian, African and Seychelles plates. Geophys. J. Int. 196, 1–14.
Edwards, R.A., Minshull, T.A., White, R.S., 2000. Extension across the Indian-Arabian plate boundary: the Murray Ridge. Geophys. J. Int. 142, 461–477.
Ellouz Zimmermann, N. et al., 2007, Offshore frontal part of the Makran accretionary prism (Pakistan) the Chamak Survey. In: Thrust Belts and Foreland Basins: From Fold Kinematics to Hydrocarbon Systems, edited by O. L. Lacombe et al., pp. 349–364, Springer, Berlin.
Faccenna, C., Becker, T.W., Conrad, C.P., Husson, L., 2013. Mountain building and mantle dynamics. Tectonics 32, 80–93. https://doi.org/10.1029/2012TC003176.
Filbrandt, J.B., Al-Dhahab, S., Al-Habsy, A., Harris, K., Keating, J., Al-Mahruqi, S., Ozkaya, S.I., Richard, P.D., Robertson, T., 2006. Kinematic interpretation and structural evolution of North Oman, Block 6, since the Late Cretaceous and implications for timing of hydrocarbon migration into Cretaceous reservoirs. GeoArabia 11, 97–140.
Fournier, M., Chamot-Rooke, N., Petit, C., Fabbri, O., Huchon, P., Maillot, B., Lepvrier, C., 2008b. In-situ evidence for dextral active motion at the Arabia-India plate boundary. Nat. Geosci. 1, 54–58. https://doi.org/10.1038/ngeo.2007.24.
Fournier, M., Petit, C., Chamot-Rooke, N., Fabbri, O., Huchon, P., Maillot, B., Lepvrier, C., 2008a. Do ridge-ridge-fault triple junctions exist on Earth? Evidence from the Aden-Owen-Carlsberg junction in the NW Indian Ocean. Basin Res. 20, 575–590. https://doi.org/10.1111/j.1365-2117.2008.00356.x.
Fournier, M., Chamot-Rooke, N., Petit, C., Huchon, P., Al-Kathiri, A., Audin, L., Beslier, M.-O., d'Acremont, E., Fabbri, O., Fleury, J.-M., Khanbari, K., Lepvrier, C., Leroy, S., Maillot, B., Merkouriev, S., 2010. Arabia-Somalia plate kinematics, evolution of the Aden-Owen-Carlsberg triple junction, and opening of the Gulf of Aden. J. Geophys. Res. 115, B04102. https://doi.org/10.1029/2008JB006257.
Fournier, M., Chamot-Rooke, N., Rodriguez, M., Huchon, P., Petit, C., Beslier, M.-O., Zaragosi, S., 2011. Owen fracture zone: the Arabia-India plate boundary unveiled. Earth Planet. Sci. Lett. 302, 247–252. https://doi.org/10.1016/j.epsl.2010.12.027.
Frizon de Lamotte, D., Raulin, C., Mouchot, N., Wrobel-Daveau, J.-C., Blanpied, C., Ringenbach, J.-C., 2011. The southernmost margin of the Tethys realm during the Mesozoic and Cenozoic: initial geometry and timing of the inversion processes. Tectonics 30, TC3002, 10.1029/2010TC002691.
Gaina, C., van Hinsbergen, D.J.J., Spakman, W., 2015. Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography. Tectonics 34, 875–906. https://doi.org/10.1002/2014TC003780.
Gibbons, A.D., Whittaker, J.M., Müller, R.D., 2013. The breakup of East Gondwana: assimilating constraints from Cretaceous ocean basins around India into a best-fit tectonic model. J. Geophys. Res. Solid Earth 118. https://doi.org/10.1002/jgrb.50079.
Gibbons, A.D., Zahirovic, S., Müller, R.D., Whittaker, J.M., Yateesh, V., 2015. A tectonic model reconciling evidence for the collisions between India, Eurasia and intra-oceanic arcs of the central-eastern Tethys. Gondwana Res. 28, 451–492.
Glennie, K.W., Boeuf, M.G.A., Hughes-Clark, M.W., Moody-Stuart, M., Pilar, W.F.H., Reinhardt, B.M., 1974. Geology of the Oman Mountains: Verh. K. Ned. Geol. Mijnbouwkd. Genoot. Ged. 31, 1–423.
Gnos, E., Khan, M., Mahmood, K., Khan, A. S., Shafique, N. A., and Villa, I. M., 1998, Bela oceanic lithosphere assemblage and its relation to the Réunion hotspot: Terra Nova 10, 90–95.
Gnos, E., Perrin, M., 1997. Formation and evolution of the Masirah ophiolite constrained by paleomagnetic study of volcanic rocks. Tectonophysics 253, 53–64.
Gnos, E., Peters, T., 2003. Mantle xenolith-bearing Maastrichtian to Tertiary alkaline magmatism in Oman. Geochem. Geophys. Geosyst. 4, 8620.
Gnos, E., Immenhauser, A., Peters, Tj, 1997. Late Cretaceous/early tertiary convergence between the Indian and Arabian plates recorded in ophiolites and related sediments. Tectonophysics 271, 1–19.
Guilmette, C., Smit, M.A., van Hinsbergen, D.J.J., Gürer, D., Corfu, F., Charette, B., Maffione, M., Rabeau, O., Savard, D., 2018. Forced subduction initiation recorded in the sole and crust of the Semail Ophiolite of Oman. Nat. Geosci. 11, 688–695. https://doi.org/10.1038/s41561-018-0209-2.
Hacker, B.R., Mosenfelder, J.L., Gnos, E., 1996. Rapid emplacement of the Oman ophiolite: thermal and geochronologic constraints. Tectonics 15, 1230–1247.
Hébert, R., Bezard, R., Guilmette, C., Dostal, J., Wang, C.S., Liu, Z.F., 2012. The Indus-Yarlung Zangbo ophiolites from Nanga Parbat to Namche Barwa syntaxes, southern Tibet: first synthesis of petrology, geochemistry, and geochronology with evidences on geodynamic reconstructions of Neo-Tethys. Gondwana Res. 22, 377–397.
Hooper, P., Widdowson, M., Kelley, S., 2010. Tectonic setting and timing of the final Deccan flood basalt eruptions. Geology 38, 839–842.
Hubert-Ferrari, A., King, G., van der Woerd, J., Villa, I., Altunel, E., Armijo, R., 2009. Long term evolution of the North Anatolian Fault: new constraints from its eastern termination. From: VAN HINSBERGEN, D. J. J., EDWARDS, M. A. & GOVERS, R. (eds) Collision and Collapse at the Africa–Arabia–Eurasia Subduction Zone. The Geological Society, London, Special Publications, 311, 133–154. 10.1144/SP311.5.
Hutchison, I., Louden, K.E., White, R.S., von Herzen, R.P., 1981. Heat flow and age of the Gulf of Oman. Earth Planet. Sci. Lett. 56, 252–262.
Immenhauser, A., 1996. Cretaceous sedimentary rocks on the Masirah Ophiolite (Sultanate of Oman): evidence for an unusual bathymetric history. J. Geol. Soc. London 153, 539–551.
Immenhauser, A., Schreurs, G., Gnos, E., Oterdoom, H.W., Hartmann, B., 2000. Late Palaeozoic to Neogene geodynamic evolution of the northeastern Oman margin. Geol. Mag. 137, 1–18.
Jagoutz, O., Royden, L., Holt, A., Becker, T., 2015. Anomalously fast convergence of India and Eurasia caused by double subduction. Nat. Geosci. 8, 475–478.
Jolivet, L., Faccenna, C., Agard, P., Frizon de Lamotte, D., Menant, A., Sternai, P.,

Guillocheau, F., 2016. Neo-Tethys geodynamics and mantle convection: from extension to compression in Africa and a conceptual model for obduction. Can. J. Earth Sci. 53, 1190–1204.
Kakar, M.I., Kerr, A.C., Mahmood, K., Collins, A.S., Khan, M., McDonald, I., 2014. Supra-subduction zone tectonic setting of the Muslim Bagh ophiolite, north-western Pakistan: insights from geochemistry and petrology. Lithos 202–203, 190–206.
Khan, S.D., Mahmood, K., Casey, J.F., 2007. Mapping of Muslim Bagh ophiolite complex (Pakistan) using new remote sensing and field data. J. Asian Earth Sci. 30, 333–343.
Kukowski, N., Schillhorn, T., Huhn, K., von Rad, U., Husen, S., Flueh, E.R., 2001. Morphotectonics and mechanics of the central Makran accretionary wedge off Pakistan. Mar. Geol. 173, 1–19.
Le Pichon, X., Sengor, A.M.C., Kende, J., Imren, C., Henry, P., Grall, C., Karabulut, H., 2016. Propagation of a strike-slip plate boundary within an extensional environment: the westward propagation of the North Anatolian Fault. Can. J. Earth Sci. 53, 1416–1439. https://doi.org/10.1139/cjes-2015-0129.
Ligi, M., Bonatti, E., Gasperini, L., Poliakov, A.N.B., 2002. Oceanic broad multifault transform plate boundaries. Geology 30, 11–14. https://doi.org/10.1130/0091-7613(2002)030 < 0011:OBMTPB > 2.0.CO;2.
Mahanjane, E.S., 2014. The Davie Fracture Zone and adjacent basins in the offshore Mozambique Margin-A new insights for the hydrocarbon potential. Mar. Pet. Geol. 57, 561–571.
Mahmood, K., Boudier, F., Gnos, E., Monié, P., Nicolas, A., 1995. 40Ar/39Ar dating of the emplacement of the Muslim Bagh ophiolite, Pakistan. Tectonophysics 250, 169–181.
Mahoney, J.J., Duncan, R.A., Khan, W., Gnos, E., McCormick, G.R., 2002. Cretaceous volcanic rocks of the South Tethyan suture zone, Pakistan: implications for the Réunion hotspot and Deccan Traps. Earth Planet. Sci. Lett. 203, 295–310.
Maia, M., Sichel, S., Briais, A., Brunelli, D., Ligi, M., Ferreira, N., Campos, T., Mougel, B., Brehme, I., Hémond, C., Motoki, A., Moura, D., Scalabrin, C., Pessanha, I., Alves, E., Ayes, A., Oliveira, P., 2016. Extreme mantle uplift and exhumation along a transpressive transform fault, Nat. Geosci. 10.1038/NGEO2759/.
Maia, M., 2018. Topographic and morphologic evidences of deformation at oceanic transform faults: far-field and local field stress. In: Duarte, J. (Ed.), Transform Plate Boundaries and Fracture Zones, pp. 61–87. https://doi.org/10.1016/B978-0-12-812064-4.00003-7.
Matthews, K.J., Seton, M., Müller, R., 2012. A global-scale plate reorganization event at 105–100 Ma. Earth Planet. Sci. Lett. 355–356, 283–298.
Matthews, K.J., Müller, R.D., Sandwell, D.T., 2015. Oceanic microplate formation records the onset of India-Eurasia collision. Earth Planet. Sci. Lett. 433, 204–214. https://doi.org/10.1016/j.epsl.2015.10.040.
Matthews, K.J., Maloney, K.T., Zahirovic, S., Williams, S.E., Seton, M., Müller, D.R., 2016. Global plate boundary evolution and kinematics since the late Paleozoic. Global Planet. Change 146, 226–250.
McCall, G.J.H., 1997. The geotectonic history of the Makran and adjacent areas of southern Iran. J. Asian Earth Sci. 15, 517–531.
Meckel, T.A., Coffin, M.F., Mosher, S., Symonds, P., Bernadel, G., Mann, P., 2003. Underthrusting at the Hjort Trench, Australian-Pacific plate boundary: incipient subduction? Geochem. Geophys. Geosyst. 12. https://doi.org/10.1029/2002GC000498.
Minshull, T.A., Lane, C., Collier, J.S., Whitmarsh, R., 2008. The relationship between rifting and magmatism in the northeastern Arabian Sea. Nat. Geosci. 1, 463–467. https://doi.org/10.1038/ngeo228.
Molnar, P., Stock, J., 2009. Slowing of India's convergence with Eurasia since 20 Ma and its implications for Tibetan mantle dynamics. Tectonics 28, TC3001, 10.1029/2008TC002271 MORRIS 2017.
Mouchot, N., 2009. Tectonique et sédimentation sur le complexe de subduction du Makran pakistanais. PhD thesis. Univ. Cergy Pontoise, 208 pp.
Mountain, G.S., Prell, W.L., 1990. A multiphase plate tectonic history of the southeast continental margin of Oman, The Geology and Tectonics of the Oman Region, edited by Robertson, A. H. F., Searle, M. P. Ries, A. C. Geological Society Special Publication 49, 725–743.
Müller, R.D., Seton, M., Zahirovic, S., Williams, S.E., Matthews, K.J., Wright, N.M., Shepard, G.E., Maloney, K.T., Barnett-Moore, N., Hosseinpur, M., Bower, D.J., Cannon, J., 2016. Ocean Basin evolution and global-scale plate reorganization events since Pangea Breakup. Annu. Rev. Earth Planet. Sci. 44, 107–138. https://doi.org/10.1146/annurev-earth-060115-012211.
Nicolas, A., Boudier, F., 2017. Emplacement of Semail-Emirates ophiolite at ridge-trench collision. Terra Nova 29, 127–134.
Norton, I.O., Sclater, J.G., 1979. A model for the evolution of the Indian Ocean and the break-up of Gondwanaland. J. Geophys. Res. 84, 6803–6830.
Patriat, P., Achache, J., 1984. India-Eurasia collision chronology has implications for crustal shortening and driving mechanism of plate. Nature 311, 615–621.
Peters, Tj, Mercolli, I., 1998. Extremely thin oceanic crust in the Proto-Indian Ocean: evidence from the Masirah Ophiolte, Sultanate of Oman. J. Geophys. Res. 103, 677–689.
Platel, J.P., Berthiaux, A., Le Métour, J., Beurrier, M., Roger, J., 1992. Geological map of Duqm and Madraka, Sultanate of Oman, sheet NE 40-03/07, scale 1: 250000, Oman Minist. of Pet. and Miner., Dir. Gen. of Miner., Muscat.
Pubellier, M., Bader, A.G., Rangin, C., Deffontaines, B., Quebral, R., 1999. Upper plate deformation induced by subduction of a volcanic arc: the Snellius Plateau (Molluca Sea, Indonesia and Mindanao, Philippines). Tectonophysics 304, 345–368.
Ravaut, P., Bayer, R., Hassani, R., Rousset, P., Al-Yahya-ey, A., 1997, Structure and evolution of the northern Oman margin; gravity and seismic constraints over the Zagros-Makran-Oman collision zone: Tectonophysics 279, 253–280.
Ravaut, P., Carbon, D., Ritz, J.F., Bayer, R., Philip, H., 1998. The Sohar Basin, Western Gulf of Oman: description and mechanisms of formation from seismic and gravity data. Mar. Pet. Geol. 15, 359–377.
Robinet, J., Razin, P., Serra-Kiel, J., Gallardo-Garcia, A., Leroy, S., Roger, J., Grelaud, C., 2013. The Paleogene pre-rift to syn-rift succession in the Dhofar margin (northeastern gulf of Aden): stratigraphy and depositional environments. Tectonophysics 607, 1–16.
Rodriguez, M., Fournier, M., Chamot-Rooke, N., Huchon, P., Bourget, J., Sorbier, M., Zaragosi, S., Rabaute, A., 2011. Neotectonics of the Owen Fracture Zone (NW Indian Ocean): structural evolution of an oceanic strike-slip plate boundary. Geochem. Geophys. Geosyst. 12. https://doi.org/10.1029/2011GC003731.
Rodriguez, M., Chamot-Rooke, N., Fournier, M., Huchon, P., Delescluse, M., 2013. Mode of opening of an oceanic pull-apart: The 20 °N Basin along the Owen Fracture Zone (NW Indian Ocean). Tectonics 32, 1–15. https://doi.org/10.1002/tect.20083.
Rodriguez, M., Chamot-Rooke, N., Huchon, P., Fournier, M., Lallemant, S., Delescluse, M., Zaragosi, S., Mouchot, N., 2014b. Tectonics of the Dalrymple Trough and uplift of the Murray Ridge (NW Indian Ocean). Tectonophysics 636, 1–17. https://doi.org/10.1016/j.tecto.2014.08.001.
Rodriguez, M., Chamot-Rooke, N., Huchon, P., Fournier, M., Delescluse, M., 2014a. The Owen Ridge uplift in the Arabian Sea: implications for the sedimentary record of Indian monsoon in Late Miocene. Earth Planet. Sci. Lett. 394, 1–12. https://doi.org/10.1016/j.epsl.2014.03.011.
Rodriguez, M., Huchon, P., Chamot-Rooke, N., Fournier, M., Delescluse, M., François, T., 2016. Tracking the Paleogene India-Arabia plate boundary. Mar. Pet. Geol. 72, 336–358. https://doi.org/10.1016/j.marpetgeo.2016.02.019.
Rodriguez, M., Fournier, M., Chamot-Rooke, N., Huchon, P., Delescluse, M., 2018. The geological evolution of the Aden-Owen-Carlsberg triple junction (NW Indian Ocean) since the Late Miocene. Tectonics 37, 1552–1575. https://doi.org/10.1029/2017TC004687.
Rohr, K.M.M., 2015. Plate boundary adjustments of the southernmost queen charlotte fault. Bull. Seismol. Soc. Am. 105. https://doi.org/10.1785/0120140162.
Royer, J.Y., Chaubey, A.K., Dyment, J., Bhattacharya, G.C., Srinivas, K., Yateesh, V., Ramprasad, T., 2002. Paelogene plate tectonic evolution of the Arabian and Eastern Somali basins, in The Tectonic and Climatic Evolution of the Arabian Sea Region, edited by P. D. Clift et al. Geol. Soc. Spec. Pub. 195, 7–23.
Sarwar, G., 1992. Tectonic setting of the Bela Ophiolites, southern Pakistan. Tectonophysics 207, 359–381.
Schlich, R., 1982. The Indian Ocean: aseismic Ridges, spreading centres and basins. In: Nairn, A.E.M., Stehli, F.G. (Eds.), The Ocean Basins and Margins. Plenum Press, New York, pp. 51–147.
Schreurs, G., Immenhauser, A., 1999. West-northwest-directed obduction of the Batain group on the eastern Oman continental margin at the Cretaceous-Tertiary boundary. Tectonics 18, 148–160.
Searle, M., Cox, J., 1999. Tectonic setting, origin, and obduction of the Oman ophiolite. Geol. Soc. Am. Bull. 111, 104–122.
Searle, M.P., Noble, S.R., Cottle, J.M., Waters, D.J., Mitchell, A.H.G., Tin Hlaing, Horstwood, M.S.A., 2007. Tectonic evolution of the Mogok metamorphic belt, Burma (Myanmar) constrained by U-Th-Pb dating of metamorphicand magmatic rocks. Tectonics 26, TC3014, 10.1029/2006TC002083.
Seton, M., Müller, R.D., Zahirovic, S., Gaina, C., Torsvik, T., Shepard, G., Talsma, A., Gurnis, M., Turner, M., Maus, S., Chandler, M., 2012. Global continental and ocean basin reconstructions since 200 Ma. Earth Sci. Rev. 113, 212–270. https://doi.org/10.1016/j.earscirev.2012.03.002.
Shackleton, R.M., Ries, A.C., 1990. Tectonics of the Masirah Fault Zone and eastern Oman. Geol. Soc. Lond. Special Publications 49 (1), 715–724.
Shipboard Scientific Party 1989, Site 731. In: Prell, W.L., Niitsuma, N., et al. (Eds.), Proc. ODP, Init.Repts., 117. College Station, TX (Ocean Drilling Program).
Shipboard Scientific Party, 1974a. Site 235, In: Fisher, R.L., Bunce, E.T. et al., DSDP Init. Repts, leg 24. 10.2973/dsdp.proc.24.1974.
Shipboard Scientific Party 1974b, Site 222. In: Whitmarsh, R.B., Weser, O.E., Ross, D.A. (Eds.), DSDP Init. Repts, leg 23 10.2973/dsdp.proc.23.106.
Shuhail, M., Yateesh, V., Bhattacharya, G.C., Müller, R.D., Kamesh Raju, K.A., Mahender, K., 2018. Formation and evolution of the Chain-Kairali escarpment and the Vishnu Fracture Zone in the Western Indian Ocean. J. Asian Earth Sci. 164, 307–321. https://doi.org/10.1016/j.jseaes.2018.06.022.
Smit, J., Brun, J.-P., Cloething, S., Ben Avraham, Z., 2010. The rift like structure and asymmetry of the Dead Sea Fault. Earth Planet. Sci. Lett. 290, 74–82.
Socquet, A., Pubellier, M., 2005. Cenozoic deformation in Western Yunnan (China-Myanmar border). J. Asian Earth Sci. 24, 495–511.
Tapponnier, P., Mattauer, M., Proust, F., Cassaigneau, C., 1981. Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan. Earth Planet. Sci. Lett. 52, 355–371.
Tréhu, A.M., Scheidhauer, M., Rohr, K.M.M., Tikoff, B., Walton, M.A., Gulick, S.P.S., Roland, E., 2015. An abrupt transition in the mechanical response of the upper crust to transpression along the Queen Charlotte Fault. Bull. Seismol. Soc. Am. 105. https://doi.org/10.1785/0120159.
Treolar, P.J., Izatt, C.N., 1993. Tectonics of the Himalayan collision between the Indian Plate and the Afghan Block: a synthesis. Geol. Soc. Spec. Pub. 74, 69–87.
van Hinsbergen, D.J.J., Steinberger, B., Doubrovine, P.V., Gassmöller, R., 2011. Acceleration and deceleration of India-Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. J. Geophys. Res. 116, B06101. https://doi.org/10.1029/2010JB0085051.
van Hinsbergen, D.J.J., Lippert, P.C., Dupont-Nivet, G., McQuarrie, N., Doubrovine, P.V.,

Spakman, W., Torsvik, T.H., 2012. Greater India Basin hypothesis and a two-stage Cenozoic collision between India and Asia. Proc. Natl. Acad. Sci. 109, 7659–7664.
Wajzer, M.R., Barber, A.J., Hidayat, S., Suharsono, S., 1991. Accretion, collision and strike-slip faulting: the Woyla group as a key to the tectonic evolution of North Sumatra. J. SE Asian Earth Sci. 6, 447–461.
Wakabayashi, J., Dilek, Y., 2003. What constitutes 'emplacement' of an ophiolite? Mechanisms and relationship to subduction initiation and formation of metamorphic soles. Geol. Soc. Lond. Special Publ. 218, 427–447. https://doi.org/10.1144/GSL.SP.2003.218.01.22.
Wyns, R., Béchennec, F., Le Métour, J., Roger, J., Chevrel, S., 1992, Explanatory notes, Geological map of Sur, sheet NF 40-08, scale 1:250'000, Muscat, Sultanate of Oman, Ministry of Petroleum and Minerals, 1–103.
Yateesh, V., Bhattacharya, G.C., Dyment, J., 2009. Early oceanic opening off Western India-Pakistan margin: the Gop Basin revisited. Earth Planet. Sci. Lett. 284, 399–408.