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From rifting to spreading in the eastern Gulf of Aden: a geophysical survey of a young oceanic basin from margin to margin

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ABSTRACT

A geophysical survey in the eastern Gulf of Aden, between the Alula–Fartak (52°E) and the Socotra (55°E) transform faults, was carried out during the Encens–Sheba cruise. The conjugate margins of the Gulf are steep, narrow and asymmetric. Asymmetry of the rifting process is highlighted by the conjugate margins (horst and graben in the north and deep basin in the south). Two transfer fault zones separate the margins into three segments, whereas the present-day Sheba Ridge is divided into two segments by a transform discontinuity. Therefore segmentation of the Sheba Ridge and that of the conjugate margins did coincide during the early stages of oceanic spreading. Extensive magma production is evidenced in the central part of the western segment. Anomaly 5d was identified in the northern and southern parts of the oceanic basin, thus confirming that seafloor spreading in this part of Gulf of Aden started at least 17.6 Ma ago.

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Introduction

The Gulf of Aden is a small oceanic basin bounded by young conjugate passive margins well preserved beneath a thin postrift sedimentary cover. This is a key region in complete investigations relating to the processes of rifting, break-up of continental lithosphere and evolution of young oceanic basin. This paper presents geophysical data gathered during a survey (Leroy *et al.*, 2000) with the objective of revealing the structure of the eastern Gulf of Aden from margin to margin. We address the following: the precise distribution, extent and boundaries of the different types of crust that form the margins; the structures that accommodated the continental break-up and the formation of the conjugate margins, together with the mechanisms involved; the geometry of the spreading axis and its history; whether the spreading is symmetric or asymmetric; and the relationship between the segmentation of continental margins and of the present-day spreading ridge?

Until recently, only the western part of the Gulf of Aden had been studied in any detail (Girdler *et al.*, 1980; Cochran, 1981; Manighetti *et al.*, 1997; Audin, 1999; Khanbari, 2000; Hébert *et al.*, 2001). Few geophysical profiles are available in the eastern part of the basin, most obtained during the 1980s (Girdler *et al.*, 1980; Cochran, 1981, 1982; Tamsett, 1984; Tamsett and Searle, 1988, 1990; Sahota, 1990).

Major features of the Gulf of Aden

Two striking characteristics of the Gulf of Aden are (1) the oblique nature of the spreading with respect to the mean trend of the Gulf (N75°E), and (2) the presence of the Afar hot spot at its western end (e.g. Courtillot *et al.*, 1999). Regional plate kinematic models predict a spreading rate for the Sheba Ridge of 2.0 cm yr^{-1} along N26°E (Jestin *et al.*, 1994; Fournier *et al.*, 2001) with an obliquity of about 45°. The structures and evolution of the Gulf of Aden margins are related to successive development of (1) the continental margin of the Indian Ocean during the Early Cretaceous up to the Paleogene (Besse and Courtillot, 1988), and (2) the formation of the Gulf of Aden during the Oligo-Miocene. These two stages of rifting are responsible for basin formation in the southern Arabian peninsula (Beydoun *et al.*, 1996) and in northern Somalia (Fantozzi and Sgavetti, 1998). The influence of the Afar hot spot results in the transition from a volcanic margin to the west to a non-volcanic margin to the east (d'Acremont, 2002). The volcanic margins (Tard *et al.*, 1991) are restricted to the area west of the Shukra el Sheik discontinuity (Fig. 1a). Further to the east, the non-volcanic margins are characterized on land by coastal plains bounded by normal faults and rift

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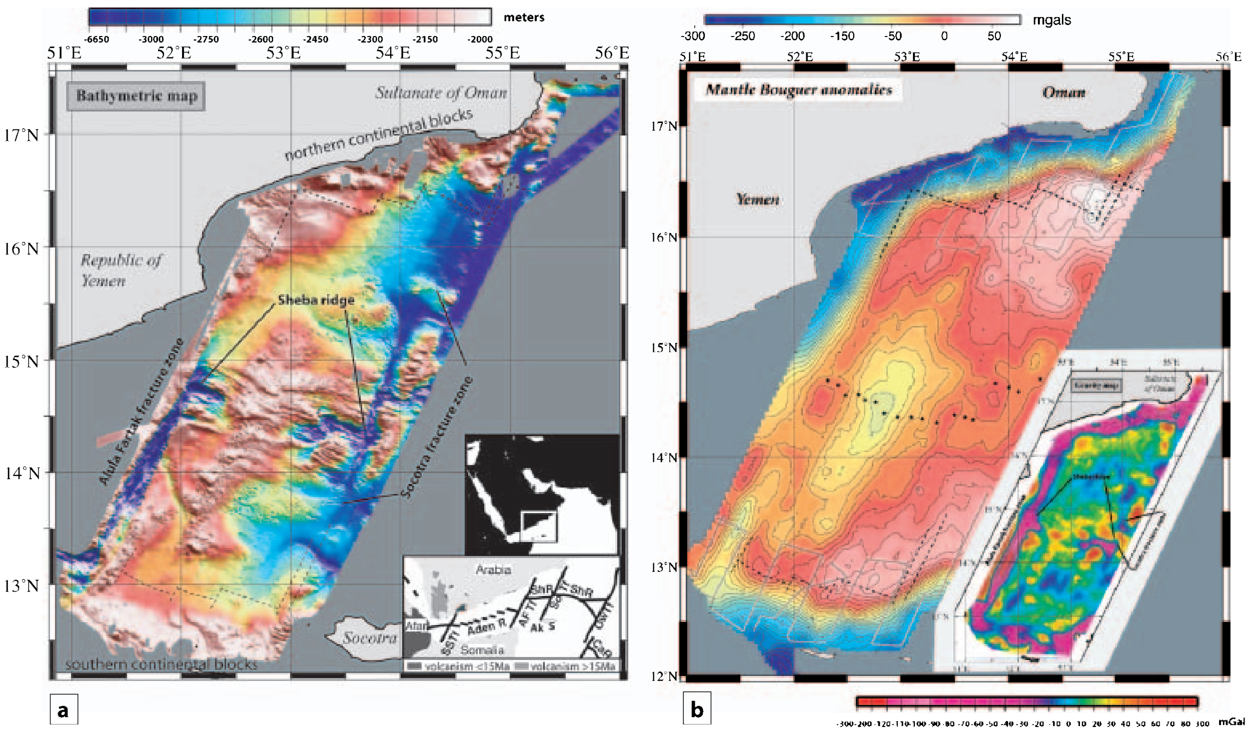

Fig. 1 (a) Shaded bathymetric map from multibeam soundings recorded during Encens–Sheba cruise (Leroy *et al.*, 2000). Processing was achieved with the aid of Caraibes software developed by IFREMER and shading by GMT software. The dashed lines represent the boundary between the continental and oceanic domains, and the location of the Alula-Fartak and Socotra fracture zones. Inset: location map of the study area and schematic map of outcrops of the volcanic rocks around the Gulf of Aden (after Menzies *et al.*, 1997). SSTf, Shukra El Sheik transform fault; AFTf, Alula–Fartak transform fault; SoTf, Socotra transform fault; OwTf, Owen Transform fault; Aden R, Aden Ridge; ShR, Sheba Ridge; CaR, Carlsberg Ridge (after Fournier *et al.*, 2001); S, Socotra Island; Ak, Abd'Al Kuri Islands. (b) Mantle Bouguer anomalies over the Encens-Sheba survey area. Anomalies were computed using standard, 6-km-thick oceanic crust following basement topography. Seawater density was taken to be 1030 kg m^{-3}, sediment density 2100 kg m^{-3}, crustal density 2900 kg m^{-3} and mantle density 3300 kg m^{-3}. Free air gravity map over the same area is shown in the inset. The stars correspond to the location of the axial valley of the Sheba ridge. Grey lines indicate the location of seismic profiles and the dashed lines are as in (a).

shoulders. The northern margin crops out in Yemen (Huchon and Khanbari, 2003) and in the Dhofar region of southern Oman (Roger *et al.*, 1989; Bellahsen, 2002; Lepvrier *et al.*, 2002). The southern margin crops out in Somalia (Fantozzi, 1996; Fantozzi and Sgavetti, 1998; Fantozzi and Ali-Kassim, 2002) and in the Socotra and Abd'Al Kuri Islands (Birse *et al.*, 1997; Samuel *et al.*, 1997; Fig. 1a). The conjugate margins of the Encens–Sheba survey area were formed during the last period of rifting. The thickness of the oceanic crust of the Gulf of Aden varies from 4.8 to 8.4 km, as interpreted from a seismic refraction survey (Cochran, 1982). Previous magnetic anomaly studies indicate that seafloor spreading is more recent in the western part of the Gulf of Aden than in its eastern part, and that a magnetic quiet zone corresponds to an area of thinned crust (Cochran, 1981).

Topography and crustal structure of conjugate passive margins

The geophysical survey of the basin, between longitude 52°E and 55°E (Fig. 1), reveals three domains with distinct morphological and sedimentological characteristics: continental, oceanic domains and ocean continent transition (OCT).

The *rifted northern margin*, located north of 16°30′N offshore Yemen and Oman, is composed of parallel tilted blocks, horsts and grabens bounded by faults striking N110°E and dipping either oceanward (Fig. 2a) or continentward (Fig. 2e). Shallow regions are observed over most of the northern margin (−300 to −2000 m), deepening eastwards (Fig. 1a). A 4500-m-deep basin in the eastern part forms the edge of the northern continental margin. The shelf is composed of several bathymetric highs corresponding to blocks of continental basement shifted northward along transfer fault zones (Fig. 1a). Profile ES12 shows a tectonized zone with well-marked acoustic basement relief buried beneath sediments at the foot of the margin (Fig. 2). The two tilted blocks of continental basement protrude from the layered sediment. Sedimentary sequences identified on all the profiles have been tentatively correlated with on-land formations (Roger *et al.*, 1989) and with sequences drilled in onshore wells (Bott *et al.*, 1992). The wells reveal a postrift sequence with various facies and thickness = 1300 m. The synrift sequence may be as thick as 2500 m at the Yemeni margin. In the survey area, submarine

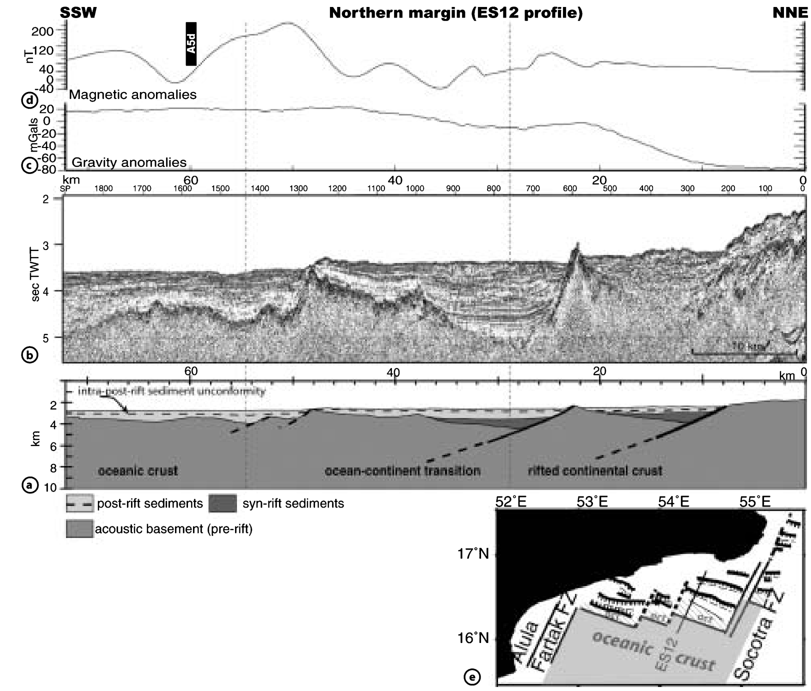

Fig. 2 ES12 profile across the northern margin. (a) Interpretative depth section of the two-way travel time seismic profile presented in (b). Different stages of rifting can be identified by the configuration of sedimentary layers (prerift, synrift and postrift). The prerift sediments constitute the tilted blocks; within the rifted basins, the synrift sediments show a characteristic fan-shaped configuration, which evolves with the tilting block. The postrift sediments infill the basin and are deposited with an onlapping configuration, indicating the end of rifting. Two sedimentary units are evidence for the postrift sequence, separated by an unconformity (dashed line). (c) Across-margin free-air gravity profile showing the negative gradient correlated with the northern boundary of the OCT. The nature of this basement is uncertain. The OCT may correspond to extremely thinned continental crust (Krawczyk *et al.*, 1996) or to thin and tectonized oceanic crust as proposed by Whitmarsh and Sawyer (1996). Alternatively, the OCT may comprise exhumed mantle uplifted during rifting and exposed in the break-up zone, similar to the serpentinized peridotites sampled in the OCT of the western Iberian margin (Beslier *et al.*, 1993; Whitmarsh and Sawyer, 1993; Boillot *et al.*, 1995). (d) Across-margin magnetic profile that displays the end of oceanic magnetic anomalies over the OCT. The last magnetic anomaly identified (A5d) is indicated on the profile. (e) Simplified structural scheme of the northern margin and location of seismic profile ES12.

synrift sediments have a maximum thickness of 1000 m. Onshore, in the Dhofar region (Fig. 1), the base of the synrift sediments is dated at 35 Ma (Upper Eocene) and the top at 18 Ma (Middle Burdigalian). The synrift series thickness is variable, with a maximum of 1400 m. The sequence is composed of lacustrine limestone at the base (100 m), overlain by platform limestone (600 m) and capped by turbidites (700 m). The turbidite sequence, although obvious onshore, could not be identified in the single-channel seismic profiles. The synrift sequence shows well-marked fan-shaped deposits (Fig. 2a,b). The postrift sediments onshore are very thin or lacking and composed mainly of conglomerates. Offshore, the postrift sequence reaches a maximum thickness of 800 m with two distinct units (Fig. 2a,b). A transparent reflective layer marks the lower postrift unit, and the upper unit displays numerous layers that pinch out against the intra-postrift unconformity (Fig. 2a,b). The second postrift sequence could indicate a second marine incursion in the basin during the postrift period.

The transition zone between purely oceanic crust (characterized by a rough seismic pattern resulting from numerous diffractions and by a clearly identified oceanic magnetic anomaly) and purely continental crust (composed of tilted blocks) occurs within a 30-km-wide area of acoustic basement ridges, both buried and exposed. Furthermore, over the transition zone between thinned continental crust and oceanic crust (Fig. 2b) each gravity profile crossing the margin presents a negative gradient (Figs 1b and 2c). The shape of the free-air gravity anomaly at the OCT could be interpreted as the free-air gravity 'edge effect' anomaly associated with passive continental margins. This effect has been traditionally interpreted as the result of the juxtaposition of thick continental crust and thin oceanic crust (Worzel, 1968). However, sediment and/or magmatic loading can also influence the free-air gravity anomaly in the same way (Watts, 2001). Two fracture zones (Alula-Fartak and Socotra) extend into the margin as former strike-slip structures that created a step-like shift in the distribution of tilted blocks and in the northern boundary of the oceanic crust (Figs 1b and 2e). Between these major fracture zones two dextral transfer fault zones offset the margin by about 30 km, segmenting and shifting them northward (Fig. 2e).

The *rifted southern margin*, is located offshore of western Socotra Island and eastern Somalia, south of 13°N. It is narrow (about 100 km; Fig. 1a). The continental basement offshore consists of a single horst, representing the continental shelf bounded by one or two northerly dipping normal faults (Fig. 3). A deep basin (5200 m) limits the main tilted block. Faults trend from N70°E and N90°E to N110°E. The ES26 profile (Fig. 3) crossing the southern margin shows this 30-km-wide tilted block and part of the deep basin bounded by normal faults dipping to the north. Maximum synrift sediment thickness here is 1200 m. The OCT zone displays features similar to those found at the northern margin, such as buried blocks (Fig. 3a,b) and a negative gravity gradient (Figs 1b and 3c). The first- and second-order segmentation of the margin by the Alula-Fartak and Socotra Fracture Zones and by the two dextral transfer fault zones is similar to that of the northern margin (Fig. 3e).

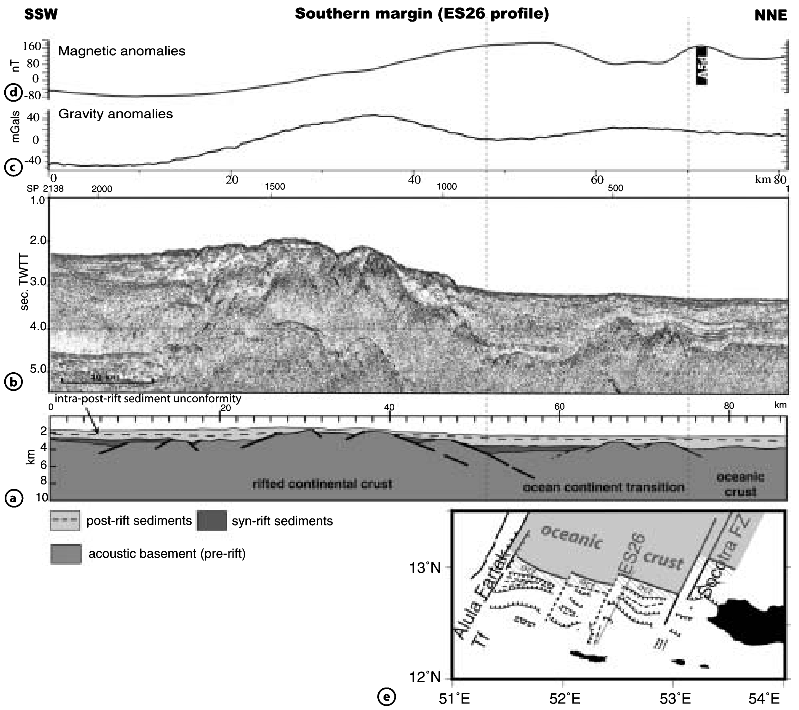

Fig. 3 ES26 profile across the southern margin. (a) Depth section of the two-way travel time seismic profile presented in (b). The different stages of rifting can also be identified in the southern margin (prerift, synrift and postrift). (c) Across-margin free-air gravity profile showing the negative gradient correlated with the southern boundary of the OCT. (d) Across-margin magnetic profile displaying the end of oceanic magnetic anomalies over the OCT. The last magnetic anomaly identified (A5d) is indicated on the profile. (e) Simplified structural scheme of the southern margin and location of seismic profile ES26.

The width of the OCT of the northern margin (30 km) is greater than that of the southern margin (20 km), and the overall width of the combined OCTs (50 km) is constant throughout the survey area (Figs 2e and 3e). At the ocean–continent boundary, the acoustic basements of both margins lie at the same depth and the postrift sedimentary sequence is thicker to the south (about 1000 m) than to the north (300 m; Figs 2 and 3). Two-dimensional gravity modelling (Fig. 4) suggests thin continental crust below the deepest block of the margins. Furthermore, the continental crust appears to be thinner at the northern margin than at the southern margin and appears to thin more rapidly (Fig. 4). Finally, the southern margin is wider in the NE–SW direction than the northern one, revealing an additional asymmetry.

Topography and crustal structure of Sheba Ridge

The Sheba oceanic ridge (between longitude 52°E and 54°30′E) displays two second-order segments between the Alula-Fartak and Socotra transform faults (Fig. 5; inset). The western segment (#1 hereafter) presents an anomalously shallow axis for a slow

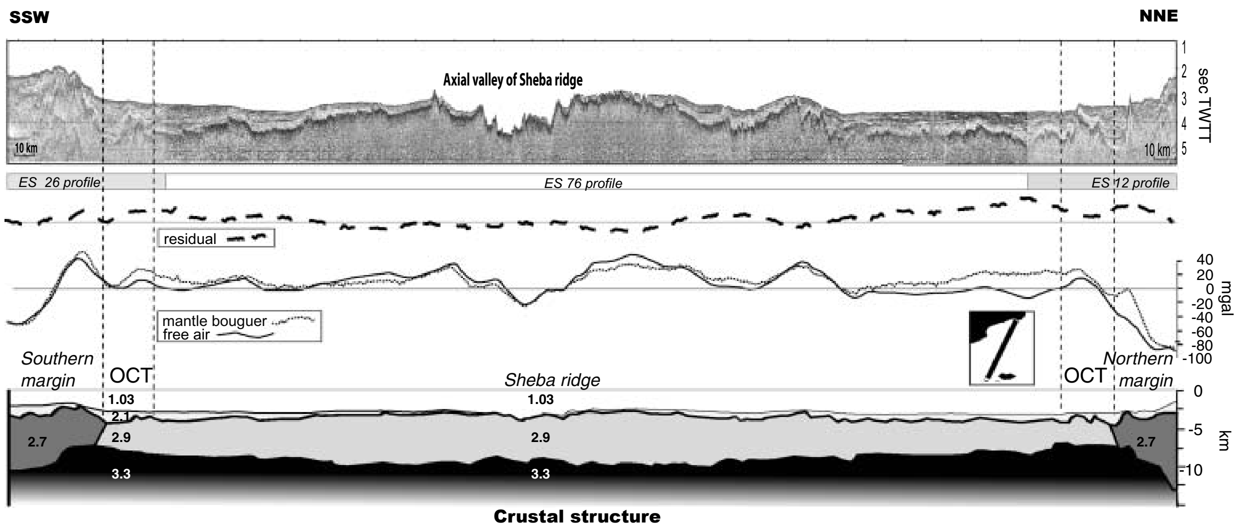

Fig. 4 Top: seismic profiles corresponding to the crustal section. The profiles of the two margins are the same as these presented in detail in Figs 2 and 3. Bottom: crustal section of the eastern Gulf of Aden oceanic basin from margin to margin (Profiles ES12–ES76–ES26) using a two-dimensional forward gravity modelling technique. Density layers used for the model are indicated beneath the section. Free air (solid line) and mantle Bouguer (dots) anomalies are drawn along the profile, as well as the residual anomaly obtained after modelling (dashed line). The crust of the OCT aera is thinner than the oceanic crust and is probably composed of a denser body that may be exhumed mantle at the palaeorift axis.

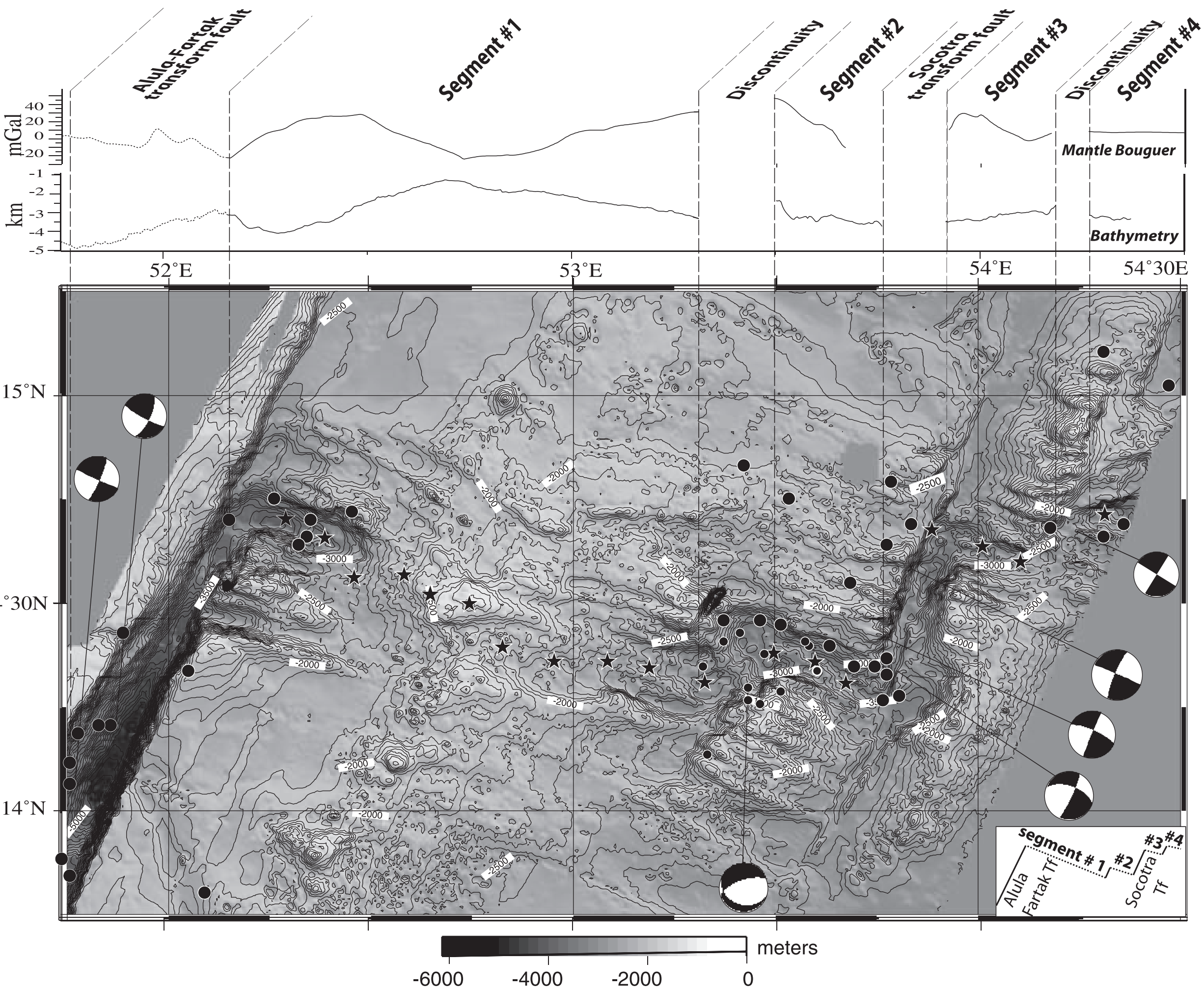

Fig. 5 Bottom: detailed bathymetric map of the Sheba spreading centre. Stars: location of the axial valley of the Sheba Ridge picked on the magnetic profiles. Circles: shallow seismicity since 1973 (focal depth < 50 km; magnitude > 2; USGS/NEIC database) and all available earthquake focal data (Harvard CMT) for this area. Centre: along-axis depth vs. longitude following the axial valley. Top: along-axis mantle Bouguer anomaly (MBA) vs. longitude extracted from the grid presented in Fig. 1(b). Inset: schematic structural map showing the geometry of the spreading centre with the segments (1 to #4) separated by two transform faults (Alula–Fartak and Socotra Tf) and by two discontinuities. The easternmost segment (#4) was not completely mapped during the Encens-Sheba cruise.

spreading ridge (Fig. 5). The shallow regions of the seafloor occur close to the axis, with the highest relief found at a depth of 1000 m. The bathymetric data reveal a peculiar fabric on the flanks and at the axis for this shallow 120-km-long spreading centre. Volcanic domes mark both the flanks and the ridge axis and are more numerous on the southern flank. Their diameters range from 1–2 km to 5–10 km. Many of these volcanoes have a well-developed summit. At the tips of the segment, tectonic scarps limit a deep axial valley (Fig. 5). The deformation, diffuse at the segment ends, focuses toward the segment centre forming an hourglass pattern, typical of slow spreading ridges (e.g. Sempéré *et al.*, 1993). A negative mantle Bouguer anomaly (MBA) elongated in the spreading direction marks segment #1 (Figs 1b and 5). The differences in MBA (~70 mgal) and in depth (more than 2 km) between the centre and the ends of this segment are high. Acoustic imagery, axial magnetic anomalies and MBA allow a precise location of the spreading axis to be made (Fig. 5). However, the neo-volcanic zone is more difficult to localize. This suggests diffuse volcanism at the centre of the segment, which has been shown on slow spreading ridges in or close to 'hot-spot' environments (e.g. Gracia *et al.*, 1996; Lagabrielle *et al.*, 1997; Pelletier *et al.*, 2001).

The 40-km-long, eastern segment (#2 hereafter) (Fig. 5) presents an axial valley more typical of slow spreading ridges (Lin *et al.*, 1990; Grindlay *et al.*, 1992; Thibaud *et al.*, 1998), as do the two other, 30-km-long segments (#3 and #4; Fig. 5) east of the Socotra transform fault. Large nodal basins occur near axial discontinuities; the deepest (3750 m) and largest of these is located at the intersection between the ridge axis and the Socotra transform fault.

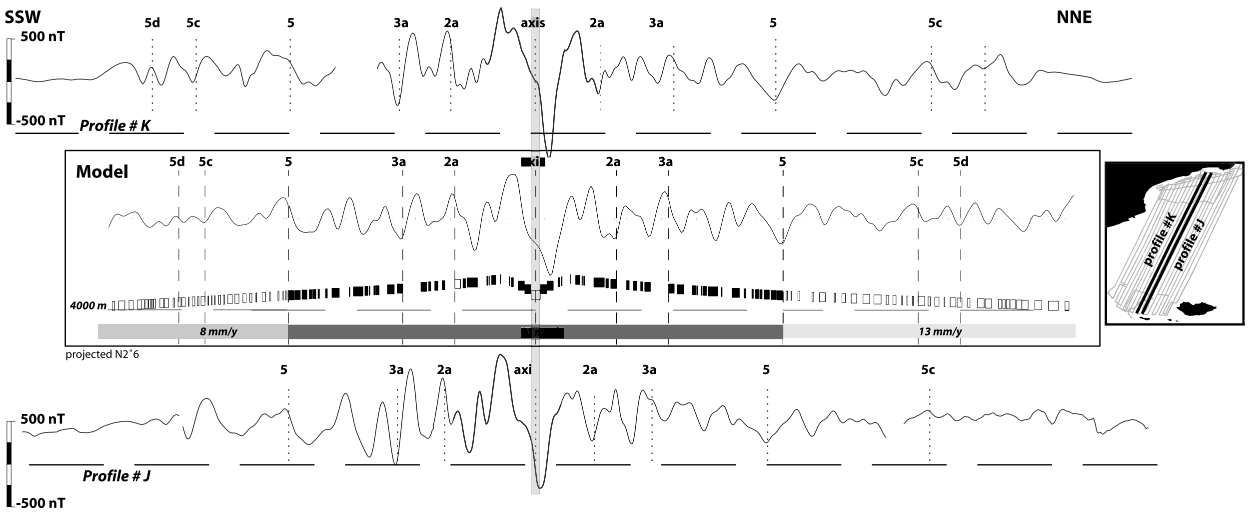

Fig. 6 Calculated magnetic model and two sample profiles: J and K. Magnetic anomaly identifications were made by comparing each magnetic anomaly profile with a two-dimensional block model (Cande and Kent, 1995). The two-dimensional block models are calculated with a half-spreading rate of 11 mm yr^{-1} (from axis to chron 5) and of 13 mm yr^{-1} (from chrons 5 to 5d) in the northern flank and of 8 mm yr^{-1} in the southern and a 400-m-thick magnetized layer. The positions of the anomaly identifications, indicated by dashed lines, are chosen at the boundary between reversed and normal blocks so that the age of each isochron is defined. Only the normal polarity blocks are shown.

Crustal thickness of the oceanic domain as computed by gravity modelling (Fig. 4) suggests that the crust is thinner on the northern flank than on the southern flank. Along the profile, the northern flank is wider (about 250 km) in the NE–SW direction than the southern flank (about 185 km). This may be due to asymmetric spreading.

Opening of the eastern Gulf of Aden

The magnetic chron 5d identified to the north and south of the axis (ig. 6) gives an age for the inception of spreading of at least 17.6 Ma instead of 12–13 Ma as previously proposed by Cochran (1981), and confirms the results of Sahota (1990). The magnetic anomalies indicate a high degree of spreading asymmetry on either side of the Sheba Ridge. Profile K shows that the spreading rate is almost identical on the northern (13 mm yr^{-1}) and southern (14 mm yr^{-1}) flanks between chrons 5d and 5c (Fig. 6). From chron 5c to 5, the spreading is clearly faster to the north (14 mm yr^{-1}) than to the south (8 mm yr^{-1}) (profiles J and K; Fig. 6). The sense of spreading asymmetry seems to be reversed from chron 2 to the present day, with a spreading rate slightly faster on the southern flanks.

Discussion

These geophysical data allowed us to map precisely the distribution of different types of crust and to show that asymmetric rifting has prevailed in the Gulf of Aden. The width of the margin is greater in the south than in the north and the crust thins more rapidly in the north than in the south. Two mechanisms of rifting could explain this asymmetry: (1) rifting by pure shear where the conjugate margins have different thicknesses before break-up, and (2) a simple shear mechanism where a lithospheric-scale detachment would then explain the differences observed between the two margins. A key domain to study these problems is the OCT, but its nature remains uncertain. Crustal thinning and tectonization of the basement obviously characterize the OCT. Moreover, the gravity model supports the presence of very thin crust probably composed of material denser than normal continental crust, which may indicate an area of exhumed mantle material (Figs 2 and 4).

The peculiar segment #1 of the Sheba Ridge may be the expression of a singular spreading history or may correspond to an end-member of the slow spreading processes. The asymmetric spreading evidenced by magnetic anomalies could be related to the migration of the spreading ridge towards the south between chrons 5c and 3a, and at present to a slight migration towards the north.

Furthermore, data analysis indicates that the configuration of the chron 5d plate boundary reflects the segmentation that occurred during continental rifting. After 1 Ma of activity, the structure, morphology and segmentation of the Sheba Ridge changed constantly until reaching its present-day geometry.

Conclusion

Analysis of the Encens–Sheba data set provides several arguments for (1) asymmetric rifting and spreading in the eastern Gulf of Aden, (2) OCT occurrence (uncertain nature) and (3) a legacy of the segmentation geometry of rifting during the inception of spreading, followed by independent evolution of the segmentation of the spreading ridge. Regional seismic tomography (Dhofar Seismic Experiment, in progress) and refraction and multichannel seismic cruises (Encens 2 proposal) are required to gain further insights into the deep structure of the eastern Gulf of Aden, and to make any conclusions regarding the style of rifting and OCT formation.

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