SUPPLEMENTAL INFORMATION

Gulf of Aden spreading does not conform to triple junction formation

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Background

The onset, structure and timing of seafloor spreading and the extent of oceanic-continent transition crust (OCT) in the Gulf of Aden and the triple junction zone remain controversial (e.g., Girdler & Styles 1978; Hempton 1987; Leroy et al. 2004; d'Acremont et al. 2005; d'Acremont et al. 2006; d'Acremont et al. 2010; Fournier et al. 2010; Leroy et al. 2010a; 2010b; Ali & Watts 2013; Nonn et al. 2017). Several studies consider a propagation of rifting at the Gulf of Aden from east to west (e.g., d'Acremont et al. 2005; Fournier et al. 2010; Leroy et al. 2010b) or a synchronous oblique rifting (e.g., Leroy et al. 2012; Bellahsen et al. 2013b) initiate as early as the Priabonian time and after the closure of the Neo-Tethys Ocean and the release of Afar plume (Bellahsen et al. 2003) with the onset of ocean crust formation initiating during the Oligocene (e.g., Girdler and Styles, 1978; Girdler et al., 1980), or the Miocene (e.g., Leroy et al. 2012; Nonn et al. 2017), or only in the last 5 Ma (e.g., Hempton 1987).

There are several tectonic and geodynamic events that have influenced the overall architecture of the Gulf of Aden including: (1) Lithospheric extension between African and Arabian plates at 30-24 Ma that led to the opening of the RS (e.g., Bosworth et al. 2005; ArRajehi et al. 2010), (2) Slowing of the convergence between Arabia and Eurasia at 25 Ma (e.g., McQuarrie et al. 2003; ArRajehi et al. 2010; McClusky et al. 2010); (3) Miocene (20-16 Ma) collision between Arabia and Eurasia (e.g., Okay et al. 2011); (4) the absence of Miocene volcanic activity between 16-13 Ma at the northern part of the Arabian plate (e.g. Al Kwatli et al. 2012); and (5) Miocene northward escape of Arabia Plate at ~ 13 Ma associated with the Anatolian and Arabian plates oblique collision; contemporaneously with the development of the Levant/Dead Sea Rift (e.g., Westaway 1994). The dates of these major events along with the results of recent high-resolution reconstructions of the Indian Ridge, Red Sea and Gulf of Aden (DeMets and Merkouriev, 2016) suggest that previous estimates of older than 16 Ma seafloor spreading in the Gulf of Aden based on sparse coverage of magnetic data (e.g., Fournier et al. 2010) is inconsistent with the reliable determinations of motion estimate between Africa-Somalia plate since 20 Ma (DeMets and Merkouriev, 2016).

The Gulf of Aden has separated into three prominent domains that are bounded by large scale transform faults (e.g. Leroy et al. 2013) (Fig. 1). The eastern domain (Sheba Ridge) is the most extensively studied part of the Gulf of Aden and extends from the Owen Fracture Zone to the Alula-Fartak Fracture Zone (AFFZ). The central domain (Aden Ridge) is confined by the AFFZ and Shukra-El Sheik Fracture Zones (SSFZ). The western domain (Junction Zone) extends from the SSFZ to the Gulf of Tadjora (GOT). These transform faults are inferred to be inherited from the highly segmented and offset Oligocene rift basin that pre-dates final break-up and oceanic spreading (e.g., Leroy et al., 2013, and reference therein), although there are several interpretations where transform fault is not attributed to the prior rift geometry (e.g., Gerya 2012). This view is supported by bathymetric analysis from incipient juvenile spreading basins,

which shows that initial offsets between spreading segments are typically not transform (Taylor et al. 2009, and reference therein).

Much of our detailed understanding of the evolution of the Gulf of Aden has been derived from the enormous amount of geological and geophysical data that has been collected to the east of the AFFZ (eastern domain or Sheba Ridge) (Fig. S1 and S2) (e.g., d'Acremont et al. 2006; Fournier et al. 2010; Leroy et al., 2012; 2013; Bellahsen et al. 2013b). These data have effectively provided snap-shots of the crustal and basin architecture along a particular segment or cross section of the Gulf of Aden. The knowledge that has been gleaned from these studies has been used to infer the evolution of the central (Aden Ridge) and western domain (Junction Zone) to the west of the AFFZ (Fig. S3), where geophysical data is less abundant (Fig. S1, S2A, and S2B).

The opportunity to understand ocean initiation and geographic spreading segments distribution in the Gulf of Aden is presented in our study because of the availability of data compilations that provide full coverage of the Gulf of Aden (Fig. 2). These previously unavailable data now have sufficient spatial resolution and precision to allow effective imaging and forward modeling of the crustal architecture along the Gulf of Aden (e.g., Ali & Watts 2013). Satellite and marine geophysical (Fig. 2) compilations show the crustal elements along the Gulf of Aden are more complex than previously proposed (Fig. S2C and Fig. S3).

Data and Method

Recently, using satellite-marine derived gravity and magnetic data (Maus and Varner, 2009; Sandwell et al. 2014; Meyer et al. 2017) is used to demarcate regions of active sea-floor spreading from regions of continental rifting (e.g., Small and Sandwell 1994; Trung et al. 2004; Almalki et al. 2016), because these setting have different characteristic long wavelength and free-air gravity and magnetic responses. Whilst this data has a lower spatial resolution compared to localised high resolution data, it nevertheless provides complete coverage of the Gulf of Aden and revealing a crustal architecture that is more complex than previous interpretations.

We used the recent satellite-marine magnetic, gravity and bathymetry data (Sandwell et al. 2014; Meyer et al., 2017; Tozer et al., 2019) (Fig. 2) to assess the location of sea-floor spreading segment, the location of transitional crust, and of the continental lithosphere in the Gulf of Aden, using the criteria developed in Almalki et al. (2016). We also present lithospheric forward models (Fig. 2), constrained by available seismic and wells data (Fig. S1), along selected profiles of magnetic and gravity data along the Gulf of Aden and the junction zone.

Low-pass filter (100 km wavelength cut-off) of the gravity (Fig. 2D); which has been re-gridded with a cell size of 450 meters, were utilized to detect the long-wavelength mantle signature (Fig. 2D), whilst removing the short-wavelength bathymetric effects. We have also calculated the tilt-derivative of the total magnetic intensity data to image and detect magnetic stripes (Fig. 2E).

This is effective for delineating oceanic/transitional crust and continental crust as tilt derivative processing improves normalized magnetic amplitude and is successful for visualizing delicate anomalies within the shallow basement (e.g. Verduzco et al. 2004). Tilt-derivative method is commonly applied to continental potential field datasets because it clearly defines anomaly edges, it equalizes amplitudes of anomalies, and will produce useful magnetic responses for induced and remanent magnetized anomalies (Verduzco et al. 2004). These characteristics make it an ideal technique to analyse oceanic datasets because linear magnetic anomalies, such as oceanic stripes, are imaged in much higher resolution.

In order to evaluate the nature of the crust and its geometry under the Gulf of Aden, and the relationship between the gulf rift system with the Afar rift, we have extracted 10 profiles for analysis and comparison and forward model five selected profiles of magnetic and gravity data (Fig. S4) along the Gulf of Aden and the junction zone to illustrate the crustal geometry. Rock property for the models features is shown in Table 1. The geometry was constrained by seismic reflection and refraction data (Laughton & Tramontini 1969; Fairhead 1973; Girdler et al. 1980; Prodehl et al. 1997; Jacques et al. 1999; Watremez et al. 2011; Ali & Watts 2013) as well as available exploration drill data (Beydoun 1989; Hughes et al. 1991; Hughes & Beydoun 1992; Beydoun & Sikander 1992; Ali & Watts 2013) (Fig. S1). Other seismic data on land that may interfere with our study area such as “ADEN” station with a suggestion of 20 km crustal thickness (Ahmed et al., 2013), has not been taken into account because such thickness did not satisfy the models. It also should be noted that there is a 2.08 km error in depth at this particular station (Ahmed et al., 2013). Also, recent localized seismic data (Nonn et al. 2019) located at the extreme northern and southern edge of the central gulf margin has not been used because neither the actual seismic profiles nor the seismic velocities are presented.

Marine-satellite potential-field data

The bathymetry data shows a distinct morphology that varies along the length of the Gulf of Aden. To the immediate west of the AFFZ (Fig. 2A), the bathymetry shows the presence of an axial trench that extends continuously for approximately 180 km before it is disrupted by a major NE-trending, linear bathymetry high, that can be correlated to a major transform fault known as Khanshir-Al Irquah Fracture Zone (KAFZ) (Fig. 1). Parallel with the axial trench are relatively bathymetry ridges that become increasingly deeper away from the axial zone before becoming shallower along the shelf regions adjacent to the present-day coastline. An abrupt change in the bathymetry signal occurs to the west of the KAFZ. The axial zone is discontinuous forming ~25-40 km length bathymetric lows between NE-trending bathymetric highs. Transform faults are continuous in the bathymetry data until they reach the shelf region of the Gulf of Aden, where they offset the bathymetric expression of the shelf, terminate against the shelf or change expression and become bathymetry lows within the shelf zone. This part of the basin is characteristically shallower than the gulf to the east of KAFZ. Another change in the bathymetric character of the Gulf of Aden occurs at the SSFZ (Fig. 2A). To the immediate west of this transform, the prominent NE-SW trending linear bathymetric highs are not present, the basin

becomes shallower, and there is a prominent narrow rift valley, characterized by a bathymetric low that extends from the Gulf of Tadjora.

The satellite-marine free-air gravity data (Fig. 2B) across the Gulf of Aden is marked by low and high anomalies between -140 and 106 mGal. The central section of the gravity belt, associated with the axial trough, is in agreement with the axial area determined by magnetic and seismic data (Fig. 2C; Fig. S1), although known spreading ridges have a low free-air gravity response. At the western domain, the free-air gravity expression is characterised by the prominent E-W-trending linear anomalies. Further, positive high gravity anomalies over the majority of the Gulf of Aden appear to be associated with NE-trending transform faults or accommodation zones, which are coincident with offset of some magnetic stripes (Fig. 2E). The distribution of anomalies reflects the topographic patterns of the gulf and therefore many of the same features identified in the bathymetry data are preserved, including the continuous axial trench and ridge topography on the flanks. Longer wavelength free air gravity anomalies that trend parallel with the axial zone are absent. Short-wavelength free gravity anomalies trend NNE and appear to reflect local topography along incipient transform faults. Between the BHFZ and the SSFZ there are three isolated gravity anomalies in the low-pass filtered gravity data (Fig. 2D).

The marine-satellite magnetic anomaly information shows that the magnetic domain over the Gulf of Aden ranges between -507 and 379 nT (Fig. 2C). The total magnetic intensity data revealed two major areas with distinct anomaly patterns. In the central domain, the area is dominated by a sequence of linear magnetic features in line with the Gulf of Aden axial trough. This area is characterized by large amplitude and short wavelength anomalies over the spreading ridge and is offset by NE-SW transform faults. The amplitude decreases away from the ridge while the wavelengths get shorter. Tilt derivative images (Fig. 2E) suggests the presence of at least eight positive magnetic stripes that extend along the Aden Ridge length, though some of them terminated against the KAFZ and/or SSFZ, and in general decreased in number towards Afar (at the junction zone area). Linear magnetic anomalies along the Yeman passive margin are less continuous and trend in a ~E-W orientation, oblique to the general trend at Sheba Ridge (Fig. 2C; Fig. 2E). Magnetic anomalies at the Somali passive margin are parallel with the Gulf of Aden axial zone magnetic anomalies but are discontinuous. In the western domain, there is a more diffuse magnetic signature characterized by magnetic anomalies with very small amplitudes and long wavelengths (Fig. 2C; Fig. S4) along the edge of the Somalian Plate (along the southern Gulf of Aden area) and in the GOT. To the immediate west of Bosasso-Hami Fracture Zone (BHFZ) the orientation of the magnetic stripes are approximately E-W and discontinuous terminating before the GOT.

Table S1. Rock property values for the calculated models shown in figure 5.

<i>Unit</i>	<i>Density (g/cm³)</i>	<i>Susceptibility (cgs) *</i>
Water	1.3	0
Sediment	2.4	0
Recent Oceanic crust	2.8	0.001-0.006
Oceanic crust	2.95	0.003-0.008
Transitional crust	3.0	0.003-0.005
Continental crust	2.76	0.0004-0.0006
Mantle	3.2	0.001

* Magnetic field 38619 nT, Inclination 21.15 degrees, Declination 2.3 degrees.

Figure S1. (A) Location of available seismic and well data from the Gulf of Aden. Drill data from Beydoun (1989), Hughes et al. (1991), Hughes & Beydoun (1992) Beydoun & Sikander (1992), and Ali & Watts (2013). (B) Seismic crustal models modified after Laughton and Tramontini (1969), Fairhead (1973), Girdler et al. (1980) Prodehl et al. (1997) Jacques et al. (1999), Watremez et al. (2011), and Ali and Watts (2013).

Figure S2. (A) Historical magnetic surveys along the Gulf of Aden. (B) Magnetic contoured map, and (C) Interpreted oceanic crust along the Gulf of Aden and its age based on magnetic isochrons. Modified from Fournier et al. (2010).

Figure S3. Synchronous opening of the Gulf of Aden after Leroy et al. (2013).

Figure S4. Profiles of magnetic, free-air gravity, low-pass filter and 2D forward models of the magnetic and gravity data constrained by geological and seismic data (refer to figure 2B, 2C and figure S1 for location, figure S1 for seismic crustal models and Table S1 for rock property values).

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