



Tectonics

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Key Points:

- We present a new tectonic model for the evolution of NW Indian Ocean
- Subducted slab under the Carlsberg Ridge resulted from Arabia-India convergence

Supporting Information:

- Data Set S1
- Supporting Information S1
- Movie S1
- Movie S2

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Tectonic interactions between India and Arabia since the Jurassic reconstructed from marine geophysics, ophiolite geology, and seismic tomography

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Abstract Gondwana breakup since the Jurassic and the northward motion of India toward Eurasia were associated with formation of ocean basins and ophiolite obduction between and onto the Indian and Arabian margins. Here we reconcile marine geophysical data from preserved oceanic basins with the age and location of ophiolites in NW India and SE Arabia and seismic tomography of the mantle below the NW Indian Ocean. The North Somali and proto-Owen basins formed due to 160–133 Ma N-S extension between India and Somalia. Subsequent convergence destroyed part of this crust, simultaneous with the uplift of the Masirah ophiolites. Most of the preserved crust in the Owen Basin may have formed between 84 and 74 Ma, whereas the Mascarene and the Amirante basins accommodated motion between India and Madagascar/East Africa between 85 and circa 60 Ma and 75 and circa 66 Ma, respectively. Between circa 84 and 45 Ma, oblique Arabia-India convergence culminated in ophiolite obduction onto SE Arabia and NW India and formed the Carlsberg slab in the lower mantle below the NW Indian Ocean. The NNE-SSW oriented slab may explain the anomalous bathymetry in the NW Indian Ocean and may be considered a paleolongitudinal constraint for absolute plate motion. NW India-Asia collision occurred at circa 20 Ma deforming the Sulaiman ranges or at 30 Ma if the Hindu Kush slab north of the Afghan block reflects intra-Asian subduction. Our study highlights that the NW India ophiolites have no relationship with India-Asia motion or collision but result from relative India-Africa/Arabia motions instead.

1. Introduction

In the west and northwest Indian Ocean old oceanic basins document the early history of East Gondwana breakup and ocean basin formation. Early Jurassic to mid-Cretaceous seafloor spreading records are preserved in the Mozambique and West Somali basins, whereas the Mascarene Basin formed from the Late Cretaceous to the Cenozoic, and the East Somali Basin in the Cenozoic (Figure 1). Knowledge about the basement age of other, smaller basins situated in the same region (North Somali, Amirante, and Owen basins) is sparse, and existing interpretations do not always agree. When combined, plate motions based on marine geophysical records of the Indian Ocean's basins suggest a complex evolution of relative motions between the Indian and Arabian plates, with multiple episodes of extension, transtension, compression, transpression, and transform motion [e.g., Cande *et al.*, 2010; Eagles and Hoang, 2014; Gaina *et al.*, 2007, 2013; Gibbons *et al.*, 2013; Leroy *et al.*, 2012].

Part of the oceanic lithosphere that was formed between India and Arabia is preserved only as ophiolites now found in eastern Oman, Pakistan, and Afghanistan [Gnos and Perrin, 1996; Immenhauser, 1996a; Peters and Mercolli, 1998]. The geochemical signatures of these ophiolites hold clues about the geodynamic context in which they formed (as mid-ocean ridge basalt, MORB, or above subduction zones, so-called suprasubduction (SSZ) ophiolites [Dilek and Furnes, 2011; Pearce *et al.*, 1984]); their age demonstrates the timing of their formation, and sheeted dyke sections may hold clues for the direction of ocean spreading. In addition, essential clues on the evolution of subduction zones that culminated in the thrusting of ophiolites onto the continental margins of Arabia and India can be derived from the structural and sedimentary evolution of the fold-thrust belts that comprise these ophiolites.

A comprehensive model for the formation and destruction of oceanic crust between India and Arabia has to reconcile geological records found on the continental margins and within oceanic basins situated in the west

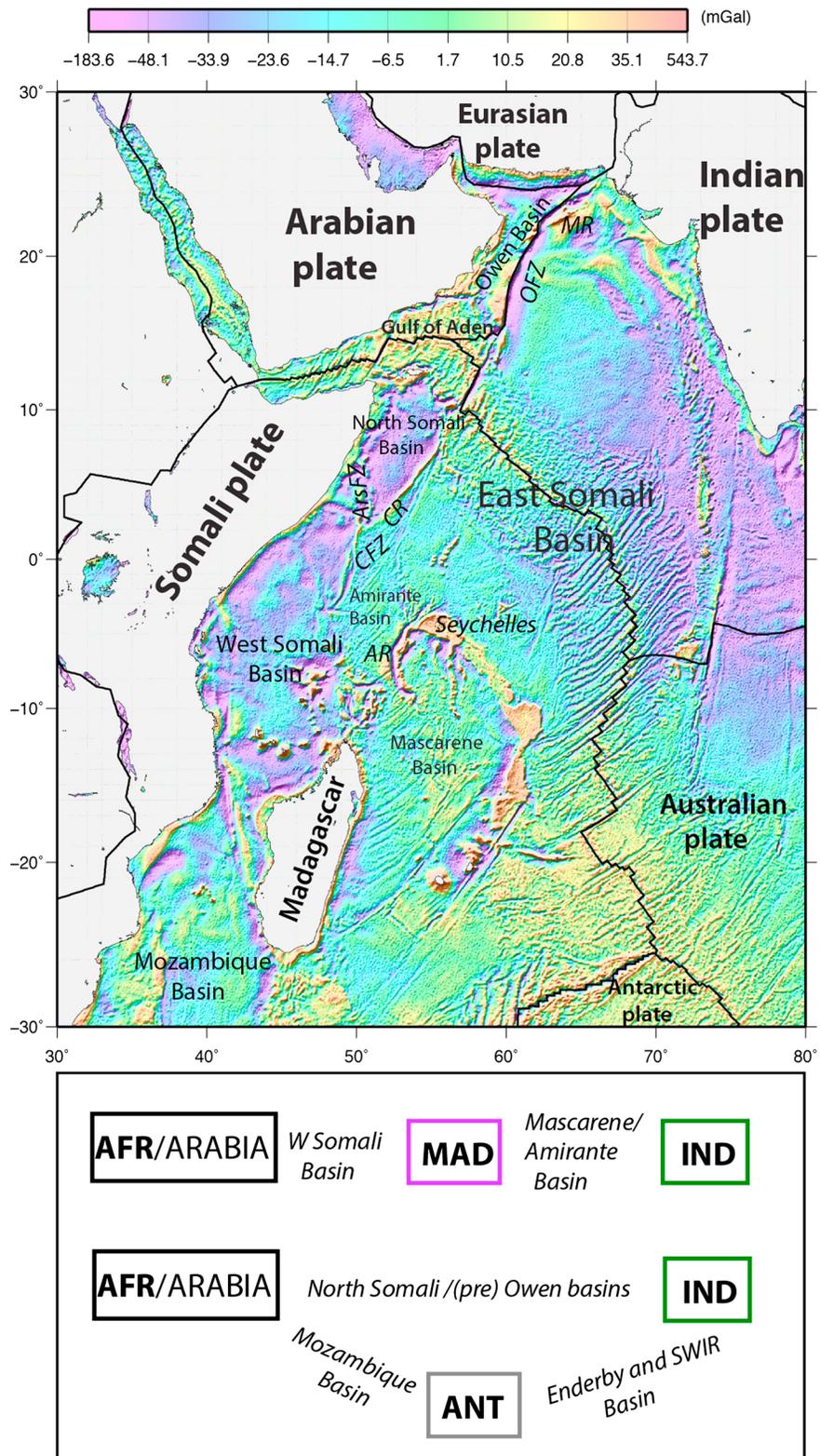


Figure 1. (top) Present-day plate boundaries [Bird, 2003] and major oceanic basins formed in the West Indian Ocean since the Jurassic. Gridded free-air gravity anomaly from satellite altimetry [Sandwell and Smith, 2009] is shown in the background. Abbreviations: Ars FZ = Ars fracture zone, CFZ = Carlsberg fracture zone, CR = Chain Ridge, OFZ = Owen Fracture Zone, MR = Murray Ridge. (bottom) Conjugate tectonic plates during the formation of main oceanic basins in the West Indian Ocean (AFR = Africa, MAD = Madagascar, IND = India, and ANT = Antarctica).

and northwest Indian Ocean. A regional model that attempted to connect knowledge about oceanic crust preserved onshore and offshore was provided nearly 20 years ago by *Gnos et al.* [1997a]. Since then, regional retrodeformations of fold-thrust belts were reconstructed, new regional and global geophysical data sets were improved, and progress has been made in restoring the Indian Ocean seafloor. In this paper, we develop an updated model taking into account recently published local kinematics and a reevaluation of magnetic and gravity data in the North Somali, Amirante, and Owen basins. The new regional kinematic model is subsequently used for defining the plate boundary evolution in the northwest Indian Ocean since the Jurassic; this model is tested against and integrated with geological constraints from the ophiolite records described in the literature. In particular, we pay attention to the deformed NW Indian margin in Pakistan and the adjacent Kabul Block of Afghanistan. This region became incorporated in intense late Cenozoic deformation as a result of the India-Asia collision [e.g., *Tapponnier et al.*, 1981]. For our plate model, we restore this deformation to reconstruct the configuration of the NW Indian margin during Late Cretaceous to early Cenozoic ophiolite emplacement onto the Indian/Kabul continental margins and to assess which deformation episodes result from India-Arabia relative motion and which ones from India-Asia relative motions. We test our model against mantle structure using two recent tomographic models (UU-P07 [*Amaru*, 2007; *van der Meer et al.*, 2010] and SRT40S [*Ritsema et al.*, 2011]). Finally, we discuss some implications of our reconstructions for ongoing discussions on absolute plate motion models and anomalous subsidence of the NW Indian Ocean.

2. Marine Geophysical Constraints From Oceanic Basins

The Indian oceanic realm hosts a number of oceanic basins with different ages. The continental margins of East Africa and Arabia are bordered from south to north by the Jurassic to Cretaceous Mozambique and West Somali basins and by the North Somali and Owen basins of disputable formation ages (Figure 1). To the east of these older basins, the Mascarene and Amirante oceanic crust formed in middle to Late Cretaceous [e.g., *Bernard and Munsch*, 2000]. Following a period of complex plate boundary reorganization that led to the formation of isolated smaller tectonic blocks including the Seychelles and Mascarene Plateau, spreading relocated to the Central Indian Mid-Ocean Ridge in the East Somali Basin, where it is still active (Figure 1). Throughout the Mesozoic and Cenozoic, microcontinents were separated from the major continents by rifting and subsequent seafloor spreading. These include not only Madagascar, the Seychelles, and part of Mauritia [*Torsvik et al.*, 2013] but also older continental fragments such as the Kabul Block, northwest of India, which is now found trapped between ophiolitic bodies and amalgamated to larger continents as a result of subduction and collisional processes.

In this paper, we study the plate boundary evolution in the northwest Indian Ocean (Figure 1) by merging a recently published kinematic model of the African Plate evolution [*Gaina et al.*, 2013] with new kinematic models of the North Somali, Amirante, and Owen basins based on marine geophysical data. The volcanic margin shared by Mozambique and East Antarctica before the opening of the Mozambique basin exhibits volcanic features that mark the onset of breakup. *Jordan et al.* [2007] proposed that the Mozambique Rooi Rand dykes (174–172 Ma) with MORB affinity may be a signal of full oceanization between eastern African coast and East Antarctica. Breakup and seafloor spreading were probably contemporaneous in the Mozambique and West Somali basins as the African Plate moved away from the Madagascar and East Antarctica. We have adopted the same kinematic model as in *Gaina et al.* [2013] where seafloor spreading east of the African margin started around 170 Ma in these basins. Seafloor spreading in the West Somali Basin ceased around 123 Ma, coinciding with changes in the plate boundaries between Antarctica and India [see also *Gaina et al.*, 2007]. The Mascarene Basin was created by seafloor spreading between Madagascar and Seychelles/India starting around 84 Ma and ceasing around 59 Ma [*Bernard and Munsch*, 2000; *Bissessur*, 2011]. Shortly before the cessation of seafloor spreading in the Mascarene Basin, rifting between India and Seychelles started to propagate from northwest to southeast forming the East Somali Basin. The plate circuit and predicted motion paths between the main tectonic plates involved in the evolution of these basins are shown in Figures 1 and 2 and summarized in Table 1.

2.1. North Somali Basin

The North Somali Basin is a deep basin (circa 5 km) [*Amante and Eakins*, 2009] with a thick sedimentary cover (3–4 km) [*Divins*, 2003] and is situated between the Jurassic-Cretaceous West Somali and the Cenozoic Gulf of

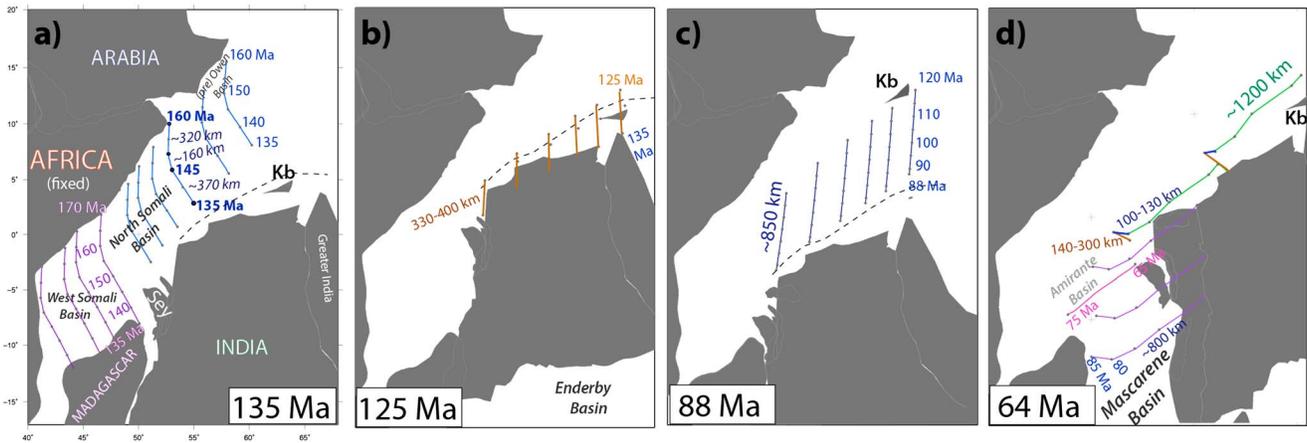


Figure 2. Modeled motion paths of Madagascar and (Greater) India relative to East and NE Africa (i.e., Somali and Arabian plates) for several stages between Early Jurassic (circa 170 Ma) and Late Cretaceous to early Cenozoic (circa 64 Ma). Also shown is the amount of extension (in different hues of blue and magenta), compression (in brown), and strike-slip motion (in green) predicted by kinematic models (in km) for different stages along selected paths. Abbreviations: Kb = Kabul Block and Sey = Seychelles microcontinent.

Table 1. Finite Rotations

Age (Ma)	Chron	Rotation (Latitude, Longitude, Angle)
<i>Madagascar Relative to Somali/Arabia Plate (Seafloor Spreading in West Somali Basin)</i>		
124.05	M2no	2.08, -42.04, 0.38
125.67	M4ny	2.08, -42.04, 0.96
130.49	M10Nn.3no	1.36, -44.40, 2.32
132.76	M12Any	1.64, -43.48, 3.34
140.51	M18ny	1.98, -42.89, 5.67
155.32	M26no	-6.35, -33.38, 9.98
158.10	M29no	-8.50, -30.40, 10.93
167.50	M40ny	-13.50, -23.30, 14.35
Breakup (170)		-14.44, -21.93, 15.30
<i>India Relative to Somali/Arabia Plate (Seafloor Spreading in North Somali and Proto-Owen Basins)</i>		
133.00		-20.30, -143.90, 62.26
137.85	M16no	-21.20, -142.40, 61.93
140.51	M18ny	-21.50, -141.90, 61.83
145.50	M21no	-22.20, -140.70, 61.64
155.32	M26no	-25.10, -139.50, 60.24
Breakup (165)		-28.70, -138.60, 58.48
<i>India Relative to Somali/Arabia Plate (Convergence)</i>		
124.10		-22.80, -144.20, 55.97
130.50		-20.80, -143.40, 61.04
133.00		-20.30, -143.90, 62.26
<i>India Relative to Kabul/Somali/Arabia Plate (Seafloor Spreading)</i>		
88.00		-19.80, -152.80, 59.16
90.00		-20.00, -152.50, 58.77
100.00		-21.30, -151.20, 56.82
120.00		-24.00, -148.00, 53.08
<i>India Relative to Kabul/Somali/Arabia Plate (Convergence/Subduction)</i>		
65.00		-24.90, -160.80, 6.72
83.00		-10.30, -174.50, 10.27
85.00		-13.40, -160.60, 12.23
88.00		-13.40, -142.80, 17.76
<i>Kabul Relative to Arabia/Somali Plate (Seafloor Spreading in the Owen Basin Followed by Strike-Slip Motion)</i>		
65.00		-11.0, -148.2, 28.40
79.00		-19.4, -152.4, 34.13
83.50		-23.9, -153.2, 33.69
<i>Seychelles/India Relative to Somali/Madagascar (Seafloor Spreading in Mascarene/Amiranse Basins)</i>		
60.00		-16.00, -148.80, 37.25
65.00		-16.00, -152.90, 42.79
67.70		-18.50, -156.50, 44.18
83.50		23.40, -160.40, 51.54

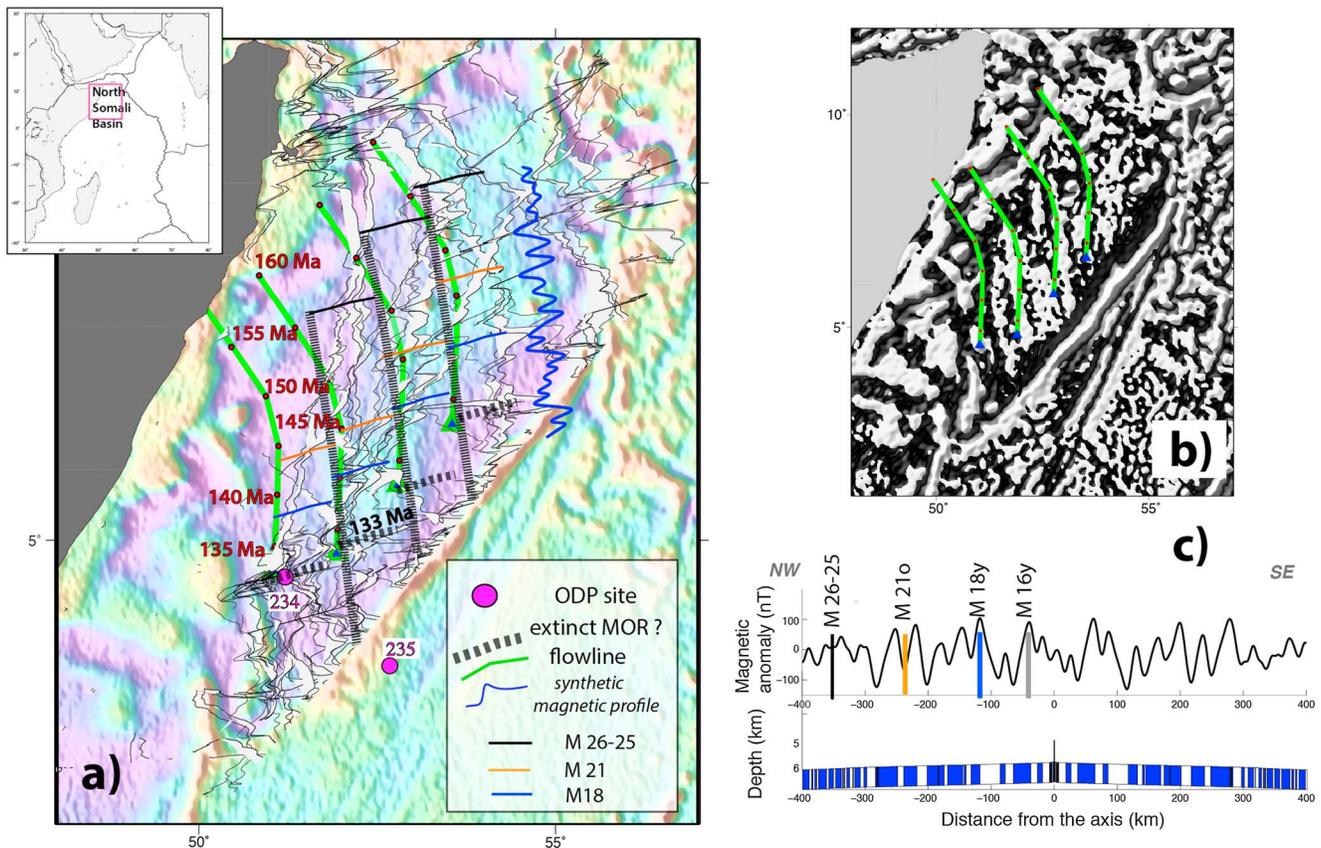


Figure 3. (a) North Somali Basin: free-air gravity anomaly [Sandwell and Smith, 2009] (color palette as in Figure 1 with 20% transparency) and ship track magnetic anomaly (black lines). (b) Gravity anomaly derivative (see text for explanations) and flow lines (in green) based on this study's kinematic model. (c) Synthetic profile of Mesozoic magnetic anomalies (M26/25 to M15) using a depth to magnetized bodies of 6 km, a paleolatitude of 25°S, and a magnetization of 10 A/m.

Aden oceanic basins (Figure 1). There are no direct indications of the oceanic crust age as the Ocean Drilling Program site 234 situated in the SW part of the basin (Figure 3) penetrated only Tertiary sediments (Pliocene, Miocene, and possibly Oligocene) without reaching basement [Davies and Kidd, 1977]. Several authors suggested that this basin opened synchronously with the West Somali Basin, as Madagascar/India drifted away from the Eastern African margin [Mountain and Prell, 1990]. The exact position and extent of the NW Indian margin (i.e., the region that continues inland from the Murray Ridge along the N-S plate boundary between the Indian and Eurasian Plates, Figure 1) is not known, but its southern end was bordered by several small continental blocks, including the Seychelles microcontinent (until at least 90 Ma) [e.g., Calvès et al., 2011; Ganerød et al., 2011; Torsvik et al., 2013]. The Late Cretaceous age of the ophiolites between India and the Kabul Block (see section 3) suggests that the Kabul Block was still contiguous with India at that time. The NW Indian margin was juxtaposed against the Somali/Arabia margin, and if no motion took place between India and Madagascar at that time, India-Somali rifting must have occurred around 160 Ma. Motion paths along the East African margin that express the amount and direction of Madagascar/India block displacement between 160 and 135 Ma were calculated based on the rotation parameters for the West Somali Basin (Gaina et al. [2010, 2013] and Table 1) (Figure 2). This model predicts that more than 800 km of displacement was created offshore the Somali coast by presumably N-S and NNW-SSE spreading. The width of the modern North Somali Basin is around 520 km along flow lines running from the continent-ocean boundary to the Chain Ridge (Figures 1 and 3).

With these constraints in mind, we inspect the gravity and magnetic data within the North Somali Basin to detect tectonic trends in the seafloor fabric and possibly to infer its age (Figure 3a). Due to the thick sedimentary cover, the tectonic fabric is not easily discernable in the free-air gravity anomaly from satellite altimetry [Sandwell and Smith, 2009], which shows only faint north-south trending linear features. We

computed the gravity residuals by removing the mantle gravity effect then upward continued (5 km) the resulting data to remove small-scale gravity signals and computed the horizontal derivative to highlight the tectonic fabric (Figure 3b). Very distinct, nearly N-S trending discontinuities are now visible, which we interpret as fracture zones that indicate north-south paleoseafloor spreading. Magnetic anomalies from the National Geophysical Data Center (NGDC) database (<http://www.ngdc.noaa.gov/mgg>) are plotted with a 90° trend (clockwise from the north) and compared with a synthetic profile constructed for east-west oriented crustal blocks that were magnetized at 25°S latitude (Figures 3a and 3c) using the timescale of *Gee and Kent* [2007]. We interpret Mesozoic chrons M26/25 (circa 155 Ma) to M16 (136.5 Ma) and suggest that extension, breakup, and seafloor spreading in the North Somali Basin started before 155 Ma (but later than 160 Ma) and ceased around 135. The northern flank and possibly the extinct mid-ocean ridge are still preserved between the Somali margin and Chain Ridge. The conjugate southern flank is missing, and we will discuss possible scenarios about the timing of tectonic episodes that led to consumption of the rest of the North Somali oceanic crust.

2.2. Owen Basin

Owen Basin is an elongated strip of oceanic crust situated between the eastern Arabian coast and the Owen Ridge and Owen Fracture Zone (Figure 1). The age of this basin remains controversial. Deep Sea Drilling Project (DSDP) drilling in the easternmost Owen Basin (site 223, Figure 4a) recovered a basal igneous unit of trachybasalt and hyaloclastic breccia overlain by upper Paleocene tuffaceous claystone [*Whitmarsh et al.*, 1974]. Basal sediments at DSDP 224 on the Owen Ridge (Figure 4a) are lower Eocene [*Whitmarsh et al.*, 1974], and their correlation with sediments from the Owen Basin predicts that the Owen Basin crust is not older than Upper Cretaceous [*Mountain and Prell*, 1990]. It is not clear whether the igneous rocks drilled at sites 223 and 224 represent true oceanic basement, and alternative hypotheses that invoke a Jurassic or even Triassic age for the Owen Basin were also put forward [*McKenzie and Sclater*, 1971; *Whitmarsh*, 1974, 1979; *Norton and Sclater*, 1979; *Stein and Cochran*, 1985]. A recent study analyzed seismic profiles across the Owen Basin and postulated that the easternmost part of the Owen Basin may be Cenozoic oceanic crust that initially formed in the Somali Basin but was transferred to the Arabian Plate by an early Oligocene counterclockwise reorientation of the plate boundary along the Chain Fracture Zone [*Rodriguez et al.*, 2014]. This study confirmed the oceanic nature of the crust in the Owen Basin and also suggested that part of the Masirah ophiolites is buried offshore. Their suggestion of a juxtaposition of old Mesozoic oceanic crust in the western Owen Basin and Cenozoic crust in the eastern part of the basin is based on the crust ages described by the two DSDP samples (see above) and strike-slip faults observed in the seismic data. However, the suggested Cenozoic basement seems to be at the same depth as the Mesozoic part, covered by the same amount of sediments, which may question the basement age and configuration proposed by *Rodriguez et al.* [2014].

According to our plate kinematic model described in the beginning of this section, the motion of western India relative to the eastern Arabian margin was transtensional between 160 and 145 Ma and extensional between 145 and 135 Ma, and therefore, the seafloor spreading episode that formed the North Somali Basin likely also formed oceanic lithosphere offshore eastern Arabia (Figure 2a). However, the age of the modern Owen Basin oceanic crust may be younger than that in the North Somali Basin as suggested by basement depth, sediment ages, and geophysical data [*Mountain and Prell*, 1990]. In addition, the eastern Oman margin contains ophiolites (e.g., the Masirah ophiolite) that were emplaced onto the East Arabian margin in latest Cretaceous to Eocene time [*Gnos et al.*, 1997a; *Immenhauser et al.*, 2000]. As a result, the pre-Cretaceous architecture of this basin may have been obliterated by subsequent convergence (see next section). Given the available constraints, our working hypothesis is that the present-day Owen Basin formed during a Late Cretaceous shorter extensional phase between Arabia and India (Figure 2c) and that the crust formed in Late Jurassic to Early Cretaceous was consumed during periods of convergence sometime in middle Cretaceous to Paleogene time. Magnetic anomalies from vintage ship track data [*Quesnel et al.* [2009] and NGDC, (<http://www.ngdc.noaa.gov/mgg>)] display a pattern that can be easily interpreted as chrons 34–33, and the seafloor fabric inferred from the gravity anomaly derivative is showing a NNE-SSW trend that may indicate WNW-ESE oriented seafloor spreading (Figure 4).

Relative motion between India and Arabia continues today and is accommodated along the Owen Fracture Zone. *Fournier et al.* [2008a, 2011] showed that since ~8 Ma, this relative motion was right lateral with a total

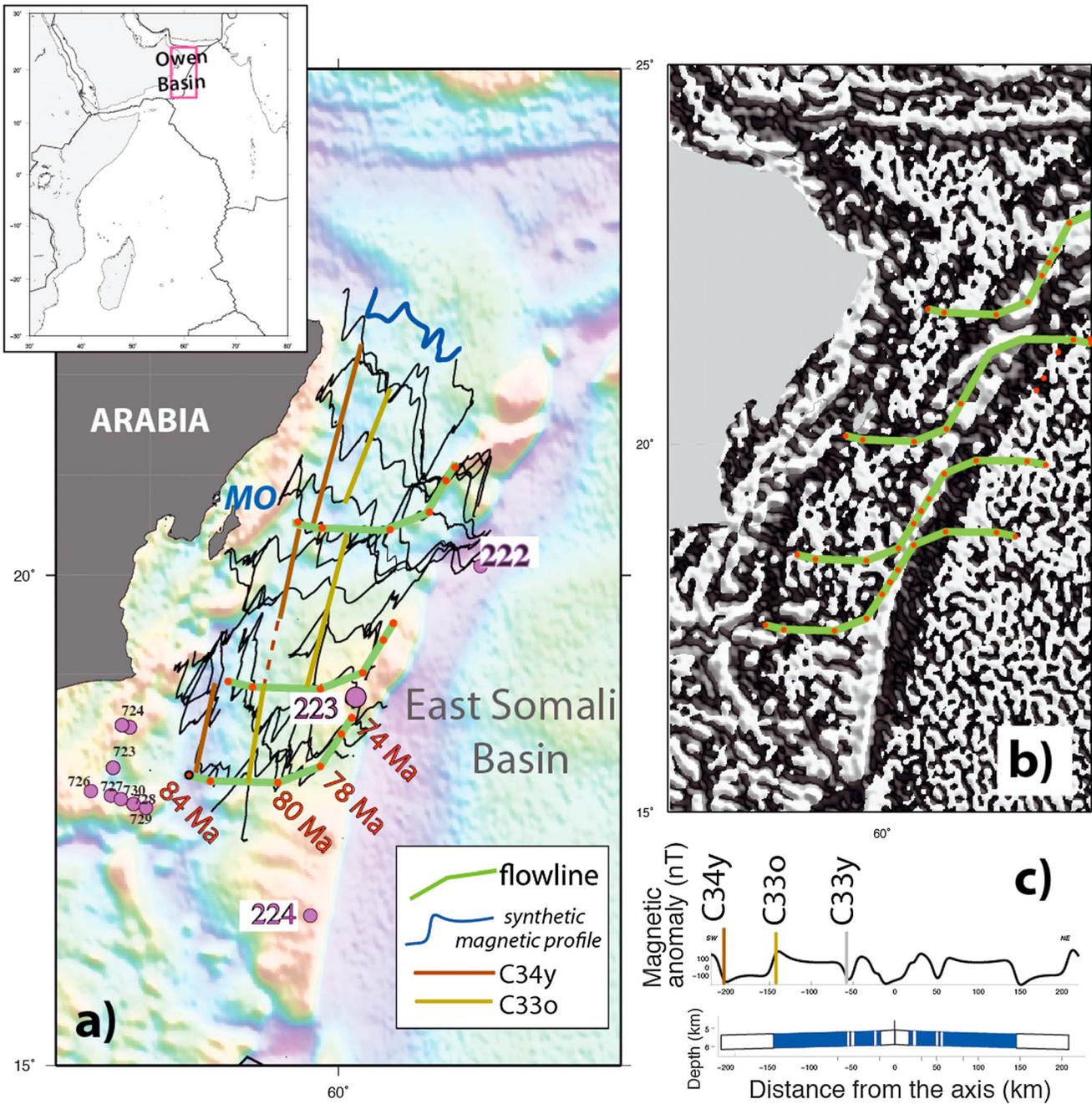


Figure 4. (a) Owen Basin: free-air gravity anomaly [Sandwell and Smith, 2009] (color palette as in Figure 1 with 40% transparency) and ship track magnetic anomaly (black lines). (b) Gravity anomaly derivative (see text for explanations) and flow lines based on this study's kinematic model. (c) Synthetic profile of Mesozoic magnetic anomalies (C34 to C32o) using a depth to magnetized bodies of 5 km, a paleolatitude of 5°, and a magnetization of 10 A/m. "MO" indicates the location of Masirah ophiolites.

displacement of ~12 km. To the north, the Owen Fracture Zone connects with the Murray Ridge, a NE-SW trending submarine high. Dredge samples from peridotites and basalts of the ridge have a suprasubduction zone geochemical affinity and a Late Cretaceous to Paleocene age [Burgath et al., 2002], also suggesting that at least part of the modern ocean floor in this region formed well after the initial separation of India from Arabia.

2.3. Amirante Basin

Very few studies dealt with the origin of the Amirante Basin, a region situated between the West and East Somali basins that is separated by two north-south trending features with distinct signatures on

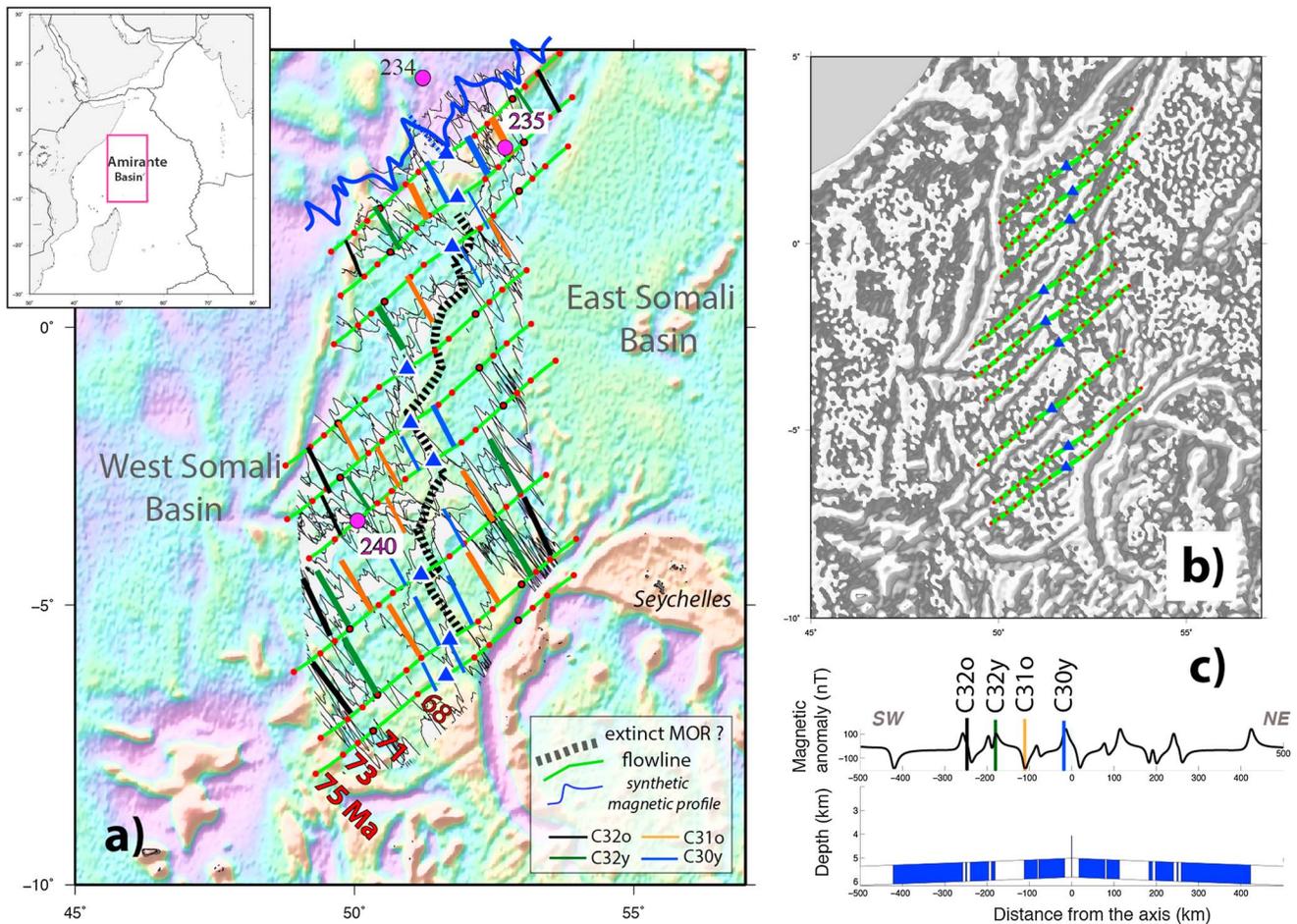


Figure 5. (a) Amirante Basin: free-air gravity anomaly [Sandwell and Smith, 2009] (color palette as in Figure 1 with 40% transparency) and ship track magnetic anomaly (black lines). (b) Gravity anomaly derivative (see text for explanations) and flow lines based on this study kinematic model (blue triangles represent seed points used to construct the flow lines and may indicate the location of an extinct ridge as observed in the gravity anomaly). (c) Synthetic profile of Mesozoic magnetic anomalies (C34 to C32) using a depth to magnetized bodies of 5 km, a paleolatitude of 13°S, and a magnetization of 10 A/m.

bathymetric and gravity maps (Figure 5). The Amirante Basin lies north of the Mascarene Basin that formed between Madagascar and Seychelles/India in the Late Cretaceous [e.g., Bernard and Munsch, 2000]. The exact timing for the opening of the Mascarene Basin is still a matter of debate. Few identifications of chron 34 (circa 84 Ma old) have been suggested by Bernard and Munsch [2000] and Eagles and Wibisono [2013] on the eastern Madagascar margin, but no conjugate isochron of that age has been found on the conjugate margin. The lack of conjugate isochrons may be explained by either (a) a series of ridge jumps (as observed for younger times and as suggested by Torsvik et al. [2013]) that may have left the older crust on the Madagascar margin or (b) subsequent volcanism overprinting and possible deformation of the conjugate flank. In any case, a simple interpolation of the half spreading rate (approximately 13 km/Myr) between the interpreted chrons 33 (79 Ma) and 34 (83–84 Ma) in the SW Mascarene Basin to the Madagascar rifted margin will result in a breakup age of approximately 88–92 Ma. This time interval also coincides with volcanic activity north of Madagascar and on the St. Mary Island offshore India [Torsvik et al., 2000]. We consider that a breakup time older than 92 Ma (as Gibbons et al. [2013] suggested) is hard to reconcile with the available geological or geophysical data.

It has been suggested that the Amirante Basin represents the northward continuation of the Mascarene Basin, because the systems of NE-SW fracture zones observed in the gravity anomaly grid are parallel or subparallel to the ones in the Mascarene Basin [e.g., Bernard and Munsch, 2000], but the presence of an enigmatic feature—the Amirante Ridge—that separates the two basins hinders the direct connection

between them. The Amirante Ridge may be of Cretaceous age according to *Fisher et al.* [1968] who published an age of 82 ± 16 Ma from K/Ar analysis of a grab sample. The predominant theory discussed in the literature (as also summarized by *Plummer* [1996]) is that the Amirante Ridge represents an extinct trench that was formed as an incipient subduction zone along a former fracture zone SW of the Seychelles [*Mart*, 1988; *Masson*, 1984; *Miles et al.*, 1998]. *Calvès et al.* [2011] proposed that a compressional event in Middle to Late Cretaceous caused by the relative motion between Madagascar and the NW margin of India was a trigger for the Amirante trench formation. Based on reevaluation for the Paleocene motion of the Seychelles microcontinent, *Ganerød et al.* [2011] added that the Amirante Ridge may have been reactivated in the Paleocene accommodating a counterclockwise rotation of the Seychelles. A short-lived Seychelles microplate with a deformable plate boundaries model was also adopted by *Torsvik et al.* [2013] and reiterated by *Eagles and Hoang* [2014], the later suggesting that the Amirante Ridge acted as a mid-ocean ridge axis during a competing ridge propagation within the Mascarene and East Somali basins.

To revisit the age of the Amirante Basin, we have inspected a clean data set of the magnetic anomaly data available from the NGDC database (<http://www.ngdc.noaa.gov/mgg>) together with derivatives of free-air gravity anomalies (Figure 5). The magnetic anomaly data were interpreted based on a synthetic model shown in Figure 5. We suggest that chrons 32 to 30 can be interpreted on several profiles on symmetric flanks that are separated by an extinct ridge (Figure 5a). We interpreted the extinct ridge as a NW-SE trending gravity low which seems to be offset by NE-SW fracture zones—well visible on the gravity derivative map (Figure 5b). Our interpreted chron 31 (about 68 Ma) seems to match well with the age of oceanic crust in the northern part of the basin, at site 235, where Maastrichtian sediments are resting on porphyritic basalt of Late Cretaceous age [*Davies and Kidd*, 1977]. Site 240, located in approximately 5000 m water depth (Figure 5), penetrated deep water sediments and basaltic “basement.” This basement was tentatively dated using the oldest sediments sitting on top of this layer. The resulting ages are lowermost Eocene (based on foraminifera) or uppermost Paleocene (based on nannofossils) [*Schlich*, 1974]—these ages are younger than our interpretation based on magnetic anomaly data which is chron 32 (Figure 5).

2.4. Predicted Relative Motions Between the Indian and African/Arabian Plates

Our composite kinematic model based on the previously published and newly derived rotations (Table 1) that describe relative motion of tectonic plates in the NW Indian Ocean is used to infer the relative motion between eastern Arabia and NW India. In the following chapters the composite kinematic model will be tested against geological data from ophiolites in eastern Oman, Pakistan, and Afghanistan (Figure 6). A summary of the main tectonic stages is presented below and illustrated in Figure 7. A first stage of N-S to NNW-SSE extension occurred between ~170 and 130 Ma, and this may have led to oceanic crust formation in the North Somali and pre-Owen basins. Subsequently, upon separation of India from Antarctica, a short phase of N-S convergence occurred between ~130 and ~125 Ma, followed by renewed N-S extension until ~90 Ma. As illustrated by the fracture zones and interpreted magnetic lineations, the initial separation of Seychelles/India from Madagascar was associated with a short period of counterclockwise rotation of India relative to Africa, leading to N-S convergence between NW India and SE Arabia between ~90 and 83 Ma. From ~83 to ~65 Ma, left-lateral motion occurred between India and Arabia parallel to their passive margins, followed by ~65–45 Ma sinistral transpression. After 45 Ma, minor E-W shortening occurred, followed in the last ~8 Ma by minor right-lateral transform motion (Figure 7).

3. Geological Constraints on the Arabia-Western India Plate Boundary Evolution

3.1. Ophiolites as Recorders of Plate Boundary Evolution

Ophiolites are portions of oceanic lithosphere consisting of mantle peridotites and crustal gabbros, dolerites, and basalts that are exposed above sea level, normally because they thrust over a continental margin or accretionary prism [*Dewey*, 1976]. Ophiolite belts thus represent leading edges of overriding oceanic plates above former subduction zones. Geochemical analyses of ophiolites have demonstrated that only a minor fraction of them contain oceanic crust that formed at a regular mid-oceanic ridge and have a MORB (mid-oceanic ridge basalt) composition; the vast majority of ophiolites has formed shortly after subduction initiation in a spreading center in a fore arc above a nascent subduction zone (SSZ or suprasubduction zone ophiolites [*Dilek and Furnes*, 2011; *Pearce*, 2003; *Pearce et al.*, 1984; *Stern et al.*, 2012]). Particularly, SSZ

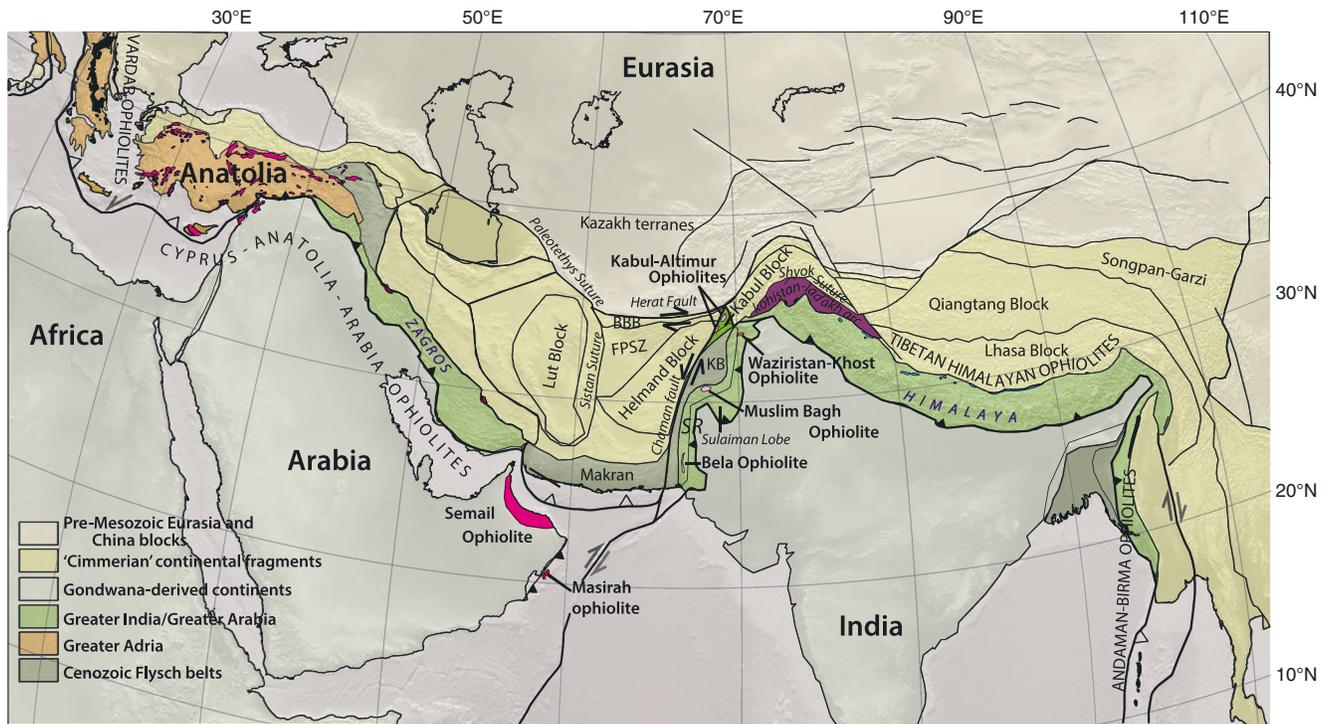


Figure 6. Regional tectonic map of the Arabia-India-Eurasia collision zone, with the location of ophiolite (in pink) (BBB = Band-e Bayan Block, FPSZ = Farah-Panjaj Suture Zone, and KB = Katawaz basin).

ophiolites are frequently underlain by the so-called “metamorphic soles”: high-grade metamorphic rocks derived from the downgoing plate that were welded to the base of the ophiolite’s mantle section when this was still very hot, shortly after subduction initiation [Dewey and Casey, 2013; Hacker and Gnos, 1997; Wakabayashi and Dilek, 2000]. Where MORB ophiolites are preserved, these may shed light on the age and possibly the paleosubduction direction of the oceanic basin within which subduction started. SSZ ophiolites, conversely, can be used to infer the timing and direction of subduction initiation and the direction of fore-arc spreading. In addition, many ophiolites overlie the so-called mélanges: chaotic mixtures of rock types with a sediment or serpentinite matrix that form at the subduction plate boundary during oceanic subduction and subsequent thrusting onto a continent or arc [e.g., Festa et al., 2010]. Rocks within such mélanges can constrain the age and composition of the lithosphere that subducted below these ophiolites. We therefore review the kinematic and temporal constraints as well as the geochemical affinity of the ophiolites exposed on the eastern Arabian and NW Indian margins, as well as the ages and compositions of ocean- and passive margin-derived rocks in the subophiolitic mélanges.

There are several belts of ophiolites in the larger Alpine-Himalayan mountain range (Figure 6), which represent the obducted fore arcs of subduction zones within the Neotethyan Ocean, thrust over margins of Gondwana-derived continents. The ophiolites of direct interest to the evolution of the India-Arabia plate boundary are found in eastern Oman (the Masirah ophiolite), thrust over the SE Arabian passive margin, in Pakistan (the Bela, Muslim Bagh, and Waziristan-Khost ophiolites), thrust over the NW Indian passive margin, and in Afghanistan (the Kabul-Altimur ophiolite), thrust over continental crust of the Kabul Block [e.g., Badshah et al., 2000; Gnos et al., 1997b].

The ophiolite geology of eastern Oman, Pakistan, and Afghanistan combined is used as a test for the complex plate motion evolution between India and Arabia inferred from the Indian Ocean basins summarized in the previous section (Figure 7). Below, we review the geology of these ophiolites in detail as this constitutes the missing information required to reconstruct the subducted oceanic basins of the NW Indian Ocean. As recently summarized by Hebert et al. [2012] and Huang et al. [2015], the ophiolites in northern Himalaya, from the Kohistan ophiolite-arc complex eastward [e.g., DiPietro et al., 2008], formed along the northern

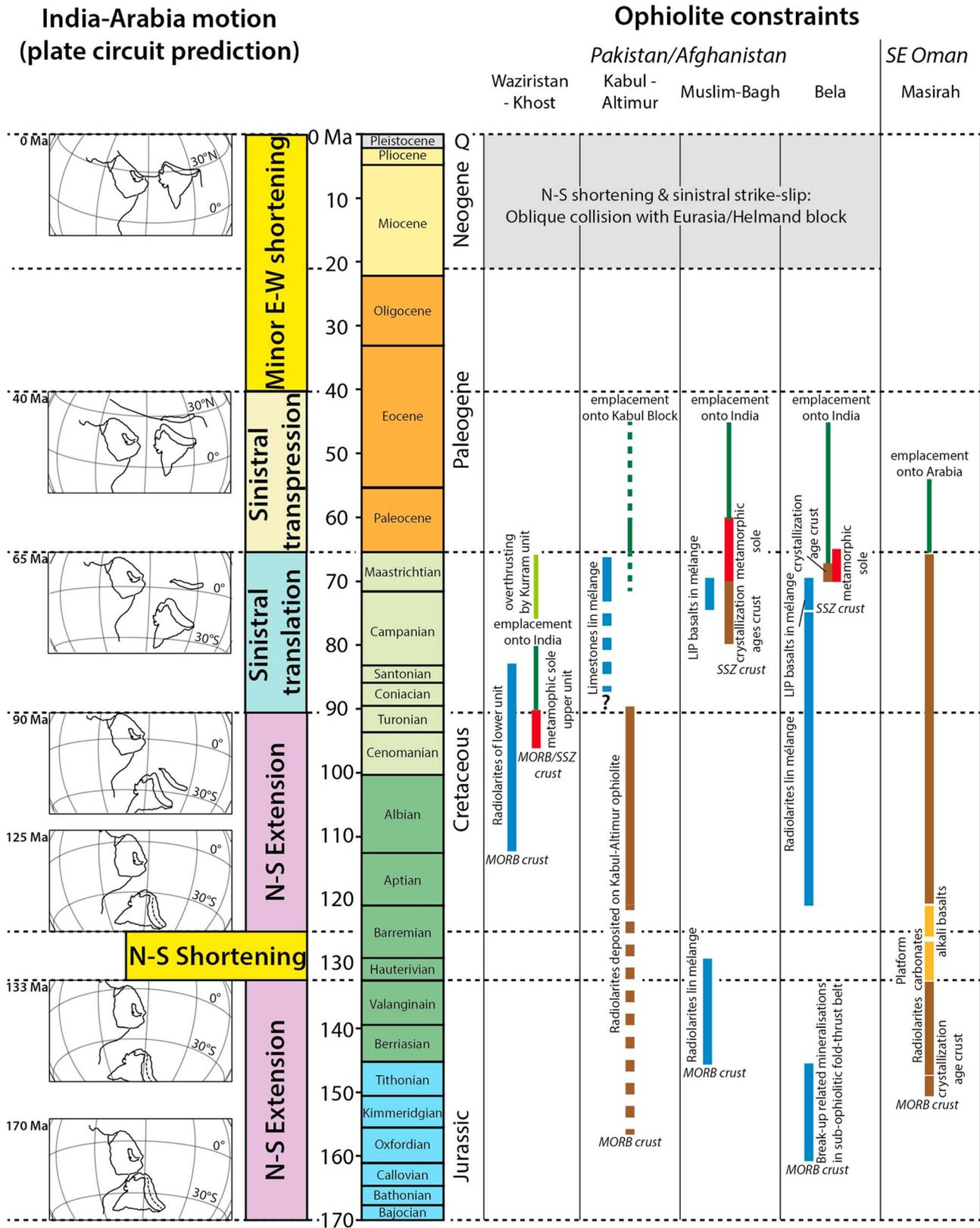


Figure 7. Timescale summary of the Jurassic to present plate tectonic regimes predicted by the plate circuit and the geological and tectonic events that can be deduced from the geology of the Masirah ophiolite of SE Oman and the Bela, Muslim Bagh, Waziristan-Khost, and Kabul-Altumur ophiolites of Pakistan and Afghanistan. Abbreviations: MORB = mid-ocean ridge basalt and SSZ = suprasubduction zone.

Indian plate boundary since Early Cretaceous time and resulted from subduction accommodating the motion of India toward Eurasia. Since our analysis focuses on reconciling India-Arabia plate motion, these ophiolites are of no direct relevance to our analysis.

3.2. Ophiolites of the Western Indian and Kabul Block Continental Margin (Pakistan and Afghanistan)

The ophiolites overlying the western Indian deformed margin form an overall NNE-SSW trending belt that marks the suture zone between India and the Helmand Block, which in turn was part of the deforming southern margin of Asia since the Mesozoic [Montenat, 2009; Tapponnier *et al.*, 1981]. In the northwest of the suture zone, the Kabul Block is sandwiched in between India and the Helmand Block and is separated by ophiolite-containing sutures from both. Four ophiolite complexes are prominent: the Waziristan-Khost ophiolite, overlying the NW Indian margin adjacent to the Kabul Block, the Kabul-Altimur ophiolite, overlying the Kabul Block adjacent to the Helmand Block, and the Muslim Bagh and Bela ophiolites, overlying the NW Indian margin adjacent to the Helmand Block (Figure 6).

The *Waziristan-Khost ophiolite* of central Pakistan-eastern Afghanistan overlies the northwestern Indian margin and is located east of the Kabul Block [Badshah *et al.*, 2000] (Figure 6). The ophiolite complex is folded and consists of ultramafic mantle rocks, underlain by a metamorphic sole consisting of strongly sheared amphibolite facies, metavolcanic, and metasedimentary rocks with a postkinematic blueschist overprint overgrowing the deformation fabrics. The ultramafic sequence continues upward into a crustal sequence of gabbros and sheeted dykes, the latter with a mixed MORB and SSZ geochemical signature [S. R. Khan *et al.*, 2007]. The sheeted dykes currently trend N-S suggesting E-W paleospreading directions if not affected by major vertical axis rotations [S. R. Khan *et al.*, 2007]. Unpublished $^{40}\text{Ar}/^{39}\text{Ar}$ ages on hornblende of the metamorphic sole mentioned in Robinson *et al.* [2000] suggest 96–90 Ma cooling ages with unknown error bars. These may provide an age close to initiation of subduction below the Waziristan-Khost ophiolite. The ophiolite overlies a strongly deformed sequence of pillow lavas and overlying Albian to Santonian cherts and a Campanian olistostrome, which were offscraped from a subducted oceanic lithosphere that was hence at least Albian (~113–100 Ma) in age. The ophiolite and underlying accreted oceanic series were emplaced onto continental margin sediments of India (suggesting a northwestward subduction polarity) around 80 Ma. This age is inferred from dated intrusions which cut the tectonic contacts within the ophiolite and is consistent with ~85 Ma flysch in a synemplacement foredeep to the east [Beck *et al.*, 1996].

The Waziristan-Khost ophiolite was overthrust by Triassic to Upper Cretaceous deep-marine rocks of the Kurram nappe, which is interpreted as the distal eastern passive margin of the Kabul Block. The contact of the Kurram nappe with the ophiolite is sealed by uppermost Maastrichtian sediments [Beck *et al.*, 1996; Robinson *et al.*, 2000]. Latest Cretaceous to Paleocene thrusting also affected the NW Indian margin and is recorded by a reversal in paleocurrent directions in the Sulaiman ranges (i.e., the N-S trending fold-thrust belt along the western Indian margin in Pakistan, Figure 6) from off craton to onto the craton and the delivery of Paleocene to early Eocene ophiolite-derived sandstones to basins on the Indian continent [Waheed and Wells, 1990].

The *Kabul-Altimur ophiolite*, which consists of serpentized harzburgite, lherzolite, dunite, and gabbros, thrusts onto the Kabul Block of Afghanistan (Figure 6). The peridotites are intruded by frequent dolerite dykes. The ophiolite is overprinted by greenschist facies metamorphism and was thrust from the NW to the SE, suggesting a northwestward subduction polarity [Badshah *et al.*, 2000]. Mélange underlying the Altimur ophiolite contains Maastrichtian limestone blocks, and the end of thrusting of the ophiolites onto the Kabul continental block was ascribed to the Paleocene-Eocene (~60–50 Ma) [Tapponnier *et al.*, 1981]. Geochemical data from the Kabul-Altimur ophiolite are lacking. Pelagic sediments overlying the Kabul-Altimur ophiolite include Aptian to Turonian radiolarian cherts [Badshah *et al.*, 2000] and carbonates containing foraminifera with a Jurassic age [Tapponnier *et al.*, 1981] (Figure 7).

The *Muslim Bagh ophiolite* complex (Figure 6) contains two structurally related subbodies of mantle rocks with a metamorphic sole at their base, overlying subophiolitic mélange and imbricated Indian passive margin sediments of Mesozoic age [Mahmood *et al.*, 1995]. The metamorphic sole beneath the peridotite mylonites includes garnet amphibolites grading downward into amphibolites, clinozoisite-amphibolites, and clinozoisite-actinolite schists with calcite-marble interlayers. Calcium-rich pelitic metasediments comprise the lower part of the section. An $^{40}\text{Ar}/^{39}\text{Ar}$ amphibole cooling age of the metamorphic sole gave 65.8 ± 5.7 Ma [Mahmood *et al.*, 1995].

The mantle sequence consists of foliated harzburgite-dunite alternations 200–1000 m thick grading upward into harzburgite with dunite pods and chromitite occurrences. The crustal sequence consists of layered, foliated, and isotropic gabbros overlain by a N140°E trending sheeted dyke complex, locally in the basal part alternating with plagiogranite dykes, yields a U-Pb age at 80.2 ± 1.5 Ma [Kakar *et al.*, 2012]. The orientation of the sheeted dykes, if not affected by major vertical axis rotations, suggests a NE-SW spreading direction, i.e., subparallel to the NW Indian margin. Large parts of the sheeted dyke sequence are metamorphosed at amphibolite facies, interpreted as seafloor metamorphism, with hydrothermal amphiboles giving a $^{40}\text{Ar}/^{39}\text{Ar}$ age of 68.7 ± 1.8 Ma [Mahmood *et al.*, 1995]. The crustal rocks have a SSZ geochemical signature [M. Khan *et al.*, 2007].

M. Khan *et al.* [2007] and Mahmood *et al.* [1995] suggested that subduction initiated along a transform boundary along the west Indian margin, with subsequent strain partitioning of the highly oblique India-Arabia convergence into a westward subduction zone and a strike-slip zone in the overriding plate with the ophiolite oceanic crust generated in a pull-apart setting (similar to the Andaman Sea today [e.g., Curray, 2005; see also Dewey and Casey, 2011]). The ages of the ophiolitic crust suggest that ocean spreading occurred from ~80 to 65 Ma, and the metamorphic sole ages of 65.8 ± 5.7 Ma give a minimum age for the onset of subduction below the ophiolite, after which time fore-arc spreading must have continued to generate the SSZ geochemical signature.

The Muslim Bagh ophiolite overlies a mélangé that contains mafic and ultramafic rocks with a MORB geochemistry, as well as cherts with Lower Cretaceous (Berriasian to Hauterivian, 145.5–130 Ma) radiolarians [M. Khan *et al.*, 2007]. We therefore infer that the west Indian passive margin crust beneath the Lower Cretaceous cherts must be Jurassic or older. In addition, this mélangé contains isolated blocks of pillow lavas that are geochemically similar to basalts of the Deccan Traps. Similar geochemical signatures are found in mafic dikes intruding the thrust passive margin sediments in the nappes underlying the Muslim Bagh ophiolite. These pillow lavas and dikes have $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 73.4–69.7 Ma and are interpreted as precursors of the Deccan large igneous province [Kerr *et al.*, 2010; Mahoney *et al.*, 2002]. The thrust slices of the Indian continental margin below the ophiolite show a shallower marine succession developed from latest Cretaceous to Eocene time when the emplacement of the ophiolites was finalized [Kassi *et al.*, 2009]. In the Miocene this region was further deformed and the NW Indian fold-thrust belt was reactivated during the collision of India with the Helmand Block (see next section and Figure 7).

The Bela ophiolite (Figure 6) is similar to the Muslim Bagh ophiolite in terms of its age, tectonostratigraphic position, and geochemistry. The ophiolite has a SSZ-type geochemistry [Ahmed and Ernst, 1999] and consists of a complete sequence, underlain by a subophiolitic mélangé that consists of ~30% Deccan Traps-related volcanics [Gnos *et al.*, 1998]. It forms a synclinal nappe that represents a klippe overlying Jurassic and Cretaceous passive margin limestones [Zaigham and Mallick, 2000]. The Bela ophiolite has an amphibolite to greenschist facies, ~70–65 Ma metamorphic sole underlying serpentinized harzburgitic mantle, layered peridotite, and gabbro yielding ~69 Ma crystallization ages [Gnos *et al.*, 1998]. Sheeted dykes of the Bela ophiolite strike N130°E (i.e., subparallel to the Muslim Bagh sheeted dykes) and are overlain by a thin extrusive sequence. Peridotite mylonites at the base of the Bela ophiolite give an east southeastward thrust direction. The underlying Kirthar fold-thrust belt that comprises thrust slices of the west Indian passive margin shows no signs of rotation [Klootwijk *et al.*, 1981], which suggests that paleospreading that formed the Bela ophiolite occurred parallel to the west Indian passive margin in a SSZ setting following subduction initiation along a transform fault [Gnos *et al.*, 1998]. The Bela ophiolite is underlain by a fold-thrust belt with up to 1500 m thick thrust slices that contain mid-ocean ridge (MOR) pillow basalts and overlying radiolarites or pelagic limestones, intruded by tholeiitic and alkaline rocks with a Deccan trap-like geochemistry. Foraminifera date the sediments directly overlying the MOR pillow basalts at Albian-Aptian (~110 Ma) to Maastrichtian (~70 Ma) [Gnos *et al.*, 1998]. These are overlain by Deccan Traps-like alkaline volcanic rocks, capped by Paleocene to lower Eocene sediments that are the youngest rocks in the Kirthar fold-thrust belt [Gnos *et al.*, 1998]. A flexural basin developed in front of the Bela ophiolite and is filled with Senonian-Maastrichtian (~75–65 Ma) India-derived sandstones after which thrusting of the ophiolite stopped in the early Eocene (Figure 7) [Allemann, 1979]. Upper Jurassic sedimentary sequences in the Kirthar fold-thrust belt underlying the mélangé contain zinc-lead sulfide and barite mineralizations, related to the Jurassic formation of the west Indian passive margin [Zaigham and Mallick, 2000].

In summary, the age of emplacement of the Bela, Muslim Bagh, and Kabul-Altumur ophiolites appears to be quasi-synchronous, occurring since latest Cretaceous to Paleocene time and lasting until early Eocene time, with a transport direction toward the east. The Kabul-Altumur ophiolite was obducted in Paleocene time following subduction below its oceanic crust. That crust is of probable Jurassic age as indicated by biostratigraphic constraints. The oceanic crust of the Bela and Muslim Bagh ophiolites formed due to NE-SW fore-arc spreading during westward subduction in Late Cretaceous time, partitioning highly oblique convergence. The Waziristan-Khost ophiolites, on the other hand, appear to be older, with subduction starting around 95–90 Ma and ending ~80 Ma, accommodating convergence between the Kabul Block and western India. Emplacement of the Waziristan-Khost ophiolite was followed by thrusting and folding until the Maastrichtian, contemporaneous with the early stages of the emplacement of the Bela, Muslim Bagh, and Kabul-Altumur ophiolites (Figure 7). Reversal of paleocurrent directions from off craton to onto craton in NW India, and delivery of ophiolite debris to the Indian continent, shows that emergence of these ophiolites occurred in the early Paleocene [Khan and Clyde, 2013] and thrusting was finalized in the early Eocene [Allemann, 1979; Kassi et al., 2009].

3.3. Eastern Oman Ophiolites

Oman harbors the famous Semail ophiolite, which is part of an ophiolite belt that formed along the NE Arabian margin during intra-Neotethys subduction accommodating Arabia-Eurasia motion [Hacker, 1994; Hacker and Gnos, 1997; Searle and Cox, 2009]. SE Oman, however, exposes ophiolites that are different in age and formed at plate boundary east of Arabia [Peters and Mercolli, 1998] (Figure 6). The best studied of these is the Masirah ophiolite (see Peters [2000] for a review). This ophiolite is imbricated into two major ophiolitic thrust slices that can be traced over Masirah Island (~20 km E-W). Seismic images suggest that currently ~250 km of Arabian margin is overlain by these ophiolites. The Masirah ophiolite has a Late Jurassic age (~150 Ma based on Tithonian radiolarians and U/Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology on gabbros and basalts), a MORB-type geochemistry, and contains an ophiolite sequence without a metamorphic sole and with a very thin gabbroic crustal sequence (~200–500 m) suggesting that it probably formed in a magma-poor environment [Peters, 2000]. The sheeted dyke complex is subvertical and generally E-W striking with locally NE-SW to N-S trending dykes resulting from local rotations. Paleomagnetic constraints [Gnos and Perrin, 1996; Peters, 2000] suggest an original approximately N-S spreading direction in Late Jurassic to Early Cretaceous time. The youngest sediments below the east Oman ophiolites belt are Maastrichtian (~66 Ma) in age, and northwestward thrusting of the east Oman ophiolites over the Arabian margin continued until the lower Ypresian (~55 Ma) [Gnos et al., 1997a; Immenhauser et al., 2000].

A striking feature of the geological history of the Masirah ophiolite is a major uplift phase in Early Cretaceous time recorded in its sedimentary cover. Very deep marine, subcarbonate compensation depth Upper Jurassic to Lower Cretaceous radiolarites are overlain by upper Hauterivian to lower Barremian (~130 Ma) platform carbonates, associated with alkalic volcanism and plutonism (123 ± 3 Ma zircons) [Immenhauser, 1996a]. Cretaceous intrusive magmatism was restricted to the upper (i.e., distal) thrust slice with 130–125 U/Pb ages; the lower nappe only contains Jurassic MORB-type magmatic rocks but is overlain by 130–123 Ma extrusive alkaline volcanics. The Early Cretaceous uplift has been interpreted as the combined effect of mantle plume activity and transform faulting [Immenhauser, 1996a; Peters, 2000].

In the Aptian to Santonian time (120–85 Ma) an episode of gradual subsidence led to renewed deposition of radiolarites. At 65 Ma a new phase of uplift elevated the ophiolites and they were finally thrust over the SE Arabian margin in the Paleocene [Peters, 2000].

4. Restoring the Cenozoic NW India/Kabul Block—Asia Collision

Before we integrate the ophiolite records and the marine geophysical constraints of Indian Ocean seafloor spreading into a Mesozoic kinematic model, we first review the geological constraints on the deformation in NW India and the Kabul Block associated with the highly oblique Cenozoic collision of India with the Helmand Block of Asia. Some confusion exists on whether the NW Indian ophiolites result from India-Arabia relative motion [e.g., Gnos et al., 1997a] or India-Asia collision [e.g., Kakar et al., 2012; Khan and Clyde, 2013]. We therefore find that understanding the deformation associated with NW India-Asia collision will help us to distinguish and separate the geological expressions of preceding relative India-Arabia motion, which is the main purpose of this paper.

4.1. Geological Constraints

Highly oblique collision between India and Asia along India's northwestern margin led, particularly since Miocene time, to transpressional deformation partitioned over major strike-slip faults and fold-thrust belts along the NW Indian margin, as well as to deformation within the overriding Eurasian Plate in Afghanistan and eastern Iran.

The Eurasian Plate in Afghanistan and Iran consists of the so-called "Cimmerian terranes," which have Proterozoic basement and Paleozoic peri-Gondwana faunas [Sengor and Kidd, 1979; Sengör, 1984; Sengör et al., 1980; Torsvik and Cocks, 2009], separated by the Triassic Paleotethys suture from the Paleozoic Kazakh terrane assemblage [Torsvik and Cocks, 2009] (Figure 6). The Cimmerian terranes are believed to have drifted off Gondwana in Permian time, opening the Neotethys in their wake and drifting toward Eurasia during closure of the Paleotethys to their north [Domeier and Torsvik, 2014; Sengör et al., 1980; Stampfli and Borel, 2002]. The Cimmerian terranes to the south of the Triassic Paleotethys suture in Afghanistan consist of the Band-e Bayan Block to the north, separated from the Helmand Block to the south by a belt of upper Triassic to Jurassic deep-marine turbidite deposits, ophiolite fragments, and blueschists that are unconformably overlain by deformed Barremian and Aptian (~130 Ma and younger) clastic rocks [Debon et al., 1987; Montenat, 2009; Tapponnier et al., 1981]. This Late Triassic-Middle Jurassic flysch belt is normally indicated as the Farah, or Farah Rud "block," separated by the Farah suture in the north and the Panjao suture in the south. Because there is no evidence that the Farah flysch belt is underlain by continental crust but rather appears to be a major accretionary prism derived from oceanic crust, we here consider this region as a wide "Farah-Panjao suture zone," equivalent in setting to, e.g., the Songpan-Garzi zone of Tibet [Yin and Harrison, 2000]. The Helmand Block has been in an overriding plate position relative to Neotethyan subduction since the Late Jurassic, as shown by the Upper Jurassic and Cretaceous Kandahar volcanic arc that has maximum ages of ~155 Ma [Montenat, 2009].

The Paleotethyan suture was reactivated in Cenozoic time as the right-lateral Herat strike-slip fault, which accommodated westward extrusion of the Helmand Block [Tapponnier et al., 1981] (Figure 6). Sedimentary basins along the Herat fault are Oligocene-early Miocene in age and in places may be pull-apart basins; post-Miocene sediments appear not to have been offset by the Herat fault [Tapponnier et al., 1981]. In addition to right-lateral wrenching, the Farah-Panjao suture zone and the Helmand Block experienced Oligocene and younger approximately NW-SE shortening [Debon et al., 1987; Treloar and Izatt, 1993]. The climax of westward extrusion of the Helmand Block thus likely occurred from the Oligocene until sometime in the late Miocene and was associated with NW-SE shortening and possibly E-W convergence in the Sistan suture of eastern Iran (Figure 6). Extrusion on a modest scale may still continue today, accommodated north of the Herat fault [Tapponnier et al., 1981].

The Sistan suture in eastern Iran is a currently N-S trending, intensely deformed belt of ophiolites underlain by a mélangé containing HP-LT metamorphic rocks (blueschists and eclogites) [Fotoohi Rad et al., 2005]. The Sistan Ocean is interpreted to have formed as part of a system of a back-arc basin within the Cimmerian terranes above the Neotethyan subduction zone [Rossetti et al., 2010]. Biostratigraphic data suggest that the Sistan oceanic basin formed in Early Cretaceous time [Babazadeh and De Wever, 2004]. Ages of high-pressure rocks of ~89–78 Ma suggest that subduction of the Sistan Ocean occurred in Late Cretaceous time [Bröcker et al., 2013], but collision-related granitoids as young as late Oligocene are interpreted to result from collision-related lithosphere removal [Rezaei-Khakhajei et al., 2010] and may indicate that shortening continued well into the Cenozoic. Middle Miocene volcanics (14–11 Ma) are only weakly deformed and postdate significant E-W shortening [Pang et al., 2012].

The overall deformation pattern in Eocene to (early) Miocene time of Afghanistan, i.e., right-lateral, E-W trending strike-slip faults in the north and E-W shortening in the Sistan suture, is consistent with a counterclockwise rotation of the Helmand Block [Treloar and Izatt, 1993], although paleomagnetic data from Afghanistan are too sparse to test this scenario. Such a counterclockwise rotation may also explain why volcanism arrested after the Eocene-Oligocene on the Helmand Block [Debon et al., 1987; Faryad et al., 2013], since a rotation would have led to an increasingly oblique India-Helmand convergence, a halt of subduction, and the formation of major left-lateral strike-slip faults.

The most prominent of these strike-slip faults is the left-lateral Chaman fault (Figure 6), which separates the Helmand Block from rocks derived from the Indian Plate. The Chaman strike-slip fault developed a branch around the eastern limit of the Kabul Block known as the left-lateral Gardez fault [Treloar and Izatt, 1993].

Table 2. Qualitative Reconstruction of Tectonic Blocks NW of India Since 50 Ma

Tectonic Block/Region	Direction of Motion	Estimated Amount	Time	Reference
Helmand Block	rotation	65° ccw ^a	50–0 Ma	<i>maximum estimate, this paper</i>
Helmand Block	rotation	45° ccw	30–0 Ma	<i>maximum estimate, this paper</i>
NE Helmand relative to Asia	N-S convergence	850 km	50–0 Ma	<i>maximum estimate, this paper</i>
NE Helmand relative to Asia	N-S convergence	575 km	30–0 Ma	<i>maximum estimate, this paper</i>
Sulaiman lobe	N-S shortening	380 km	21–0 Ma	<i>Jadoon et al. [1994]</i>
Katawaz basin	N-S shortening	140 km	5–0 Ma	<i>this paper; see text</i>

^accw = counter clockwise.

Highly oblique strain between India, the Kabul Block, and the Helmand Block was partitioned into the above described strike-slip faults and the formation of the Sulaiman fold-thrust belt that reformed the western Indian margin and overlying ophiolites. A balanced cross section across the Sulaiman lobe based on seismic sections, boreholes, and field observations, restored 378 km of approximately N-S shortening since 21 Ma (or since late Oligocene) [Métais et al., 2009; Welcomme et al., 2001]. This shortening involved thrusting of an 8–10 km thick sedimentary cover of Paleozoic and Mesozoic Indian continental margin rocks that are underlain by 15–27 km thick crust [Jadoon and Khurshid, 1996]. The main décollement is formed by a salt or marble horizon, and the thrust belt is duplexed beneath a passive roof of Cretaceous and younger carbonates [Banks and Warburton, 1986; Jadoon et al., 1994]. This shortening reflects the late Oligocene-Miocene motion of the Kabul Block relative to India [Haq and Davis, 1997; Jadoon et al., 1994].

Finally, shortening was accommodated in the Katawaz basin, which formed in the suture zone between India and the Helmand Block [Tapponnier et al., 1981; Treloar and Izatt, 1993] (Figure 6). The Katawaz basin (or Belouch range of Afghanistan) is a major, 700 km long, NE-SW trending sedimentary basin filled with mass-transported clastic sediments. It formed in between the western Indian Plate fold-thrust belts to the east and is bordered to the west by the Chaman fault [Treloar and Izatt, 1993]. The basin contains a stratigraphy of Eocene limestones overlain by Oligocene to middle Miocene (~34–14 Ma) turbidite sequences [Carter et al., 2010; Treloar and Izatt, 1993]. The basin extends between the Kabul Block and India and unconformably overlies both. It was probably underlain by transitional to oceanic crust, and the sediments are continental to shallow marine around the edges and deep marine in the interior. The basin deepens and widens toward the SW. Deep-marine turbidites grade upward to lower Miocene shallow marine shales and sandstones. Total stratigraphic thickness exceeds 8 km. The clastic sequence consists of north to NE derived deep-marine turbidites with recycled orogenic compositions, which formed the locus of the proto-Indus fan extending into the Makran [Critelli et al., 1990; McCall, 1997; Qayyum et al., 1996, 1997a, 1997b, 2001].

The Katawaz basin became inverted and intensely shortened in late Cenozoic time during oblique India-Helmand collision [Treloar and Izatt, 1993]. Shortening in the Katawaz basin was parallel to that of the Sulaiman range, but there is no estimate of the total shortening in the Katawaz basin. A Plio-Pleistocene age of Katawaz shortening seems likely given the unconformable cover of a Pleistocene unit over deformed Katawaz stratigraphy and a lower Pliocene unit that is folded with the rest of the sequence [Treloar and Izatt, 1993].

4.2. Eocene-Present India/Kabul-Asia Reconstruction

This reconstruction aims to test whether the Paleocene to early Eocene thrusting of the Pakistan-Afghanistan ophiolites over the west Indian margin reflects the collision of India with Asia, as suggested by, e.g., Khan and Clyde [2013] or occurred prior to this collision, and far south of Asia, as suggested by Gnos et al. [1997a]. We place our reconstruction in the Eurasia-North America-Africa-India plate circuit as detailed in van Hinsbergen et al. [2011a], with updated rotations for the Indian Ocean as detailed in section 2 (Table 1), and we use reconstructions of intra-Asian deformation in Iran and Tibet detailed in McQuarrie and van Hinsbergen [2013] and van Hinsbergen et al. [2011b], respectively. The reconstruction is made using GPlates plate reconstruction software (www.gplates.org [Boyden et al., 2011]), and the digital model is available as supporting information. Estimates for amounts of rotation and shortening predicted based on arguments below or given in the literature are listed in Table 2.

We estimate the maximum age of collision of India with the Helmand Block by reconstructing the amount of shortening and extrusion in the overriding, southern portions of Asia, i.e., in Afghanistan, as well as the amount of shortening in the Sulaiman ranges and Katawaz basin. In particular, the amount of shortening

in Afghanistan, accommodated within and particularly to the north of the Helmand Block, is poorly constrained. To arrive at the oldest reasonable collision age of NW India with the Helmand Block, we therefore reconstruct a scenario of maximum overriding plate shortening. This may be tested in the future when more geological data from Afghanistan become available.

To estimate the maximum reasonable amount of Cenozoic intra-Asian deformation in Afghanistan, we make the assumption that the uppermost Jurassic and Cretaceous Kandahar volcanic arc formed part of a contiguous volcanic arc, connecting to the west to the contemporaneous arc of Iran [Agard *et al.*, 2011], and to the east to the Gangdese volcanic arc of Tibet [Chiu *et al.*, 2009], connected through either the Kohistan intraoceanic arc segment [Heuberger *et al.*, 2007] or through the arc north of the Shyok suture of the Hindu Kush region [Bouilhol *et al.*, 2010, 2013]. This would suggest that the Helmand Block may be equivalent to the Lhasa block of southern Tibet, as postulated by Tapponnier *et al.* [1981]. This reconstruction would suggest up to $\sim 65^\circ$ counterclockwise rotation of the Helmand Block since ~ 50 Ma around a rotation pole in the southeast of the block and $\sim 45^\circ$ since ~ 30 Ma. In addition, such a reconstruction would suggest as much as 850 and 575 km of intra-Asian convergence since 50 and 30 Ma, respectively, which should be accommodated between the Helmand Block and semirigid Asia. Such a large amount of convergence in such a narrow region should lead to intracontinental subduction, similar to subduction in the Pamir [Negredo *et al.*, 2007; Sobel *et al.*, 2013] (Figure 8), of which evidence should be found in the present-day mantle structure. Our maximum intra-Asian convergence scenario would hence require that the Hindu Kush slab, a >500 km long, E-W striking and northward dipping slab in the upper mantle to the north of the Helmand Block (see Figure 8 for location), represents Asian lithosphere (as suggested by Kazmin *et al.* [2010]) instead of Indian Plate lithosphere as normally interpreted [e.g., Lister *et al.*, 2008; Negredo *et al.*, 2007]. If the Hindu Kush slab represents Indian lithosphere instead, the amount of intra-Asian shortening in Afghanistan should be much less, and the NW India-Helmand collision age will be younger than reconstructed here.

The best constraints on the amount of shortening accommodated by Indian continental underthrusting come from the balanced sections of the Sulaiman lobe, giving ~ 380 km N-S shortening since 21 Ma [Jadoon *et al.*, 1994] between the Kabul Block and India [Haq and Davis, 1997]. We reconstruct this amount of shortening and assume a constant 21–0 Ma shortening rate. The amount of shortening accommodated in the Katawaz basin is unconstrained, but the timing of its intense shortening is constrained to Pliocene, with Pleistocene sediments unconformably covering the basin [Treloar and Izatt, 1993] (here reconstructed to be between 5 and 1 Ma). In this time period, the Herat fault accommodating rotation and extrusion of the Helmand Block was inactive [Treloar and Izatt, 1993] and we accommodate all India-Asia convergence between 5 and 1 Ma in the Katawaz basin, i.e., ~ 150 km (Table 2). The resulting reconstruction is portrayed in Figure 8. The assumption of an intra-Asian origin of the Hindu Kush slab yields a maximum collision age between the Kabul Block and the Helmand Block of ~ 30 Ma; if the Hindu Kush slab represents Asian lithosphere, this collision age would be close to 20 Ma.

To the northeast of our study area, geological and paleomagnetic evidence constrains collision of the Tibetan Himalaya, representing the northernmost continental lithosphere of the Indian Plate, with the Lhasa terrane of southern Tibet, around 55–50 Ma [e.g., Najman *et al.*, 2010; Dupont-Nivet *et al.*, 2010; Garzanti, 2008; Huang *et al.*, 2013]. Along the NNE-SSW stringing, NW Indian margin, however, oceanic subduction likely continued much longer into the Oligocene and continental rocks of Greater India did not extend sufficiently far westward to undergo collision with the Helmand Block before that time. At 55 Ma, when sedimentological data demonstrate that the ophiolites of Pakistan were emplaced onto the NW Indian margin [Khan and Clyde, 2013], the position of NW India (corrected for Miocene shortening) was at least ~ 2000 km from the Helmand Block (Figure 8). We therefore conclude that Paleocene-early Eocene ophiolite emplacement onto the NW Indian margin was unrelated to the India-Asia collision.

5. Mid-Jurassic-Paleocene Kinematic Model

The geophysical and geological information presented in the previous sections are now used to develop a new kinematic model for the NW Indian Ocean. This model is presented as a series of reconstructions from Mid-Jurassic (170 Ma) to early Cenozoic (50 Ma) illustrating the evolution of plate boundaries between East Africa/East Arabia and west India and their continuation toward the Neotethys realm (Figure 9).

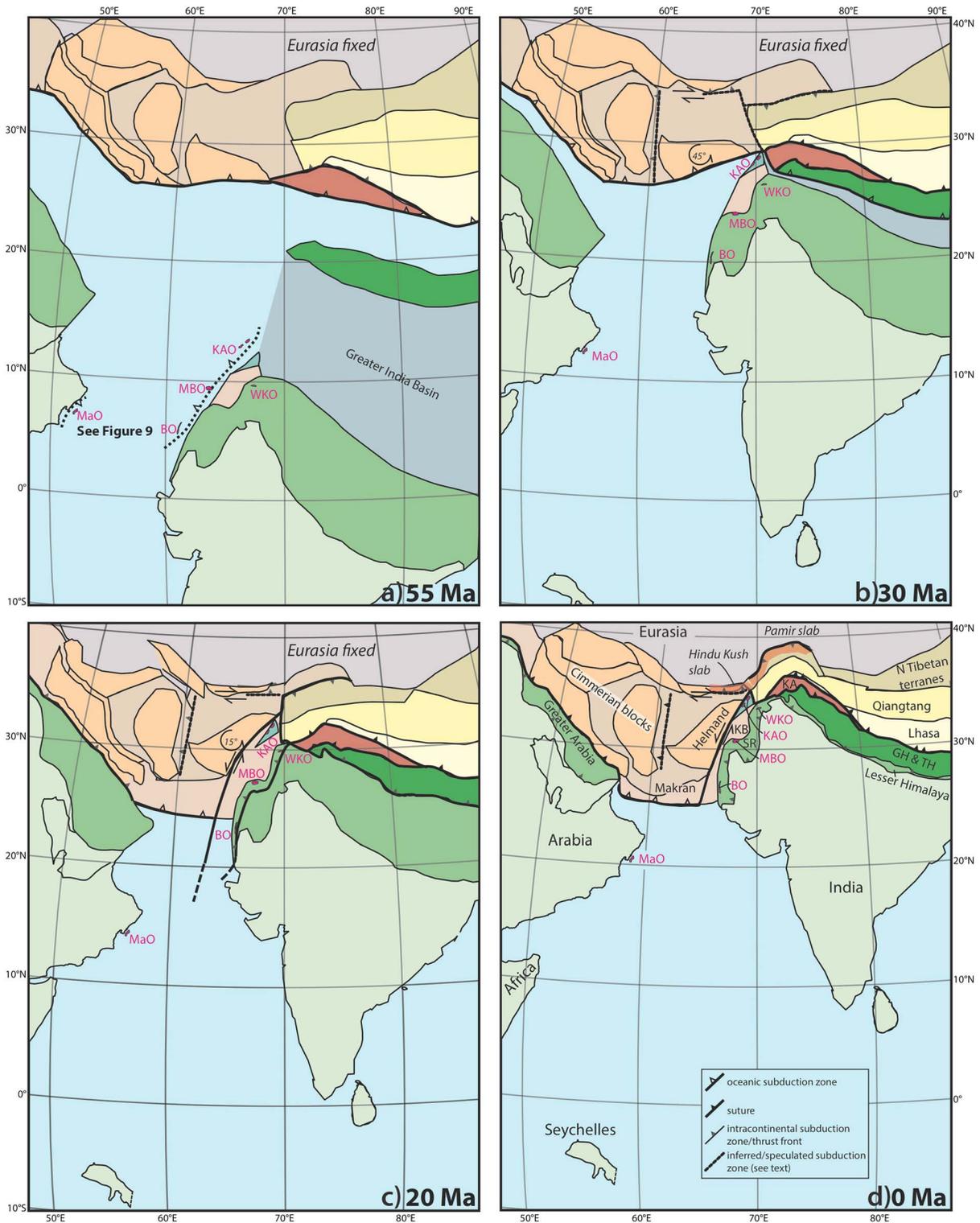


Figure 8. Reconstruction of the collision between NW India/Kabul Block and the Helmand Block of Asia collision in the Cenozoic. This reconstruction is a maximum collision age end-member, using a maximum intra-Afghanistan shortening assuming that the Hindu Kush slab resulted from intracontinental subduction in Asia. Plate circuit is as in *van Hinsbergen et al.* [2011a], with modifications for the Indian Ocean as in Table 1. Reconstruction of intra-Asian deformation in Iran adopted from *McQuarrie and van Hinsbergen* [2013], intra-Asian deformation in Tibet from *van Hinsbergen et al.* [2011b], and paleogeography of Greater India from *van Hinsbergen et al.* [2012]. Abbreviations: BO = Bela ophiolite, GH and TH = Greater Himalaya and Tibetan Himalaya, KA = Kohistan Arc, KAO = Kabul-Altimur ophiolite, KB = Katakawaz basin, MaO = Masirah ophiolite, MBO = Muslim Bagh ophiolite, SR = Sulaiman ranges, and WKO = Waziristan-Khost ophiolite. See supporting information for GPlates reconstruction files.

5.1. Middle Jurassic (Bajocian, 170 Ma)

The Neotethyan Ocean bordered northern Gondwanaland, including the Arabian northeastern margin, the Indian northern margin, and the western and northern Australian margins (Figure 9a). The Cimmerian blocks collided with Eurasia in the Late Triassic [e.g., *Muttoni et al.*, 2009], and ongoing Neotethys spreading was accommodated by subduction below the Iranian and perhaps Helmand margin in Jurassic time [Agard *et al.*, 2011; *Montenat*, 2009]. The reconstructed Neotethyan mid-ocean ridge (Figure 9a) is positioned assuming symmetric seafloor spreading between the Cimmerian blocks and the northern margins of Arabia and India. The Karoo rifting, which started in the Permian within Gondwanaland, resulted in breakup between the East African margin, Madagascar, and East Antarctica by 170 Ma leading to the formation of the Mozambique [Leinweber and Jokat, 2012] and West Somali oceanic basins [Gaina *et al.*, 2010, 2013]. The Tibetan Himalayan block was located within 1000 km of the modern northern limit of undeformed India [Ali and Aitchison, 2005; van Hinsbergen *et al.*, 2012], and the eastern continuation of the Tibetan Himalayan lithosphere was juxtaposed to the western Australian margin (Figure 9a).

Note that in our prebreakup reconstruction, a number of microcontinents (like the Elan Bank [Gaina *et al.*, 2007], Seychelles [e.g., *Ganerød et al.*, 2011], and Socotra [Denele *et al.*, 2012]) are also restored close to the rifted margins from where they originated, but we show their present-day shapes and sizes. Thus, present-day continent-ocean boundaries border the main continental blocks, and the overlap shown in the reconstructions between microcontinental margins and adjacent passive margins indicates the location and inferred amount of extension during breakup.

5.2. Late Jurassic (Tithonian, 150 Ma)

Vigorous southeastward motion of the India/Madagascar/Antarctica/Australia relative to Eastern Africa (i.e., Somali block, to which Arabia was attached until the Miocene opening of the Gulf of Aden [Fournier *et al.*, 2010]) created a long stripe of oceanic crust, first in the Mozambique and West Somali basins [Gaina *et al.*, 2010; Leinweber and Jokat, 2012] and subsequently in the North Somali Basin (see section 2.1). Extension created oceanic crust (and thinned continental margins, as shown by the stratigraphy of the southern Sulaiman ranges [Zaigham and Mallick, 2000]) between the northwestern margin of India and eastern Arabia and likely continued within the Neotethyan domain along a zone parallel to the expected fracture zone direction that formed during Permian to Jurassic Neotethys opening. The Late Jurassic age of the crust of the Masirah and probably also the Kabul-Altinur ophiolites and the MORB composition of the former (Figures 7 and 9b) suggest that these formed along the mid-ocean ridge at this time (see section 3) and were subsequently transferred to the African/Arabian and Indian Plates, respectively (Figure 9b). Upper Jurassic radiolarites and MORB basalts preserved in the mélanges below the Bela and Muslim Bagh ophiolites are consistent with the ocean spreading phase portrayed in Figure 9b. The paleolatitude of basalt sample from Masirah ophiolite was constrained by paleomagnetic studies at $38 \pm 12^\circ\text{S}$ [Gnos and Perrin, 1996]. The Global Apparent Polar Wander Path of Torsvik *et al.* [2012] places our reconstructed position of the Masirah ophiolite at $20\text{--}26^\circ\text{S}$ between 150 and 130 Ma, just within the error bars of paleomagnetic constraints; a paleolatitude of 38°S overlaps with India or Madagascar at this time.

5.3. Early Cretaceous (Hauterivian, 130 Ma)

The Indian Plate rifted and drifted off eastern Gondwana around 132 Ma when it changed its direction toward the north upon opening of the Enderby basin (Figure 9a) between its southeastern margin and the Enderby Land region of East Antarctica [Gaina *et al.*, 2007]. An oceanic age of at least Early Cretaceous age (coinciding with chron M9–128 or 129 Ma according to the *Gee and Kent* [2007] or *Gradstein et al.* [1994] timescales, respectively) has been interpreted in the Perth Abyssal Plain, west of Australia [Gibbons *et al.*, 2012; Williams *et al.*, 2013], indicating that India drifted away from both Antarctica and west Australia at the same time (Figure 9c). Seafloor spreading ceased in the North Somali Basin (see section 2.1 and Figure 3), and the seafloor spreading rate dropped in the West Somali Basin. A convergent plate boundary bordered the entire northwestern and northern part of the Indian Plate (Figure 9c). Although no direct evidence of subduction is found in the geological record, we note that this predicted phase of convergence between India and Arabia coincides with the rapid uplift of Masirah ophiolites to sea level around 130 Ma [A. Immenhauser, 1996b]. The ocean island basalt composition of contemporaneous volcanics in the stratigraphy of the Masirah ophiolite led these authors to suggest that uplift resulted from a plume-related

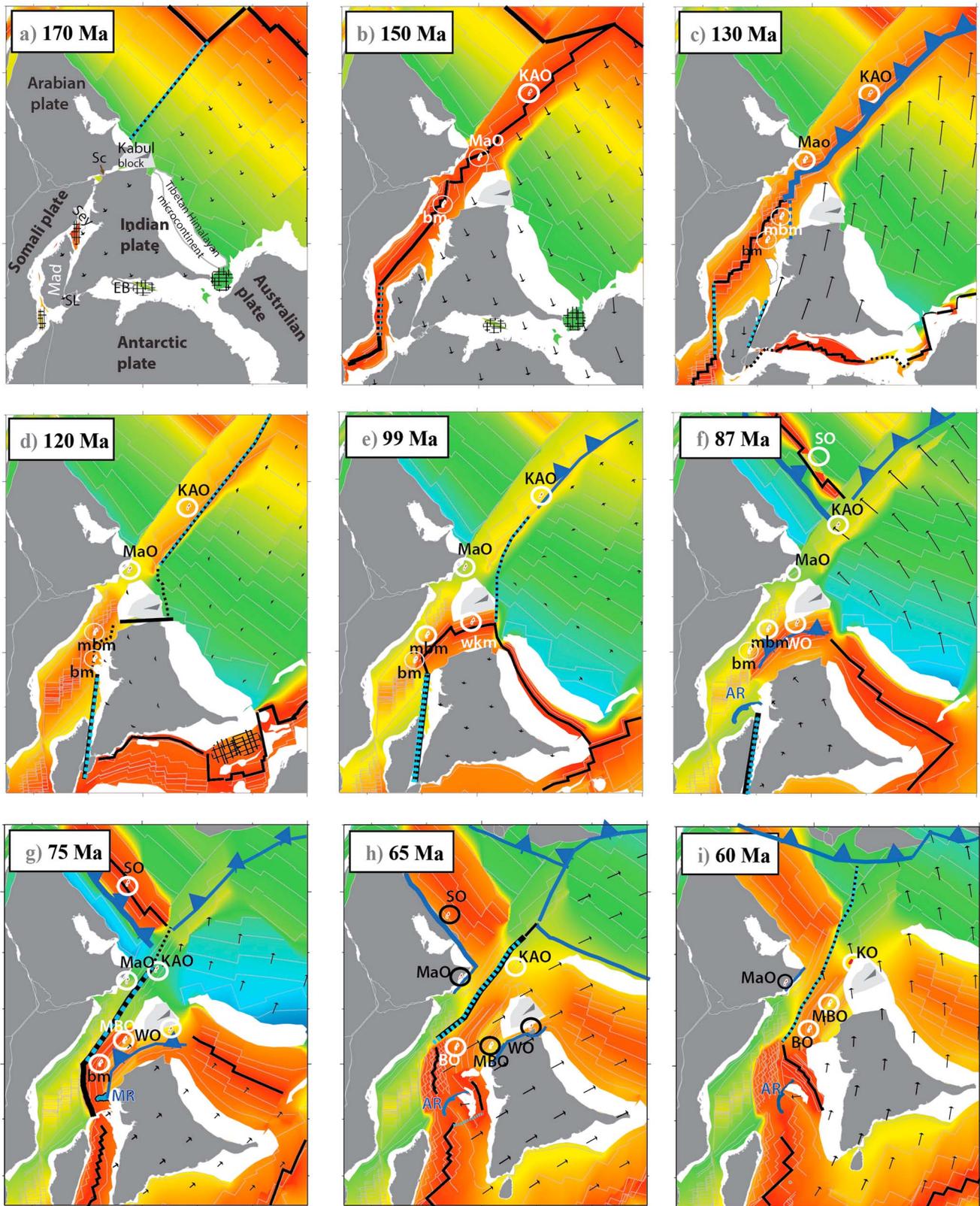


Figure 9. Reconstructions of continental blocks and oceanic basins in the NW Indian Ocean since the Jurassic (Somali Plate is shown in its present-day position). Abbreviations: AR = Amirante Ridge, EB = Elan Bank, Mad = Madagascar, MR = Murray Ridge, Sey = Seychelles, and Sc = Socotra. Ophiolite abbreviations as in Figure 8.

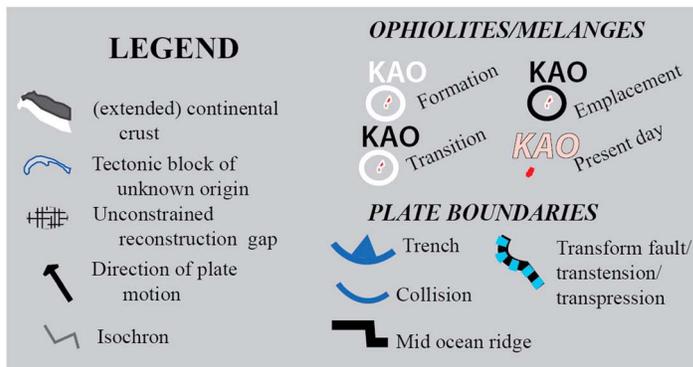
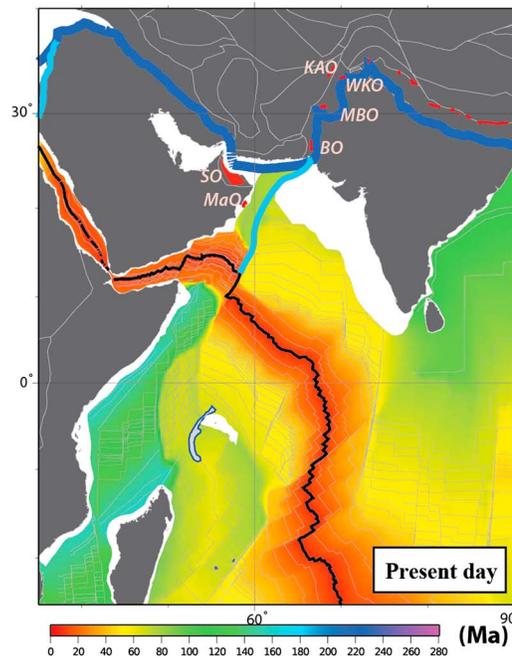
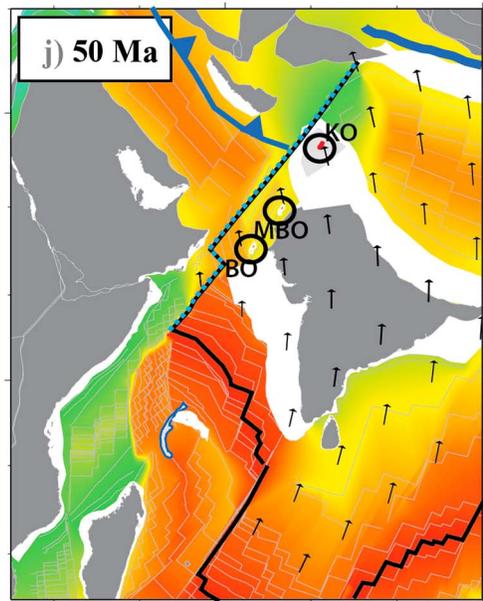


Figure 9. (continued)

thermal mantle anomaly, but our reconstruction suggests that compression-related uplift may have at least contributed to this uplift. *Smewing et al.* [1991] dated small granite bodies in the Masirah ophiolite with K-Ar geochronology at 146–124 Ma, and based on their potassic nature, they inferred that these must have been derived from continental crust. Consequently, this has been interpreted as evidence for an early phase of thrusting of the Masirah ophiolites onto continental margin rocks. Modern dating and geochemical analyses are required to draw firm conclusions, but the Lower Cretaceous of the Masirah ophiolite may reflect the convergence predicted by the plate circuit.

We postulate that shortly after this time the eastern and southeastern parts of the North Somali Basin were also consumed due to the convergence between western India and Somalia/Arabia. The Ars and Carlsberg fracture zones and the Chain Ridge (Figure 1) may have originated as compressional features in the Early Cretaceous and acted as weakness zones in subsequent tectonic plate reorganizations.

5.4. Early Cretaceous (Barremian/Aptian, 120 Ma, to Turonian, 90 Ma)

A change in plate boundary locations within 2–3 Ma have been reconstructed from the southern, eastern, and northeastern Indian Plate margin around 120 Ma. A ridge jump occurred after chron M2 in the Enderby basin [*Gaina et al.*, 2007] and after M0 in the Perth Abyssal Plain [*Williams et al.*, 2013]. India's convergence toward the East African/Arabian margin ceased soon after it started. Around 120 Ma, divergence between India and Arabia (with the Kabul Block being attached to the Arabian Plate) was reestablished (Figures 9d and 9e), lasting until the breakup of India/Seychelles and Madagascar that occurred after 92 Ma and led to the opening of the Mascarene Basin [*Bernard and Munsch, 2000*]. Radiolarites of Albian to Santonian age in the accreted units below the Waziristan-Khost ophiolite (Figure 7) suggest that oceanic crust of 112 to 84 Ma old may have been created between India and the Kabul Block which confirms that the Kabul Block was probably attached to the African/Arabian Plate in this time interval (Figures 9d and 9e).

5.5. Coniacian (87 Ma)

The breakup of India/Seychelles from Madagascar and the early opening stages of the Mascarene Basin led to a counterclockwise rotation of India relative to Arabia and up to ~400 km of convergence. The timing of this event is not well constrained and started from an ill-defined stage during the Cretaceous Quiet Zone likely commencing with the emplacement of the Madagascar Large Igneous Province (starting around ~92 Ma [*Torsvik et al.*, 2000]) and ended at chron 34 (83–84 Ma). The metamorphic sole of the Waziristan-Khost ophiolite with an age of ~96–90 Ma, and the geochemical suggestion that it formed at least in part above an active subduction zone (Figure 7), suggests that this convergence was accommodated by subduction between India and the Kabul Block (Figure 9f). The emplacement of the Waziristan-Khost ophiolite onto the west Indian margin around 80 Ma (Figure 7) is consistent with the end of convergence predicted from the plate circuit.

We also speculate that the Amirante Ridge may have been formed between 87 and 80 Ma as a direct result of the counterclockwise motion of India and the convergence with the neighboring old crust from the West Somali Basin. The 82 ± 16 Ma age from K/Ar analysis of a grab sample collected from this ridge [*Fisher et al.*, 1968] fits well with this interpretation.

5.6. Campanian, 75 Ma, to Maastrichtian, 65 Ma

From approximately 83–70 Ma, India-Arabia motion was essentially parallel to the NW India and SE Arabia, respectively, passive margins (Figures 9g and 9h). The recent U/Pb age of 80.2 ± 1.5 Ma from plagiogranites in the Muslim Bagh ophiolite [*Kakar et al.*, 2012] and the SSZ geochemical signature recorded from crustal rocks in that ophiolite [*M. Khan et al.*, 2007] (although these were not obtained from the same outcrop) suggest that subduction already occurred at that time at the Arabia-India plate boundary. As interpreted before by *Mahmood et al.* [1995] and *M. Khan et al.* [2007], spreading at the plate boundary probably occurred in narrow ridge segments along an overall transform plate boundary. We provide a 3-D block diagram of the proposed configuration in Figure 10. If there was already subduction at this plate boundary around 80 Ma, it was likely highly oblique, similar to the modern Andaman Sea basin above the Andaman subduction zone [*Curry, 2005*].

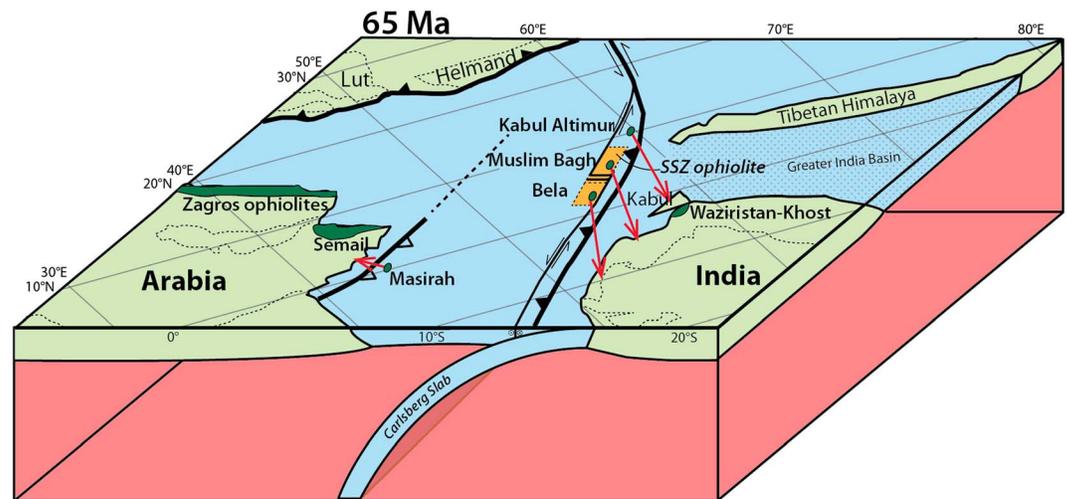


Figure 10. Three-dimensional block diagram of the uppermost Cretaceous to early Eocene plate boundary configuration between India and Arabia as inferred from the ophiolite ages, chemistry, and spreading directions summarized in this paper. Highly oblique convergence is partitioned into overriding plate strike slip with a pull-apart basin above a subduction zone that consumes Indian plate subduction. Underthrusting below the overriding oceanic plate obducted suprasubduction zone (SSZ) ophiolites (Bela and Muslim Bagh) that formed in the pull-apart basin above the oblique subduction zone, as well as ophiolites that contain much older, presubduction oceanic crust of the Jurassic or Early Cretaceous (e.g., Kabul-Altimur ophiolite).

Note that two features located in the proximity of the western/northwestern Indian margin—the Murray and Amirante ridges—may have formed or been affected by the changes in plate boundaries between the NW Indian margin, the Kabul Block, and the Seychelles block. The Murray Ridge was described as a partly continental sliver and a partly volcanic ridge of Late Cretaceous to Paleocene age, and its position at 75 Ma is at the southern end of the trench between the Kabul and Indian margin (Figure 9g). This is in accordance with the results of *Burgath et al.* [2002], who described a SSZ geochemical signature of dredge samples from peridotites and basalts of the ridge. Subsequent detachment of the Seychelles block as an independent microplate from the western Indian margin and its counterclockwise rotation created compression at its northwestern corner and may have affected (or created) the Amirante Ridge, as also suggested by *Ganerød et al.* [2011] (Figure 9h).

5.7. Paleocene, 60 Ma, to Early Eocene, 50 Ma

From ~63 to 50 Ma, India and Arabia underwent highly oblique convergence (Figures 9i and 9j). The ages of the metamorphic soles of the Bela and Muslim Bagh ophiolites are circa 65 Ma [*Gnos et al.*, 1998; *Mahmood et al.*, 1995] demonstrating that subduction was active between India and Arabia at this time, either starting or continuing with ongoing trench-parallel spreading in the immediate fore arc [e.g., *Dewey and Casey*, 2011]. During this time period, the Bela, Muslim Bagh, and Kabul-Altimur ophiolite were thrust over the continental margins of India and the Kabul Block, respectively, and the Kabul Block thrust over the already emplaced Waziristan-Khost ophiolite forming the Kurram Nappe (Figures 6 and 7). Simultaneously, the Masirah ophiolite was uplifted and thrust over the Arabian margin between circa 65 and 55 Ma [*Gnos et al.*, 1997b; *Immenhauser et al.*, 2000] showing that the plate boundary zone between India and Arabia was complex, with the convergent component partitioned over at least two thrust/subduction systems. The final oceanward limit of the western Indian margin which is preserved today is shown in Figure 9i and includes several continental ridges (like the Laxmi and Murray ridges) and basins that formed before 60 Ma as described by several authors [e.g., *Calvès et al.*, 2011].

5.8. Eocene to Present

Relative motion between India and Arabia slowed down after the early Eocene, mainly owing to the dramatic deceleration of India after 50 Ma [*Copley et al.*, 2010; *Molnar and Stock*, 2009; *Patriat and Achache*, 1984; *van Hinsbergen et al.*, 2011a]. Deformation of the NW Indian margin and overlying ophiolites after the Eocene was related to its collision with the Helmand Block of Afghanistan (Figure 8), and deformation features

related to relative India-Arabia motion were restricted to the Owen Fracture Zone [Fournier *et al.*, 2008b, 2011]. The present-day position of the ophiolites described in this study and the age and configuration of oceanic basins in the NW Indian Ocean are shown in Figure 9.

6. Tomographic Constraints

As a critical test of our model, we explore modern mantle structure for positive seismic velocity anomalies that could correspond to lithosphere that subducted along the Arabia-India plate boundary since the Cretaceous. We focus on the Upper Cretaceous to lower Eocene subduction zone that culminated in the emplacement of the Bela, Muslim Bagh, and Kabul-Altimur ophiolites. Although deep mantle anomalies below the Indian Ocean, consistent with mid-Mesozoic subduction, were previously tentatively interpreted as slabs [van der Meer *et al.*, 2010], we refrain from linking these to the ~130–125 Ma and ~88–84 Ma phases of convergence in our model. The low amount of convergence (330–400 km and 140–300 km, respectively, Figure 2) and the short time spans of subduction, as well as the uncertainties in absolute plate motion reconstructions for those time intervals, render a meaningful correlation not possible at this stage. We also refrain from interpreting the mantle structure below Iran, where among others the Sistan Ocean must have closed from Late Cretaceous time onward. Such interpretations require a kinematic reconstruction and understanding of the history of back-arc basin opening and closure in the Cimmerian terranes at a level of precision that is currently unavailable.

Previous tomographic studies have predominantly focused on anomalies in the upper and lower mantle below India, to identify Neotethyan crust that was consumed as a result of the N-S closure of the Neotethys (Figure 11a). Major E-W to NW-SE trending high wave speed anomalies were identified in the lower and upper mantle below Iran [Agard *et al.*, 2011; Hafkenscheid *et al.*, 2006; van der Meer *et al.*, 2010] and India and Tibet [Hafkenscheid *et al.*, 2006; Li *et al.*, 2008; Replumaz *et al.*, 2004, 2010; Van der Voo *et al.*, 1999; van Hinsbergen *et al.*, 2012]. In addition, a WNW-ESE trending belt of lower mantle anomalies was identified to the south of the main Neotethyan anomaly below Iran, interpreted by van der Meer *et al.* [2010] as representing intraoceanic subduction that culminated in the emplacement of the Anatolian-Arabian ophiolites. Because of the overall E-W trend of these subduction zones, most published seismic tomographic cross sections are N-S in orientation.

The oblique Late Cretaceous to Eocene subduction zone between Arabia and India in our model (Figures 9 and 10) must have had a NNE-SSW to NE-SW strike and should have accommodated at least ~850 km of subduction (alongside at least 1200 km of left-lateral transform motion, Figure 2). To test whether an anomaly consistent with these minimum dimensions can be identified in tomography, we explore the mantle structure below western India, eastern Arabia, and the West Indian Ocean as depicted by tomographic models (Figure 11 and supporting information) and shown in horizontal and vertical cross sections of the UU-PO7 *P* wave model [Amaru, 2007; van der Meer *et al.*, 2010] as well as the S40RTS *S* wave model of Ritsema *et al.* [2011].

To explore the regions in the mantle where the slabs predicted by our model are expected, we place the reconstruction in a mantle reference frame and rotate the plates back to ~60 Ma, when the plate circuit and geological record indicate that a substantial amount of shortening/subduction already occurred between Arabia and India. In addition, the geological evidence shows that subduction that led to emplacement of the Semail ophiolite had arrested around 70 Ma [Searle and Cox, 2009] and anomalies related to that subduction zone are thus expected to reside deeper in the mantle. These should thus be discernable from anomalies associated with emplacement of the west Indian ophiolites (assuming that slab sinking rates do not vary greatly over short distances). We have tested two global reference frames: one based on global hot spot tracks [Dobrovine *et al.*, 2012] and another one a modified version of the subduction global reference frame [van der Meer *et al.*, 2010]. The model using the global moving hot spot reference frame of Dobrovine *et al.* [2012] suggests that the ocean between India and Arabia had a longitudinal span from ~50 to 65°E, and subduction is expected to occur somewhere between the equator and 25°N, depending on the way oblique subduction was partitioned (Figure 11b). The true polar wander-corrected paleomagnetic reference frame adjusted in longitude using the slab-fitting approach of van der Meer *et al.* [2010] suggests a similar longitude and places the continents a few degrees farther south. The area occupied by the latest Cretaceous to early Paleocene ocean between India and Arabia thus corresponds to the area offshore Somalia and SE Arabia, presently mainly occupied by the East Somali Basin (Figure 1).

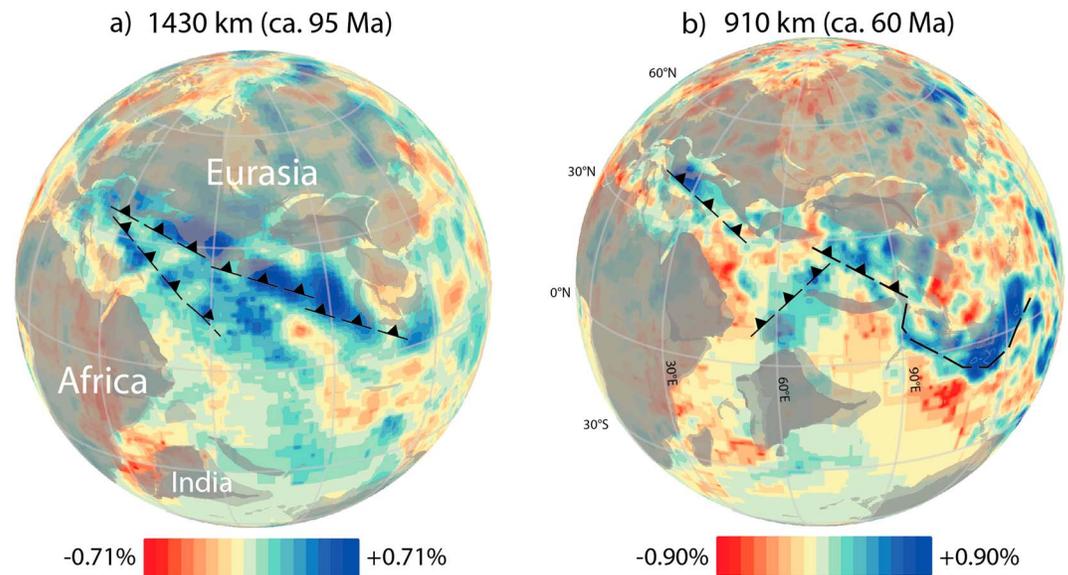


Figure 11. Horizontal cross sections through the UU-07 tomographic model [Amaru, 2007; van der Meer et al., 2010] at 910 and 1430 km (roughly corresponding to subducted slabs of 60 and 95 Ma—see text for discussions) with paleopositions of tectonic blocks and inferred subduction zone locations in the global absolute reference frame of Doubrovine et al. [2012]. Note the NNE-SSW oriented group of positive seismic anomalies which we have identified as the Cretaceous “Carlsberg slab.”

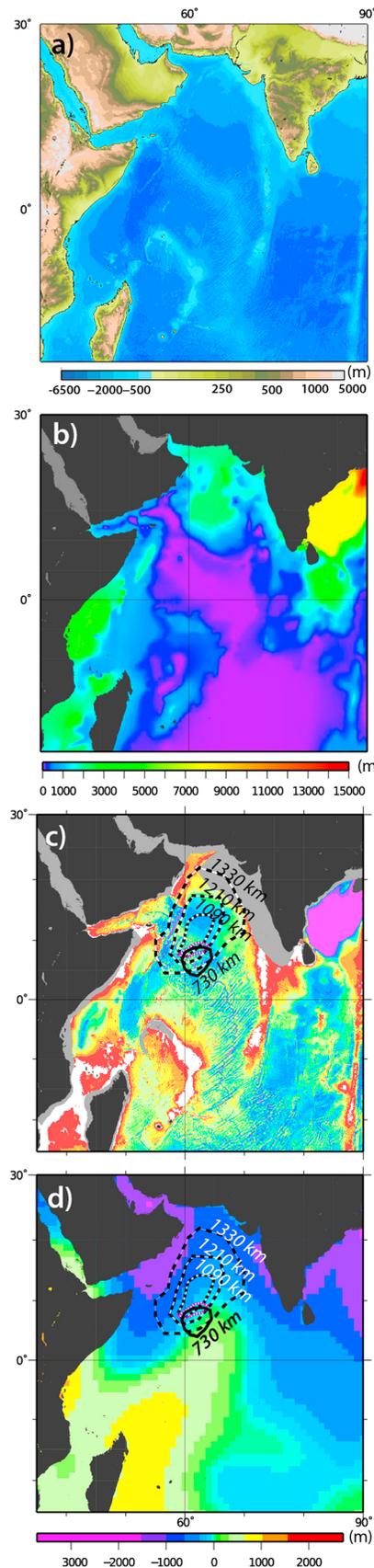
Cross sections across the UU-P07 model (Figure 11 and supporting information) reveal a high-velocity anomaly below the present-day East Somali Basin at a depth of ~800–1400 km. A similar, albeit more smeared anomaly is identified in the S40RTS model (supporting information). The anomaly is oriented NNE-SSW between latitudes of ~5 and ~25°N, consistent with the orientation and location predicted by our model. If this anomaly represents at least 850 km of lithosphere, the slab should have been thickened by at least a factor of ~1.5. Previous estimates of slab thickening associated with lower mantle penetration ranged from 1.5 to 2 [Hafkenscheid et al., 2006; van Hinsbergen et al., 2005]. Assuming that the top of the slab visible at 910 km depth is 60 Ma old, the average slab sinking rate should be ~15 mm/yr, which is within the range of the global average estimated at 12 ± 3 mm/yr [van der Meer et al., 2010] or 13 ± 3 mm/yr [Butterworth et al., 2014].

We thus argue that seismic tomographic images of the upper part of the lower mantle are consistent with the inferred Late Cretaceous to Paleocene/early Eocene subduction history between India and Arabia (and the Kabul Block situated between them). Since this NE-SW striking slab has not been identified before, we propose to refer to it as the Carlsberg slab, named after its modern geographic location below the active Carlsberg Ridge.

7. Discussion

7.1. Constraints on Absolute Plate Motions

A regional tectonic plate circuit in the Indian Ocean suggests that several phases of compression and extension occurred between the northwestern/western Indian margin and the Somali/Arabia margin since the Jurassic. Oceanic crust preserved in the North Somali, Owen, and Amirante basins holds clues to the timing and orientation of relative motion between these margins, but the interpretation of geophysical data is nonunique. When combined with information from obducted ophiolites on these margins and other geological data, a more robust kinematic scenario can be constructed. Three episodes of convergence and possible subduction may have taken place from the Cretaceous to early Cenozoic—and the remnants of the resulted subducted slabs may be imaged by recent tomographic models. The longest-lived compressional episode took place from the Late Cretaceous to Eocene (as dated through the Indian Ocean plate circuit) and probably formed a NNE-SSW striking, subduction zone between India and Arabia (Figure 9). The 80 Ma age of the Muslim Bagh ophiolite would show that (highly oblique) subduction



between India and Arabia started at least by 80 Ma. Note that this prediction is based on the assumption that the SSZ geochemical signature reported by *M. Khan et al.* [2007], is characteristic for the entire ophiolite. In the previous section we showed that a NE-SW striking slab is present at the predicted location of this subduction zone at a depth of 800 to 1400 km, corroborating the predictions from the marine geophysical and geological records.

This NNE-SSW striking slab can play an important role in further constraining absolute plate motions. *van der Meer et al.* [2010] and recently *Butterworth et al.* [2014] have used a “slab-fitting” approach to constrain absolute plate motions. This approach uses the global plate circuit placed in a true polar wander-corrected paleomagnetic reference frame, and adjusts this reconstruction in (paleomagnetically unconstrained) longitude to yield an optimal fit between subduction zones predicted by the plate circuit and constrained in the geological record, and slabs in the underlying mantle. Longitudinal oriented slabs, such as the ones identified and tied to the plate tectonic and geological record in this paper, are keys to this approach, as they span a narrow paleolongitudinal band. We foresee that the India-Arabia plate boundary, which can be recognized in the structure of the deep mantle and has a history dating back to at least the Late Cretaceous, can play a key role in further improving absolute plate motion reconstructions.

7.2. The Carlsberg Slab and Dynamic Topography in the NW Indian Ocean

The fact that negative buoyancy due to subducted slabs can be observed in the long-wavelength signal of the topography and bathymetry and can be geodynamically modeled by computing the dynamic topography due to mantle dynamics has been demonstrated by numerous studies [e.g., *Flament et al.*, 2013; *Steinberger*, 2007; *Lithgow-Bertelloni and Gurnis*, 1997; *Gurnis*, 1993]. If the newly identified Carlsberg slab is located 700–1300 km below the surface, we may be able to see its effect in the present-day bathymetry of the NW Indian Ocean. To test this hypothesis, we compute the residual bathymetry of that region where we correct for the sedimentation and sediment loading (using NGDC global sediment thickness v2. grid [*Whittaker et al.*, 2013]) and for the thermal subsidence of the oceanic crust. For the latter, our input oceanic crust age grid is the one we have constructed in this study (Figure 9), and we use *Crosby and McKenzie* [2009] model for computing the depth as a function of oceanic crust

Figure 12. (a) Present-day topography and bathymetry (ETOPO1) [*Amante and Eakins*, 2009]. (b) Sediment thickness [*Whittaker et al.*, 2013]. (c) Computed residual bathymetry (see section 7.2 for data input and method). (d) Dynamic topography [*Steinberger*, 2007]. Contours of positive seismic anomalies identified as subducted slab(s) at various depths were extracted from the tomographic model UU-07 and are shown in Figures 12c and 12d as dashed lines. These contours overlap an area that has negative residual bathymetry and dynamic topography.

age. The input data and the resulting residual topography are shown in Figure 12. An area characterized by negative residual topography (approximately 500–750 m) is clearly observed NNE of the Carlsberg Ridge. This region overlies the Carlsberg slab identified in the tomographic models (as shown by digitized fast region contours from selected tomographic cross sections, Figure 12c). For comparison, we also show a model of dynamic topography [Steinberger, 2007] calculated by advecting the present mantle density anomalies derived from seismic mantle tomography (in this case S20RTS [Ritsema *et al.*, 1999]). This model indicates that indeed negative dynamic topography could be expected from a mantle whose present-day structure is inferred from converting seismic velocities (as described by mantle tomography) to mantle density and using the present-day plate kinematics from the NUVEL model.

8. Conclusions

Our concluding remarks based on the synthesis and analysis of geological and geophysical data in the NW Indian Ocean and adjacent margins combined with mantle tomography models can be summarized as follows:

1. The North Somali Basin and oceanic crust in the proto-Owen Basin formed as a result of approximately N-S extension between the NW Indian margin and the eastern Somali/Arabia margins. In the North Somali Basin preserved oceanic crust is dated by magnetic anomalies as 160 to circa 133 Ma old. Most of the conjugate oceanic flank was probably deformed and consumed during the subsequent compressional event that started at circa 132 Ma. The same event destroyed the proto-Owen Basin and led to the emplacement and uplift of the Masirah ophiolites on the SE Arabian margin.
2. Our review of the geological constraints on the age and geochemical setting of formation of the Kabul-Altimur ophiolite overlying the Kabul Block, the Waziristan-Khost, Muslim Bagh, and Bela ophiolites overlying the NW Indian margin, and the Masirah ophiolites from the SE Arabian margin, as well as from rocks derived from lithosphere that subducted underneath these preserved in mélanges, shows that the first-order timing and motion between India and the Arabian margin could accommodate first the formation of Cretaceous oceanic crust and then its subsequent obduction as ophiolites. Detailed information of the age and affinity of these ophiolites were used to define the motion of the Kabul Block in our regional model.
3. We suggest that the adjustments of plate boundaries around the NW corner of the Indian Plate from compressional regime in the Late Cretaceous to an extensional regime in the Paleocene may have created and modified the Amirante and Murray ridges—two volcanic features on the ocean floor of (poorly constrained) Cretaceous ages. The Late Cretaceous extension between the NW Indian and Arabian margins probably led to the formation of the Owen Basin whose oceanic crust fabric and magnetic data suggest an age of circa 84 to 74 Ma. A somewhat younger oceanic basin (Amirante Basin) was formed between the western Indian margin and the north Madagascar and eastern West Somali Basins between 75 and 65 Ma, as predicted by the plate circuit and confirmed by magnetic anomaly data. Seafloor spreading in this basin was abandoned when the Seychelles microplate became part of the African Plate, and a new mid-ocean ridge was established in the East Somali Basin.
4. Phases of (oblique) convergence between India and Arabia led to the emplacement of ophiolites onto the NW Indian and SE Arabian margins. A first phase between ~90 and 84 Ma led to the inception of subduction between the Kabul Block and India reflected by metamorphic soles below the Waziristan-Khost ophiolite and the subsequent thrusting of the ophiolite onto the NW Indian margin. A phase of oblique convergence between ~84 and 45 Ma was partitioned into northwestward Indian Plate subduction below oceanic Neotethyan lithosphere of Jurassic age reflected in the Kabul-Altimur ophiolite, and formation of new ocean floor in a pull-apart basin in which the Bela and Muslim Bagh ophiolite formed, similar in style to the modern Andaman Sea. Simultaneously, ocean floor was thrust westward onto SE Arabia forming the Masirah ophiolite. Obduction of these ophiolites onto the continents continued until the early Eocene.
5. The NW Indian ophiolites have no relationship to the India-Asia plate boundary, or the India-Asia collision, but formed along the India-Africa (Arabia) plate boundary instead.
6. NW India-Asia collision in Afghanistan occurred at the latest around 20 Ma as constrained in the Sulaiman ranges. The maximum collision age would be 30 Ma if the Hindu Kush slab resulted from intra-Asian subduction north of the Helmand Block.
7. Seismic tomographic images of the mantle below the northwest Indian Ocean, below the Carlsberg Ridge, are used to identify a lithospheric slab at the top of the lower mantle that is consistent in dimension and orientation with the Late Cretaceous to early Eocene highly oblique subduction zone between India and

Arabia that we predict in our model. The presence of this slab may explain the negative dynamic topography identified in NW of East Somali Basin.

8. The NNE-SSW orientation of this slab may provide a key paleolongitudinal constraint for future absolute plate motion reconstructions back to the Late Cretaceous.

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