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Crustal structure of the Gulf of Aden southern margin: Evidence from receiver functions on Socotra Island (Yemen)

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ABSTRACT

Breakup of continents in magma-poor setting occurs primarily by faulting and plate thinning. Spatial and temporal variations in these processes can be influenced by the pre-rift basement structure as well as by early syn-rift segmentation of the rift. In order to better understand crustal deformation and influence of pre-rift architecture on breakup we use receiver functions from teleseismic recordings from Socotra which is part of the subaerial Oligo-Miocene age southern margin of the Gulf of Aden. We determine variations in crustal thickness and elastic properties, from which we interpret the degree of extension related thinning and crustal composition. Our computed receiver functions show an average crustal thickness of ~28 km for central Socotra, which decreases westward along the margin to an average of ~21 km. In addition, the crust thins with proximity to the continent–ocean transition to ~16 km in the northwest. Assuming an initial pre-rift crustal thickness of 35 km (undeformed Arabian plate), we estimate a stretching factor in the range of ~2.1–2.4 beneath Socotra. Our results show considerable differences between the crustal structure of Socotra's eastern and western sides on either side of the Hadibo transfer zone; the east displays a clear intracrustal conversion phase and thick crust when compared with the western part. The majority of measurements across Socotra show V_p/V_s ratios of between 1.70 and 1.77 and are broadly consistent with the V_p/V_s values expected from the granitic and carbonate rock type exposed at the surface. Our results strongly suggest that intrusion of mafic rock is absent or minimal, providing evidence that mechanical thinning accommodated the majority of crustal extension. From our observations we interpret that the western part of Socotra corresponds to the necking zone of a classic magma-poor continental margin, while the eastern part corresponds to the proximal domain.

1. Introduction

The eastern Gulf of Aden continental margins are magma-poor oblique-rifted margins (Fig. 1a) (Bellahsen et al, 2013a; Leroy et al, 2010a). As such, long fracture zones generated by transform faults impose a first order control on the along-rift segmentation of the young ocean basin (Bellahsen et al, 2013b; Leroy et al., 2012). The Arabian plate is thought to have broken away from the Somalian plate at 20–18 Ma, with the young passive rifted conjugate margins still largely exposed subaerially (d'Acremont et al., 2010; Fournier et al., 2010). This makes it easy to interpret the extensional and sedimentary processes active during continental breakup. Post-rift sedimentary cover is generally relatively thin (0.5–1 km) (d'Acremont et al., 2005; Leroy et al., 2004) and seismic reflection profiles show an absence of seaward dipping reflectors (Autin et al., 2010a,b; d'Acremont et al., 2005; Leroy et al., 2010a,b) making syn/post-rift sediment and basement easily identifiable and mappeable. The structure of the margin is therefore interpretable on upper-crustal and crustal scale cross sections (Autin et al., 2010a; d'Acremont et al., 2005, 2006, 2010; Leroy et al., 2004, 2010a, 2012; Tiberi et al., 2007).

Magma-poor rifted margins show a characteristic architecture within three distinct divisions from continent to ocean: the proximal, distal, and ocean-continent transition domains. The proximal domain is characterized by rift-basins bound by high-angle listric faults with

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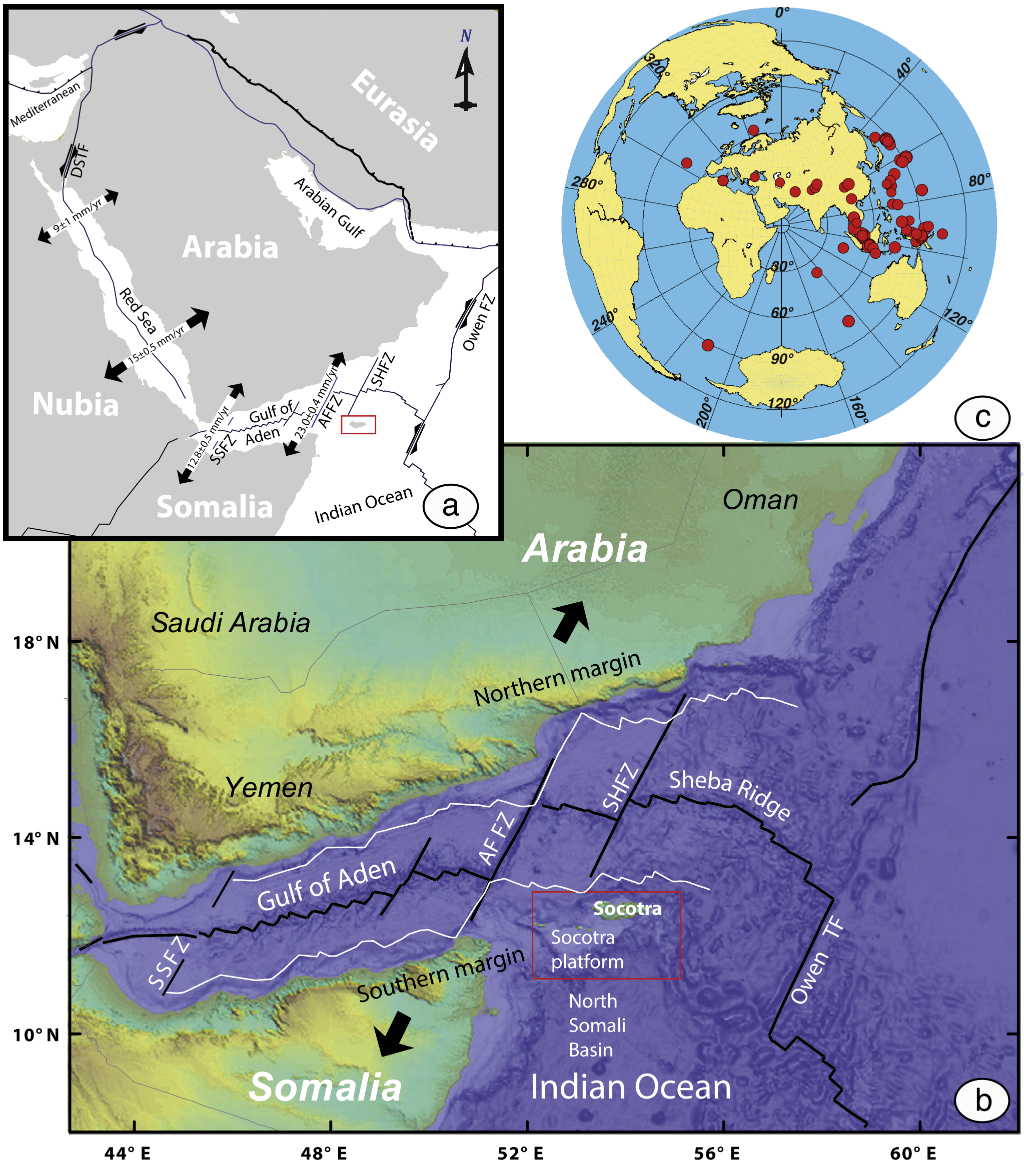

Fig. 1. a) and b) Landsat imagery and Sea-sat bathymetry showing the main tectonic features of the Gulf of Aden and surrounding areas. The large black arrows indicate the direction of plate motion in the region. The white lines show the location of the first magnetic anomaly (5d = 17.6 Ma) identified in the Gulf of Aden (d'Acremont et al., 2006; Leroy et al., 2010a, 2012). c) Polar projection shows the distribution of seismic events, small circle interval is 30°. SSFZ: Shukra el Sheik fracture zone; AFFZ: Alula Fartak fracture zone; SHFZ: Socotra Hadbeen fracture zone; DSTF: Dead Sea transform fault, Owen TF: Owen transform fault.

limited crustal thinning ($\beta < 2$) (e.g. Mohn et al., 2012). The crust of the distal domain is extremely thin with listric detachment faults commonly penetrating the whole crust. This differs from the proximal domain where fault does not cut through the whole crust (Franke, 2013; Péron-Pinvidic and Manatschal, 2008; Whitmarsh et al., 2001). Mohn et al. (2012) defined a narrow necking zone between proximal and distal domains. Necking of the continental crust occurs in a narrow transition zone from slightly stretched and thinned crust (~30 km) to extremely thinned crust (<10 km) with $\beta > 2$ (Mohn et al., 2012). The ocean-continent transition (OCT) is defined as the domain of exhumed sub-continental mantle (Franke, 2013; Mohn et al., 2012) if it has been sampled. If no samples are available then the OCT is defined as a domain of uncertain affinity between the thinned continental crust and the crust that displays clear oceanic geophysical characteristics (see Leroy et al., 2010a for details). Hence, crustal thickness variation along rifted margins from the proximal domain to the distal domain is a key parameter required to assess structural segmentation and the strain localization during the transition from continental break-up to active oceanic spreading.

During the last few decades, detailed geophysical and geological studies have been carried out within the Gulf of Aden to evaluate the initiation and development of the active spreading ridge (Sheba ridge) (Fig. 1a and b). These studies have provided bathymetric (Leroy et al., 2004), seismic (Autin et al., 2010a; Bache et al, 2011; d'Acremont et al., 2005, 2010; Laughton et al., 1970; Leroy et al., 2004, 2010a,b; Stein and Cochran, 1985; Watremez et al., 2011), gravity, magnetic (Ali and Watts, 2013; d'Acremont et al., 2006; Fournier et al., 2010; Leroy et al., 2010a; Leroy et al, 2012), and heat flow (Lucazeau et al., 2008, 2009, 2010; Rolandone et al, 2013) constraints. The interpretation of these data has resulted in a detailed model of the evolution of the eastern Gulf of Aden from rifting to oceanic spreading. In addition to these marine geophysical studies, detailed onshore stratigraphical, geological, structural, and geophysical studies have been carried out on the northern continental margin of the Gulf in eastern Yemen and Oman (Ahmed et al, 2013; Al- Hashmi et al., 2011; Al-Lazki et al., 2012; Basuyau et al., 2010; Bellahsen et al., 2006, 2013a,b; Chang and Van der Lee, 2011; Corbeau et al, 2014; Denèle et al, 2012; Huchon and Khanbari, 2003; Korostelev et al, 2014; Leroy et al., 2012; Menzies