Tectonophysics 628 (2014) 123–139

Contents lists available at ScienceDirect

Tectonophysics

journal homepage: www.elsevier.com/locate/tecto

Nature of crust in the central Red Sea

Neil C. Mitchell [a,*], Yongcheol Park [b]

[a] School of Earth, Atmospheric and Planetary Sciences, University of Manchester, Williamson Building, Oxford Road, Manchester M13 9PL, UK
[b] Korea Polar Research Institute, 213-3, Songdo-dong, Yeonsu-gu, Incheon 406-840, Republic of Korea

ARTICLE INFO

Article history:
Received 20 September 2013
Received in revised form 14 April 2014
Accepted 21 April 2014
Available online 30 April 2014

Keywords:
Salt tectonics
Red Sea deeps
Ocean–continent transition
Thetis Deep
Seismic refraction
Gravity

ABSTRACT

A transition between continental crust in the northern Red Sea and oceanic crust in the southern Red Sea coincides broadly with a southward increase in plate tectonic separation rate and with a decrease in upper mantle seismic velocity. We re-evaluate here the nature of crust in the intervening central Red Sea with the results of legacy seismic refraction experiments and recently released marine gravity anomalies derived from satellite altimeter measurements. In the refraction data, collected east of Thetis Deep, velocities of 6.6–6.9 km s^{-1} of a deep refracting layer, which are similar to measured velocities of unaltered gabbro samples, extend outside the deep to 65 km from the axis. The new version of the marine gravity field reveals trends crossing the central Red Sea. Whereas some of them connect with major lineaments in the surrounding African-Arabian shield, those around Thetis Deep die out towards the coastlines. They can be paired across the ridge and lie slightly oblique to plate motions, as is typical of oceanic fracture zones or non-transform discontinuities migrating away from hotspots. Taken together these observations support the view that an oceanic rather than extended continental crust underlies this part of the central Red Sea.

The crestal mountains around the median valleys of slow-spreading ridges are typically 500–1000 m lower at spreading discontinuities. Around Thetis Deep, the similar pattern in the gravity field to those of slow-spreading ridges suggests that the crestal mountains may variably block or impede flowage of evaporites towards the spreading centre, whereas the discontinuities may mark areas where flowage is unobstructed. Limited multibeam data collected in transits outside Thetis Deep show oblique fabrics as expected from these predicted movements.

1. Introduction

The change in type of crust in the Red Sea from continental in the north (Cochran, 2005; Cochran and Karner, 2007; Gaulier et al., 1986, 1988; Martinez and Cochran, 1988) to oceanic in the south (Allan, 1970; Cochran, 1983; Roeser, 1975; Vine, 1966) has been suggested to be a consequence of total extension increasing southwards away from the pole of opening between Arabia and Nubia (Bonatti, 1985; Bosworth et al., 2005), which has lain to the northwest of the Red Sea for at least the last few million years (Chu and Gordon, 1998). According to that view, the northern Red Sea is at an early stage of development and will proceed to seafloor spreading with further extension (Cochran, 2005). More recently, however, Cochran and Karner (2007) have suggested that the lack of seafloor spreading in the northern Red Sea is instead a result of lower mantle temperature and hence greater lithospheric strength there, which is manifested in larger fault blocks interpreted from seismic, magnetic and gravity data. A stronger lithosphere may have prevented the transition to seafloor spreading.

Large-scale tomographic studies reveal upper-mantle (200 km depth) S- and P-wave seismic velocities increasing by up to a few percentages from south to north in the Red Sea and away from the Afar hotspot (Fig. 1), consistent with lower temperatures and hence thicker lithosphere in the north (Begg et al., 2009; Debayle et al., 2001; Pasyanos and Nyblade, 2007; Priestly et al., 2008; Ritsema and van Heijst, 2000; Sicilia et al., 2008). Most of these studies lacked the configuration of seismograph stations necessary to record the structure beneath the Red Sea in detail. However, Park et al. (2007) used teleseismic records from stations within Saudi Arabia distributed across the kingdom, along with public Global Seismograph Network station data. Although still not resolving structure beneath all the Red Sea, their model provides a vertical section along the Arabian Red Sea coast, which at depth may mimic that beneath the Red Sea and the variation prior to rifting. Their profile B–B' is reproduced in Fig. 1. At 200 km depth, they resolved a −1.5% shear wave velocity (V_s) anomaly beneath the coast of the southern Red Sea, increasing to around −1% in the central Red Sea (profile distances 700 − 800 km) and to 0% or more in the northern Red Sea. A somewhat similar structure at 200 km depth was found by Park et al.

---

* Corresponding author.
E-mail addresses: neil.mitchell@manchester.ac.uk (N.C. Mitchell), ypark@kopri.re.kr (Y. Park).

http://dx.doi.org/10.1016/j.tecto.2014.04.029

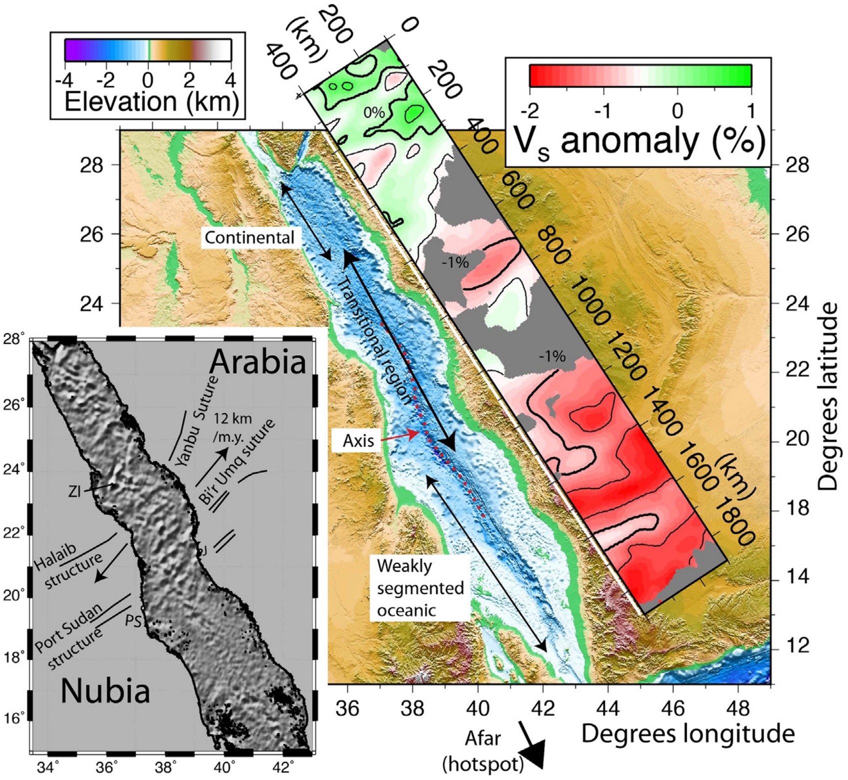

Fig. 1. Overview of the Red Sea physiography and upper mantle velocity structure. Elevations are from Becker et al. (2009) and are shown with a simple linear map projection to preserve latitudinal distances (spacing of latitude degrees is uniform up the page). Vertical cross-section of the upper mantle V_s structure shown is from Park et al. (2007, their B–B' slice) based on teleseismic delays recorded at stations mainly on the Arabian peninsular. The line of the section (white line) runs along the base of the V_s anomaly graph (distances shown are in km; V_s data are plotted at the same scale as the map). V_s contours are shown every 0.5% with 1% changes in bold. Areas of poor ray coverage are shown grey. Inset (lower-left) shows the configuration of the continental areas and major crustal lineaments of the African-Arabian shield (see text for details). Grey image in sea areas is from version 18 of the satellite-derived marine gravity field (Sandwell and Smith, 1997) shaded from N030°W. Plate separation rate shown is the full spreading rate at 21.5°N computed from the pole of Chu and Gordon (1998). Further annotation: (ZI) Zabargad Island, (J) Jeddah and (PS) Port Sudan.

(2008) using Rayleigh wave tomography, though with a less clear northward progressive increase in V_s. Combined with S-wave polarisation analysis and SKS splitting results, they interpreted the structure as indicating impact of part of the Afar plume beneath the southern Arabian shield and flow of some of the plume material beneath the rift as far as the central Red Sea. This general pattern is corroborated by geochemical analyses of lavas corrected for shallow fractionation ($Na_{8.0}$), which suggest that upper mantle temperatures generally decline going from 18°N to 26°N by about 60°C (Haase et al., 2000).

A transitional region exists (Fig. 1) extending roughly from 19°N where the sea floor spreading magnetic anomalies are well defined and confirm oceanic crust (Izzeldin, 1987; Zahran et al., 2003) to 25°N, beyond which trends in free-air gravity anomalies are oblique and continental fault blocks have been interpreted (Cochran, 2005; Cochran and Karner, 2007). The nature of the crust in this region is important for testing the above ideas but collecting new deep geophysical data has proved to be difficult. However, recent scientific developments make a re-evaluation of existing data in this region now worthwhile. For example, the estimates of gravity anomalies from satellite altimeter data have greatly improved (Marks et al., 2013; Sandwell and Smith, 2009). We show that the depths of a crustal seismic refractor of Tramontini and Davies (1969) co-vary somewhat with the gravity anomalies in the central Red Sea. The plan-view pattern in the gravity field therefore mimics the topography of the crust underlying the evaporites. This allows us to interpret the segmented pattern in the gravity field in this area, which is similar to that of segmented slow-spreading ridges (Schouten et al., 1987; Sempere et al., 1990). Laboratory measurements of velocities and knowledge gained by drilling of the seismic layer 2–3 boundary in the Pacific (Carlson, 2001, 2010; Gilbert and Salisbury, 2011; Swift et al., 2008) allow a re-evaluation of the seismic refraction velocities (Davies and Tramontini, 1970; Tramontini and Davies, 1969). In combination, these observations lead us to suggest that much of the central Red Sea is indeed probably underlain by oceanic crust as originally claimed (Tramontini and Davies, 1969). The Red Sea has an unusual geomorphology for a spreading centre of deeps (volcanic-floored depressions commonly containing sea-floor spreading magnetic anomalies) with elevated regions ("inter-trough zones") between them floored with evaporites (Bonatti et al., 1984). We extend the discussion to consider the issue of whether flowage is modulated by crustal topography to the extent that the ridge segmentation controls the pattern of deeps and inter-trough zones as originally suggested by Searle and Ross (1975).

2. Previous work on seismic and magnetic data in the central Red Sea

The plate tectonic setting is illustrated in the inset of Fig. 1, which shows major crustal lineaments of the African-Arabian shield (Camp, 1984; Stoeser and Camp, 1985). These structures represent the structure of the shield before breakup, which we consider later in evaluating whether features in the gravity field within the Red Sea are oceanic or continental. According to Stoeser and Camp (1985), the shield is late Proterozoic in age and the major crustal lineaments in the inset of Fig. 1 represent ophiolite-bearing suture zones where the shield was assembled from microplates. According to Stern and Johnson (2010), that assembly occurred between 630 and 600 Ma, with major tectonic activity continuing to 550 Ma.

Interpretation of the existing marine geophysical data from the transitional region has been controversial. A refractor in seismic data from there with P-wave velocities (V_p) a little less than 7 km s^{-1} and typical of gabbro implies that oceanic crust dominates (Davies and Tramontini,