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Mantle Exhumation and Post-Rift Magmatism at an Oblique Magma-Poor Continental Margin

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Key Points:

- 3-D crustal structure at a magma-poor continental margin of the north-eastern Gulf of Aden is imaged by a seismic velocity tomography
- A 45° obliquity of crustal thinning is observed, causing margin segmentation and inherited by ongoing seafloor spreading
- Mantle exhumation by detachment faults and post-rift magmatism shape margin crusts and build a V-shaped Continent-Ocean Transition

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Continental breakup is a fundamental tectonic process, which leads to seafloor spreading and the generation of oceanic crust. However, the current understanding of continental margins, based largely on 2-D seismic transects, is inadequate to capture the spatial complexity of crustal evolution. Here we present a 3-D seismic velocity model through a young, magma-poor margin at the north-eastern Gulf of Aden. Our results highlight the 45° obliquity between the strike of crustal thinning and extension direction, which is accommodated by two transfer zones during the formation of the Continent-Ocean Transition (COT). This obliquity causes the margin to be segmented, which predates seafloor spreading. Along strike, we find a progressive eastward crustal thinning from 13 to 5 km, corresponding to a V-shaped COT. This eastward variation is characterized by (a) an eastward increase of mantle exhumation due to detachment faulting, and (b) post-rift magmatism emplaced onto serpentinized mantle in the west.

Plain Language Summary This study explores how continents break apart, focusing on the north-eastern Gulf of Aden, where the continental crust stretched and thinned to form a new ocean. Using 3-D seismic data, we examined changes in crustal thickness and structure during this process. We found a 45° angle (obliquity) between directions of crustal thinning and extension, a feature that significantly impacts the pattern of seafloor spreading as the ocean grows. In the region known as the Continent-Ocean Transition (COT), the crust progressively thins from 13 to 5 km toward the east. By combining these observations with earlier studies of magnetism and heat flow, we identified two distinct stages of crustal thinning. First, the mantle rock beneath the crust is exposed through faulting, especially in the east. Later, volcanic activity in the west adds new material onto the stretched mantle. This study shows how different processes, both during and after continental breakup, shape the crust, improving our understanding of this fundamental global tectonic process.

1. Introduction

Passive continental margins are crucial for understanding the onset of the seafloor spreading at mid-ocean ridges and the evolution from continental to oceanic crust. Two endmembers of margin types—magma-rich and magma-poor—have been defined based on the degree of magmatism in syn-rift processes (Brune et al., 2023; Geoffroy, 2005; Minshall, 2009). At magma-rich margins, syn-rift magmatism produces a thick igneous crust at the Continent-Ocean Transition (COT), usually related to mantle plumes (Geoffroy, 2005; White & Smith, 2009). Such margins may be found at the Paraná-Etendeka igneous province of the South Atlantic margin (Sauter et al., 2023) and the western Gulf of Aden (Leroy et al., 2012; Tard et al., 1991). At magma-poor margins, for example, the Iberia-Newfoundland conjugate margin (Péron-Pinvidic & Manatschal, 2009; Van Avendonk et al., 2006) and the eastern Gulf of Aden (Leroy et al., 2012), serpentinized mantle is exhumed at the COT through detachment faults (Lavie & Manatschal, 2006; Minshall, 2009; Pérez-Gussinyé & Reston, 2001; Tucholke et al., 2007). However, in addition to syn-rift magmatic variations, continental margins are also subject to various processes, such as (a) margin segmentation and oblique extension (Leroy, Lucazeau, et al., 2010; Lizarralde et al., 2007; Zhang et al., 2023), (b) post-rift volcanism (Lucazeau et al., 2008; Pallister et al., 2010), and (c) subsidence and sedimentation (Winterer & Bosellini, 1981). Understanding such spatial variability along and across continental margins remains a fundamental research objective in plate tectonics, which necessitates 3-D seismic volumes (Boddupalli et al., 2022; Zhang et al., 2023).

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The Gulf of Aden is a young continental rifted margin (rifting at 34–17.6 Ma ago) (Figure 1), which shows a magma-rich margin structure toward the west, related to the Afar mantle plume, and a magma-poor margin structure to the east, with a possible zone of exhumed mantle (d’Acremont et al., 2005; Leroy et al., 2012; Leroy, Lucazeau, et al., 2010; Nonn et al., 2017, 2019; Tard et al., 1991). The oblique rifting (40–60° relative to the extension direction) leads to segmentation and fracture zones at the margin, which is covered by thin sediments and scattered post-rift volcanism (Figure 1) (Autin et al., 2010; d’Acremont et al., 2010; Fournier et al., 2004; Korostelev et al., 2015; Leroy, Lucazeau, et al., 2010; Watremez et al., 2011). This provides a unique opportunity to study spatial variations in the tectonic evolution of continental margins during both syn-rift and post-rift processes. Here we report tomographic P-wave velocity (V_p) observations from an active source, onshore-offshore, three-dimensional (3-D) wide angle seismic experiment (data acquisition in Text S1 in Supporting Information S1) conducted over three second-order margin segments (Seg-1, Seg-2, and Seg-3, also named as Ashawq-Salalah, Taqah, and Mirbat segments in previous studies (Leroy, Lucazeau, et al., 2010)), at the north-eastern Gulf of Aden between Alula-Fartak (AFFZ) and Socotra-Hadbeen (SHFZ) Fracture Zones (Figure 1). These three segments all display a magma-poor margin structure, and are offset by two transfer zones, which show an eastward widening of a V-shape COT (Autin et al., 2010; Leroy, Lucazeau, et al., 2010) (Figure 1c). Despite no evidence of syn-rift volcanism (Autin et al., 2010; Leroy et al., 2012; Leroy, Lucazeau, et al., 2010), post-rift volcanism has been discovered over the western Seg-1, probably occurring until as recently as ~100 ka ago, as indicated by an elevated heat flow values observed on the present-day seafloor (Leroy, d’Acremont et al., 2010; Lucazeau et al., 2008, 2009, 2010).

2. Results and Discussion

The First Arrival Seismic Tomography (FAST) software (Zelt & Barton, 1998) is used to compute the 3-D V_p model (data processing in Text S1). The final 3-D V_p model covers an area of 5–165 km and 5–115 km in X (east-west) and Y (south-north) directions, respectively (Figures 2 and 3), with a good spatial resolution at Z (depth below sea level) ≤ 12 km, where features larger than 10 km near the COT can be well imaged without notable smearing or distortion (spatial resolution in Figures S8 and S11E in Supporting Information S1 and checkerboard test in Figures S13 and S14 in Supporting Information S1).

By comparing coincident 2-D layered models that include a Moho interface (determined using reflected PmP phases) (Leroy, Lucazeau, et al., 2010; Watremez et al., 2011), we find that the 7.5 km/s iso-velocity contour in our 3-D model is a good proxy of the Moho location at the COT and oceanic crusts (Text S1 and Figure S15 in Supporting Information S1). The total crustal thickness, measured between the oceanic basement or the land’s surface and the 7.5 km/s iso-velocity contour, decreases from >20 km to 13–5 km from continental to oceanic crusts within ~60 km (Figure 2b). The 6.4 km/s iso-velocity contour is used to distinguish the boundary between the upper and lower crust, with the upper crust in the COT and oceanic crust domains approximately limited above a vertical V_p gradient of 0.5/s (Figure S11B in Supporting Information S1).

Vertical 1-D V_p profiles of the continental crust (Panels A in Figure S12 in Supporting Information S1) are consistent with the continental velocity structure of the north-eastern Gulf of Aden derived from previous 2-D seismic V_p tomography (Leroy, Lucazeau, et al., 2010; Watremez et al., 2011). The map of stretching factor β (Figure 2c), calculated as the ratio of the maximum, un-thinned, continental crustal thickness (36.6 km inferred by receiver functions (Tiberi et al., 2007)) to the total crustal thickness, indicates that the study area is a typical magma-poor margin with a β factor of mostly >4 within the COT (Watremez et al., 2011).

Tomography models, showing velocities increasing from 1.5 km/s in water to over 8 km/s in the mantle, are used to interpret the nature of crustal and uppermost mantle materials (Dunn et al., 2005; Minshull, 2009; White et al., 2008). We define (a) a layer between the 6.0 and 6.4 km/s iso-velocities as the middle crust (Figure 2d) to delineate the boundary between continental and oceanic crusts, and (b) a layer between the 7.0 and 7.5 km/s iso-velocities as intermediate velocities (Figure 2e), which are typically too fast for crustal material (Carlson & Miller, 2004) and too slow for the unaltered mantle (Christensen, 2004). Depth uncertainties of iso-velocities at 6.0, 6.4, 7.0, and 7.5 km/s are shown in Figure S10 in Supporting Information S1.

Serpentinization can lower the V_p of mantle rocks from 8 to 5 km/s (Christensen, 2004), overlapping igneous crustal V_p values, which creates ambiguity in distinguishing between igneous crust and serpentinized mantle. Here we use vertical V_p gradient as a proxy to define the intermediate layer (Watremez et al., 2011), whether it consists of: (a) an igneous body at the base of the crust with a nearly-uniform composition (low velocity

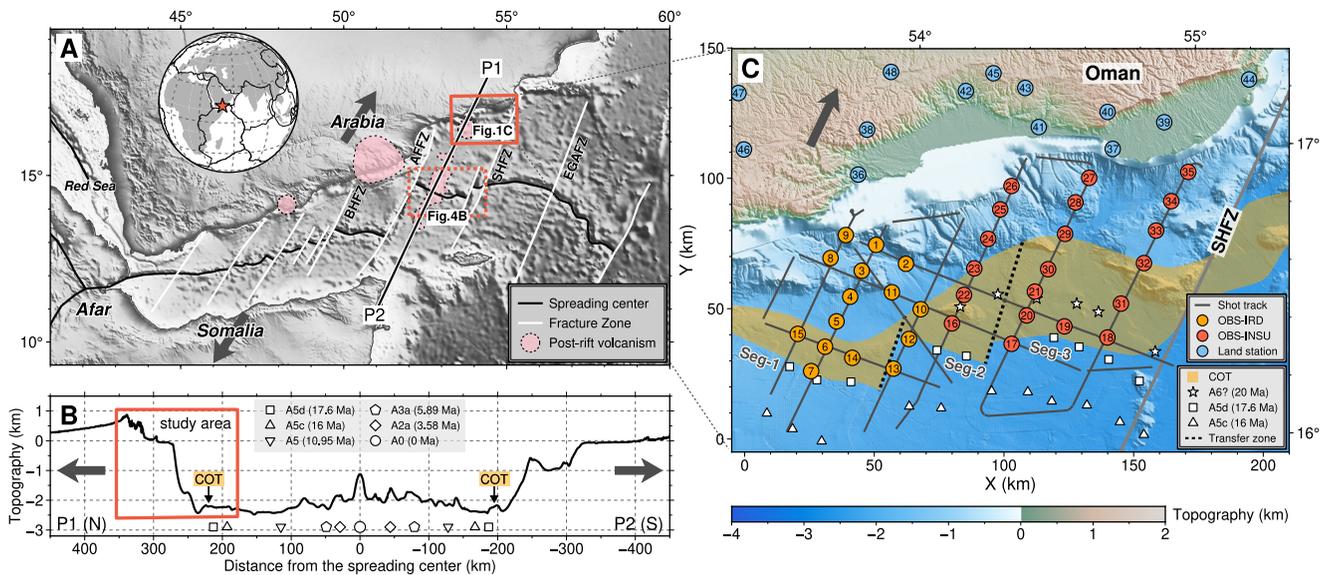


Figure 1. Tectonic setting of the Gulf of Aden and the 3-D seismic refraction experiment. Gray arrows show the extension direction. (a) Shaded topographic map. Pink areas indicate post-rift volcanism (Korostelev et al., 2015; Leroy, d’Acremont et al., 2010; Lucazeau et al., 2010). Black and white lines mark spreading centers and fracture zones, respectively. The inset hemisphere shows the location of the study area. (b) Topographic cross-section along P1–P2 located in panel (a). See legend for symbols of magnetic anomalies (d’Acremont et al., 2006; Leroy et al., 2004). (c) Combined onshore-offshore seismic survey during the Encens cruise in 2006 (Leroy, 2006), conducted over three second-order margin segments (Seg-1, Seg-2, and Seg-3) at the north-eastern Gulf of Aden. See legend for symbols of OBSs, land stations, and wide-angle seismic shot tracks. OBSs were provided by IRD and INSU institutions. Orange shaded area indicates the extent of the Continent-Ocean Transition (COT), inferred from previous geophysical observations, that is, seismic reflection/refraction, magnetism, and heat flow (Autin et al., 2010; d’Acremont et al., 2006; Leroy et al., 2004; Leroy, Lucazeau, et al., 2010; Lucazeau et al., 2008). Fracture zones: Socotra-Hadbeen (SHFZ), Alula-Fartak (AFFZ), Bosaso-Hami (BHFZ), and Eastern Gulf of Aden (EGAFZ).

gradients), (b) a transition from partly serpentinized exhumed mantle material (<30% serpentinization according to Christensen (2004)) to unaltered mantle (higher velocity gradients), or (c) the Mohorovičić discontinuity, marking the sharp boundary between the crust and mantle (no intermediate layer with highest velocity gradients).

2.1. Oblique Crustal Thinning

Oblique crustal thinning is observed within Seg-1 and Seg-2, at an angle of $\sim 45^\circ$ relative to the extension direction, roughly perpendicular to the coastline (Figure 2). Dense contours of the total crustal thickness near the northern limit of the COT are parallel to the coastline, for example, the 10 km contour (Figure 2b). The middle crust (Figure 2d) and the intermediate velocities (Figure 2e) also show a clear boundary with an oblique strike between the continental and COT crusts, which are both thicker toward the continental domain. The depth slice of $Z = 12$ km (~ 10 km below seafloor) shows that the 7.5 km/s iso-velocity shallows toward the oceanic domain, also following a trend parallel to the coastline (Figure 2f).

The obliquity (45°) between the strike of crustal thinning and extension direction at Seg-1 and Seg-2 (Figure 2) is consistent with the regional obliquity of the northern margin of the Gulf of Aden (Fournier et al., 2004), relative to the direction of seafloor spreading. It also aligns with the trend of a high Residual Mantle Bouguer gravity Anomaly (RMBA) near the COT (d’Acremont et al., 2010) (Figure S9D in Supporting Information S1). However, the second-order segmentation, related to the nascent spreading center near the southern limit of the COT, displays a strike almost perpendicular to the extension direction (Figure 1c). This is corroborated by the first magnetic anomaly, that is, A5d (17.6 Ma; Figure 1c), which indicates the formation of the earliest oceanic crust in this region (d’Acremont et al., 2006, 2010; Leroy et al., 2004). Such segmentation also pre-existed for the ongoing seafloor spreading, which then shows its own distinct segmentation processes (Figures 4a and 4b). We, therefore, propose that during the formation of the COT, the regional extension obliquity was accommodated by the lateral offset of two second-order transfer zones that correspond to locally thin crusts (Figure 2b). The margin segments were cut to be nearly perpendicular to the extension direction, probably due to the thinning of the continental mantle lithosphere (Duclaux et al., 2020). Such a mechanism could also be applicable to slow and ultraslow spreading mid-ocean ridges, such as the Southwest Indian Ridge (SWIR), where regional spreading obliquity is

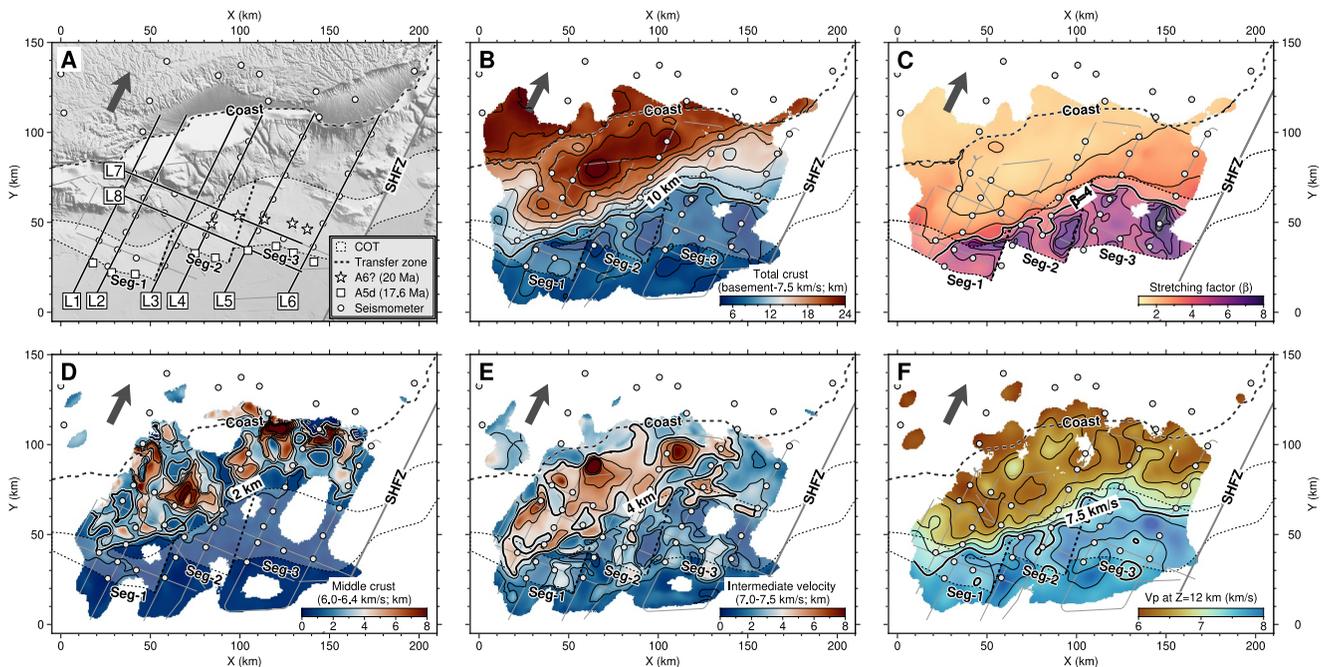


Figure 2. Map view of the final 3-D V_p model. White masks correspond to areas without ray coverage. Gray arrows show the extension direction. (a) Shaped topographic map. See legend for the COT, transfer zones, magnetic anomalies, and seismometers. Solid lines (L1–L8) oriented parallel and perpendicular to the extension direction are the locations of vertical slices in Figure 3. (b) Total crustal thickness, calculated between the basement top and the 7.5 km/s iso-velocity. Contour interval is 2 km. (c) Stretching factor (β), calculated as the ratio of the maximum continental crustal thickness (36.6 km inferred by receiver function (Tiberi et al., 2007)) and the total crustal thickness (b). Oceanic crust is excluded. Contour interval is 1. (d) Middle crustal thickness, calculated between the 6.0 and 6.4 km/s iso-velocities, contoured at 1 km intervals. (e) Thickness of the intermediate velocity layer, calculated between the 7.0 and 7.5 km/s iso-velocities. Contour interval is 1 km. (f) Depth slice at $Z = 12$ km, within the well-resolved part of the 3-D V_p model at a resolution of <10 km (Figure S8D in Supporting Information S1), contoured at 0.3 km/s intervals.

inherited from the initial rifting system and then accommodated by ridge-perpendicular transform faults and ridge-oblique non-transform discontinuities that bound nearly-orthogonal ridge segments (Cannat et al., 1999; Chen et al., 2023; Sauter et al., 2001).

2.2. Post-Rift Magmatism Emplacing Onto Exhumed Mantle

Along the COT, our 3-D seismic velocity volume shows a high spatial variation of the crustal structure across the three margin segments. From west to east, the seismic crustal thickness decreases from 13 to 5 km, coinciding with an eastward widening (from 15 to 50 km) of the V-shaped COT (Figure 2). At the western Seg-1 (94 km long), the presence of a >10 km-thick crust (Figure 2b) and a >4 km-thick intermediate layer (Figure 2f) at the COT is unexpected for a magma-poor rifted margin (Watremez et al., 2011), particularly the 13 km-thick crust (Figures 3A–1) with a low ($<0.2/s$) vertical V_p gradient in the intermediate layer (Figure S11B–1 in Supporting Information S1) at the profile L1. In addition, an extremely high heat flow (~ 900 mW/m²) and a series of volcanic-flow reflectors have been observed over a seamount at the profile L2, indicating that post-rift magmatism may be responsible for the crustal thickening (Autin et al., 2010; Leroy, d’Acremont et al., 2010; Lucazeau et al., 2010). Because the upper crustal thickness (basement to 6.4 km/s iso-velocity) and the crustal thickness without the intermediate velocities (basement to 7.0 km/s iso-velocity) are relatively uniform along the COT (Figures S9A and S9C in Supporting Information S1), this post-rift magmatism dominantly appears to take the form of underplated materials and/or magma-intruded lower crust (Figure 4c), which mainly contributes to the low-gradient intermediate velocity (between the 7.0 and 7.5 km/s iso-velocities; Figure 2e in Supporting Information S1).

Two stages of rifting have been proposed for the COT formation in the western part of Seg-1 (Autin et al., 2010; Leroy, Lucazeau, et al., 2010; Watremez et al., 2011): (a) mantle exhumation along detachment faults, followed by (b) post-rift magmatism soon after the continental breakup and/or during early seafloor spreading. Previous studies suggest that the evidence of the exhumed mantle during stage-1 may have been fully overprinted by post-

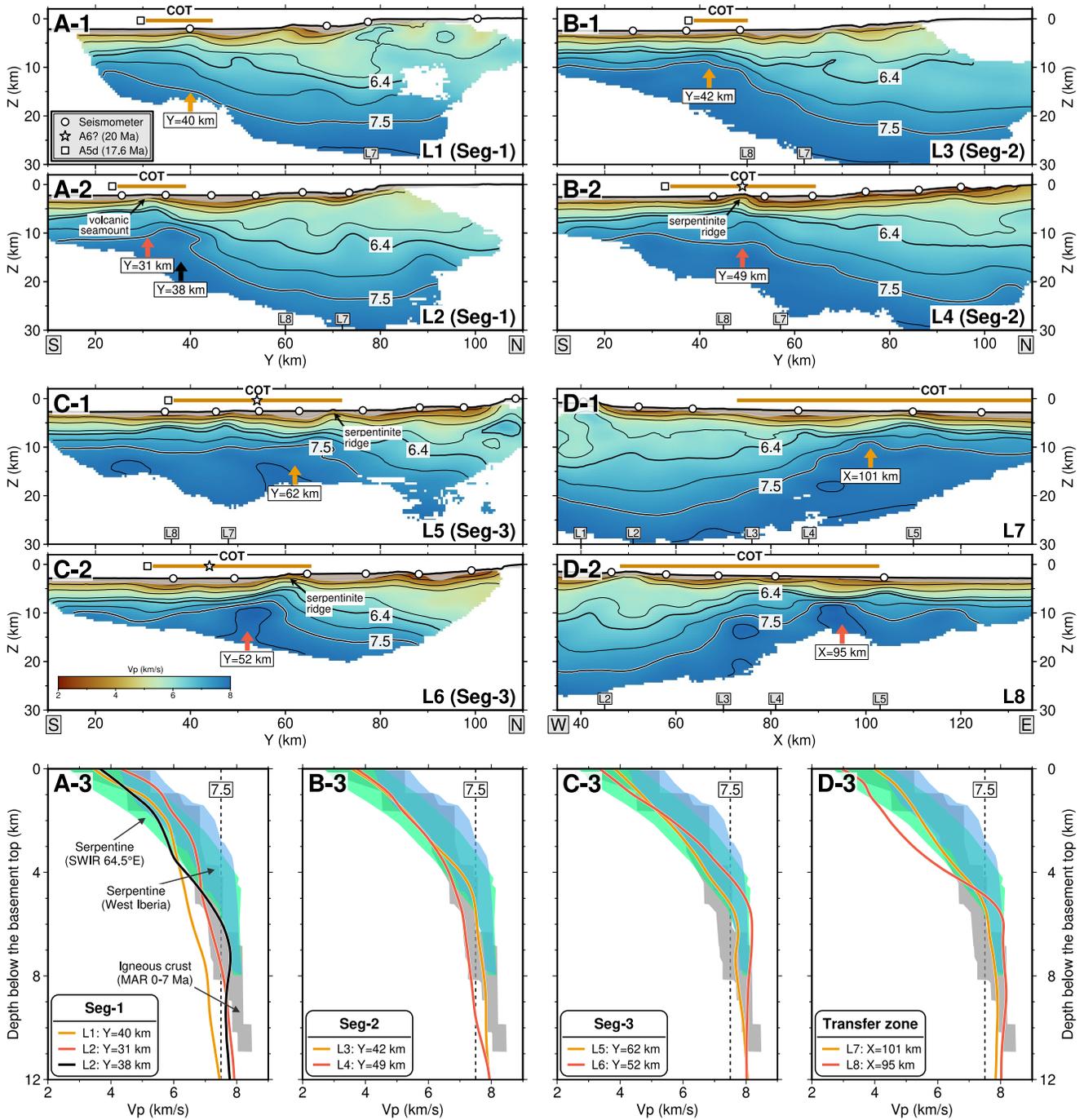


Figure 3. Vertical Vp slices and 1-D profiles along acquisition lines. Profile locations oriented parallel (L1–L6) and perpendicular (L7–L8) to the extension direction are shown in Figure 2a. Color bar of Vp is shown in C-2. (A-1) and (A-2) Profiles L1 and L2 across the western Seg-1. (B-1) and (B-2) Profiles L3 and L4 across the central Seg-2. (C-1) and (C-2) Profiles L5 and L6 across the eastern Seg-3. (D-1) and (D-2) Profiles L7 and L8 across transfer zones. (A-3) - (D-3) 1-D Vp profiles, extracted from corresponding segments and transfer zones. Gray envelope represents the igneous crust at the age of 0–7 Ma of the Mid-Atlantic Ridge (MAR) (White et al., 1992). Green and blue envelopes represent serpentinized mantle of the ultraslow-spreading SWIR 64.5°E (Corbalán et al., 2021; Momoh et al., 2017) and the magma-poor West Iberia rifted margin (Davy et al., 2016), respectively.

rift volcanism during stage-2 (Autin et al., 2010; Nonn et al., 2017; Watremez et al., 2011). This could be shown near $Y = 40$ km along profile L1 and $Y = 31$ km on profile L2 (Figures 3A-1, 3A-2, and 3A-3), where magmatism was substantial and 1-D velocity profiles lie within or below the envelope of Mid-Atlantic Ridge (MAR) igneous crustal values (White et al., 1992). Elevated Vp with a locally increased Vp gradient ($>0.5/s$) in the intermediate

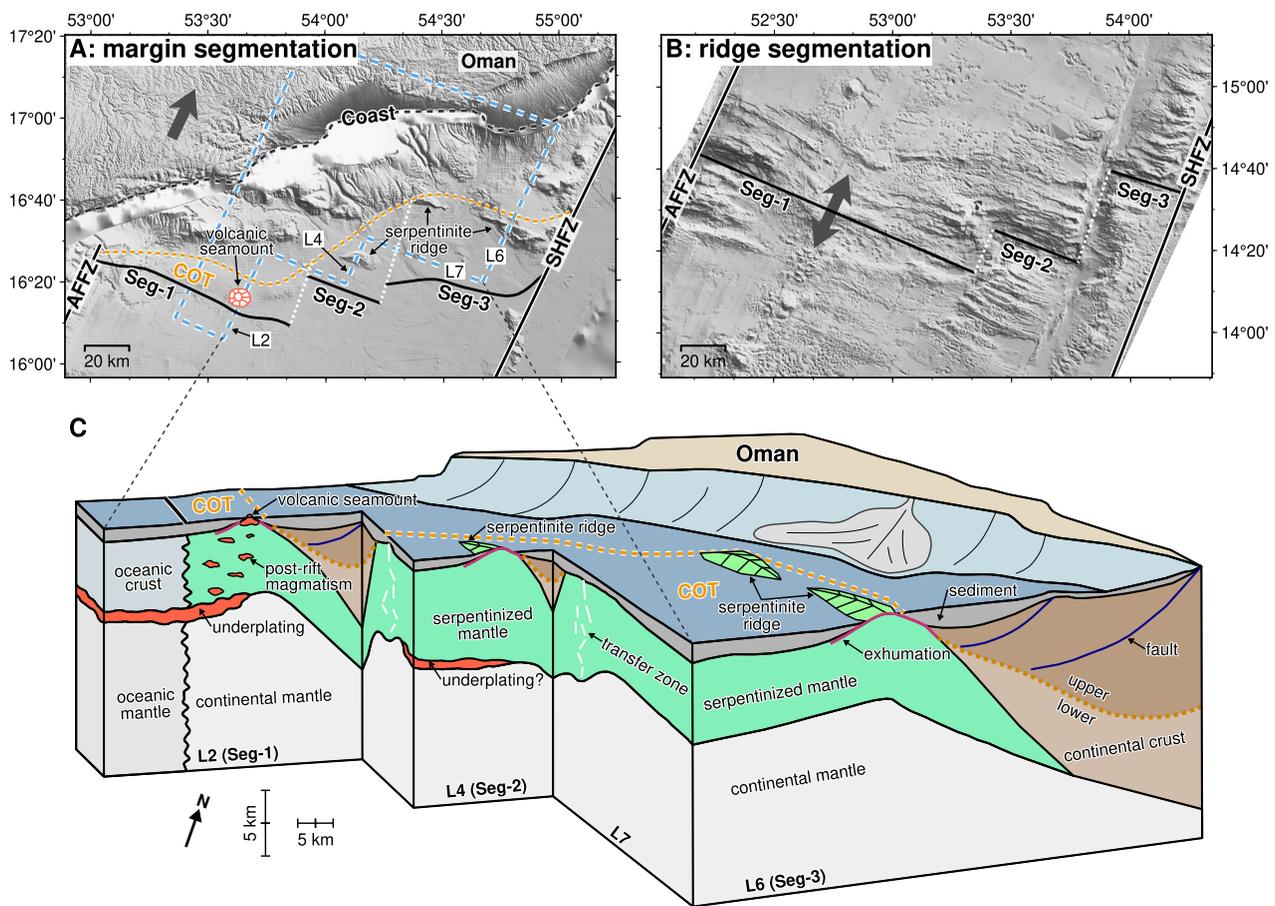


Figure 4. Interpretative sketch for segmentation and modes of continental breakup. (a, b) Segmentation of the rifted margin and the ongoing spreading center, respectively. See locations in Figure 1a. Both depict three segments (black line) separated by two fracture zones (dashed white lines). Blue dashed polygon along profiles L2, L4, L7, and L6 shows the boundary of the 3-D sketch. (c) 3-D schematic diagram showing the modes of continental breakup along and across the COT ($VE = 2$). Serpentinized mantle is exhumed by detachment faults in all three profiles, with a prevalence that increases eastwardly (i.e., from L2 to L6). Underplating and post-rift magmatism occurred at L2 and possibly at L4.

layer is observed near $Y = 38$ km along profile L2 (Figures 3A-2 and S11B-2 in Supporting Information S1), where 1-D velocity profile (Figure 3A-3) shows similarity to exhumed serpentinized mantle materials, for example, at the ultraslow spreading SWIR 64.5°E (Corbalán et al., 2021; Momoh et al., 2017; Robinson et al., 2024) and the magma-poor West Iberia rifted margin (Davy et al., 2016), and may be subsequently modified by post-rift magmatic intrusions. To the east of profile L2 within the western Seg-1, the crustal thickness rapidly diminishes to 6–8 km toward the ocean (Figure 2b), and the 1-D V_p profiles of this region do not clearly match the envelopes for igneous crust or serpentinized mantle (orange lines in Figure S12B-2 in Supporting Information S1). The source of this post-rift magmatism during stage-2 is not clear, but may be related to the Afar mantle plume and/or small-scale mantle convection (Korostelev et al., 2015; Leroy, d’Acremont et al., 2010; Lucazeau et al., 2008, 2009). Recent studies also suggest that small-scale mantle convection under hyperextended margins may cause a delay in thermal relaxation, potentially triggering post-rift magmatism with elevated heat flow (Pérez-Gussinyé et al., 2024; Zhu & Liu, 2025).

Our 3-D seismic volume, therefore, provides evidence supporting the two-stage COT formation, that is, continental mantle exhumation followed by post-rift magmatism. The base of the crust is defined by the 7.5 km/s isovelocity. Thus, it includes V_p of peridotites with different degrees of serpentinization, igneous rocks, and hybrid peridotite-igneous rocks around intrusion contacts (Figure 4c). Massive magmatic intrusions and associated heat could also reduce the degree of mantle serpentinization through olivine recrystallization and dehydration (Albers et al., 2019; Brindley & Hayami, 1963; Raleigh & Paterson, 1965). The serpentinized mantle near profile L1 is significantly overprinted by robust magmatism, correlated with the reduced crustal velocity (Figure 3A-3). To the

east of profile L2, the residual serpentinized mantle may persist due to limited magmatism. Besides, no serpentinization-related magnetic anomaly is observed at the western Seg-1 (d'Acremont et al., 2006, 2010; Leroy et al., 2004).

2.3. Mantle Exhumation and V-Shaped Continent-Ocean Transition

Mantle exhumation with detachment faulting is typical at magma-poor margins (Minshull, 2009; Pérez-Gussinyé & Reston, 2001; Tucholke et al., 2007), as is the case at the north-eastern Gulf of Aden, evidenced from our 3-D seismic volume. At the central Seg-2 (36 km long) and the eastern Seg-3 (65 km long), where the COT widens from ~10 to 30–50 km, the seismic crustal thickness ranges between 5 and 8 km mostly with a 1–2 km-thick intermediate layer (Figures 2b and 2e), suggesting very little syn-rift or post-rift magmatism. We observe evidence for serpentinized mantle within these segments, particularly at profiles L3 and L6 (Figures 3B-1 and 3C-2). Velocities increase sharply from 3.5 km/s to 7–8 km/s within 4–5 km below the basement, followed by a lower Vp gradient at greater depths (Figures 3B-3 and 3C-3), which mostly matches serpentinized mantle at the SWIR 64.5°E (Corbalán et al., 2021; Momoh et al., 2017) and the West Iberia margin (Davy et al., 2016), except for the deep part (>4 km below the basement), near Y = 49 km of profile L4 (Figures 3B-2 and 3B-3). High Vp gradients (>0.5/s) of the intermediate layer within the COT at profiles L3, L5, and L6 also support this interpretation (Figures S11B-3, S11B-5, and S11B-6 in Supporting Information S1). In addition, linear basement highs, perpendicular to the extension direction, are observed on the seafloor (Figure 4a), spatially linking to the uplifted Vp structures in across-COT profiles L4, L5, and L6 (Figures 3B-2, 3C-1, and 3C-2). Therefore, we interpret these features as serpentinite ridges formed by one or several detachment faults, similar to the West Iberia margin (Davy et al., 2016) and the SWIR 64.5°E (Corbalán et al., 2021; Momoh et al., 2017). These ridges display decreased heat flows, suggesting that they act as recharge zones for hydrothermal circulation (Leroy, Lucazeau, et al., 2010; Lucazeau et al., 2010).

Low-amplitude magnetic anomalies have been observed at the central Seg-2 and the eastern Seg-3 but not at the more volcanic western Seg-1 (Figure 2a), which are locally interpreted as magnetic A6 (20 Ma). These anomalies are likely not an isochron due to the formation of oceanic crust but support peridotite serpentinization (d'Acremont et al., 2006; Leroy et al., 2004; Leroy, Lucazeau, et al., 2010), due to detachment faulting or continuous fault back-rotation (Liu et al., 2022). However, few S reflectors of detachment faults are observed in the multichannel reflection data (Autin et al., 2010; Leroy, Lucazeau, et al., 2010). Assuming that the velocity at depth correlates with the degree of mantle rock serpentinization (Christensen, 2004), our study area shows heterogeneous serpentinization along the strike (Figures 3b and 3c, S12B-2, and S12B-3 in Supporting Information S1). For example, vertical slices across the eastern transfer zone that offsets Seg-2 and Seg-3, show an uplift of Vp and a high Vp gradient (>0.5/s) near X = 101 km of profile L7 (Figures 3D-1 and S11B-7 in Supporting Information S1) and X = 95 km of profile L8 (Figures 3D-2 and S11B-8 in Supporting Information S1), which is likely associated with serpentinized mantle, due to fluid circulation within the fractured crust and mantle. A relatively high degree of serpentinization likely occurred at X = 95 km of profile L8, with a notably low Vp at shallow depths (Figure 3D-3). We interpret this as arising due to increased cracking during COT-perpendicular shearing, which occurred during the period when the eastern transfer zone was accommodating the obliquity, leading to more extensive hydrothermal circulation and thus a higher degree of serpentinization at shallow depths.

Low Vp is observed at depths >4 km below the serpentinite ridge near Y = 38 km of profile L4 (the center of Seg-2), and the seismic crustal thickness is locally up to >8 km and extends into the oceanic crustal domain (Figure 2b), which coincides with a ~4-km-thick intermediate velocity layer (Figure 2c). This may be attributed to a small amount of magmatic underplating during the COT formation (Figure 4c), due to along-strike melt focusing to the center of the segment, a phenomenon widely observed at slow and ultraslow spreading ridges (Cannat et al., 1999; Lin et al., 1990). Such magmatic underplating is not observed at Seg-3, where the crustal thickness is nearly uniform at 5–6 km (Figure 2b), and its 1-D Vp profiles mostly match serpentinized mantle (Figure 3C-3 and S12B-2 in Supporting Information S1).

The amount of magma supply of the COT, therefore, decreases from the western Seg-1 to the eastern Seg-3, corresponding to an increasing prevalence of serpentinized mantle exhumed by detachment faults (Figure 4c). More detachment faults may accommodate more tectonic strain asymmetrically in the Arabian plate, eventually resulting in a higher time-averaged extension rate and the V-shaped COT (Leroy, Lucazeau, et al., 2010).

Alternatively, the V-shaped configuration of the COT may relate to a westward propagation of the rifting system, similar to the West Iberia margin (Murillas et al., 1990; Pérez-Gussinyé et al., 2003; Péron-Pinvidic & Manatschal, 2009), although no evidence has been found regarding the timing of different propagating phases, such as the graben deepening (Figure 1c) or the sediment thickening (Figure S3B in Supporting Information S1) in the westward direction.

3. Conclusion

Our 3-D seismic velocity model at the north-eastern Gulf of Aden reveals the spatial complexity in crustal evolution of a magma-poor margin during continental breakup. The 45° oblique crustal thinning, coupled with the integration of transfer zones, generates the initial margin segmentation that persists into the progression of seafloor spreading. Our data also display high lateral heterogeneity in crustal features along the Continent-Ocean Transition (COT). Specifically, the narrow COT with thick crusts at the western Seg-1 is influenced by post-rift magmatism emplacing onto exhumed mantle. At the central Seg-2 and eastern Seg-3, where the crusts are relatively thin, mantle exhumation increases eastwardly, interpreted as an eastward increase in time-averaged extension rate due to detachment faulting. This may be ultimately responsible for the formation of the V-shaped COT. We propose that rifted margins naturally exhibit significant along-strike variability in response to different modes and stages of continental breakup, including syn- and post-rift processes, as well as possible pre-rift mantle fertility/hydration (Lizarralde et al., 2007).

Data Availability Statement

Raw seismic data of this study are available (Leroy, 2006). First-arrival picks and the final 3-D Vp model are available (Chen et al., 2024).

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