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# Contrasted styles of rifting in the eastern Gulf of Aden: A combined wide-angle, multichannel seismic, and heat flow survey

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[1] Continental rifts and passive continental margins show fundamental along-axis segmentation patterns that have been attributed to one or a number of different processes: extensional fault geometry, variable stretching along strike, preexisting lithospheric compositional and structural heterogeneities, oblique rifting, and the presence or absence of eruptive volcanic centers. The length and width scales of the rift stage fault-bounded basin systems change during the late evolution of the new plate boundary, and the role of magmatism may increase as rifting progresses to continental rupture. Along obliquely spreading ridges, first-order mid-ocean ridge geometries originate during the synrift stage, indicating an intimate relationship between magma production and transform fault spacing and location. The Gulf of Aden rift is a young ocean basin in which the earliest synrift to breakup structures are well exposed onshore and covered by thin sediment layers offshore. This obliquely spreading rift is considered magma-poor and has several large-offset transforms that originated during late stage rifting and control the first-order axial segmentation of the spreading ridge. Widely spaced geophysical transects of passive margins that produce only isolated 2-D images of crust and uppermost mantle structure are inadequate for evaluation of competing rift evolution models. Using closely spaced new geophysical and geological observations from the Gulf of Aden we show that rift sectors between transforms have a large internal variability over short distances (~10 km): the ocean-continent transition (OCT) evolves from a narrow magmatic transition to wider zones where continental mantle is probably exhumed. We suggest that this small-scale variability may be explained (1) by the distribution of volcanism and (2) by the along-strike differences in time-averaged extension rate of the oblique rift system. The volcanism may be associated with (1) the long-offset Alula-Fartak Fracture Zone, which may enhance magma production on its younger side, or (2) channeled flow from the Afar plume material along the newly formed OCT and the spreading ridge. Oblique extension and/or hot spot interactions may thereby have a significant control on the styles of rifting and continental breakup and on the evolution of many magma-poor margins.

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## 1. Introduction

[2] Continental rifting leading to plate rupture is achieved through lithospheric crust and mantle thinning in a direction parallel to the plate opening; the resulting margin architecture constrains crust and mantle processes [e.g., *Buck*, 2004]. Variability of crust and mantle structures along the strike of the rift also influence processes, further restricting acceptable models: where the production of melt is large (volcanic margins), the transition from continent to ocean is narrow and substantial amounts of magma are added to the lower crust; where melt production is small (magma-poor margins), the transition can extend over hundreds of kilometers with possible exhumation of the continental mantle

along low-angle detachment faults [*Hopper and Buck*, 1996; *Buck et al.*, 1999]. Along-axis mid-ocean ridge segmentation may be related to one or several processes such as extensional fault geometry, variable rate of extension along strike, structural inheritance and presence or absence of volcanism [e.g., *Ebinger et al.*, 1987; *Dunbar and Sawyer*, 1989; *Hopper et al.*, 1992; *Brun*, 1999; *Buck et al.*, 1999; *Lizarralde et al.*, 2007; *Péron-Pinvidic and Manatschal*, 2009]. The geometry of the fault-bounded systems may change during rifting, and the influence of magmatism may differ when it occurs before or after the continental breakup [*White*, 1992; *Yamasaki and Gernigon*, 2009]. Zones that accommodate deformation between extensional basins of obliquely spreading rift systems during late synrift stages could be precursors of the first-order transform faults that appear along the OCT during or soon after continental rupture [*Corti et al.*, 2003; *d'Acremont et al.*, 2005]. It has also been proposed that transform fault configuration may not be inherited from earlier structures at all [*Taylor et al.* 2009]. Finally, long-offset transform fault and fracture zone geometry at obliquely spreading ridges may affect melt supply to axial segments from the onset of seafloor spreading following rifting [*Hooft et al.*, 2000] and possibly control magma flow in plume-ridge interactions [*Georgen et al.*, 2001].

[3] Lateral structure of rifted margins can be highly variable, but is poorly constrained due to the wide spacing between geophysical transects (more than 100 km). This was the case for the Gulf of Aden where previously sparse studies consisted of seafloor bathymetry, limited gravity transects and seismic profiles that gave the impression that there was a lack of east-west structural variation. In this paper, we focus on the structure of the northern margin of the Gulf of Aden between the Alula-Fartak Fracture Zone (AFFZ) and the Socotra Hadbeen Fracture Zone (SHFZ). Each of these sections of the margin corresponds to a first-order ridge segment. This study of this first-order segment of the rifted margin is based on new detailed geological and geophysical observations and analysis, including seismic velocity models from wide-angle data, colocated with multichannel seismic (MCS) profiles and high-resolution heat flow measurements. Because of its recent formation and the absence of salt deposits, the Gulf of Aden provides ideal conditions to study the processes of rifting and continental breakup with seismic imaging techniques. This part of the margin reveals a complexity unexpected at this scale. Our analysis reveals significant change in the width and character of the OCT over a lateral distance of only 10 km. From 15 km wide with postbreakup magmatism, the OCT broadens to 50 km with low-angle detachment faults and little or no magmatism.

## 2. Tectonic Setting

[4] The Gulf of Aden is an active oblique rift system with young margins [*d'Acremont et al.*, 2005] along the Arabia-Somalia plate boundary connects to the Indian Ocean to the east and to the Red Sea to the west (Figure 1). Extension began at 35 Ma [*Roger et al.*, 1989; *Watchorn et al.*, 1998] following the closure of the Neo-Tethys Ocean and the development of the Afar plume [*Bellahsen et al.*, 2003]. Earliest rift structures strike N110°E, ca. 40° from the strike of late synrift structures and from the strike of the Gulf [*d'Acremont et al.*, 2005; *Bellahsen et al.*, 2006] (Figure 1). Seafloor spreading followed at 17.6 Ma in the eastern part of the Gulf [*Leroy et al.*, 2004; *d'Acremont et al.*, 2006] as far west as the Shukra-El Sheik transform fault (SSTf) [*Leroy et al.*, 2010] (Figure 1). Finally, the rift propagated toward the Afar plume [*Audin et al.*, 2001]. The along-axis segmentation, controlled by continental margin structure during the early stage of rifting, was replaced during the late rifting stage by a new geometry of shorter axial segments [*d'Acremont et al.*, 2010]. This late stage segmentation persisted through the onset of seafloor spreading and continues to evolve along the present-day spreading ridge [*Leroy et al.*, 2004; *d'Acremont et al.*, 2006, 2010]. The high degree of margin segmentation is attributable to oblique rifting. As a consequence of margin segmentation, the nascent OCT of the study area is located along the eastern side of the Mesozoic Jeza-Qamar basin, which was reactivated during the opening of the Gulf of Aden (Figure 1 [*Bellahsen et al.*, 2006; *d'Acremont et al.*, 2006]).

## 3. Data Acquisition

[5] A combined onshore-offshore survey was carried out in 2006 along the southern part of Oman in order to image the deep structures of the eastern Gulf of Aden margin (Figure 1). We have collected a large amount of geological and geophysical data in the study area, including multibeam bathymetry, gravity, magnetism and heat flow in addition to the multichannel and wide-angle seismic studies. Thirty-five Ocean Bottom Seismometers (OBS) deployed at 10–15 km intervals and 19 broadband seismometers onshore in Oman recorded the air gun shots

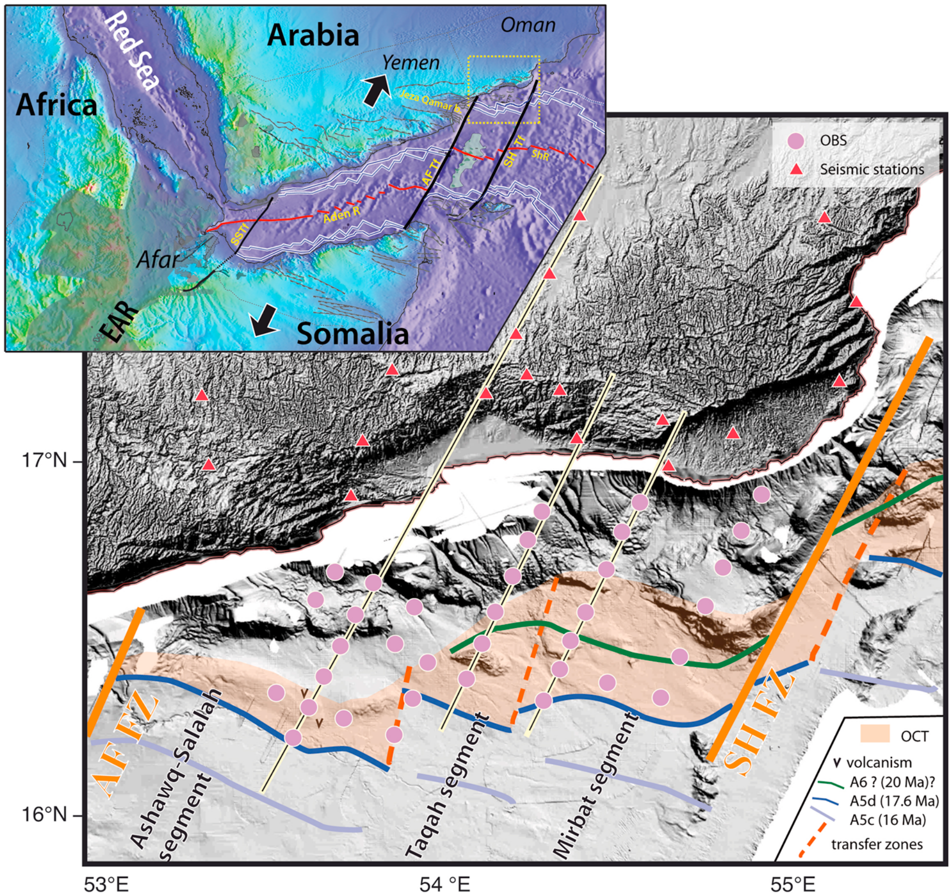


**Figure 1.** Map of the Encens experiment in the northeastern Gulf of Aden. (top) Gray shading denotes the Afar-related volcanism. SSTf, Shukra el Sheik transform fault; AFTf, Alula Fartak transform fault; Aden R, Aden ridge; ShR, Sheba ridge; Jeza Qamar b., inherited Jeza Qamar basin. The red line indicates the active oceanic ridge, and blue indicates the spreading axis at Chron 5c (16 Ma) and in the east of AFFZ; the dark blue line indicates Chron 5d (17.6 Ma) [*Leroy et al.*, 2010]. The black arrows show relative plate motions. (bottom) Shaded bathymetric map from multibeam soundings recorded during the Encens cruise. The Ashawq-Salalah, Taqah, and Mirbat segments are separated by dashed lines (accommodation zones). Purple dots and red triangles are seismic instrument locations of the overall experiment, and the three yellow and black lines are locations of the three seismic transects presented here. Salmon-colored shading indicates the extent of the ocean-continent transition (OCT) data coverage. AFFZ, Alula Fartak fracture zone; SHFZ, Socotra Hadbeen fracture zone.

up to 150 km inland (Figure 1). Source and receiver placement allowed for acquisition of excellent quality data along the margin between the AFFZ and SHFZ. We focus in this paper on one first-order segment of the margin.

## 4. Margin Structure

[6] Our results reveal fundamental differences in the crust and upper mantle structure of the second-order Ashawq-Salalah, Taqah, and Mirbat segments over short distance (Figure 1 and Table 1). We identified three second-order segments within the first-order AFFZ-SHFZ segment. The structure of these second-order segments is interpreted in the following subsections from the P wave velocity, magnetic, gravity, MCS and heat flow data (Figures 2 to 4 and auxiliary material).[1] Based upon these interpretations, we define the location of the OCT as the domain in the distal margin where (1) the crust has neither geophysical nor geological characteristics of classical continental crust or of classical oceanic crust, (2) syn-OCT sediments are observed rather than typical synrift wedges, and (3) no oceanic magnetic anomalies are clearly identifiable. The tran-

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009GC002963.

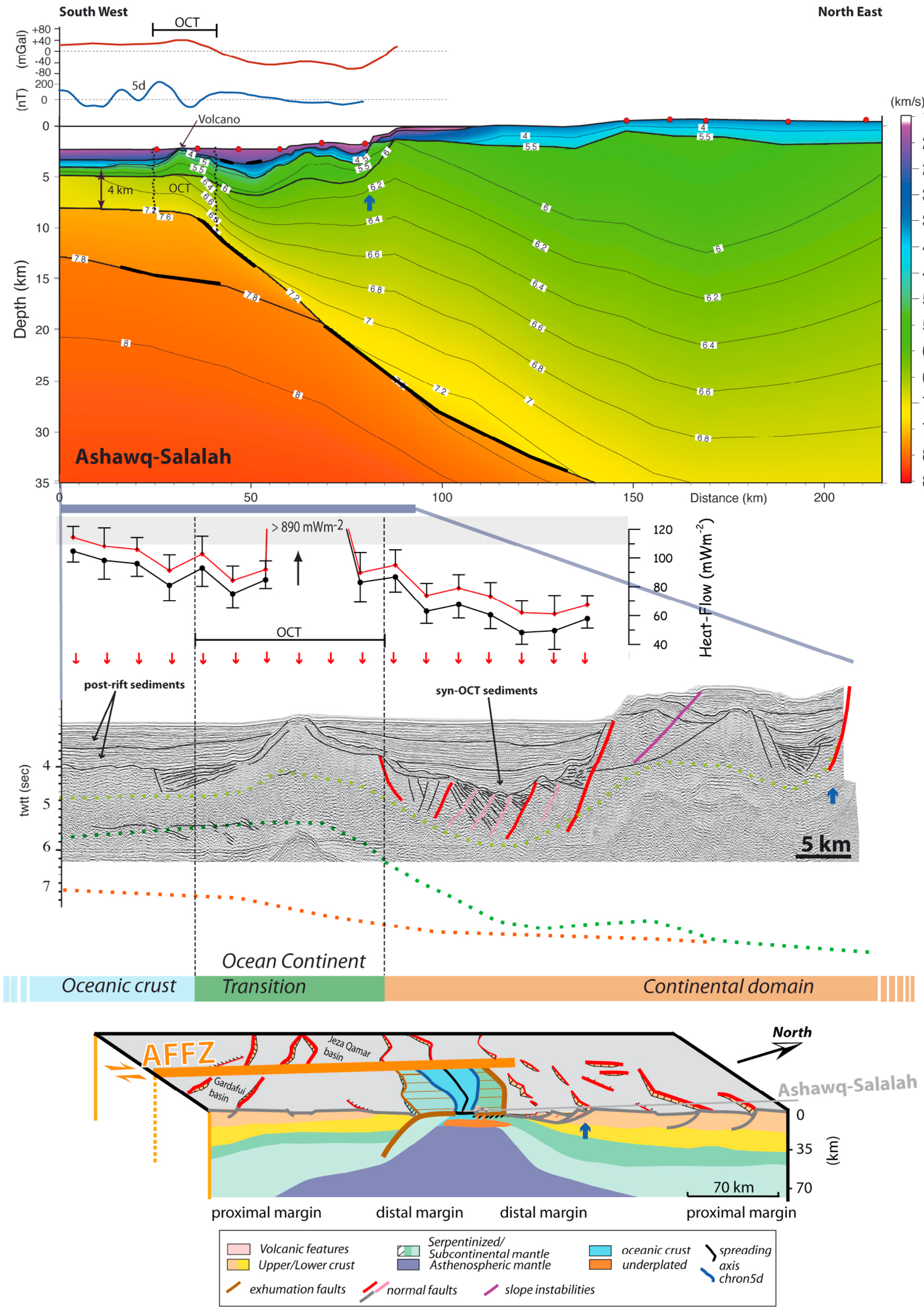
South West
North East
OCT
5d
Volcano
4 km
Depth (km)
Distance (km)
(km/s)
Ashawq-Salalah
> 890 mWm-2
Heat-Flow (mWm-2)
post-rift sediments
syn-OCT sediments
twtt (sec)
5 km
Ocean Continent Transition
Oceanic crust
Continental domain
AFFZ
Jeza Qamar basin
Gardafui basin
North
proximal margin
distal margin
distal margin
proximal margin
70 km
(km)
Volcanic features
Upper/Lower crust
Serpentinized/ Subcontinental mantle
Asthenospheric mantle
oceanic crust
underplated
spreading axis
chron5d
exhumation faults
normal faults
slope instabilities

**Figure 2**

sition from continental domain also corresponds to an increase in the seismic velocities from 6 to 7.6 km $s^{-1}$ for the lower crust, in the surface heat flow from 40 to 120 $mWm^{-2}$, and in the free-air gravity anomaly from −40 to 40 mGals (Figures 2–4 and auxiliary material). The OCT, which includes a zone of exhumed continental mantle (ZECM [*Péron-Pinvidic and Manatschal*, 2009]) is considered as the locus of change in crustal character between classical continental and oceanic. The formation of the OCT occurred when the continental crust broke up leaving behind no lower and/or upper continental crust. It extends from this point to the location where oceanic crust formed at the onset of seafloor spreading.

### 4.1. Western Segment: Ashawq-Salalah

[7] The Ashawq-Salalah subsegment has a length of 94 km (along margin, Figure 1). The OCT in this second-order segment is very narrow (15 km across margin); its 13 km thick crust is composed of two main parts separated by an internal reflector at ~7.5 km depth (Figure 2 and auxiliary material). The upper part is 5.5 km thick (P wave velocity of 4 to 7.2 km $s^{-1}$) and the lower, 7.5 km thick, has high P wave velocity ranging from 7.6 to 7.8 km $s^{-1}$. The mantle beneath the crust of the OCT and oceanic crust has slow P wave velocity (7.8 to 7.9 km $s^{-1}$; Figure 2). The oceanic crust has a total thickness of 9 km, with an internal reflector at 4 km. Although a clearly identifiable oceanic magnetic anomaly exists to the south of the OCT (the 5d anomaly [*d'Acremont et al.*, 2006, 2010]), the oceanic crust does not have a typical low-velocity gradient (Figure 2 and auxiliary material). There is evidence of volcanic activity after continental breakup. A volcano has been identified on the seafloor within the OCT based on morphology, thick seismic reflection patterns typical of volcanic flows [*Autin et al.*, 2010] with the associated crustal velocities ranging from 5 to 6 km $s^{-1}$, and by an extremely high heat flow (~900 $mWm^{-2}$). These observations suggest the persistence of activity until recent times (~100,000 yr) [*Lucazeau et al.*, 2009] (Figure 2). Dipping thick deep reflectors are also observed in the oceanic crust (Figure 2) and have been related to magmatism [*Autin et al.*, 2010]). Deformation of this margin segment is characterized in the north by large-offset normal faults dipping seaward that define two rifted basins and in the south by closely spaced normal faults (5 km) that thinned the continental crust during late stage rifting (Figures 2 and 5) [*Autin et al.*, 2010].

### 4.2. Central Segment: Taqah

[8] In the 36 km long Taqah subsegment, the characteristic of the margin changes significantly: there is no evidence of postbreakup extrusive magmatism, the OCT is wider (35 km) with thinner crust (8 km) where the internal reflector observed in the other two segments is not present (Figures 1 and 3). Lower crustal velocities contrast with the high velocities observed in the Ashawq-Salalah adjoining segment. A mussel-shaped topographic high emerges from the morphology in the OCT (Figure 1). P wave velocities increase within this high with a continuous gradient from 5 km $s^{-1}$ at the seafloor to 7.9 km $s^{-1}$ at the base of the crust, a characteristic typical of serpentinized rocks [*Christensen*, 1972; *Dean et al.*, 2000; *Minshull*, 2009]. Similar features at other margins have been related to

**Figure 2.** The Ashawq-Salalah segment of the Encens experiment. (top) Model of seismic velocity structure. Velocity contours are color coded and labeled in units of km $s^{-1}$. Red circles are the instrument locations. OCT indicates the interpreted ocean-continent transition located in between the vertical dashed lines. Models are determined using a combined forward/inverse traveltime modeling approach (see auxiliary material). Examples of data are presented in the auxiliary material (Chi2 = 1.358; Nrays = 5101; thick solid lines are the reflection points). The crustal seismic models are shown with marine magnetic anomalies (blue line) from shipboard data with interpreted chrons and the free-air gravity anomaly (red line), both acquired jointly during the experiment. (middle) Deep seismic reflection and heat flow profiles and interpretation. Red arrows show the locations of the heat flow measurements in the seismic profile. The black circles are uncorrected heat flow, and red circles are corrected for sedimentation, topography, and refraction. Error bars represent a 68% confidence interval. The seismic profile is presented with interpretation of faults (faults active during early synrift are shown in red, faults active during late synrift are shown in pink [*Autin et al.*, 2010], and faults associated with active landslides are shown in purple) and of the main sedimentary units. Blue arrow indicates the location of the major fault imaged and reported on the model in Figure 2 (top). The colored dotted lines are derived from the velocity models converted in two-way traveltime seconds corresponding to main interfaces below the acoustic basement. (bottom) Schematic representation of the segment reconstructed with the southern conjugate margin [*d'Acremont et al.*, 2006], showing the margin style prior to seafloor spreading along the Ashawq-Salalah profile near the Alula Fartak Fracture zone (AFFZ). The 3-D block diagram shows the location of the AFFZ in relation to the segment and the distribution of the faults close to the cross section. Sedimentary series are not shown.

exhumed continental mantle that was serpentinized to within a few km of the surface rather than continental or basaltic crust [*Boillot et al.*, 1989; *Brun and Beslier*, 1996; *Whitmarsh et al.*, 1998; *Dean et al.*, 2000; *Lavier and Manatschal*, 2006; *Minshull*, 2009]. The mantle here also has low P wave velocities (7.8 to 7.9 km $s^{-1}$; Figure 3) as observed in margins in Newfoundland [*Reid*, 1994], Nova Scotia [*Funck et al.*, 2004] and Goban spur [*Bullock and Minshull*, 2005]. In addition, in the northern part of the mussel-shaped high, low-amplitude magnetic anomalies are present, which is also a characteristic of serpentinized rocks. These anomalies are interpreted as Chron 6 (20 Ma) in the northern part of the OCT domain (Figures 1 and 3). The oceanic domain displays typical crustal thickness (7.5 km) for an oceanic crust aged 18 Ma (Chron 5d), a flat Moho, a very steep P wave velocity gradient, high heat flow values and identifiable oceanic magnetic anomalies (Chron 5d; Figures 1 and 3). As in the previous subsegment, normal faults dipping seaward are closely spaced near the OCT and within the OCT domain. The mussel-shaped bathymetric high has been recently faulted as evidenced by many submarine landslides observed on the seafloor morphology (Figure 3). Other sedimentary instabilities are located in the continental domain (Figures 1 and 3 and auxiliary material), revealing active uplift of this margin segment.

### 4.3. Eastern Segment: Mirbat

[9] In the 65 km long Mirbat subsegment, the characteristics of the margin is again different from the two others. The OCT is wider (50 km) and its crustal thickness decreases from more than 8 km near the continental domain to 5.5 km near the oceanic domain with notable necking (Figure 4). A spur-shaped basement structure is observed in the OCT at its boundary with continental domain (Figure 1) where P wave velocities in the crust increase from 6 to 7.3 km $s^{-1}$ and the surface heat flow increases abruptly to a value of 120 $mWm^{-2}$, close to that expected for seafloor (Figure 4) [*Lucazeau et al.*, 2008]. As in the Taqah subsegment, there is no evidence of volcanism at the surface or at depth and the mantle here also has low P wave velocities (7.8 to 7.9 km $s^{-1}$; Figure 4). The continuous gradient of P wave velocity in the OCT from 5 to 7.8 km $s^{-1}$ from the surface to the base of the crust, and especially for the spur–shaped basement high, as well as low-amplitude magnetic anomaly (possibly Chron 6) (Figures 1 and 4) suggest the presence of serpentinized continental mantle which may have been exhumed by one or several faults [*Dean et al.*, 2000; *Funck et al.*, 2003; *Bullock and Minshull*, 2005; *Minshull*, 2009]. Further south in the OCT domain, a buried isolated basement structure displays velocities that could be attributable to the presence of continental crust material (between 5 and 5.4 km $s^{-1}$ abscissa 40–55 km; Figure 4). The deformation of this segment is characterized (1) by two major seaward normal faults that bound blocks of thinned continental crust (one is imaged by the seismic profile and the other one crops out onshore; Figure 5), (2) possibly by exhumed serpentinized mantle, and (3) possibly by an extensional allochthon of continental crust (Figure 4). In the continental slope, active sedimentary instabilities also reveal persistent uplift of the margin during postrift (Figures 1 and 4 and auxiliary material).

## 5. Interpretations and Discussion

[10] Our primary observations are variations in margins geometry, OCT width and magmatism over small spatial scales. We describe a wide OCT for the magma-poor rifted margin segment (two eastern segments) and a narrow OCT associated with postbreakup magma-rich segment (western segment). Why do such extreme differences exist between these three segments of the eastern Gulf of Aden margin? We consider possible interpretations based on the P wave velocities, MCS, gravity, heat flow and magnetism such as postbreakup volcanism, exhumation of subcontinental mantle and widening of the OCT in relation to the increase of average rate of extension.

### 5.1. Postbreakup and Postrift Volcanism

[11] Based on the presence of internal reflectors and unusually high P wave velocities at large depth, we propose that the high-velocity body existing exclusively at the base of the crust in the Ashawq-Salalah segment is related to an underplated magmatic body. Its origin may not be related to the other volcanic activity along the margin. Its seismic velocities are much higher than those reported for underplated material along the North Atlantic margins [*Raum et al.*, 2002]. Also, the volume of magmatism is smaller in the eastern Gulf of Aden than for other volcanic margins where underplating has been interpreted. Moreover, in a magma-poor margin setting where no synrift volcanism has been documented [*d'Acremont et al.*, 2005; *Autin et al.*, 2010], it is unlikely that igneous underplated body

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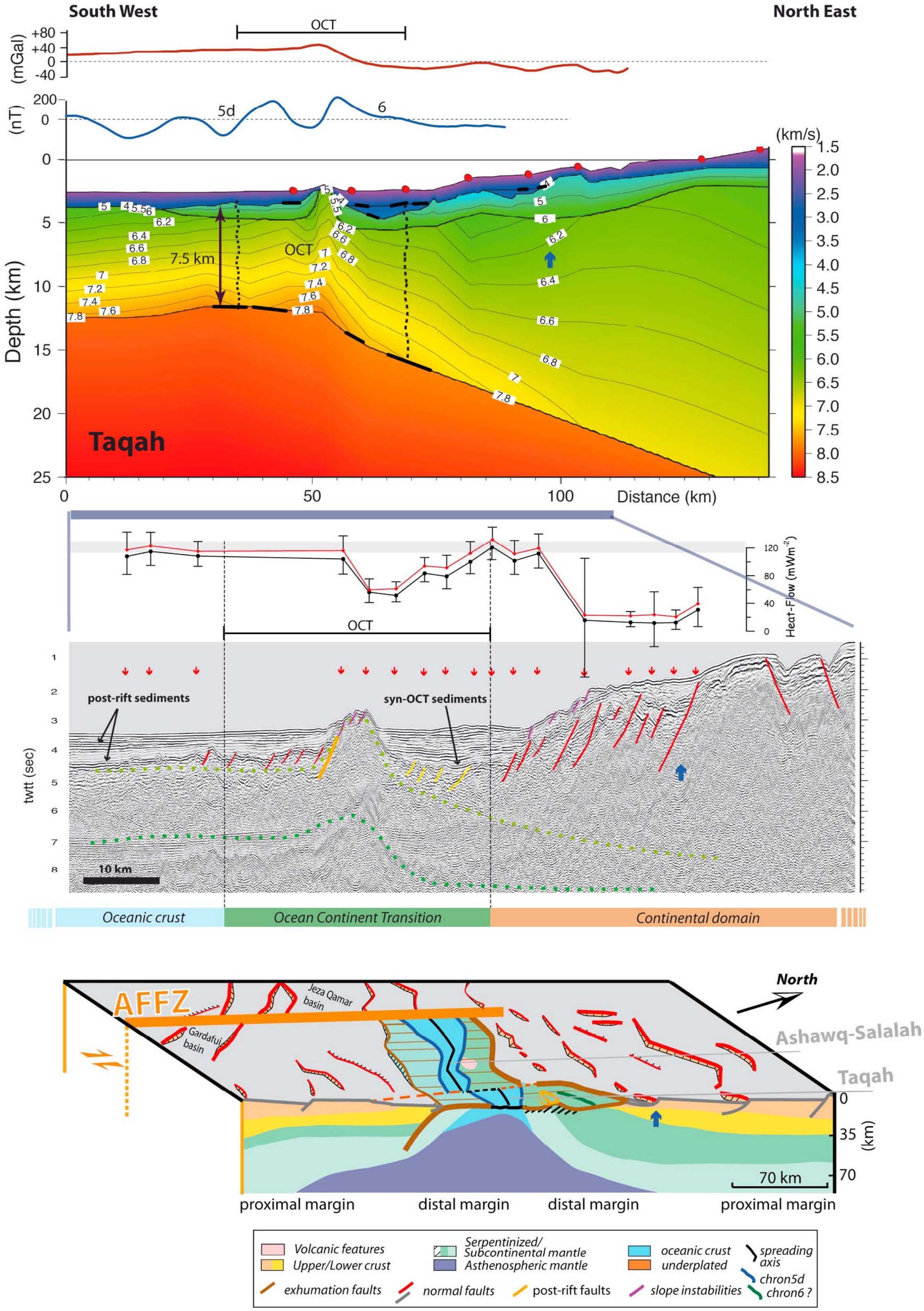



**Figure 3**

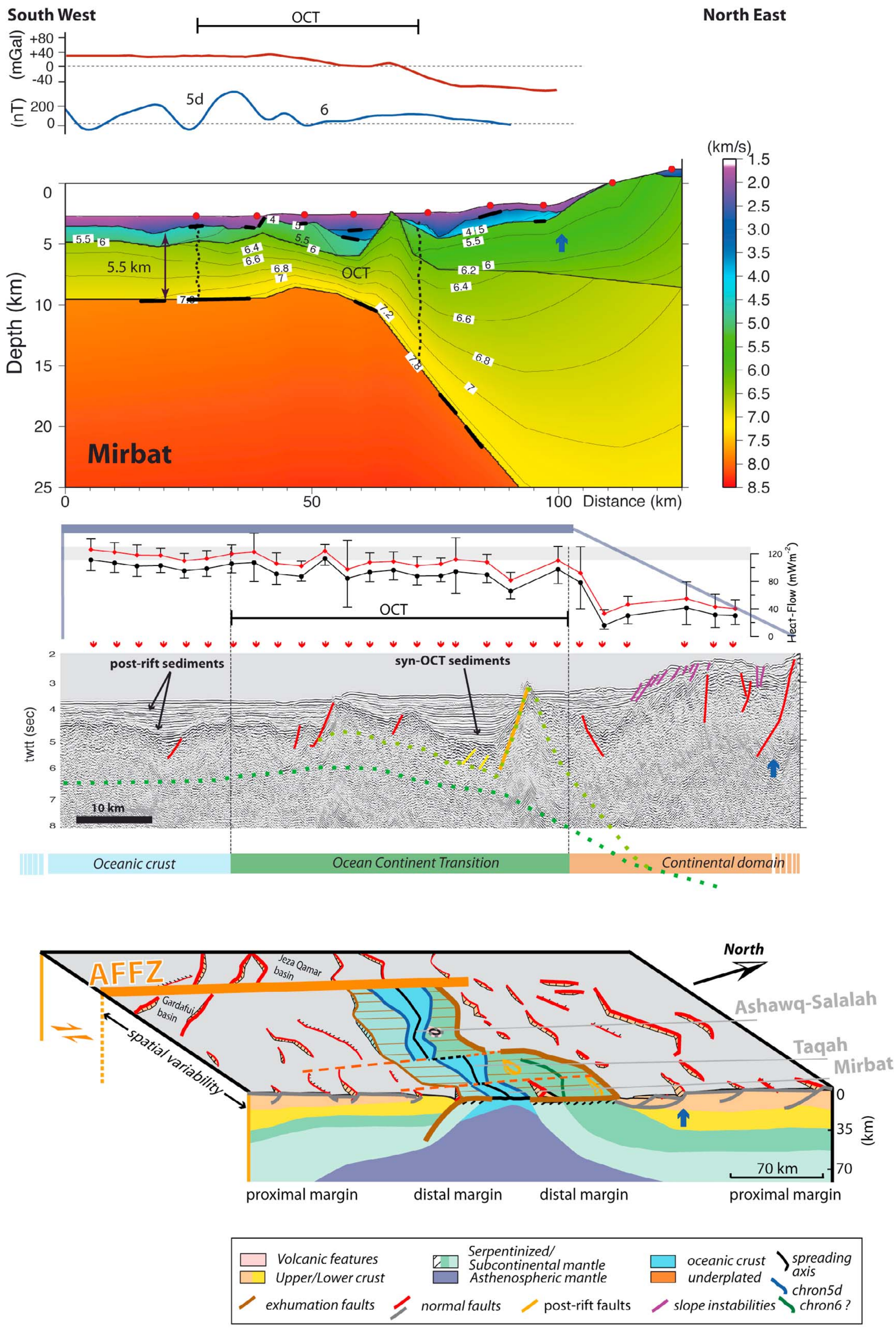
has an origin similar to that of the volcanic rifted margins [e.g., *Hirsch et al.*, 2009]. In Atlantic margins, high-velocity bodies are usually associated with flood basalt volcanism [*Meyer et al.*, 2007]. Here, at the top of the crust, volcanism is observed in the OCT and occurs soon after the breakup, as the OCT formed, and persists during the onset of seafloor spreading [*Lucazeau et al.*, 2009; *Autin et al.*, 2010; *Leroy et al.*, 2010]. If the origin of this high-velocity body in the lower crust corresponds to magmatic sills accreted after the breakup and/or early during the seafloor spreading phase, we would expect dikes to appear within the crust. We do not observe any dikes, but they are probably below the resolution of our seismic profiles. Volcanism is observed within the OCT of the longest margin segment and close to the long-offset AFFZ. At the ridge segment that corresponds to this section of the OCT, oceanic crust production is greater than the global average [*d'Acremont et al.*, 2010]. The origin of this postrift volcanism within the OCT may be related either to crustal thickening and magma production at the edge of the long-offset transform [*Hooft et al.*, 2000; *Gregg et al.*, 2007] as proposed by *d'Acremont et al.* [2010] for the 180 km long AFFZ offset, which has been active at least since the time of OCT formation [*d'Acremont et al.*, 2010]. Alternatively, the volcanism and associated underplated body may be related to the anomalous presence of melt beneath the Gulf of Aden fed by channeled flow of plume material from the Afar hot spot along the nascent ridge in a context of plume-ridge interaction as suggested by *Leroy et al.* [2010]. In other segmented margins with long-offset fracture zones, the oceanic transforms may act as long-lived magmatic pathways for melt in the lithosphere [*Gernigon et al.*, 2009]. Thus, the relatively sharp along-strike change in the OCT structure between the Ashawq-Salalah segment and the two others that are not associated large-offset transform faults may be related to the postbreakup volcanism that controlled the geometry of the OCT and that of the nascent spreading ridge. Volcanism is indeed considered to be capable of reducing fault spacing and heave and as a result decreasing the width of the axial valley [*Behn and Ito*, 2008].

## 5.2. Exhumation of Subcontinental Mantle

[12] Based on the observations of a continuous gradient of P wave velocity from surface to depth on the two basement highs (mussel-shaped and spur-shaped) and the presence of low-amplitude magnetic anomaly in the OCT of the Taqah and Mirbat segments, we propose that continental crust breakup first began by the exhumation of the subcontinental mantle by faults that flatten near the seafloor [*Brun and Beslier*, 1996; *Lavier and Manatschal*, 2006] (Figure 3–5). In the Ashawq-Salalah segment, exhumation of the continental mantle may also have occurred [*Autin et al.*, 2010], but evidence for this may have been overprinted by the postrift volcanic activity (Figures 2 and 5).

[13] Examples of fault systems that exhume continental mantle have been imaged by seismic studies [*Dean et al.*, 2000] and drilled [*Boillot et al.*, 1988; *Whitmarsh et al.*, 1998] in the Iberia abyssal plain or exposed in the Alps [*Lavier and Manatschal*, 2006] and Pyrenees [*Lagabrielle and Bodinier*, 2008]. In these locations, exhumed mantle in the OCT is associated with shallow crustal detachment systems, and is serpentinized at temperatures under 600°C at depths shallower than 10 km where hydrothermal circulation is supposed to have occurred [*Lavier and Manatschal*, 2006; *Cannat et al.*, 2009]. We believe that the very low-amplitude Chron 6 magnetic anomaly could be associated with serpentinization of the exhumed mantle and not formed as a typical oceanic magnetic anomaly would be. The contribution of peridotites to magnetic anomalies becomes significant only where they are affected by a high degree of serpentinization and associated presence of magnetite [*Oufi et al.*, 2002]. Here the low-amplitude anomalies, which are not centered over the basement highs, may be associated with low degrees of serpentinization. In the Ashawq-Salalah segment, the recent volcano lying on the OCT [*Autin et al.*, 2010] may have modified the magnetic signal. This may be why Chron 6 was not

**Figure 3.** The Taqah segment of the Encens study. (top) Model of seismic velocity structure (Chi2 = 1.919; Nrays = 2689; thick solid lines are the reflection points), marine magnetic anomalies (blue line) from shipboard data with interpreted chrons, and the free-air gravity anomaly (red line). (middle) Deep seismic reflection and joint heat flow profiles and interpretation. The seismic profile is presented with interpretation of faults (faults active during early synrift are shown in red, faults active during exhumation phase are shown in yellow, faults active during postrift are shown in orange, and faults associated with active submarine landslides are shown in purple). (bottom) Schematic 3-D representation of the spatial evolution of the segment reconstructed with the southern conjugate margin.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200
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Jeza Qamar basin
Gardafui basin
spatial variability
Ashawq-Salalah
Taqah
Mirbat
proximal margin
distal margin
distal margin
proximal margin
70 km
(km)
Volcanic features
Upper/Lower crust
Serpentinized/ Subcontinental mantle
Asthenospheric mantle
oceanic crust
underplated
spreading axis
chron5d
chron6 ?
exhumation faults
normal faults
post-rift faults
slope instabilities

**Figure 4**

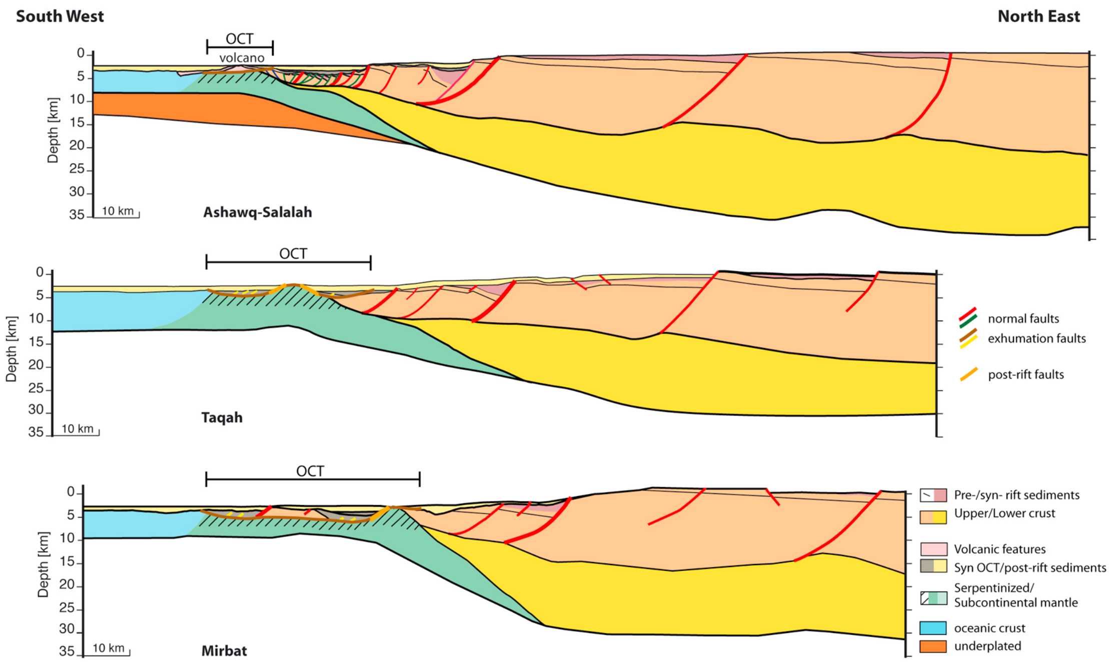


**Figure 5.** Modes of extension leading to continental breakup. Conceptual crustal sections without vertical exaggeration of the three different segments based on observations and data interpretation. The thickness of the crust in the proximal margin is from receiver function study [*Tiberi et al.*, 2007]. The crust is thinned by seaward dipping normal faults that slipped during different stages of rifting. The earliest faults form the main grabens, and the latest localize deformation at the axis of paleorifts or are responsible for exhumation of the subcontinental mantle.

recorded in the western segment. The P wave velocity versus serpentinization rate [*Horen et al.*, 1996] however suggests 100% and 60% of serpentinization rate for mussel-shaped and spur-shaped highs, respectively. These basement highs are controlled by recently active faults that reach the surface and may be acting as recharge zones for fluid circulation within the crust. This notion is supported by the decreased heat flow over these two highs (Figure 3). The recently active faults uplifted the ridges of serpentinized peridotites to their present-day positions. Mantle with a velocity of 7.8 km/s underlies both the thinned continental and oceanic crust. A gradual downward increase to normal mantle velocities has been interpreted to reflect decreasing degree of serpentinization with depth [*Funck et al.*, 2003]. Normal mantle velocities of 8.0 km/s are observed ~6 km below the base of the crust as it is the case in several others margins such as Newfoundland [*Reid*, 1994].

## 5.3. Widening of the OCT

[14] We propose that the widening of the OCT toward the east between AFFZ and SHFZ is related to the oblique opening of the Gulf of Aden and could be explained either by an eastward increase in the amount of extension or by a westward propagating rift system. In the absence of well data to constrain ages, we rely on magnetic chron patterns and analogue modeling (J. Autin et al., Analogue models of oblique rifting in a cold lithosphere, submitted to *Tectonics*, 2010). In the highly segmented margins, distal grabens present a morphology related to an opening system, with deepening toward the wider eastern side caused by rotation of

**Figure 4.** The Mirbat segment of the Encens experiment. (top) Model of seismic velocity structure (Chi2 = 2.407; Nrays = 3546; thick solid lines are the reflection points), marine magnetic anomalies (blue line) from shipboard data with interpreted chrons, and the free-air gravity anomaly (red line). (middle) Deep seismic reflection and joint heat flow profiles and interpretation. The seismic profile is presented with interpretation of faults (faults active during early synrift are shown in red, faults active during exhumation phase are shown in yellow, faults active during postrift are shown in orange, and faults associated with active submarine landslides are shown in purple). (bottom) Schematic 3-D representation of the spatial evolution of the segment reconstructed with the southern conjugate margin.

**Table 1.** Summary of Across-Margin Characteristics of Segments on the Profiles

| | Ashawq-Salalah | Taqah | Mirbat |
|---|---|---|---|
| Segment length (km) | 94 | 36 | 65 |
| OCT width (km) | 15 | 35 | 50 |
| OCT crust thickness (km) | 13 | 8 | 7–8 |
| Oceanic crust thickness (km) | 9 | 7.5 | 5.5 |

tilted blocks at the end of rifting [*Autin*, 2008]. Evidence for such block rotations in the young obliquely opening Main Ethiopian Rift can be seen in paleomagnetic analysis [*Kidane et al.*, 2006]. In a V-shaped basin such as the Woodlark basin or West Iberia margin for instance, widening of the rift is often related to the propagation of the rift system [*Taylor et al.*, 1999; *Péron-Pinvidic and Manatschal*, 2009]. In such propagating systems, different phases of extension must be occurring coincidentally [*Lavier and Manatschal*, 2006]. In our study area, the grabens deepen and widen toward the east and no propagation is observed (Figure 1). We, therefore, prefer a rifting model without propagation in an oblique rifting context added to the effects of the volcanism in the western segment of the OCT. We believe that the OCT formed with a higher extension rate where there is exhumed continental mantle and no magmatism. Where the OCT is wide, allochthonous relics of continental crust lying on the exhumed mantle are observed (Figure 4) as in the West Iberia margin [*Péron-Pinvidic and Manatschal*, 2009].

## 6. Concluding Remarks

[15] The rifted margin sectors between large offset transforms in the eastern Gulf of Aden reveal fundamental along-strike variations in distribution and in style of lithospheric strain over distances < 50 km. Our primary observations indicate the presence of a narrow segment of OCT within an otherwise wide magma-poor OCT rift sector that may have been produced by enhanced melting or by a supply of Afar plume material channeled by the ridge to the large-offset transform fault zone that bounds the segment. We believe the two rifting mechanisms led to the observed structure of the margin and present-day seafloor spreading system: oblique rifting near evolving large-offset transform faults, and lithospheric weakening by magma and localized mantle exhumation associated with margin segmentation. Studies of other passive margins with along-strike changes show similarities with our interpretations although published data sets from these other locations cannot constrain the lateral evolution over such a short distance (Figure 4, middle). Studies in the Gulf of California and northwestern Australia show that synrift and early postrift magmatism varies between rift segments [*Hopper et al.*, 1992; *Lizarralde et al.*, 2007], but the short lateral changes, which may be related to the geological and tectonic setting, are unknown. The results presented in the Gulf of California highlight the importance of inherited mantle fertility/hydration resulting from the presence of prerift ignimbrites of the former arc system [*Lizarralde et al.*, 2007]. The structural inheritance of the Gulf of Aden consists of previous episodes of rifting with some associated rifted basins [*d'Acremont et al.*, 2005]. In the case of the Gulf of Aden, the proximity of the Afar plume may have had an influence on the rift system since its inception [*Bellahsen et al.*, 2003]. Therefore, unlike the interpretation proposed for the Gulf of California [*Lizarralde et al.*, 2007], the along-axis variations in the Gulf of Aden margin do not seem to be related only to mantle depletion versus mantle fertility. Instead, we believe that the genetic link between the widening of the OCT toward the east, the exhumation of subcontinental mantle, and the postrift volcanism is due to the obliquity of the rifting as well as in the influence of the Afar plume. Plume-ridge interaction may have affected the rift system and its margins as early as immediately after OCT emplacement [*Leroy et al.*, 2010].

[16] Similar processes have affected other margins either in a context of oblique opening with strike-slip components as has been proposed for the Woodlark basin [*Taylor et al.*, 1999] or for some segments of Atlantic margins where influence of plume material during the OCT formation may have occurred [e.g., *Moulin et al.*, 2005]. Thus it is important to consider these profound along-axis variations in lithospheric strain accommodation and OCT structure, which can affect sedimentary and thermal structure of continental margins as well as evolution of petroleum systems located there. Our observations and interpretations demonstrate the need for a fully 3-D approach to rifted margin studies.

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