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The Amirante Ridge and Trench System in the Indian Ocean: the southern termination of the NW Indian subduction

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The Amirante Ridge and Trench System in the Indian Ocean: the southern termination of the NW Indian subduction

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Abstract. The Amirante Ridge and Trench System forms a 600-km-long arcuate structure in the Mascarene Basin (Indian Ocean), whose origin remains enigmatic. Here, I provide a paleogeographic reconstruction of the NW India margin for the Late Cretaceous–Paleocene interval, compiling information from ophiolites surrounding the Arabian Sea and data collected at sea. This reconstruction shows that the Amirante Ridge and Trench System constitutes the southern termination of a ~1500-km-long subduction, which used to run along the NW Indian margin during the Late Cretaceous–Paleocene. The dislocation of the NW Indian subduction, recorded at the Amirante Ridge and Trench System and the Bela ophiolites, may have played a role in the plate reorganization event recorded at 73–63 Ma.

1. Introduction

The Amirante Ridge and Trench System is located south of the Seychelles within the Mascarene Basin (Figure 1). It consists in a ~600-km-long, up to 5300-m-deep arcuate trench, flanked on its eastern side by a basaltic ridge, which supports some reef atolls [Johnson et al., 1982]. The Amirante Ridge and Trench System is still one of the most enigmatic features of the Indian Ocean, with various origins proposed so far, from an extinct plate boundary [Masson, 1984, Damuth and Johnson, 1989, Mart, 1988, Mukhopadhyay et al., 2013, Eagles and Hoang, 2014] to a remnant of a meteorite impact [Hartnady, 1986]. Although the hypothesis of a crater has been dismissed [Plummer, 1996], the nature and origin of the fossil plate boundary preserved at the Amirante Ridge and Trench System remain unclear [Damuth

and Johnson, 1989, Mukhopadhyay et al., 2013], as the structure ambiguously shares some morphological and structural characteristics of subduction zones [Johnson et al., 1982, Mart, 1988], transform faults [Plummer, 1996] and mid-oceanic ridges [Eagles and Hoang, 2014]. The age of basalts dredged at the Amirante Ridge spans the Late Cretaceous–Early Paleocene period [Fisher et al., 1968, Johnson et al., 1982], a period marked by drastic changes in the configuration of the Indian Ocean's plate boundaries (i.e. curvature of fracture zones at the SW Indian Ridge, Cande and Patriat, 2015; migration of the India–Africa transform boundary; Rodriguez et al., 2016, 2020; extinction of the Mascarene and East Somali Basin spreading centers and rifting between Seychelles and India; Gaina et al., 2015, Yatheesh, 2020).

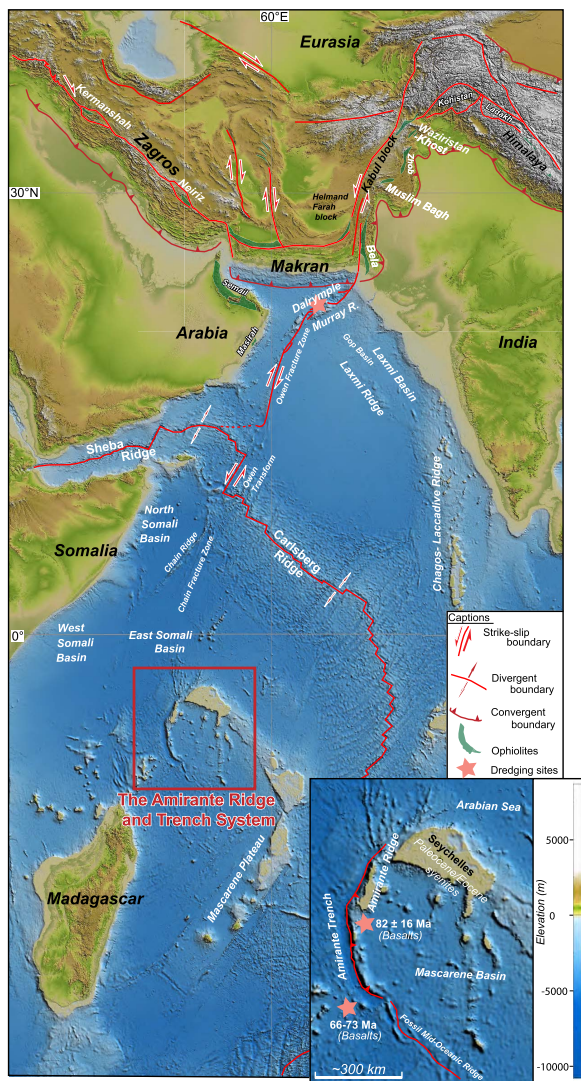The objective of this paper is to determine how

Figure 1. Topographic and structural map of the western Indian Ocean. The inset shows a close view of the Amirante Ridge and Trench System.

the Amirante Ridge and Trench System fits in the complex framework of the Indian Ocean's fabric during the Late Cretaceous–Early Paleocene interval in order to unravel its tectonic origin. I provide a comprehensive paleogeographic reconstruction of the NW Indian Ocean from the Late Cretaceous to the Early Paleocene (Figure 2), based on magnetic anomalies recorded in the oceanic basins [Dyment, 1993, 1998, Bernard and Munschy, 2000, Royer et al., 2002, Chaubey et al., 2002, Yatheesh, 2020] and the distribution of ophiolites surrounding the Arabian

Sea [Gnos et al., 1998, Mahoney et al., 2002, Khan et al., 007b,a, Kakar et al., 2012, 2014, Siddiqui and Ma, 2017]. I show that prior to the eruption of the Deccan Traps and India–Seychelles breakup circa 65 Ma [Yatheesh et al., 2009, Calv ès et al., 2011], the Amirante Ridge and Trench System was in line with a ~1500-km-long subduction zone running along NW India, nowadays preserved in the ophiolites running from Bela to Waziristan in Pakistan (Figure 1). I finally propose that the Amirante Ridge and Trench System constitutes the southern termination of the NW India subduction zone and discuss the implications for the evolution of the NW India passive margin during the India–Seychelles breakup episode and prior to the India–Eurasia continental collision.

2. Geological background

2.1. *Opening of the NW Indian Ocean*

The opening of the NW Indian Ocean results from the fragmentation of Gondwana since the Late Jurassic [McKenzie and Sclater, 1971, Norton and Sclater, 1979, Schlich, 1982, Besse and Courtillot, 1988], in response to complex interactions between subduction zones and mantle plumes [Coltice et al., 2009, Gaina et al., 2013, Matthews et al., 2012], which led to the separation of the India–Seychelles–Madagascar block from Africa and Australia [Gibbons et al., 2013]. The initiation of the Southern Neotethys Subduction documented around 110–105 Ma from metamorphic soles of the related ophiolites [Guilmette et al., 2018, Pourteau et al., 2018] drove the India's drift toward Eurasia, while the Marion and Deccan plumes acted as rheological facilitators over the breakup of the Madagascar–Seychelles–India continent [Torsvik et al., 2000, Minshull et al., 2008, van Hinsbergen et al., 2011], which occurred in three major steps (see paleogeographic reconstructions of McKenzie and Sclater, 1971, Norton and Sclater, 1979, Schlich, 1982, Calv ès et al., 2011, Gaina et al., 2015, Yatheesh et al., 2019, Yatheesh, 2020).

First, the ophiolites scattered from Bela to Waziristan in Pakistan [Tapponnier et al., 1981] testifies that a mid-oceanic ridge separated the Kabul block from NW India during Albian–Senonian (Figure 2; Gnos and Perrin, 1997, Gaina et al., 2015).

Second, the opening of the Mascarene and the East Somali Basins records the Late Cretaceous
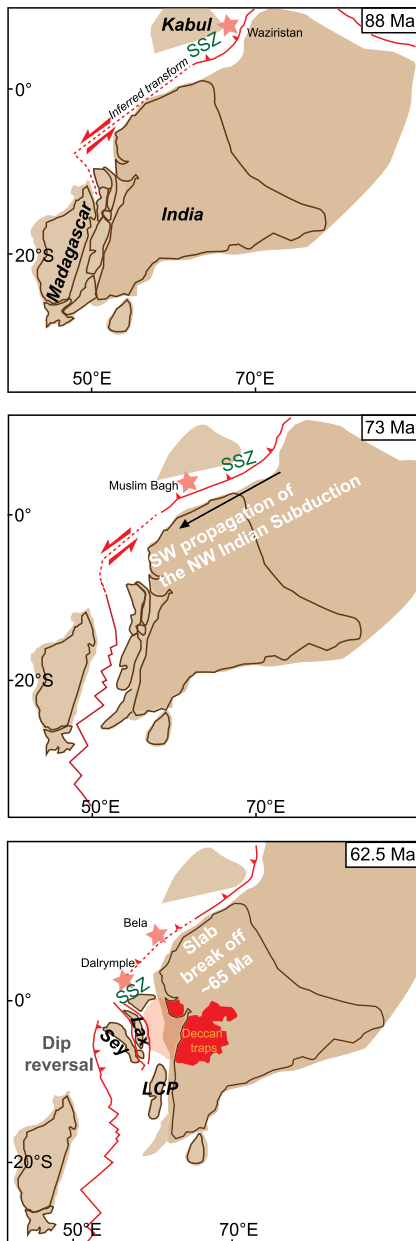
Figure 2. Paleogeographic reconstructions of the NW Indian Ocean during the Late Cretaceous–Early Paleocene interval, with a particular emphasis over the evolution of the NW Indian Subduction. The position of India, Madagascar, and the continental blocks formed during the India–Seychelles breakup is derived from Yatheesh [2020]. Lax: Laxmi Ridge; LCP: Laccadive Plateau; Sey: Seychelles; SSZ: supra-subduction zone.

breakup between Madagascar and the India–Laxmi–Seychelles continental blocks (Figure 2; Schlich, 1982, Bernard and Munschy, 2000, Calvès et al., 2011, Gibbons et al., 2013, 2015, Bhattacharya and Yatheesh, 2015, Shuhail et al., 2018).

Third, the breakup between the Seychelles–Laxmi block and India formed the Gop Basin (between magnetic chrons 31 (68 Ma) and 30 (67 Ma; Minshull et al., 2008, Yatheesh et al., 2009). Following the culmination of the Deccan trap volcanism at ~65.5 Ma [Courtillot and Renne, 2003, Hooper et al., 2010, Verma and Khosla, 2019], the rifting migrated between the Laxmi Ridge and the Seychelles block (Figure 2) and led to the formation of the Carlsberg mid-oceanic ridge since chron 28 (63 Ma) [Dyment, 1998, Chaubey et al., 2002, Royer et al., 2002].

2.2. *The Amirante Ridge and Trench System: geological observations*

The Amirante Ridge and Trench puzzle only relies on a few ground-truth geological constraints. The Amirante Ridge is capped by tholeiitic basalts, dated at 82 ± 16 Ma according to K/Ar method [Fisher et al., 1968]. This age reflects the formation of the oceanic lithosphere exposed at the Amirante Ridge, but does not necessarily indicate the age of uplift of the ridge. Pelagic chalk cored at the Amirante Passage, located at the southwestern termination of the Amirante Trench, gives a minimum age of 73–66 Ma [Masson, 1984, Johnson et al., 1982]. Ponded turbidites, mass transport deposits, and pelagic sediments filled in the Amirante Trench [Masson, 1984]. There, the sedimentary record does not reveal any major tectonic deformation, which makes the tectonic origin of the system difficult to decipher. The Seychelles Island displays some calcalkaline dolerite dykes and syenite batholiths, formed until 50–46 Ma [Mart, 1988].

2.3. *Previous interpretations of the Amirante Ridge and Trench System*

The presence of a trench on the seafloor morphology (Figure 1), together with the calcalkaline lavas at the Seychelles suggest that the Amirante Ridge and Trench System may correspond to a fossil sub-

duction zone, as initially proposed by Fisher et al. [1968]. However, the geochemistry of basalts dredged at the Amirante Ridge itself does not reflect the influence of a subduction (Mid-Oceanic Ridge Basalt signature, Mart, 1988). The free-air gravity field of the Amirante Ridge and Trench System can be reproduced by considering only a very limited length of the slab, no more than 100 km [Miles, 1982]. The lack of deformation within the trench does not necessarily rule out the interpretation as a subduction zone, as numerous subduction zones do not display any accretionary wedge. Moreover, the sedimentation rates were quite low during the Late Cretaceous–Paleocene in the NW Indian Ocean (mainly pelagic sediments, Shipboard Scientific Party, 1989, Rodriguez et al., 2016), or poorly preserved since then [Willenbring and von Blackenburg, 2010], making the record of tectonic events difficult.

As a result, the Amirante Ridge and Trench System is either interpreted as a remnant of a subduction segment, which did not consume an important amount of oceanic lithosphere [Miles, 1982], or a mixed system of mid-oceanic ridge and transform fault surrounding the Seychelles microplate [Damuth and Johnson, 1989, Plummer, 1996], which was formed during its isolation from India subsequent to the underplating of the Deccan plume [Eagles and Hoang, 2014]. Rotation of microplates may indeed induce local compression or extension leading to formation of structures comparable to the Amirante Ridge and Trench System [Hey, 2004, Matthews et al., 2015]. However, the rotation of such microplates affects the fabric of the surrounding oceanic lithosphere (e.g. rotation of nearby ridges), which is not observed in the vicinity of the Amirante System for the Late Cretaceous fabric [Bernard and Munschy, 2000]. Yet, the interpretation of the Amirante Ridge and Trench System as a subduction zone suffers from the difficulty to determine how a 600-km-long subduction initiated south of the Seychelles during the Late Cretaceous, coeval with the rifting and oceanic accretion episodes that contributed to the fragmentation of the India–Seychelles–Madagascar block.

3. Reconstructions of NW India Margins during the Late Cretaceous–Paleocene

The basin that used to be located between the NW Indian margin and the Kabul block (Figure 2) has been subducted during the Late Cretaceous–Early Paleocene interval, giving birth to a series of ophiolites including, from North to South, the Waziristan-Kost, Zhob, Muslim Bagh, and Bela ophiolites (Figure 1). The slab penetrated down to at least ~1000 km depth in the mantle, according to tomography [Gaina et al., 2015]. The obduction of eastern Pakistan ophiolites initiated around 70–65 Ma, prior to the onset of the Deccan traps, and ended no later than 55 Ma, according to the dating of the carbonate platform that sealed the ophiolites [Beck et al., 1995] and detrital remnants of these ophiolites encountered in the earliest Indus River sediments [Zhuang et al., 2015].

Most of these ophiolites display metamorphic soles at their base. Metamorphic soles correspond to thin metamorphosed tectonic slivers detached from the downgoing plate during the first few million years of intra-oceanic subduction [Agard et al., 2018]. The dating of the amphibolite facies of the metamorphic soles provides clues over the timing of subduction initiation. In addition, most of these ophiolites display a supra-subduction zone signature, with sometimes traces of Oceanic Island Basalts corresponding to a pre-Deccan plume [Mahoney et al., 2002]. Supra-subduction zone basins correspond to the oceanic lithosphere accreted in the upper plate, at the corner of the subduction interface. These basins are generally composed of Mid-Oceanic Ridge Basalts, marked by a negative Nb and Ta anomaly in rare-earth elements patterns. The direction of thrusting of the ophiolites can be deciphered from the related structures. This set of observations constrains the vergence of the subduction zone.

Here, we provide an update of the detailed reconstructions of the India–Seychelles breakup based on magnetic anomalies of the seafloor and seismic profile analysis [Dyment, 1998, Chaubey et al., 2002, Calvès et al., 2011, Yatheesh, 2020], which includes the configuration of the NW India subduction deduced from the ophiolite record (Figure 2). We do not address the problem of the shape of Greater India and choose a configuration where the entire India is composed of continental lithosphere, with a northern passive margin of about 1000 km in length [Ali and Aitchison, 2008, Guillot et al., 2008], although alternatives may be considered [van Hinsbergen et al., 2012].

The amphibolite facies of the metamorphic soles document a series of ages of subduction initiation

(Figure 2) no later than 90 Ma at the latitude of the Waziristan ophiolite (K/Ar dating of the amphibolite facies; Gnos et al., 1998), 70.7 ± 5 Ma at the latitude of the Muslim Bagh ophiolite (amphibolite facies [Mahmood et al., 1995], and ~65 Ma at the latitude of the Bela Ophiolite (Ar/Ar dating of hornblende; Gnos et al., 1998). The accretion of the Muslim Bagh ophiolite started at 80 Ma from the dating of plagiogranites preserved in the sequence. Considering the supra-subduction origin of this basin would imply subduction initiation at this latitude around 80 Ma [Kakar et al., 2012]. The configuration of supra-subduction zone basins recorded between the Waziristan and Bela ophiolites suggests a northwestwards subduction of India beneath the plate supporting the Kabul block, with ophiolites thrusted over the Mesozoic Indian passive margin [Kakar et al., 2012]. The NW Indian subduction therefore propagated from north (Waziristan) to south over a period of ~30 Myrs and reached the area of India–Seychelles breakup around 73–63 Ma. A slab break-off event is recorded at Bela ophiolites around 70–65 Ma [Gnos et al., 1998].

In these reconstructions, the Amirante Ridge and Trench System is in line with the NW Indian subduction during the 73–63 Ma period. The configuration of the Amirante Ridge and Trench System is in agreement with a vergence of the subduction to the North East, that is, a subduction beneath the NW Indian margin.

The maturation of the Gop Basin and the accretion of oceanic lithosphere within the East Somali Basin from 73 to 68 Ma [Gaina et al., 2015] are coeval with the slab break-off event and mark the disconnection of the Amirante Ridge and Trench System from the segment of the subduction nowadays preserved in the Eastern Pakistan ophiolites. The Amirante segment of the subduction remained active until the Eocene, feeding the calkalkaline volcanism of the Seychelles [Mart, 1988], while a subduction segment remained active until 55 Ma at the suture zone marked by eastern Pakistan ophiolites.

In this framework, the Dalrymple Trough and the Murray Ridge (Figure 1) are located at the transition between the NW and NE dipping subduction. The present-day configuration of the Dalrymple Trough and the Murray Ridge results from a series of Late Miocene–Early Pleistocene tectonic events related to the structural evolution of the India–Arabia plate boundary (i.e. the Owen Fracture Zone, Rodriguez

et al., 2014, 2018). This series of vertical motions of the lithosphere opened a window to the lithospheric mantle. Peridotites dredged at the Murray Ridge–Dalrymple Trough reveal a supra-subduction signature [Burgath et al., 2002]. The area of the Dalrymple Trough and the Murray Ridge consists in a thinned continental lithosphere [Minshull et al., 2015], commonly attached to the segment of the Indian margin formed during the Late Jurassic–Early Cretaceous opening of the Western Somali Basin [Calv ès et al., 2011, Minshull et al., 2015]. In this configuration, the supra-subduction signature of the peridotites dredged at Murray Ridge records the NE dip of the subduction. An alternative would be to consider that the area of the Dalrymple Trough derives from the Kabul Terrane, accreted to India since Paleocene [Tapponnier et al., 1981]. In this case, the supra-subduction zone preserved there is in line with the supra-subduction domains marking the NW dip of the subduction.

4. Discussion

4.1. *The nature of the Amirante Ridge and Trench System*

The paleogeographic reconstructions (Figure 2) suggest that the Amirante Ridge and Trench System is the southern termination of more than 1500-km-long subduction that used to run along NW India. However, several alternative interpretations remain for the precise nature of the Amirante Ridge and Trench System. The source of the uncertainties relies in (1) the lack of documentation of the potential supra-subduction zone signature of the Amirante Ridge, which makes difficult to discriminate if it is related to a subduction zone or another type of plate boundary; (2) the lack of the precise dating of the formation of the Amirante Ridge and Trench System; (3) the difficulty to decipher the nature of the connection between the Mascarenes spreading center and the NW Indian subduction.

Ramana et al. [2015] suggest that a major transform was running along India and Seychelles prior to their breakup, hence acting as a boundary with the plate supporting the Kabul block, which connected the Mascarenes spreading center to the NW Indian subduction (Figure 2). Such a transform could have progressively turned into a subduction during

the southwestwards propagation documented in the metamorphic soles of the Pakistan ophiolites (Figure 2).

If the formation of the Amirante Ridge and Trench System pre-dates the dislocation of the NW Indian Subduction documented around 73–68 Ma, then the Amirante Trench probably reflects a short subduction zone segment connecting the transform proposed by Ramana et al. [2015] and the Mascarenes spreading center, similar to the present-day configuration of the Hjort trench and ridge system at the Pacific–Australia boundary [Meckel et al., 2003]. In this case, the transform connects two subduction zones: the subduction at the Amirante System and the NW Indian Subduction. The transform progressively vanishes as the NW subduction propagates southwestwards. This interpretation goes along with a mixed transform and subduction origin for the Amirante Ridge and Trench.

If the formation of the Amirante Ridge and Trench system post-dates the dislocation of the NW Indian Subduction, then the dip reversal of the subduction in the Amirante area reflects the slab break-off event recorded at the Bela ophiolites around 65–70 Ma [Gnos et al., 1998]. Most of the ophiolites exposed between Bela and Waziristan display a Mid-Oceanic Ridge Basalt geochemical signature, in addition to some traces of Ocean Island Basalts due to interactions with the Deccan plume and Island Arc Basalts formed within the back-arc domain [Kakar et al., 2012, Siddiqui and Ma, 2017]. In this framework, the Amirante Ridge and its Mid-Oceanic Ridge Basalt signature may represent a natural example of the ridge formed during the earliest stages of an intra-oceanic subduction in thermo-mechanical models, prior to the full development of an obduction [Duretz et al., 2016].

4.2. *Relationships between the Amirante Ridge and Trench system and the Indian passive margin*

The segment of the NW Indian subduction zone running from Bela to the Amirante was dipping beneath the Indian margin. It explains the supra-subduction zone signature recognized at the Dalrymple Trough (Figure 2; Burgath et al., 2002), which used to be a distal part of the Indian passive margin [Edwards et al., 2000, 2008]. A supra-subduction zone signature has

been suggested as far as the Laxmi Ridge [Pandey et al., 2019], although many ambiguities need to be deciphered [Clift et al., 2020]. In our framework, the supra-subduction zone signature identified along the NW Indian margin at the Dalrymple Trough and Murray Ridge reflects the influence of the NW Indian Subduction, deactivated during the Paleocene–Eocene, instead of a subduction induced by the enhanced activity of the Deccan plume around 65 Ma, as proposed by Pandey et al. [2019].

4.3. *The Amirante Ridge and Trench system in the frame of the 73–63 Ma plate reorganization event*

During the 73–63 Ma interval, the Western Indian Ocean's plate boundaries experienced a series of drastic changes in their configuration, recorded by the ridge jump from the Mascarene Basin to the Gop Basin and the Carlsberg Ridge [Yatheesh, 2020], the curvature of fracture zone at the SW Indian Ridge [Cande and Patriat, 2015], and a major migration of the India–Africa transform boundary from Chain Ridge to the Chain Fracture Zone offshore Somalia [Rodriguez et al., 2020]. This episode of plate reorganization is commonly attributed to the enhanced activity of the Deccan plume, through the action of plume head forces [Cande and Stegman, 2011] or the coupling of the subducting plates with large-scale mantellic conveyor belts [Jolivet et al., 2016]. Other invoked driving mechanisms involve the penetration of the Indonesian Slab in the lower mantle during the Late Cretaceous/Early Tertiary period, which affects the slab pull force [Faccenna et al., 2013], or collision of continental terranes, such as the 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.

The NW Indian subduction zone, and its segment running from Bela to the Amirante, may have played a key role in this episode of plate reorganization event. While the subduction branch of the Neotethys running along Africa deactivated at Troodos (Cyprus) ~75 Ma [Robertson, 1977], the NW Indian subduction deactivated ~63 Ma, following the slab break-off recorded at the Bela ophiolites [Gnos

et al., 1998]. India was therefore bounded to its northern and northwestern boundaries by major subduction zones, which likely contributed to the faster motion of India compared to Africa during the Late Cretaceous. The slab break-off at Bela, together with the separation of the Amirante segment in the wake of the India–Seychelles breakup events, occurred around 63–65 Ma and likely contributed to the end of the episode of plate reorganization affecting the Indian Ocean at this period.

In detail, the short (~100 km) amount of subducted material deduced from gravity models [Miles, 1982] may be explained either by a low subduction rate after the isolation of the Amirante subduction, or by the formation of a slab tear, resulting in the detachment of a longer slab, as suggested from backward mantle tomography [Glisovic and Forte, 2017]. The plate kinematics analysis by Cande et al. [2010] requires a diffuse area of compression in the area of the Amirante System and along NW India to accommodate at least ~100 km of convergence during the Paleocene–Early Eocene. Considering the NW Indian subduction and the Amirante Ridge and Trench System as part of the same plate boundary (between India and the microplate supporting the Kabul block) may provide an explanation for the origin of this enigmatic episode of convergence.

5. Conclusions

Paleogeographic reconstructions of the NW Indian margin reveal that the Amirante Ridge and Trench System was the southern termination of a major subduction zone running along the NW Indian margin. The NW Indian subduction split in two parts in the wake of a slab break-off event recorded around 70–65 Ma and the series of breakup and seafloor spreading events at the origin of the Gop Basin and a part of the East Somali Basin, prior to the formation of the Carlsberg Ridge 63 Ma. Considering the Amirante subduction further explains the supra-subduction signature identified along the NW Indian passive margin.

The reconstructions suggest that the Amirante Ridge may represent either a rare case of a ridge formed during the earliest stages of an intra-oceanic subduction or a mixed transform and subduction feature, similar to the present-day Hjort trench at the

Australia–Pacific boundary. A more complete geochemical analysis of the basement rocks outcropping at the Amirante Ridge may help to buttress the scenario of its origin.

References

Agard, P., Plunder, A., Angiboust, S., Bonnet, G., and Ruh, J. (2018). The subduction plate interface: rock record and mechanical coupling (from long to short timescales). *Lithos*, 320–321:537–566.

Ali, J. R. and 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.

Beck, R. A., Burbank, D. W., Sercombe, W. J., Riley, G. W., Barndt, J. K., Berry, J. R., Afzal, J., Khan, A. M., Jurgen, H., Metje, J., Cheema, A., Shafique, N. A., Lawrence, R. D., and Khan, A. (1995). Stratigraphic evidence for an early collision between northwest India and Asia. *Nature*, 373:55–58.

Bernard, A. and 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? *C. R. Acad. Sci. Paris*, 330:777–783.

Besse, J. and 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. and 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., editor, *Petroleum Geoscience: Indian Contexts*, pages 1–61. Springer International Publishing, Switzerland.

Burgath, K.-P., Von Rad, U., Van Der Linden, W., Block, M., Khan, A. A., Roeser, H. A., and Weiss, W. (2002).

Basalt and peridotite recovered from Murray Ridge: are they of supra-subduction origin? In Clift, P. D., Kroon, D., Gaedicke, C., and Craig, J., editors, *The Tectonic and Climatic Evolution of the Arabian Sea Region*, volume 195 of *Special Publications*, pages 117–135. Geological Society, London.

Calvès, G., Schwab, A. M., Huuse, M., Clift, P. D., Gaina, C., Jolley, D., Tabrez, A. R., and Inam, A. (2011). Seismic volcanostratigraphy of the western Indian rifted margin: The pre-Deccan igneous province. *J. Geophys. Res.*, 116:1–28.

Cande, S. C. and Patriat, 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., Patriat, P., and Dyment, J. (2010). Motion between the Indian, Antarctic and African plates in the early Cenozoic. *Geophys. J. Int.*, 183:127–149.

Cande, S. C. and Stegman, D. R. (2011). Indian and African plate motions driven by the push force of the Réunion plume head. *Nature*, 475:47–52.

Chaubey, A. K., Dyment, J., Bhattacharya, G. C., Royer, J. Y., Srinivas, K., and 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., and Craig, J., editors, *The Tectonic and Climatic Evolution of the Arabian Sea Region*, volume 195 of *Special Publication*, pages 71–85. Geological Society, London.

Clift, P. D., Calvès, G., and Jonell, T. N. (2020). Evidence for simple volcanic rifting not complex subduction initiation in the Laxmi Basin. *Nat. Commun.*, 11:2733.

Coltice, N., Bertrand, H., Rey, P., Jourdan, F., Phillips, B. R., and Ricard, Y. (2009). Global warming of the mantle beneath continents back to the Archean. *Gondwana Res.*, 15:254–266.

Courtillot, V. E. and Renne, P. R. (2003). On the ages of flood basalt events. *C. R. Géosci.*, 335:113–140.

Damuth, J. E. and Johnson, D. A. (1989). Morphology, sediments and structure of the Amirante trench, western Indian Ocean: implications for trench origin. *Mar. Petrol. Geol.*, 6:232–242.

Duretz, T., Agard, P., Yamato, P., Ducassou, C., Burov, E. B., and Gerya, T. V. (2016). Thermo-mechanical modelling of the obduction process based on the Oman Ophiolite case. *Gondwana Res.*, 32:1–10.

Dyment, J. (1993). Evolution of the Indian Ocean Triple Junction between 65 and 49 Ma (anomalies 28 to 21). *J. Geophys. Res.*, 98:13863–13877.

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.

Eagles, G. and 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., Flueh, E. R., and Kopp, C. (2008). Dalrymplte Trough: an active oblique-slip ocean-continent boundary in the Northwest Indian Ocean. *Earth Planet. Sci. Lett.*, 272:437–445.

Edwards, R. A., Minshull, T. A., and White, R. S. (2000). Extension across the Indian–Arabian plate boundary: the Murray Ridge. *Geophys. J. Int.*, 142:461–477.

Faccenna, C., Becker, T. W., Conrad, C. P., and Husson, L. (2013). Mountain building and mantle dynamics. *Tectonics*, 32:80–93.

Fisher, R. L., Engel, C. G., and Hilde, T. W. C. (1968). Basalts dredged from the Amirante Ridge, western Indian Ocean. *Deep-Sea Res.*, 15:521–534.

Gaina, C., Torsvik, T. H., van Hinsbergen, D. J. J., Medvedev, S., Werner, S. C., and Labails, C. (2013). The African Plate: a history of oceanic crust accretion and subduction since the Jurassic. *Tectonophysics*, 604:4–25.

Gaina, C., van Hinsbergen, D. J. J., and 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.

Gibbons, A. D., Whittaker, J. M., and 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*, 118:808–822.

Gibbons, A. D., Zahirovic, S., Müller, R. D., Whittaker, J. M., and 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.

Glisovic, P. and Forte, A. M. (2017). On the deep-mantle origin of the Deccan traps. *Science*, 355:613–616.

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. and Perrin, M. (1997). Formation and evolution of the Masirah ophiolite constrained by paleomagnetic study of volcanic rocks. *Tectonophysics*, 253:53–64.

Guillot, S., Mahéo, G., de Sigoyer, J., Hattori, K. H., and Pêcher, A. (2008). Tethyan and Indian subduction viewed from the Himalayan high- to ultrahighpressure metamorphic rocks. *Tectonophysics*, 451:225–241.

Guilmette, C., Smit, M. A., van Hinsbergen, D. J. J., Gürer, D., Corfu, F., Charette, B., Maffione, M., Rabeau, O., and Savard, D. (2018). Forced subduction initiation recorded in the sole and crust of the Semail Ophiolite of Oman. *Nat. Geosci.*, 11:688–695.

Hartnady, C. J. H. (1986). Amirante Basin, western Indian Ocean: possible impact site of the Cretaceous/Tertiary extinction bolide? *Geology*, 14:423–426.

Hey, R. N. (2004). Propagating rifts and microplates at mid-ocean ridges. In Selley, R. C. et al., editors, *Encyclopedia of Geology*, pages 396–405. Academic Press, London.

Hooper, P., Widdowson, M., and Kelley, S. (2010). Tectonic setting and timing of the final Deccan flood basalt eruptions. *Geology*, 38:839–842.

Johnson, D. A., Berggren, W. A., and Damuth, J. E. (1982). Cretaceaous ocean floor in the Amirante Passage: Tectonic and oceanographic implications. *Mar. Geol.*, 47:331–343.

Jolivet, L., Faccenna, C., Agard, P., Frizon de Lamotte, D., Menant, A., Sternai, P., and 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., Collins, A. S., Mahmood, K., Foden, J., and Khan, M. (2012). U-Pb zircon crystallization age of the Muslim Bagh ophiolite: enigmatic remains of an extensive pre-Himalayan arc. *Geology*, 40:1099–1102.

Kakar, M. I., Kerr, A. C., Mahmood, K., Collins, A. S., Khan, M., and McDonald, I. (2014). Suprasubduction zone tectonic setting of the Muslim Bagh ophiolite, north-western Pakistan: Insights from geochemistry and petrology. *Lithos*, 202–203:190–206.

Khan, M., Kerr, A. C., and Mahmood, K. (2007b). Formation and tectonic evolution of the Cretaceous-Jurassic Muslim Bagh ophiolitic complex, Pakistan: implications for the composite tectonic setting of ophiolites. *J. Asian Earth Sci.*, 31:112–127.

Khan, S. D., Mahmood, K., and Casey, J. F. (2007a). Mapping of Muslim Bagh ophiolite complex (Pakistan) using new remote sensing and field data. *J. Asian Earth Sci.*, 30:333–343.

Mahmood, K., Boudier, F., Gnos, E., Monié, P., and Nicolas, A. (1995). 40 Ar/39 Ar dating of the emplacement of the Muslim Bagh ophiolite, Pakistan. *Tectonophysics*, 250:169–181.

Mahoney, J. J., Duncan, R. A., Khan, W., Gnos, E., and 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.

Mart, Y. (1988). The tectonic setting of the Seychelles, Mascarene and Amirante Plateaus in the Western Equatorial Indian Ocean. *Mar. Geol.*, 79:261–274.

Masson, D. G. (1984). Evolution of the Mascarene Basin, western Indian ocean, and the significance of the Amirante arc. *Mar. Geophys. Res.*, 6:365–382.

Matthews, K. J., Müller, R. D., and Sandwell, D. T. (2015). Oceanic microplate formation records the onset of India–Eurasia collision. *Earth Planet. Sci. Lett.*, 433:204–214.

Matthews, K. J., Seton, M., and Müller, R. D. (2012). A global-scale plate reorganization event at 105–100 Ma. *Earth Planet. Sci. Lett.*, 355–356:283–298.

McKenzie, D. P. and Sclater, J. G. (1971). The evolution of the Indian Ocean since the late Cretaceous. *Geophys. J. R. Astron. Soc.*, 24:437–528.

Meckel, T. A., Coffin, M. F., Mosher, S., Symonds, P., Bernardel, G., and Mann, P. (2003). Underthrusting at the Hjort Trench, Australian–Pacific plate boundary: incipient subduction? *Geochem. Geophys. Geosyst.*, 4(12).

Miles, P. R. (1982). Gravity models of the Amirante Arc, western Indian Ocean. *Earth Planet. Sci. Lett.*, 61:127–135.

Minshull, T. A., Edwards, R. A., and Flueh, E. R. (2015). Crustal structure of the Murray Ridge, northwest Indian Ocean, from wide angle seismic data. *Geophys. J. Int.*, 202:454–463.

Minshull, T. A., Lane, C., Collier, J. S., and Whitmarsh, R. (2008). The relationship between rifting and magmatism in the northeastern Arabian Sea. *Nat. Geosci.*, 1:463–467.

Mukhopadhyay, R., Karisiddaiah, S. M., and Ghosh, A. K. (2013). Geodynamics of the Amirante Ridge and Trench Complex, Western Indian Ocean. *Int. Geol. Rev.*, 54:81–92.

Norton, I. O. and 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.

Pandey, D. K., Pandey, A., and Whattam, S. A. (2019). Relict subduction initiation along a passive margin in the northwest Indian Ocean. *Nat. Commun.*, 10.

Plummer, P. S. (1996). The Amirante ridge/trough complex: response to rotational transform rift/drift between Seychelles and Madagascar. *Terra Nova*, 8:34–47.

Pourteau, A., Scherer, E. E., Schorn, S., Bast, R., Schmidt, A., and Ebert, L. (2018). Thermal evolution of an ancient subduction interface revealed by Lu-Hf garnet geochronology, Halilbağı Complex (Anatolia). *Geosci. Front.*, 10:127–148.

Ramana, M. V., Desa, M. A., and Ramprasad, T. (2015). Re-examination of geophysical data off Northwest India: Implications to the Late Cretaceous plate tectonics between India and Africa. *Mar. Geol.*, 365:36–51.

Robertson, A. H. F. (1977). Tertiary uplift history of the Troodos massif, Cyprus. *Geol. Soc. Am. Bull.*, 88:1763–1772.

Rodriguez, M., Chamot-Rooke, N., Huchon, P., Fournier, M., Lallemant, S., Delescluse, M., Zaragosi, S., and Mouchot, N. (2014). Tectonics of the Dalrymple Trough and uplift of the Murray Ridge (NW Indian Ocean). *Tectonophysics*, 636:1–17.

Rodriguez, M., Fournier, M., Chamot-Rooke, N., Huchon, P., and Delescluse, M. (2018). The geological evolution of the Aden–Owen–Carlsberg triple junction (NW Indian Ocean) since the Late Miocene. *Tectonics*, 37:1552–1575.

Rodriguez, M., Huchon, P., Chamot-Rooke, N., Fournier, M., Delescluse, M., and François, T. (2016). Tracking the Paleogene India–Arabia plate boundary. *Mar. Petrol. Geol.*, 72:336–358.

Rodriguez, M., Huchon, P., Chamot-Rooke, N., Fournier, M., Delescluse, M., Smit, J., Plunder, A., Calvès, G., Ninkabou, D., Pubellier, M., François, T., Agard, P., and Gorini, C. (2020). Successive shifts of the India–Africa transform plate boundary during the Late Cretaceous-Paleogene interval: implications for ophiolite emplace-ment along transforms. *J.Asian Earth Sci.*, 191. doi:10.1016/j.jseaes.2019.104225.

Royer, J. Y., Chaubey, A. K., Dyment, J., Bhattacharya, G. C., Srinivas, K., Yateesh, V., and Ramprasad, T. (2002). Paelogene plate tectonic evolution of the Arabian and Eastern Somali basins. In Clift, P. D. et al., editors, *The Tectonic and Climatic Evolution of the Arabian Sea Region*, volume 195 of *Geological Society Special Publication*, pages 7–23. Geological Society of London.

Schlich, R. (1982). The Indian Ocean: aseismic Ridges, spreading centres and basins. In Nairn, A. E. M. and Stehli, F. G., editors, *The Ocean Basins and Margins*, pages 51–147. Plenum Press, New York.

Searle, M. P., Noble, S. R., Cottle, J. M., Waters, D. J., Mitchell, A. H. G., Hlaing, T., and Horstwood, M. S. A. (2007). Tectonic evolution of the Mogok metamorphic belt, Burma (Myanmar) constrained by U–Th–Pb dating of metamorphic and magmatic rocks. *Tectonics*, 26(3).

Shipboard Scientific Party (1989). Site 731. In: Prell, W. L., Niitsuma, N., et al., editors, Proc. ODP, Init. Repts., 117. College Station, TX (Ocean Drilling Program).

Shuhail, M., Yateesh, V., Bhattacharya, G. C., Müller, R. D., Raju, K. A. K., and 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.

Siddiqui, R. H. and Ma, C. (2017). Petrogenesis of Late Cretaceous Volcanism in Kazhaba Area and its relationship with mantle plume activity of Reunion hotspot. *J. Asian Earth Sci.*, 28:229–240.

Socquet, A. and Pubellier, M. (2005). Cenozoic deformation in Western Yunnan (China–Myanmar border). *J. Asian Earth Sci.*, 24:495–511.

Tapponnier, P., Mattauer, M., Proust, F., and Cassaigneau, C. (1981). Mesozoic ophiolites, sutures, and large-scale tectonic movements in Afghanistan. *Earth Planet. Sci. Lett.*, 52:355–371.

Torsvik, T. H., Tucker, R. D., Ashwal, L. D., Carter, L. M., Jamtveit, B., Vidyadharan, K. T., and Venkataramana, P. (2000). Late Cretaceous India–Madagascar fit and timing of break-up related magmatism. *Terra Nova*, 12:220–224.

van Hinsbergen, D. J. J., Lippert, P. C., Dupont-Nivet, G., McQuarrie, N., Doubrovine, P. V., Spakman, W., and Torsvik, T. H. (2012). Greater India Basin hy-

pothesis and a two-stage Cenozoic collision between India and Asia. *Proc. Natl Acad. Sci. USA*, 109:7659–7664.

van Hinsbergen, D. J. J., Steinberger, B., Doubrovine, P. V., and Gassmöller, R. (2011). Acceleration and deceleration of India–Asia convergence since the Cretaceous: roles of mantle plumes and continental collision. *J. Geophys. Res.*, 116.

Verma, O. and Khosla, A. (2019). Developments in the stratigraphy of the Deccan Volcanic Province, peninsular India. *C. R. Geosci.*, 351:461–476.

Wajzer, M. R., Barber, A. J., Hidayat, S., and Suharsono, S. (1991). Accretion, collision and strike-slip faulting: the Woyla group as a key to the tectonic evolution of North Sumatra. *J. Southeast Asian Earth Sci.*, 6:447–461.

Willenbring, J. K. and von Blackenburg, F. (2010). Long-term stability of global erosion rates and weathering during late-Cenozoic cooling. *Nature*, 465:211–214.

Yatheesh, V. (2020). Structure and tectonics of the continental margins of India and the adjacent deep ocean basins: current status of knowledge and some unresolved problems. *Episodes*, 43:586–608.

Yatheesh, V., Bhattacharya, G. C., and Dyment, J. (2009). Early oceanic opening off Western India–Pakistan margin: the Gop Basin revisited. *Earth Planet. Sci. Lett.*, 284:399–408.

Yatheesh, V., Dyment, J., Bhattacharya, G. C., Royer, J. Y., Kamesh Raju, K. A., Ramprasad, T., Chaubey, A. K., Patriat, P., Srinivas, K., and Choi, Y. (2019). Detailed structure and plate reconstructions of the Central Indian Ocean between 83.0 and 42.5 Ma (Chrons 34 and 20). *J. Geophys. Res.*, 124:4305–4322.

Zhuang, G., Najman, Y., Guillot, S., Roddaz, M., Antoine, P.-O., Métais, G., Carter, A., Marivaux, L., and Solangi, S. H. (2015). Constraints on the collision and the pre-collision tectonic configuration between India and Asia from detrital geochronology, thermochronology, and geochemistry studies in the lower Indus basin, Pakistan. *Earth Planet. Sci. Lett.*, 432:363–373.