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Segmentation and along-strike asymmetry of the passive margin in Socotra, eastern Gulf of Aden: Are they controlled by detachment faults?

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Abstract.

On the island of Socotra, the southern passive margin of the Gulf of Aden displays along its strike two different types of asymmetric structures. Western Socotra is made up of a series of southward-tilted blocks bounded by consistently northward-dipping normal faults. Eastern Socotra consists of a broad asymmetric anticline with a steep northern limb and a gently dipping southern limb. A zone of NE-SW-striking strike-slip and normal faults separates the two areas. The overall structure is interpreted as representing two rift segments separated by a transfer zone. The along-strike juxtaposition of crustal-scale asymmetric structures on the southern margin of the Gulf of Aden is complemented by the asymmetry of the conjugate margins on either side of the gulf. Whereas the western Socotra margin is narrow and characterized by oceanward-dipping normal faults, the conjugate Oman margin is broader and dominated by horsts and graben. Considering that asymmetric structures in the upper crust are often associated with synthetic shear zones at deeper ductile levels, we propose that the western and eastern Socotra margin segments were controlled at depth by two detachment faults with opposite dips and senses of shear. The normal faults of western Socotra would sole out into a top-to-the-north ductile shear zone, whereas the asymmetric anticline of eastern Socotra would be associated with a top-to-the-south detachment fault.

Introduction

The processes of continental rifting and break-up, which precede the emplacement of an oceanic spreading ridge, lead to the formation of a pair of conjugate margins on either side of the nascent oceanic basin. The so-called passive margins are remnants of the continental lithosphere that was stretched during rifting. Like continental rifts, passive margins have been investigated to determine which mechanical properties of the lithosphere influence the style of extension. In particular, many studies have tackled the question of whether extension is symmetric or asymmetric at the lithospheric scale (McKenzie, 1978; Wernicke and Burchfiel, 1982; Wernicke, 1985; Lister et al., 1986, 1991; Brun and Beslier, 1996; Huismans and Beaumont, 2003; Nagel and Buck, 2004).

Several continental rifts, including the Gulf of Suez (Coletta et al., 1988; Patton et al., 1994), Rhine Graben (Brun et al., 1991; Wenzel et al., 1991), Corinth Rift (Rigo et al., 1996; Sorel; 2000), Baikal Rift (Hutchinson et al., 1992; Petit and Deverchère, 2006), and several segments of the East African rift system (Morley, 1988; Ebinger, 1989a; Rosendahl et al., 1992), display an asymmetric structure at the crustal scale. The asymmetry is expressed in present-day topography and sediment thickness, i.e., uplift-subsidence pattern, structural style, and distribution of volcanics. The asymmetry is generally related to the existence of a bounding master fault on one side of the rift, which accommodates a large amount of extension. The sense of asymmetry of continental rifts may even change along strike across transfer (or accommodation) zones (Bosworth, 1985; Ebinger, 1989b; Scott et al., 1992; Brun and Gutscher, 1992; McClay and White, 1995; Hayward and Ebinger, 1996).

On passive margins, symmetry sometimes prevails, as for example in the northern Red Sea where the continental margins display symmetric sets of fault blocks stepping down to an axial depression (e.g., Bosworth et al., 1998). In this area, a large geophysical data set, including heat flow (Buck et al., 1988) and gravity (Cochran et al., 1991) data, is satisfactorily explained with a symmetric overall geometry of the rift (Cochran, 2005). In the case of the conjugate margins of the North Atlantic Ocean, the Iberian and Canadian (Newfoundland) margins (Boillot et al., 1980; Keen et al., 1989; Beslier et al., 1993; Manatschal et al., 2001; Whitmarsh et al., 2001; Wilson et al., 2001; Manatschal, 2004; Reston, 2005) and the Labrador Sea margins (Chian et al., 1995; Chalmers and Pulvertaft, 2001), available data point to an overall asymmetry of the margins (Sibuet, 1992; Boillot et al., 1992; Louden and Chian, 1999). Recent multichannel seismic reflection results on the Canadian margin have demonstrated the first-order asymmetry of one pair of conjugate margin segments with the absence of a detachment fault analogous to the S reflector on the Galician margin (Funck et al., 2003; Hopper et al., 2004). However, analogue and numeric models have shown that the observation of crustal-scale asymmetric features on passive margins may be consistent with a symmetric extension process at a lithospheric scale (e.g., Brun and Beslier, 1996; Nagel and Buck, 2004).

In conceptual models of asymmetric extension, the asymmetry is often related to the presence of one or more detachment faults cutting through the crust or the lithosphere and separating a collapsing hanging wall from an uplifted and denuded footwall (e.g., Wernicke, 1985; Davis and Lister, 1988; Lister and Davis, 1989). Detachment faulting has been recognized to play an important role in continental extensional tectonics (Wernicke, 1981) and in the formation of passive margins (Boillot et al., 1987; Lemoine et al., 1987). On passive margins, evidence for detachment faults comes from seismic reflection profiles where strong sub-horizontal reflectors are interpreted as shallow-dipping shear zones (Krawczyk et al., 1996; Reston et al., 1996; Reston, 1996; Barker and Austin, 1998; Maillard et al., 2005). Rift-related detachment faults have also been recognized onland on the Red Sea margin (Talbot and Ghebreab, 1997) and in the Alps where detachment faults from the ancient Tethyan margins are exposed (Froitzheim and Eberli, 1990; Froitzheim and Manatschal, 1996; Manatschal and Bernouilli, 1999). In addition, seismogenic moderate to shallow-dipping normal faults, interpreted as detachment faults, are currently active in the Woodlark and Corinth rifts (Abers et al., 1997; Bernard et al., 1997; Abers, 2001).

In contrast with the mature submarine margins of the Atlantic Ocean, the young margins of the Gulf of Aden offer the opportunity to study on land the deformation and to take into account the along-margin 3D evolution of rifting. Results obtained onland on the northern margin have demonstrated the along-strike variability of the structure of the margin segments, in particular on either side of the Socotra fracture zone (Figure 1; Fournier et al., 2004). Here, we combine the results of a field survey conducted on the southern margin in Socotra, with the analysis of Landsat images, SRTM (Shuttle Radar Topography Mission) elevation data (sample spacing of 3 arc-seconds, approximately 92 m at the latitude of Socotra; Farr and Kobrick, 2000), and offshore seismic profiles acquired during the Encens-Sheba cruise/MD 117 on board the R/V Marion Dufresne (Leroy et al., 2004), to describe the structure of the southern margin and compare it to the conjugate Oman margin. From these observations, we infer information about the deep structure of the margins.

1. Tectonic framework: oblique opening and segmentation of the Gulf of Aden

Socotra is located on the southern continental margin of the Gulf of Aden, offshore from the Horn of Africa (Figure 1). Separation of the Arabia and Somalia plates was achieved by rifting of continental lithosphere in the Gulf of Aden during the Oligocene and early Miocene (Roger et al., 1989; Hughes et al., 1991; Bott et al., 1992; Watchorn et al., 1998; Bosworth et al., 2005), followed by seafloor spreading along the Sheba Ridge, which was initiated 18 Ma ago (early Miocene) in the eastern part of the gulf (magnetic anomaly 5d; Sahota, 1990; Leroy et al., 2004). The current full spreading rate at the longitude of Socotra is 22 mm/yr along N25°E (Jestin et al., 1994; Fournier et al., 2001). The direction of opening of the Gulf of Aden is thus ~40° from orthogonal to its overall N75°E trend (Laughton et al., 1970; Cochran, 1981; Fournier and Petit, 2006). The opening obliquity is accommodated by segmentation of the ridge axis by transform faults, including the major Alula-Fartak and Socotra transform faults (Figure 1; Laughton, 1966; Tamsett and Searle, 1990; Manighetti et al., 1997). The *en échelon* pattern of the ridge segments is mirrored in the stepped shape of the continental margins of Arabia and Somalia. On the basis of field observations on the northern margin of the eastern Gulf of Aden, Fournier et al. (2004) showed that the segmentation of the Sheba Ridge by the Socotra transform fault coincided with, and was likely inherited from, the prior segmentation of the continental margin.

The first-order segment of the Gulf of Aden located between the Alula-Fartak and Socotra transform faults has been recently studied onshore (Fournier et al., 2004; Bellahsen et al., 2006) and offshore (d'Acremont et al., 2005, 2006). The main faults of this segment are reported in Figure 1. The northern margin is dominated onshore and offshore by a succession of horsts and graben. The faults of the upper part of the margin (onshore) generally have a sigmoidal shape in plan view with an overall trend parallel to the Gulf of Aden (N75°E), whereas the faults of the lower part of the margin (offshore) appear more linear and consistently strike N110°E-N120°E. The lower part of the margin seems to be segmented by second-order transfer faults, which are not observed in the upper part of the margin. The comparison of the conjugate margins points to an overall asymmetry, with the northern margin displaying horsts and graben, and the southern margin being dominated by one major normal fault, which limits the continental shelf, and a deep basin at the toe of the margin. Seismic data however lack the penetration necessary to address the deep structure of the margins.

South and southwest of Socotra, oil industry seismic profiles across the Socotran shelf do not reveal any significant extension in the post-Cretaceous series (Richardson et al., 1994, 1995; Birse et al., 1997). E-W normal faults of Neogene age are restricted to the northern edge of the Socotran Platform along the margin of Gulf of Aden (Richardson et al., 1994).

2. Along-strike evolution of the structure of the southern margin on Socotra

A field survey conducted on Socotra reveals that the NE-SW-striking Hadibo fault system divides the island into two parts exhibiting distinct stratigraphic and structural features (Figure 2).

2.1. Stratigraphy of Socotra

Socotra is covered by a carbonate-dominated Cretaceous and Tertiary succession unconformably overlying a Proterozoic and Paleozoic basement (Figures 2a and 2b; Beydoun and Bichan, 1969; Bott et al., 1994). Triassic and Jurassic deposits are locally preserved in a fault bounded area at the eastern end of the island (Samuel et al., 1997).

The basement mainly includes Panafrican granites, which make up the 1500-m-high Haggier massif. At a regional scale, Triassic and Jurassic deposits are only found in localised grabens on the Socotran platform (Morrison et al., 1997). Like in southern Oman, where upper Permian to Jurassic deposits are generally absent (Béchennec et al., 1993; Le Métour et al., 1995), the region was largely emergent from the late Permian to the early Cretaceous and shallow-marine sedimentation resumed during the Barremian-Aptian transgression with the deposition of the Qishn Formation (Roger et al., 1989; Platel et al., 1992b; Morrison et al., 1997; Samuel et al., 1997). The Cretaceous sequence is characterized by an alternation of clastic and carbonate strata of variable thickness (< 300 m). A gentle angular unconformity of the Tertiary deposits with the underlying Cretaceous deposits has been described (Samuel et al., 1997), and locally, lower Tertiary deposits rest directly on the basement. The presence of Cretaceous strata all around the Haggier massif however suggests that there was little erosion prior to the deposition of the Paleocene sediments.

The Tertiary series is dominated by upper Paleocene to Eocene continental shelf carbonates, up to 600 m thick, including the massive cliff-forming limestone succession of the Umm Er Radhuma Formation, also recognized on the Yemeni, Omani, and Somali coasts of the Gulf of Aden (Beydoun, 1964, 1970; Roger et al., 1989; Fantozzi and Sgavetti, 1998). The platform deposits are overlain by calciturbidites of the Shihr Group of late Oligocene to early Miocene age, which are restricted to localised basins in western Socotra. The Shihr Group succession consists of carbonate conglomerates at the base, overlain by slope deposits that testify to rapid deepening in environments of deposition. These deposits display a variety of chaotic facies, likely produced by seismic activity and steep slopes developed in the localised deep-marine basins (Samuel et al., 1997). On the basis of facies and biostratigraphic analyses, these deposits are correlated with those of Mughsayl Formation of southern Oman (Samuel et al., 1997) and interpreted as syn-rift deposits coeval with the rifting of the Gulf of Aden (Roger et al., 1989; Platel and Roger, 1989).

Significant uplift of the passive margin occurred after the rifting episode, leading to the emergence of the syn-rift basins, and continues at present as evidenced by uplifted Quaternary terraces (Beydoun and Bichan, 1969). Post-rift uplift reported on passive margins is generally attributed to a combination of erosional processes and flexural response of the lithosphere to the corresponding redistribution of mass across the landscape (e.g., Japsen et al., 2006; Petit et al., 2006).

2.2. *Asymmetric marginal anticline of eastern Socotra*

In eastern Socotra, the Haggier basement massif is flanked to the south and the east by Cretaceous and Paleocene-Eocene strata gently dipping to the south (dip angle < 10°; Figure 2b). This sub-horizontal platform is devoid of major structures and affected only by a few minor normal faults. On the northern side of the Haggier massif, the Cretaceous and Paleocene-Eocene beds dip towards the north, at up to 45°. At the scale of the island, these strata form a broad, asymmetric anticline flexure with a steep northern limb and a gently dipping southern limb (Figures 2c). The axis of the anticline trends approximately E-W (Figure 2e). No reverse fault related to folding could be observed in the field. The age of folding is not well constrained. It postdates the deposition of the Eocene formations, which are deformed, and is sealed by Quaternary deposits. In the absence of deposits of Oligocene-early Miocene age in eastern Socotra, the exact age of folding cannot be ascertained more precisely. An attempt has been made to explain the formation of the Haggier Massif and the basement highs of western Socotra in Ra’s Shu’ab and Qalansiyah (Figure 2b) in terms of post-early Miocene compression (Bott et al., 1994). However, as noticed by Beydoun and Bichan (1969), “the abundance of normal tensional faults [in Socotra], often with considerable throw, […] and the lack of any evidence of compressional forces” (p. 434) do not favour this hypothesis. Moreover, with the exception of the rifting of the Gulf of Aden, no major tectonic event occurred in this part of Africa since the early Tertiary. We therefore consider that the large-scale folding in eastern Socotra is related to the syn- and post-rift evolution of the margin.

2.3. Array of tilted fault blocks of western Socotra

Western Socotra is dominated by a series of tilted blocks bounded by WNW-ESE-striking normal faults consistently dipping toward the north (Figures 2b, 2d, and 3). The faults display vertical throws between 200 and 1000 m down to the north (Figure 2d). They post-date the deposition of Eocene formations and controlled the formation of southward-dipping half graben, in which the Oligo-Miocene deposits of the Shihr Group were trapped. Proterozoic basement crops out in the uplifted footwall of the normal faults in Ra’s Shu’ab, Qalansiyah, and Ra’s Kadarma (Figure 2b). Bathymetric data indicate that the shelf is very narrow to the north of Socotra and likely limited by a normal fault synthetic to the normal faults onshore (Figure 1). The width of the tilted blocks thus decrease northwards from 13-11 km to 7 km and to ~3-4 km for the northernmost block (Jabal Kadarma; Figures 2d and 3), while their dip increases up to 50° to the north in Jabal Kadarma (Figures 2d and 2f). The decreasing spacing of normal faults toward the Gulf of Aden and the increasing block rotation is probably indicative of higher crustal thinning toward the rift axis.

Meso-scale striated fault planes were examined in several localities of western Socotra in pre- and syn-rift formations (Figure 2). All fault planes are of normal or strike-slip type. At sites where normal and strike-slip fractures were observed, two subsets were distinguished and identified with A and B suffixes (sites 6 and 7). Conjugate normal faults predominantly strike between N80°E and N120°E (sites 3, 4A, 5, 6B, and 7B). These directions are representative of the strike of the major normal faults bounding the tilted blocks. The orientation of the principal stress axes determined by inversion of fault slip data sets (Table 1; Angelier, 1984) indicates a direction of extension between N and N30°E (Figure 2; sites 1, 3, 4A, 5, 6B, and 7B). In one site, an oblique N145°E direction of extension has also been documented (site 4B). The two approximately N20°E and N150°E directions of extension are characteristic of the rifting of Gulf of Aden and were identified all along the northern margin of the Gulf of Aden in Oman (Lepvrier et al., 2002; Fournier et al., 2004; Bellahsen et al., 2006) and Yemen (Huchon et al., 1991; Huchon and Khanbari, 2003), and further north in the Huqf area and the Oman mountains (Fournier et al., 2005, 2006).

2.4. Hadibo transfer zone

The Hadibo fault system transects Socotra and separates the Haggier massif to the east from the tilted blocks of western Socotra (Figures 2b and 3). It is marked in the topography by a series of down-to-the-northwest escarpments. The fault zone is made up of several rectilinear faults striking N50°E and steeply dipping toward the northwest (Figure 2b). Broad flexures of the Eocene strata in the fault zone attest to normal motion along the main faults. The Hadibo fault system terminates to the south with a horsetail geometry as it connects with the E-W-striking normal fault that bounds the southernmost tilted block of western Socotra (Figure 2d). The fault zone was probably inherited from linear NE-SW fracture zones in the basement, which is at shallow depth throughout the area (Beydoun and Bichan, 1969).

A study of minor faults in the vicinity of the Hadibo fault system helps to clarify its motion. The only site located within the fault zone (site 2) displays conjugate strike-slip faults. The N50°E- to N70°E-striking faults parallel to the Hadibo fault system accommodate right-lateral motions. Two other sites display conjugate sets of strike-slip faults (sites 6A and

7A). The right-lateral faults strike N70°E to N90°E and the left-lateral faults strike N120°E to N140°E. Stress inversion of the strike-slip fault data sets gives $\sigma_{Hmax} = \sigma 1$ trending N90°E to N120°E and $\sigma_{Hmin} = \sigma 3$ trending N to N30°E. Since the strike-slip and normal paleostress tensors have similar directions of extension, they likely pertain to the same regional stress field and reflect a unique transtensional deformation regime. The stereodiagrams of Figure 2 even suggest that the direction of extension tends to rotate counterclockwise toward the Hadibo fault zone, from N30°E away from fault zone (sites 7A, 7B, and 3) to N close to it (sites 1 and 2). These observations are consistent with a right-lateral component of displacement along the Hadibo fault system. With respect to the stable southern Socotran platform, the dextral motion accounts for the relative motion between the western part of Socotra stretched by normal faulting and the eastern part shortened by large-scale folding.

The Hadibo fault system thus appears as a transfer zone, or accommodation zone, between two rift segments, as illustrated in Figures 2e and 3. The direction of the maximum horizontal principal stress σ_{Hmax} rotates counterclockwise toward the dextral transfer zone, and σ_{Hmax} switches from σ_2 to σ_1 within the transfer zone, in a way similar to the transform faults in the oceanic domain (Figure 4). As can be observed in Figure 1, the Hadibo transfer zone does not appear to pass laterally offshore into an oceanic transform fault.

In summary, the southern continental margin of the Gulf of Aden on Socotra is made up of two segments separated by the Hadibo transfer zone. In N-S cross-section, each margin segment displays an overall structure which is asymmetric. The western segment consists of a series of consistently southward-tilted blocks bounded by northward-dipping normal faults, whereas the eastern segment consists in an E-W-trending anticline with a steep northern limb and a gently dipping southern limb. Thus, the margin structure changes dramatically across the Hadibo transfer zone. The origin of these along-strike changes in structure will be discussed in section 4.

3. Offshore seismic data and comparison with the conjugate Oman margin

Two single-channel seismic profiles (ES18 and ES20) have been shot during the Encens-Sheba cruise (Leroy et al., 2004) across the conjugate margins, immediately to the east of the Socotra transform fault (Figure 5; location in Figure 1). The southern profile (ES20; Figure 5a) cuts across the western Socotra margin segment. The seismic line shows that the margin offshore Socotra is steep, narrow, and dominated by a major, northward-dipping normal fault with a moderate dip and a minimum displacement of 2 km (d'Acremont, 2002). A large graben occurs at the toe of the normal fault, containing about 2 km of flat-lying sediments including 500-900 m of the syn-rift series (d'Acremont, 2002). In map view, the main normal fault of profile ES20 is located more or less in line with the northernmost normal fault of western Socotra (Figure 1). It could correspond to the eastward continuation of this fault, which however displays a much smaller vertical throw (Figure 2d). More likely, the normal fault runs eastward along the northern coast of Socotra and bounds to the north the tilted block of Jabal Kadarma (Figure 2d).

The northern profile (ES18; Figure 5b), shot across the conjugate margin segment, shows that the Oman margin is relatively broad and gentle. It is bounded to the north, on the edge of the continental shelf, by a major southward-dipping normal fault (SP 001), and it displays widely spaced, conjugate, normal faults bounding horsts and graben. Syn- and post-rift sediments were deposited in these N100°-110°E-trending grabens (d'Acremont, 2002). A synthetic cross-section from margin to margin, including the seismic profiles ES18 and ES20 and the cross-section of western Socotra (Figure 2d), highlights the contrasted structures of the opposite margins (Figure 5c; location in Figure 1).

Differences between the conjugate margins are also observed in map view (Figure 1). The conjugate margin of western Socotra in Oman, to the east of the Socotra transform fault, is entirely submerged with the exception of the Al Hallaniyah islands, which form a low-elevated rift shoulder (~400 m) made up of Proterozoic basement unconformably overlain by

Eocene deposits. No major normal fault has been observed onland on this margin segment and no flat-lying fault with mylonite between the basement and the sedimentary cover has been described on the Al Hallaniyah islands. Moreover, the Hadibo transfer zone does not seem to extend in the northern continental margin. To the east of the Al Hallaniyah islands, the Oman margin that is conjugate to eastern Socotra is entirely submerged. No offshore data are currently available for this margin. Onshore, the margin consists of a monotonous plateau ca. 200 m above sea level, capped by Oligo-Miocene platform carbonates (Béchennec et al., 1993; Le Métour et al., 1995), and devoid of extensional tectonic structures. In the absence of seismic profile across this margin, the structure of the conjugate margins cannot be accurately compared on the eastern Socotra transect.

Thus, the overall structure of the conjugate margins differs significantly. The different styles of normal faulting suggest different mechanisms of deformation from one margin to the other. As will be discussed in the next section, one margin could be the footwall and the other the hanging wall of an asymmetric rift basin.

4. Discussion : Is asymmetry controlled by detachment faults?

The continental margin on Socotra consists of two juxtaposed rift segments displaying an asymmetric structure. They testify to the deformation regime prevailing during the rifting.

Lister et al. (1986, 1991) presented detachment models for the formation of passive continental margins, in which they predicted that the structure of passive margins should change along strike across transfer zones and that juxtaposed asymmetric rift segments should be observed, as in Socotra (insert in Figure 6). They introduced the concept of upper-plate and lower-plate conjugate margins on either side of a detachment fault. Lower-plate margins are characterized by numerous rotated tilt blocks and half-graben, and the presence of a detachment fault in the crust, dipping towards the ocean. Upper-plate margins are characterized by widely spaced faulting and generally by a so-called “marginal anticline”.

Marginal anticlines correspond to flexures of the edge of the upper plate as the result of thermal buoyancy related to rise of the asthenosphere, and/or igneous underplating due to partial melting of the mantle, and/or the presence of listric detachment faults progressively flattening towards the continent (rollover structure).

The models of Lister et al. (1986, 1991) account satisfactorily for the surface structures observed on Socotra, in the hypothesis where western Socotra would correspond to a lower-plate margin and eastern Socotra margin to an upper-plate margin (Figure 6). Considering that (1) asymmetric structures are indicative of a simple shear deformation regime, and (2) asymmetric structures in the brittle upper crust are often associated with synthetic shear zones at deeper ductile levels, we further explore the hypothesis that the shallow asymmetric structures of Socotra may be associated at depth with detachment faults.

Western Socotra displays an array of tilted blocks bounded by consistently oceanward-dipping normal faults. Repetitive and asymmetrical normal faulting in the upper crust may be associated with a synthetic ductile shear zone at depth, which controls the sense of tilt of crustal blocks (e.g., Wernicke, 1981; Faugère and Brun, 1984; McClay and Ellis, 1987; Brun et al., 1994). This suggests that the normal faults of western Socotra could be connected at depth to a ductile shear zone with a top-to-the-north sense of shear. They could form a series of northward-flattening, listric normal faults merging into the detachment surface underneath the tilted blocks of western Socotra, as illustrated in Figure 6. Alternatively, the shallow high-angle normal faults could sole into master normal faults with moderate dips (> 25-30°), which in turn could sole into a subhorizontal ductile shear zone. The northward-increasing tilt of the fault blocks would be indicative of a northward-increasing shear along the ductile shear zone. In response to tectonic unloading, an upward flexure of the detachment surface would be expected to the north (Figure 7a and b). Further north offshore, the normal fault with moderate dip observed on seismic data could truncate the detachment fault of western Socotra and correspond to a new detachment fault propagated from the broad culmination of the older one, as proposed in Figure 7b and c. This interpretation would be in agreement with a migration of the deformation towards the rift axis during rifting, as often observed (e.g., Cowie et al., 2005). In this hypothesis, synrift sediments would lie directly above the first-stage detachment surface (Figure 7c), as observed in the distal parts of the Iberian margin and the Tethys margin in the Alps (Manatschal and Bernouilli, 1999). There is consequently the possibility of the presence of exhumed mantle in the transition zone (between shot points 2400 and 2700 in Figure 5a), although this remains to be better imaged.

Eastern Socotra consists of a broad E-W-trending asymmetric anticline related to the rifting of the Gulf of Aden. The uplift and erosion of the Haggier massif could be attributed to post-rift erosion and flexural rebound (Gilchrist and Summerfield, 1990), as proposed by Petit et al. (2006) for the Marbat escarpment on the Oman margin (Figure 1). However, eastern Socotra, with the rounded shape in map view of the erosional window of basement rocks, does not resemble typically rectilinear retreating rift escarpments. Alternatively, the high topography of the Haggier Mountains and the tilted strata on their flanks could be explained by upwarping from rift-related plutonism or underplating. However, the complete absence of volcanism on the continental margins of the eastern Gulf of Aden (in contrast with the western Gulf of Aden) does not favor this hypothesis. An alternative way to exhume the basement rocks exposed in eastern Socotra may be found in the detachment models of Lister et al. (1986, 1991) with the formation of marginal anticlines. In these models, detachment faulting causes horizontal translation (beneath the detachment fault) of relatively cool and dense lithosphere toward the developing oceanic basin, thus exposing the base of the continental margin to warmer, and hence relatively less dense, rising asthenosphere. The result is a broad flexure of the margin and the formation of a marginal anticline. Marginal anticlines may display a steeper limb towards the ocean due to sediment loading at the toe of the margin or due to a listric detachment fault progressively flattening at depth (rollover structure). This model requires the existence of a southward-dipping detachment fault with a top-to-the-south sense of shear beneath eastern Socotra, as shown in Figure 6.

In this hypothesis, Socotra would be made up of two crustal-scale asymmetric structures juxtaposed on either side of the Hadibo transfer zone and controlled by two detachment faults with opposite dips and senses of shear. Of course, the extrapolation from observed shallow crustal features to the crustal scale remains speculative and has to be tested: seismic information would be needed to elucidate the deep structure of the two margin segments.

The comparison with the models of Lister et al. (1986, 1991) can be extended to the conjugate Oman margin. A reconstitution of the eastern Gulf of Aden rift before the onset of seafloor spreading, encompassing the western Socotra margin and its conjugate Oman margin, is presented in Figure 8. The conjugate margins are asymmetric: the southern margin is dominated by tilted fault blocks above a detachment fault dipping towards the oceanic basin, whereas the northern margin is characterized by widely spaced conjugate normal faults. On this reconstruction, the locus of the breakup of the continental lithosphere does not coincide with the middle of the paleo-rift, but is offset towards the Socotra margin. The overall structure corresponds fairly well to the detachment models of Lister et al. (1986, 1991) where the Oman margin would represent the upper-plate margin and the western Socotra margin to the lower-plate margin, even though the Oman margin does not display a marginal anticline.

Seismic data are presently non sufficient to provide a cross-section of the eastern Socotra transect comparable to Figure 8 and discuss the possibility for the margin conjugate to eastern Socotra of being the footwall of a basin-forming detachment.

Conclusion

The eastern Gulf of Aden provides a unique example of an asymmetric passive margin with the sense of asymmetry reversing along strike. In Socotra, the passive margin alternates from east to west from marginal anticline to rotated tilt blocks and would pass laterally across the Hadibo transfer zone from an upper-plate margin to a lower-plate margin, according to the detachment models of passive margins of Lister et al. (1986; 1991). The detachment faults, which are supposed to be associated with the asymmetric surface structures, would change sense of shear across the transfer zone (top-to-the-north to the west, top-to-the-south to the east). This example shows that the asymmetry of the rifting process, which is commonly tested by comparing conjugate margins, may also be revealed by the along-strike 3D evolution of the structure of margins segmented by transfer zones. In the eastern Gulf of Aden, crustal asymmetry appears as a major feature of passive margin development.

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Figure captions

Figure 1. Geodynamical setting of the eastern Gulf of Aden and Socotra Island. Topogragraphy and bathymetry compiled from SRTM data onland (Farr and Kobrick, 2000) and multibeam soundings bathymetry from Encens-Sheba cruise (Leroy et al., 2004) superimposed on the world bathymetric map of Sandwell and Smith (1997) in the oceanic domain. Black arrows show plate relative motions (Fournier et al., 2001). The dashed line shows location of the margin to margin cross section of Figure 5, and solid portions correspond to seismic reflection profiles ES18 and ES20 acquired during the Encens-Sheba cruise. Soc is Socotra. TF is transform fault.

Figure 2. (a) Landsat image and (b) structural map of Socotra (after Landsat imagery and SRTM data interpretation, and Geological Map of Suqatra, 1990) with stress field recorded in Tertiary formations. Stars in stereonets (equal-area lower hemisphere projection) correspond to the principal stress axes: σ_1 (five branches), σ_2 (four branches), and σ_3 (three branches). Arrows show the trend of the horizontal principal stresses computed from fracture analysis. Dashed line is for the bedding plane. (c) Cross section of eastern Socotra (location in Figure 2b). (d) Cross section of western Socotra. (e) Simplified structural map of Socotra. (f) Southward tilted fault block in Ra’s Kadarma. Basement is exposed to the north along the coast and capped by tilted Cretaceous and Eocene strata. The tilt block has undergone rotation of ~50° about a horizontal ~E-W axis.

Figure 3. Segmentation of the continental margin by the Hadibo transfer zone illustrated by the SRTM digital elevation model of Socotra view from the east (N110°E). The broad asymmetric anticline of eastern Socotra in the foreground is separated from the four tilted blocks of western Socotra in the background by the right-lateral Hadibo transfer zone.

Figure 4. Comparison of maximum horizontal stress trajectories (σ_{Hmax}) for a right-lateral continental transfer zone and an oceanic transform fault. In the vicinity of the transfer zone or transform fault, σ_{Hmax} switches from σ_2 to σ_1 and its direction rotates counterclockwise.

Figure 5. ES18 and ES20 seismic profiles off Oman and Socotra, respectively, from the Encens-Sheba cruise (d'Acremont, 2002), located in Figure 1. The ocean-continent transition (OCT) has been defined from joint analysis of seismic reflection, and free-air gravity and magnetic anomalies (d'Acremont et al., 2005). (a) Offshore Socotra, the continental margin is steep, narrow, and dominated by a northward shallow-dipping normal fault with a deep sedimentary basin at its toe. (b) The Oman margin displays horsts and grabens bounded by widely spaced conjugate faults with little block rotation. (c) Crustal cross-section of the eastern Gulf of Aden combining the interpretations of seismic profiles ES18 and ES20, and the cross section of western Socotra in Figure 2d (location in Figure 1). The Moho geometry is speculative. SP are shot points.

Figure 6. Along-strike change of sense of asymmetry of the southern margin of the Gulf of Aden on either side of the Hadibo transfer zone. It is proposed that the asymmetric structures of western and eastern Socotra are controlled at depth by detachment faults with opposite dips and senses of shear. The normal faults of western Socotra would sole out into a detachment surface with a top-to-the-north sense of shear, whereas the asymmetric anticline of eastern Socotra would be associated with a southward flattening detachment fault with a top-to-the-south sense of shear. Inset shows the detachment model of passive margins of Lister et al. (1986) with the possible location of Socotra.

Figure 7. Conceptual model for the development of detachment faults onshore and offshore western Socotra (not to scale). (a) Stage 1: formation of the first detachment (D1). (b) Stage 2:

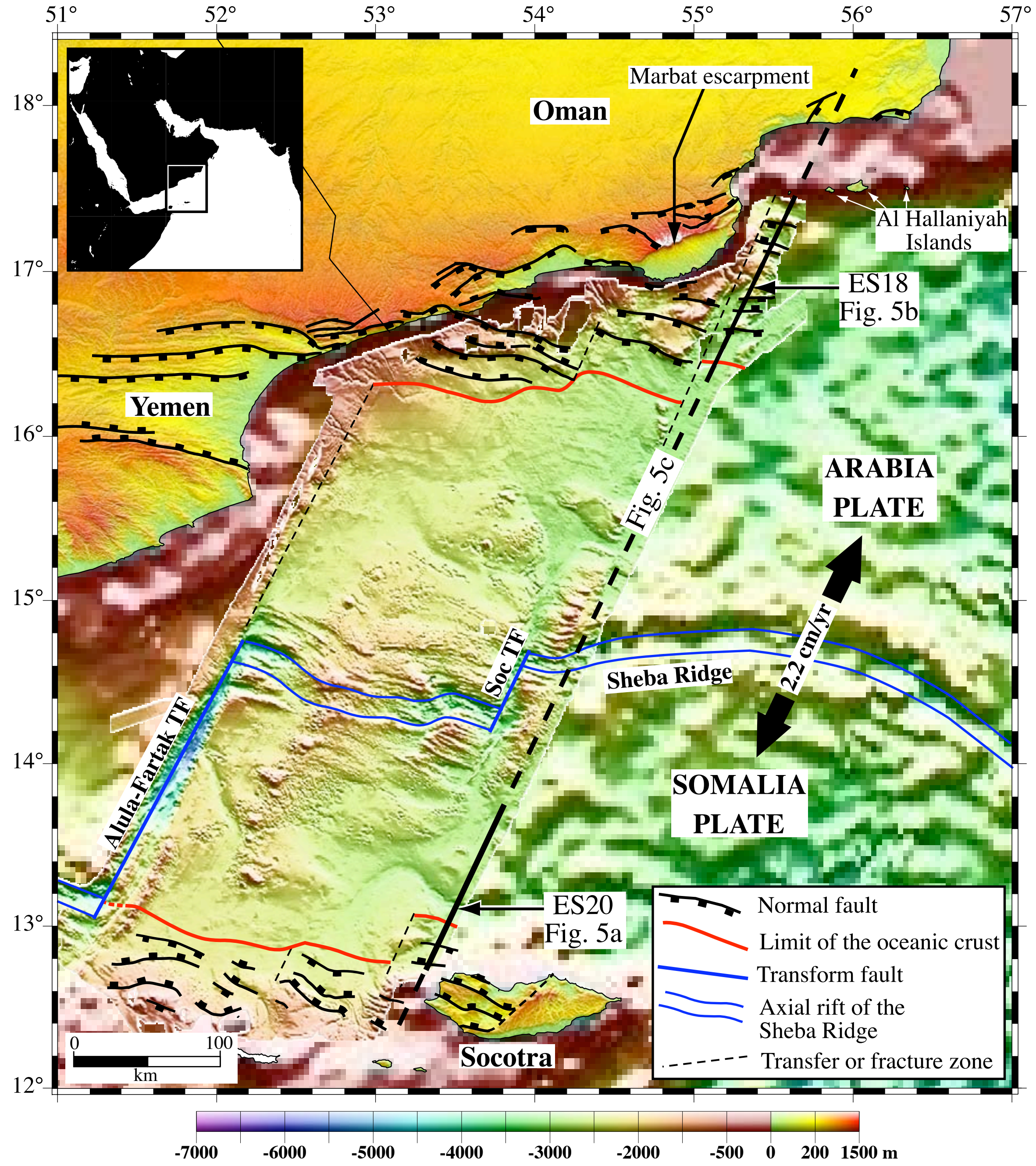
isostatic uplift of the distal part of D1, which became inactive. (c) Stage 3: formation of the second detachment (D2) or low-angle normal fault. NF3: antithetic normal fault cutting D1.

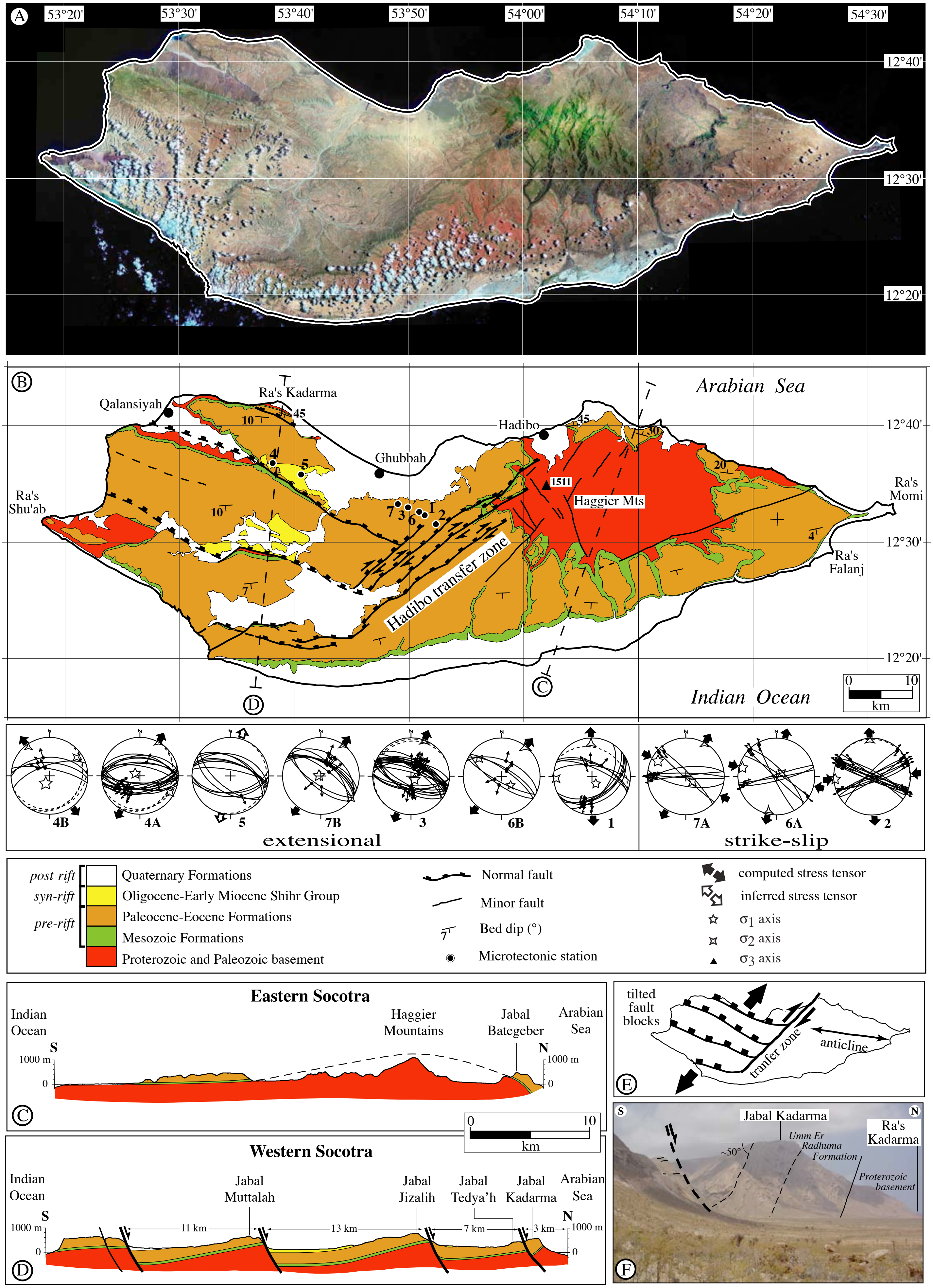
Figure 8. Prebreakup reconstruction of the eastern Gulf of Aden rift showing the complementary asymmetry of the opposing margins. The location of the breakup is offset towards the Socotra margin.

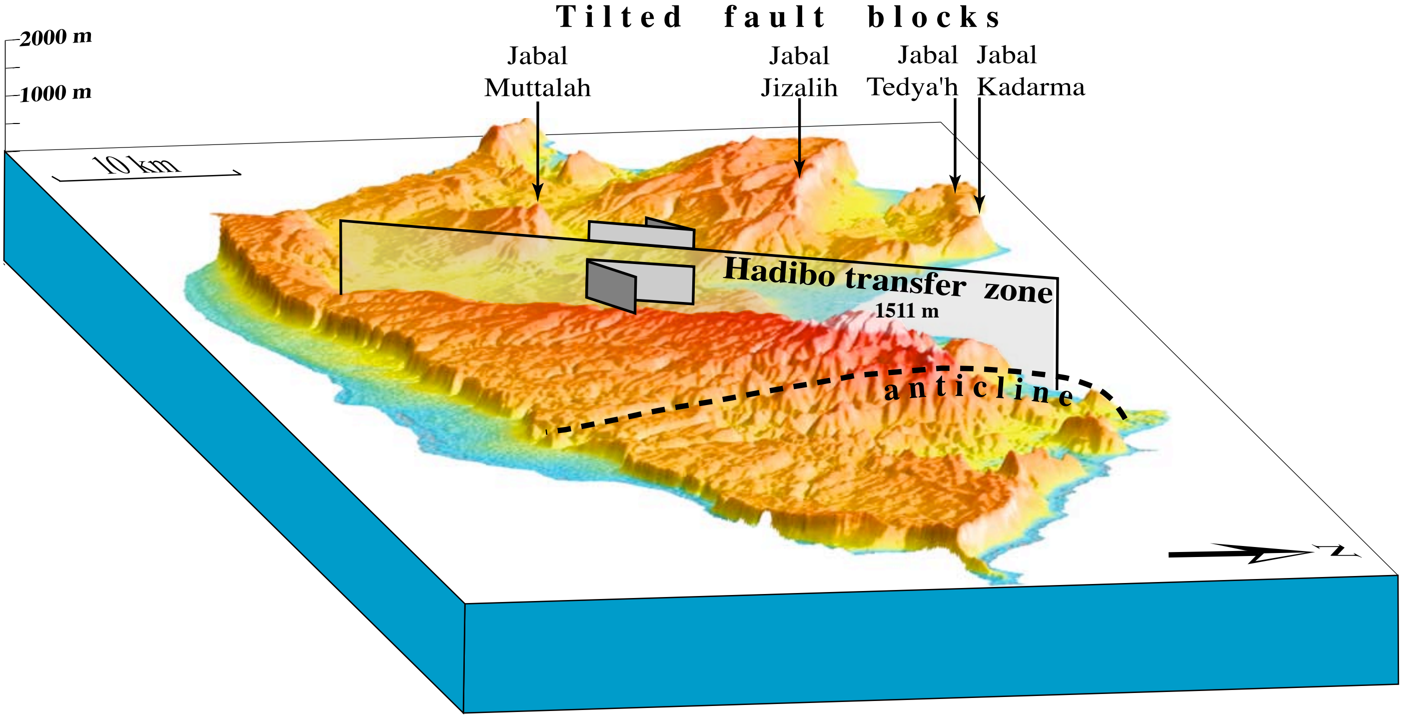
Table 1. Trend and Dip of Principal Stress Axes Computed From Fault Slip Data[a]

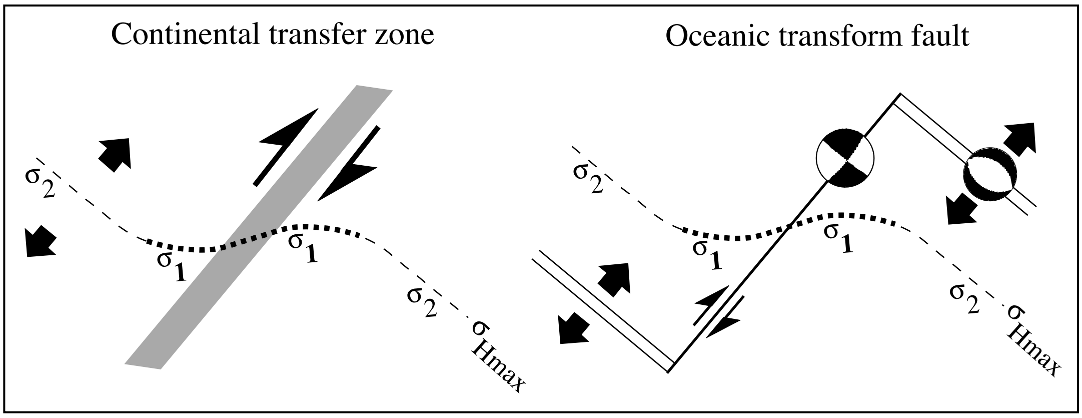
Site	Latitude	Longitude	Altitude m	Number of Faults	Formation	Age	σ_1 Strike, Dip, deg	σ_2 Strike, Dip, deg	σ_3 Strike, Dip, deg	Φ
1	12°32.485'	053°51.499'	457	10	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	153, 72	266, 07	358, 16	0.64
2	12°31.696'	053°52.602'	476	18	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	266, 04	142, 83	357, 06	0.48
3	12°33.456'	053°49.975'	277	27	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	134, 80	290, 09	021, 04	0.43
4A	12°37.239'	053°37.464'	222	12	Shihr Group	Oligocene - Early Miocene	295, 79	119, 11	029, 01	0.48
4B	12°37.239'	053°37.464'	222	4	Shihr Group	Oligocene - Early Miocene	206, 72	056, 16	324, 09	0.22
5	12°36.009'	053°41.138'	96	1, 12 joints	Shihr Group	Oligocene - Early Miocene				
6A	12°32.726'	053°51.214'	425	7	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	284, 10	060, 77	193, 09	0.43
6B	12°32.726'	053°51.214'	425	5	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	135, 63	308, 27	039, 03	0.80
7A	12°33.650'	053°49.622'	195	7	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	299, 18	131, 71	030, 04	0.38
7B	12°33.650'	053°49.622'	195	10	Umm Er Radhuma - Jeza	Late Paleocene - Eocene	279, 86	126, 04	036, 02	0.39

[a] Here σ_1, σ_2, and σ_3 are maximum, intermediate, and minimum principal stress axes. Φ is the ratio $(\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$.

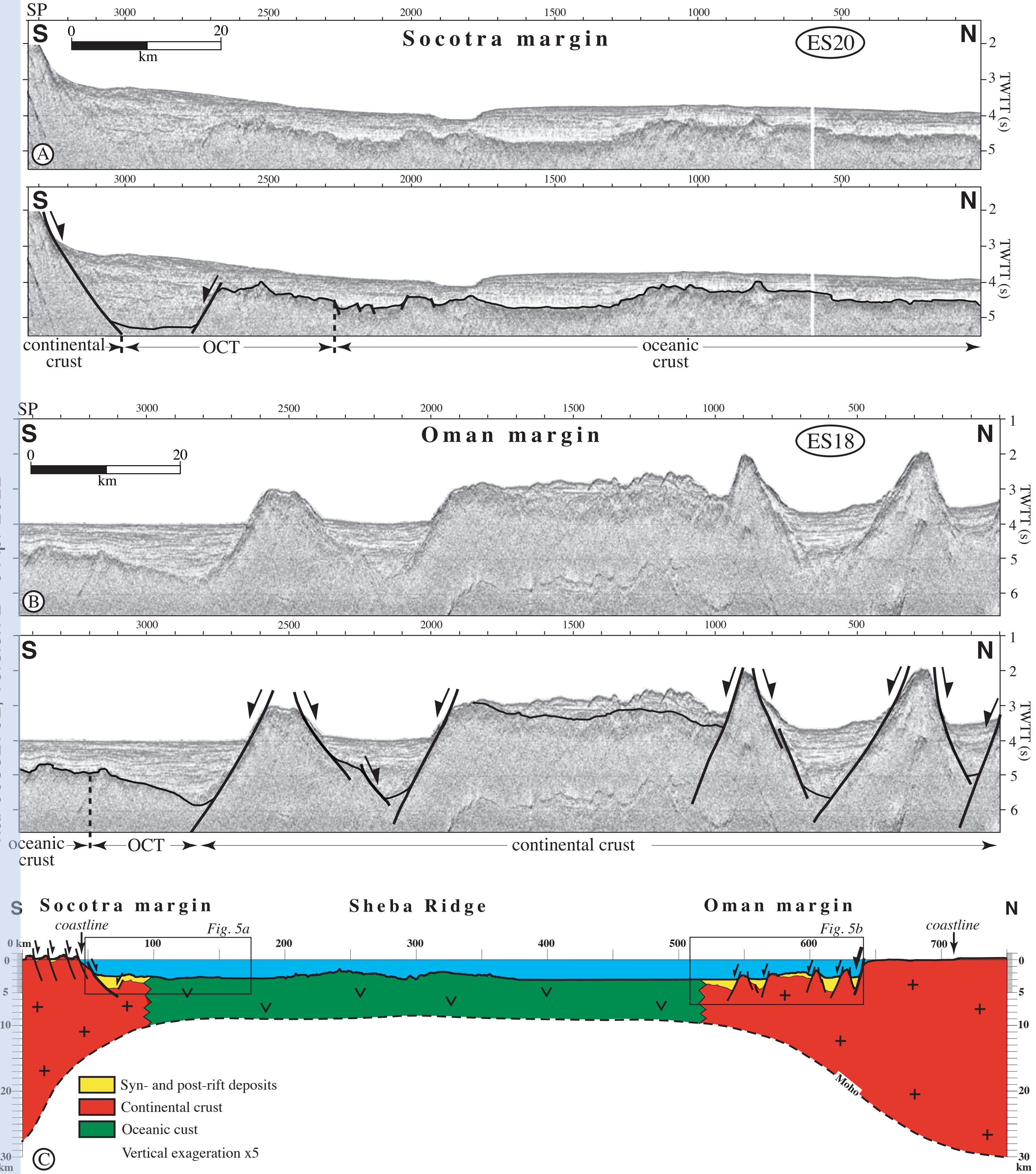

51°
52°
53°
54°
55°
56°
57°
18°
17°
16°
15°
14°
13°
12°
Marbat escarpment
Oman
Al Hallaniyah Islands
ES18
Fig. 5b
Yemen
Fig. 5c
ARABIA PLATE
2.2 cm/yr
Soc TF
Sheba Ridge
Alula-Fartak TF
SOMALIA PLATE
ES20
Fig. 5a
Normal fault
Limit of the oceanic crust
Transform fault
Axial rift of the Sheba Ridge
Transfer or fracture zone
0
100
km
Socotra
-7000
-6000
-5000
-4000
-3000
-2000
-500
0
200
1500 m

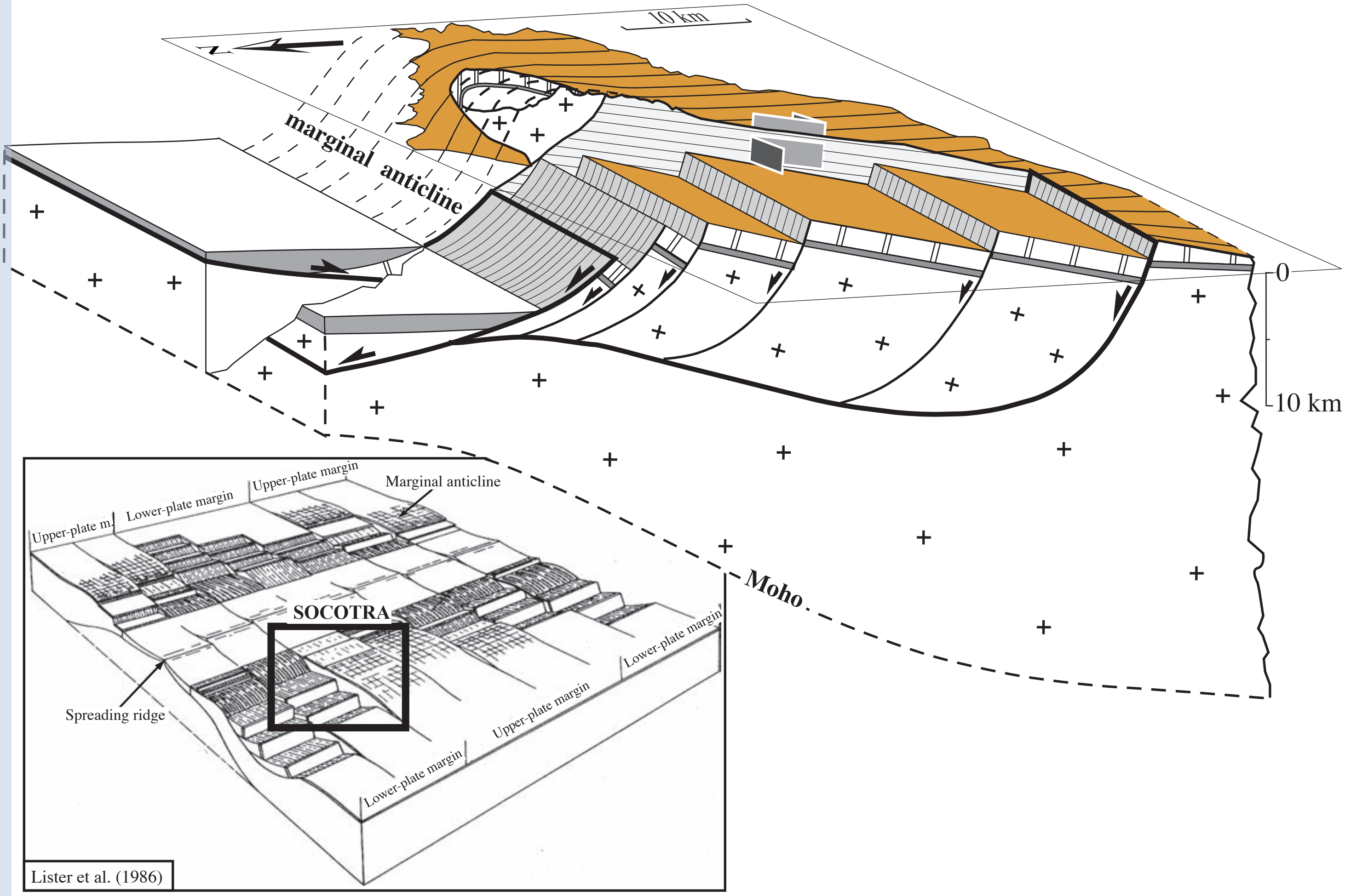

A
53°20'
53°30'
53°40'
53°50'
54°00'
54°10'
54°20'
54°30'
12°40'
12°30'
12°20'
B
Arabian Sea
Indian Ocean
Ra's Kadarma
Qalansiyah
Hadibo
Ghubbah
Ra's Shu'ab
Ra's Momi
Ra's Falanj
Haggier Mts
1511
Hadibo transfer zone
45
10
10
7
45
30
20
4
4
5
7
3
6
1
2
0
10
km
C
D
4B
4A
5
7B
3
6B
1
extensional
7A
6A
2
strike-slip
N
post-rift
syn-rift
pre-rift
Quaternary Formations
Oligocene-Early Miocene Shihr Group
Paleocene-Eocene Formations
Mesozoic Formations
Proterozoic and Paleozoic basement
Normal fault
Minor fault
Bed dip (°)
Microtectonic station
computed stress tensor
inferred stress tensor
σ1 axis
σ2 axis
σ3 axis
Eastern Socotra
Indian Ocean
Haggier Mountains
Jabal Bateqeber
Arabian Sea
S
N
1000 m
0
0
10
km
Western Socotra
Indian Ocean
Jabal Muttalah
Jabal Jizalih
Jabal Tedya'h
Jabal Kadarma
Arabian Sea
11 km
13 km
7 km
3 km
E
tilted fault blocks
tranfer zone
anticline
F
S
N
Jabal Kadarma
Ra's Kadarma
~50°
Umm Er Radhuma Formation
Proterozoic basement


Tilted fault blocks
2000 m
1000 m
10 km
Jabal Muttalah
Jabal Jizalih
Jabal Tedya'h
Jabal Kadarma
Hadibo transfer zone
1511 m
anticline
N

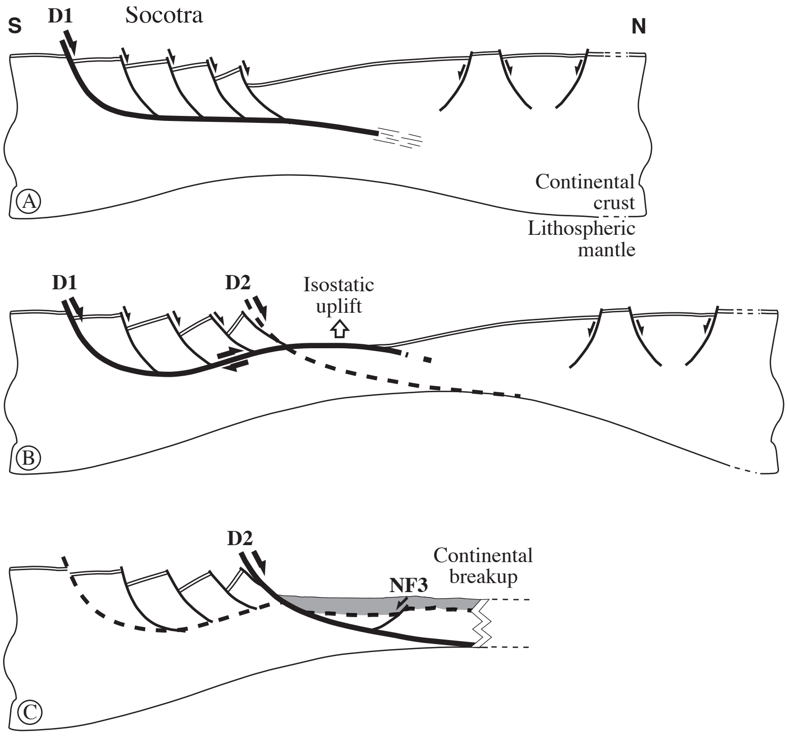

Continental transfer zone

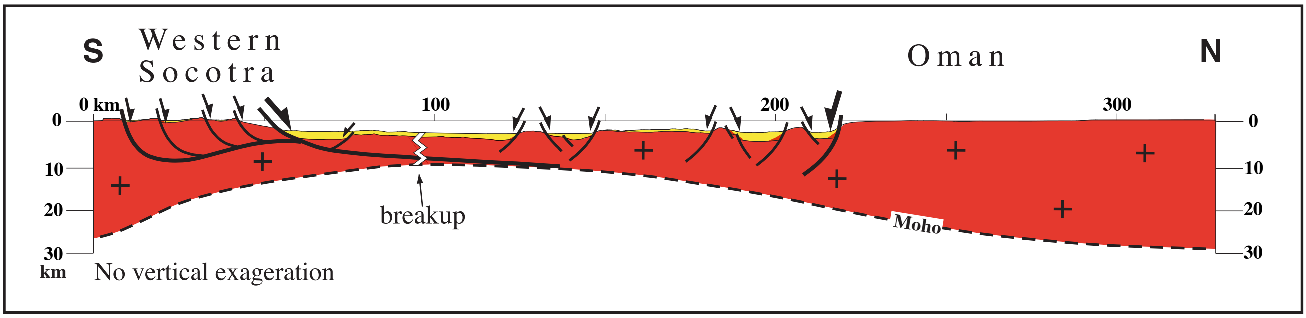
Oceanic transform fault


SP
3000
2500
2000
1500
1000
500
S
0
20
km
Socotra margin
ES20
N
2
3
4
5
TWTT (s)
A
continental crust
OCT
oceanic crust
Oman margin
ES18
1
6
B
oceanic crust
continental crust
Socotra margin
Sheba Ridge
Oman margin
coastline
Fig. 5a
Fig. 5b
0 km
100
200
300
400
500
600
700
0
5
10
20
30 km
Moho
Syn- and post-rift deposits
Continental crust
Oceanic cust
Vertical exageration x5
C



Lister et al. (1986)


S
D1
Socotra
N
Continental
crust
Lithospheric
mantle
Ⓐ
D1
D2
Isostatic
uplift
Ⓑ
D2
Continental
breakup
NF3
Ⓒ


S
Western Socotra
Oman
N
0 km
100
200
300
0
10
20
30
km
0
10
20
30
breakup
Moho
No vertical exageration