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Red Sea extension influenced by Pan-African tectonic grain in eastern Eritrea

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Abstract

Middle to lower crustal rocks with dominantly flat-lying Pan-African fabrics at amphibolite metamorphic facies are exposed along the actively extending Red Sea lowlands of Eritrea. West of a major escarpment, these rocks are structurally overlain in the plateau by greenschist facies metamorphic rocks with steep fabrics dominant. Three Pan-African phases of deformation in eastern Eritrea (PAD1-3) were superposed during the Cenozoic by three phases of Red Sea lateral extension (RSE1-3). PAD1 is characterised by steep penetrative foliation S_1, which is axial planar to upright F_1 folds. These folds were distorted at depth by F_2 recumbent folds and subhorizontal shear zones during PAD2. PAD3 deformation resulted mainly in steep strike-slip shear zones.

All phases of NE–SW lateral extension of the Red Sea exploited steep PAD1 and PAD3 and flat-lying PAD2 fabrics and structures. RSE1 was semi-brittle and resulted in top-to-basin low-angle (=35°) NW–SE-trending normal faults that sole out to subhorizontal detachments at deep exposure levels. RSE2 involved seaward block tilting on a new system of moderate to steep (≥40°) domino-style normal faults and dykes with NW–SE strikes above a younger detachment inferred beneath exposure levels. RSE2 structures concentrate in zones of maximum crustal flexure across the escarpment and were preceded and/or accompanied by reverse faults near the foot of the escarpment. RSE2 structures truncate RSE1 and PAD2 subhorizontal shear zones in the lowlands by exploiting steep PAD3 structures along the escarpment and the in the plateau. The away-from-basin dip of the RSE2 faults and dykes is attributed to isostatic rise of the asthenosphere offshore. RSE3 involved NNW–SSE- to NNE–SSW-trending strike-slip faults associated with counterclockwise opening of the hinge where the Danakil block is still joined to Africa. The overall geometric relationships between Cenozoic faults and dykes and the Pan-African tectonic grain suggest that the Red Sea escarpment in eastern Eritrea is closer to a monoclinal flexure rather than a rift.

1. Introduction

The formation of the Arabian–Nubian Shield of NE Africa has been ascribed to the accretion of a series of inter-oceanic island arcs (e.g. Gass, 1981) and a plume-generated oceanic plateau (Stein and Goldstein, 1996). Ophiolite belts mark the sutures between previously separate crustal blocks (e.g. Bakor et al., 1976; Gass, 1981; Vail, 1985; Berhe, 1990). These sutures (Fig. 1a) constitute a mega-suture along which East and West Gondwana converged during the Pan-African time (~900–550 Ma) to form a transpressive orogenic belt (Rogers et al., 1995) termed the East African Orogen (EAO) by Stern (1994). Most of the Mesozoic–Cenozoic rifts in Africa, including the Red Sea, (Fig. 1b) exploited these sutures or other weak zones (McConnell, 1972; Baker et al., 1972).

The Red Sea overlying the Afar mantle plume (White and McKenzie, 1989) now separates the Neoproterozoic Arabian–Nubian shields which were together until about 25 Ma (e.g. Cochran and Martinez, 1988). There is controversy (reviewed in Gheb-

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reab, 1998) about whether Red Sea extension occurred in a single stage since the Oligocene (e.g. Cochran, 1981; Bonati, 1985; LaBreque and Zitellini, 1985) or in two stages at ~23.5–16 Ma and 5–4 Ma (e.g. Girdler and Styles, 1978; Hempton, 1987; Girdler, 1991).

Early work on the structures of continental rifts such as the Afro-Arabian Rift System (Baker et al., 1972; Fig. 1b) was revolutionised in the 1980s by new field observations and seismic reflection data that led to the recognition of extensional low-angle ($\leq 30°$) detachments in basement rocks of the Basin and Range tectonic province of the western United States (e.g. Wright and Troxel 1973; Wernicke, 1985). Although doubted by some (e.g. Mohr, 1987; Morley, 1995), it has been considered that the structural style of East African Rift System (EARS) and the Basin and Range to be similar; the Red Sea probably evolved from narrower and more restricted thermal anomalies (Bosworth, 1989). The occurrence of low-angle detachments on the western side of the Red Sea was predicted by Wernicke (1985), assumed by Bohannon (1989) and Drury et al. (1994) and observed on the surface by Talbot and Ghebreab (1997). Along the Arabian side, surface expression of these detachments were described by Bohannon (1986) and Voggenreiter et al. (1988). Several rifting mechanisms have been proposed for the Red Sea (reviewed by Ghebreab, 1998). Low-angle simple shear (Wernicke, 1985) and pure shear (McKenzie, 1978) of the lithosphere are the end members.

The influence of pre-existing structures on the geometry of faults and the evolution of continental rifts has been described in the EARS (McConnell, 1972; Baker, et al., 1972), Gulf of Suez (Moustafa, 1997) and the Red Sea (Dixon et al., 1987). It is generally accepted that the main Red Sea extension started in Late Oligocene–Early Miocene and exploited steep NW-trending late Pan-African shear zones. Steep faults of the rifting phase reactivated high-angle ductile shear zones inherited from the phase of Pan-African

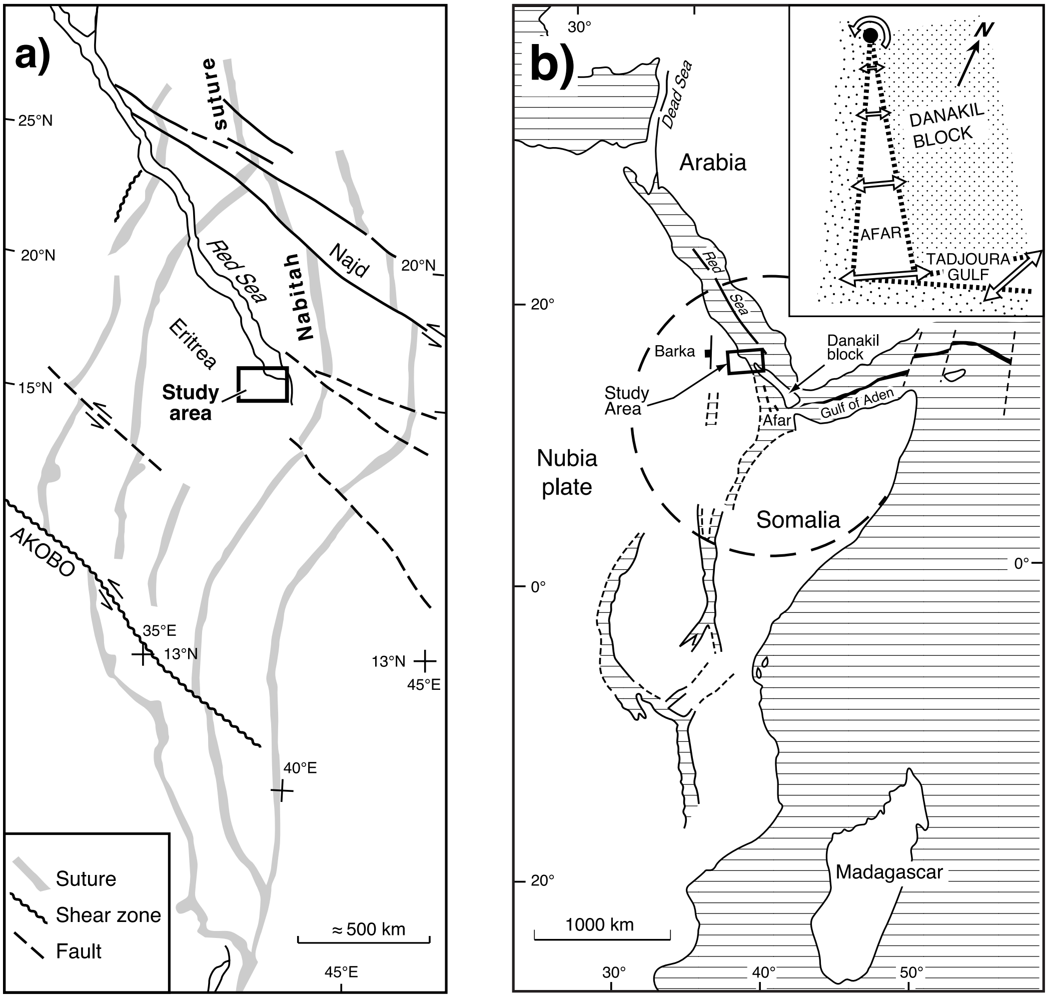

Fig. 1. Location of the study area (a) in a simplified map of the East African Orogen (EAO) modified after Shackleton (1996). (b) The Afro-Arabian rift system; continental graben and depressions are hatched (modified after Baker et al., 1972). Inset shows 'crank-arm model' for the counterclockwise rotation of the Danakil block to open the Danakil–Afar depression (after Souriot and Brun, 1992).

crustal construction in the Pan-African basement of Eritrea (Mohr, 1979; Berhe, 1986; Drury et al., 1994) and the margin of the Red Sea in Egypt (Greiling et al., 1988). However, we add here the concept that the lateral extension of the western margin of the Red Sea over large areas of eastern Eritrea reactivated subhorizontal mylonites and shear zones inherited from the second phase of Pan-African deformation (PAD2). The aim of this paper is thus to show how three phases of Cenozoic Red Sea extension in eastern Eritrea were influenced by the older tectonic grain of the Pan-African crust. We focus on (1) the relationship between Pan-African low-angle shear zones and fabrics and the Cenozoic Red Sea semi-brittle low-angle detachments and (2) the monoclinal nature of the western margin of the Southern Red Sea in eastern Eritrea, hereafter referred to as the 'Eritrean monocline'.

2. Geologic setting

Neoproterozoic low-grade volcano-sedimentary rocks with a steep foliation intruded by weakly deformed granitoid rocks are exposed in crust ~35 km thick in the Eritrean plateau and in the Danakil block (Fig. 1b). The Danakil block is skewed 10° counterclockwise across the Red Sea from a northern hinge near Massawa in the study area (Souriot and Brun, 1992; Fig. 1b inset). Exposed crust, thinned to ~10–14 km beneath the adjoining Red Sea coastal lowlands, consists of rocks of higher metamorphic grade (Gherardi, 1951; Merla et al., 1979) with gently dipping foliations (Talbot and Ghebreab, 1997). The Pan-African basement of the region was below sea-level from the late Cretaceous (Bohannon, 1989) and had developed a distinctive red lateritic and white kaolinitic palaeosol on a crust of normal thickness before it was buried beneath ~600 m thick Oligocene trap basalts that heralded the future opening of the Red Sea. Vertical offsets of the lateritic and kaolinitic paleosols identify minor faults along the uplifted shoulders of the Red Sea rift (Dainelli, 1943; Drury et al., 1994).

The grade of metamorphism, style of deformation and spatial distribution of the rocks divide the Neoproterozoic rocks in eastern Eritrea into two domains named the Ghedem and Bizen (Fig. 2). The Ghedem and Bizen domains are separated by a transition zone that dips moderately to gently westward. This zone has an average outcrop width of 2–3 km but may be only a few hundred metres thick and is characterised by intense alteration.

2.1. Ghedem domain

The Ghedem domain is dominated by two tectonostratigraphic units of orthogneiss and paragneiss/schists (Fig. 2). These units consist of amphibolite facies metamorphic rocks with dominant sub-horizontal shear zones and fabrics (Fig. 2; stereoplot d) and are exposed mainly along the foot of the escarpment and in the coastal hills. The paragneisses and schists unit is structurally over the orthogneisses (profiles on Fig. 2). The orthogneisses are locally capped by the unit of paragneisses and schists and represent lower to mid crustal rocks unroofed beneath late Pan-African subhorizontal ductile shear zones with top-to-the-west or -southwest sense of shear. By contrast, the structurally overlying paragneisses and schists are characterised by top-to-the-east or -northeast subhorizontal ductile shear zones. Voluminous Pan-African pegmatites with a variety of orientations occur in aureoles around pegmatitic granitoid plutons emplaced in the Ghedem domain.

2.2. Bizen domain

Supracrustal rocks of the Bizen domain structurally overlie rocks of the Ghedem domain and are exposed on the plateau and along the escarpment (Fig. 2); they also occur in the Danakil block to the SE of the study area. The Bizen domain rocks consist of various types of metavolcanic and metasedimentary rocks with steep fabrics (Fig. 2; stereoplots a–c) intruded by large granitoid plutons. Probable late Neoproterozoic felsic to intermediate and mafic dykes with N–S and NW–SE trends and steep dips locally traverse these rocks. Steep left-lateral and right-lateral strike-slip shear zones with NW–SE and N–S strikes and associated asymmetric reclined folds characterise rocks of both the plateau and the escarpment. Low-angle top-to-the-northwest PAD2 brittle shear zones are also not uncommon. In contrast to the Ghedem domain, pegmatites are rare in the Bizen domain at the present level of exposure. Instead, en-échelon quartz veins developed within the semi-brittle shear zones.

The Neoproterozoic basement rocks in the Ghedem and Bizen domains of eastern Eritrea are locally covered by Phanerozoic volcano-sedimentary rocks and traversed by dykes (Fig. 3). Sporadic outliers of fine-grained and strongly varved tillites of Late Carboniferous age (?) also occur on the plateau (Fig. 3). In the Red Sea basin within Eritrea, Mesozoic–Cenozoic rocks have been grouped as pre-, syn- and post-rift sequences (e.g. Savoyat et al., 1989). Rifting of the Red Sea is assumed to have begun in Oligocene time.

2.3. Pre-rift deposits

Pre-rift deposits consist of Lower to Middle Jurassic continental to fluviatile cross-bedded sandstones. Thin remnant outliers of these sandstones locally overlying patches of the tillites have survived erosion on small

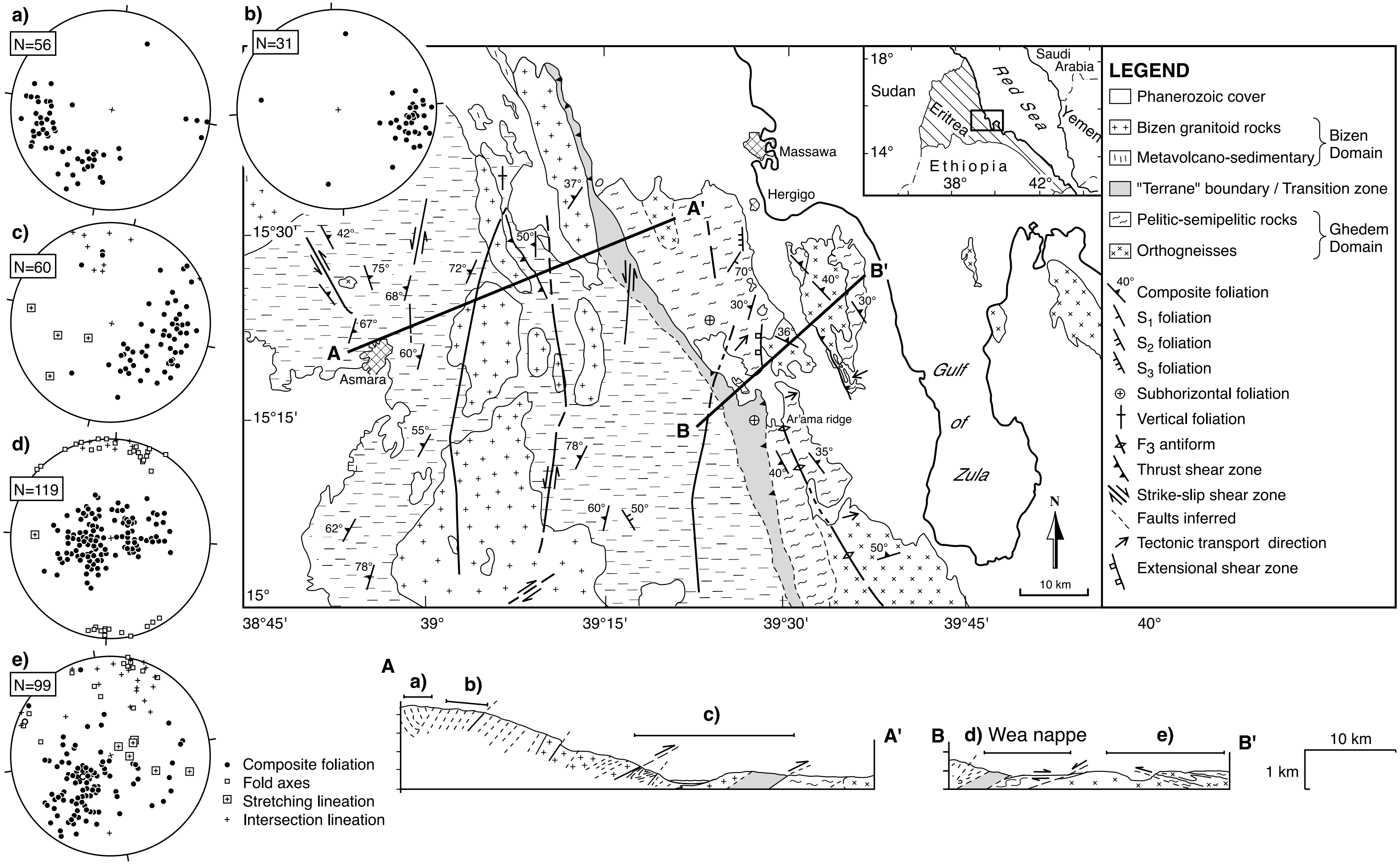

Fig. 2. Sketch map of major Pan-African rock types, fabrics and structures in eastern Eritrea. Lower hemisphere equal area stereographic projections are to poles of composite foliation for localities (a–e) along schematic ENE–WSW profiles.

flat-topped hills on the plateau along the south-south-western margin of the study area (Fig. 3). Exposures of these rocks in the plateau thicken to the south, southeast and beyond Fig. 3. Thin layers of pre-rift sediments are also locally preserved between the basement and Tertiary volcanic rocks in south of the Bizen domain. Most exposures of Mesozoic sedimentary rocks are on the plateau (and these may extend further to both the west and north than shown in Fig. 3) with small patches near sea level in the NE of Buri peninsula (Fig. 3) and slightly SE off the map-area (Frazier, 1970). Mesozoic sedimentary rocks are also well exposed in the Danakil block where they unconformably overlie the greenschist facies basement rocks and are strongly faulted.

2.4. Syn-rift deposits

The syn-rift succession is represented by Oligocene detrital Dogali Formation associated with initial rift volcanic rocks of the 'trap series' followed by the Lower–Middle Miocene ~1550 m thick sand–shale Habab Formation capped by the mobilised Amber salt

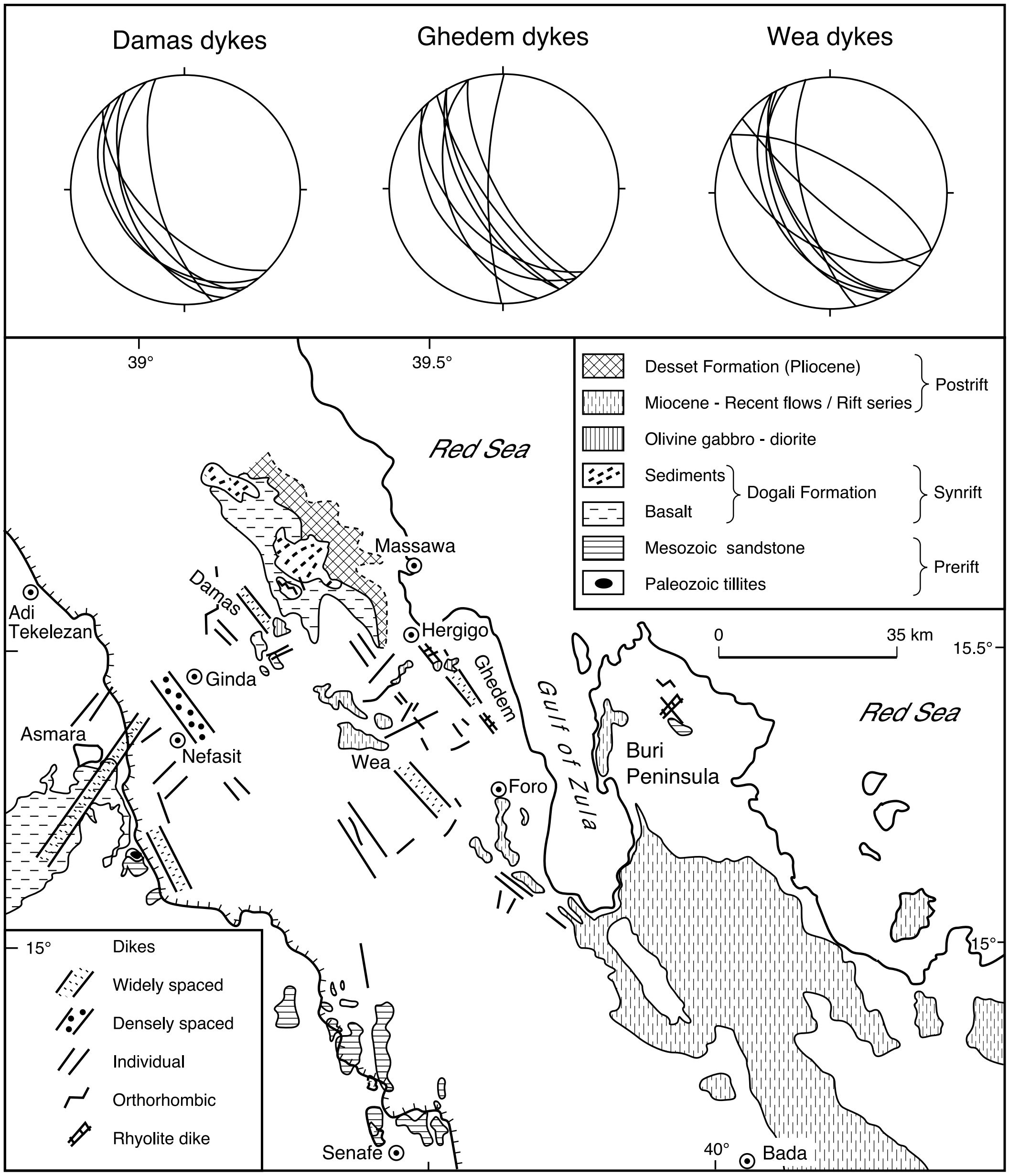

Fig. 3. Sketch map showing distribution of representative Oligocene to Recent dykes and related igneous rocks with the syn-rift (Dogali), post-rift (Desset) Formations and pre-rift Palaeozoic and Mesozoic sequences in eastern Eritrea. Most dykes dip steeply to moderately landward and areas without data are poorly exposed or have not been visited. Ends of the dykes are not shown. Lower hemisphere stereographic projections of some representative dykes are included.

offshore (Savoyat et al., 1989). The entire sequence dips at ~30° consistently seaward.

2.5. Post-rift deposits

In Upper Miocene to Quaternary times the separation of continental blocks and the generation of oceanic crust along parts of the Red Sea axial trough resulted in subsidence and post-rift deposition of the 3875-m-thick Desset Formation. Deposition of these mainly of coarse clastic sediments near restricted depocenters both inland and offshore might have been accompanied by lavas of the 'rift series'. Islands of the Dahlak Archipelago (NE of Fig. 3) are capped by carbonate platforms and coral reefs rimming the coastline. Faulted terraces of desert-varnished gravel and

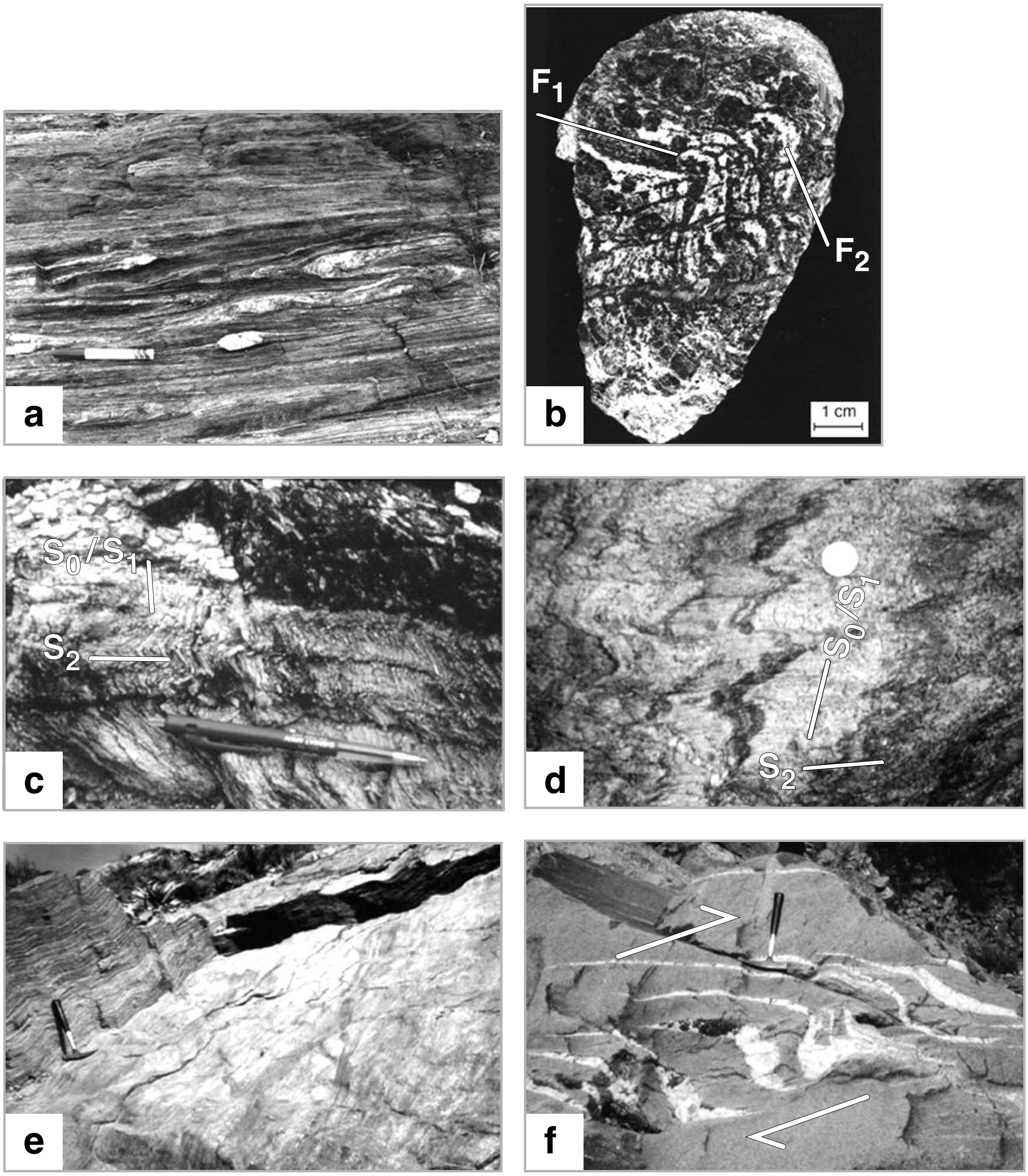

Fig. 4. Mesoscopic Pan-African PAD1-2 fabrics. (a) Formerly subvertical S_1 foliation now refolded to horizontal S_2 fabric due to marked coaxial flattening in semipelites of the We'a nappe looking south. Notice the top-to-the-east sense of shear, marker is 14 cm long. (b) Interference patterns between F_1 and F_2 folds in garnetiferous amphibole gneiss. (c) S_0, S_1 and subhorizontal S_2 surfaces in a semipelite west of Gulf of Zula, pen is 13.5 cm long. (d) Steep S_0/S_1 refolded during PAD2 to produce subhorizontal S_2 fabric, coin is 2.5 cm across. (e) Conjugate S_2 kind bands with moderate east-southeastward dips in low-grade rocks of the Bizen Domain. (f) Rotated subhorizontal S_2 en-échelon tension gashes in metavolcanic rocks in the plateau NE of Asmara. Hammer is 30 cm long.

recent sediment locally cover different parts of the map area.

Basinward dips of ~30° in the syn-rift Dogali Formation and ~20° in post-rift Desset Formations west of Massawa (Fig. 3) suggest a roll-over anticline with normal growth faults dipping landward. During the Cenozoic, older rocks of the region were locally intruded by small Oligocene–Miocene (?) olivine gabbro-diorite intrusions and dolerite dyke swarms with NNW–SSE strikes dominant. NE–SW-trending dyke swarms also intrude the Bizen domain. Sills locally parallel lithological layering and the subhorizontal Pan-African foliation in the Ghedem domain are joined locally by NW–SE dykes to develop orthorhombic networks, probably near the centre of dyke swarms (Ghebreab, 1998).

3. Neoproterozoic tectonics

The Neoproterozoic rocks in eastern Eritrea display evidence of repeated deformation. Three major Pan-African deformation phases designated PAD1, PAD2 and PAD3 are recognised. These deformation phases were distinguished on superposition criteria (Hobbs et al., 1976) and are described below.

3.1. PAD1 deformation

The oldest PAD1 structures were upright F_1 folds of the original compositional layering, S_0, with a steep pervasive S_1 axial planar foliation trending N–S or NNE–SSW. The S_1 foliation occurs both in symmetric and asymmetric minor folds between S_2 shear bands and occasional metre-scale F_1 folds of S_0 are recognisable locally. Places, marked flattening along subhorizontal axes during PAD2, resulted in parallelism between S_1 and S_2 where S_1 was isoclinally folded as F_2 intra-folial folds (Fig. 4a). Refolding of S_1 during D_2 shearing resulted in mesoscopic interference patterns between F_1 and F_2 folds with axes plunging gently to the NNW (Fig. 4b). Where S_2 is not intense, S_1 also makes a small angle with S_0.

3.2. PAD2 deformation

S_0 and S_1 were left generally steep by PAD1 until they were refolded during PAD2. They then developed F_2 recumbent folds with axes that generally plunge either to the north or south at $< 10°$ with a well-developed subhorizontal axial planar S_2 fabric (Fig. 4c–d). The S_2 foliation is mylonitic in the gneisses of the Ghedem domain at low structural levels near sea level but gives way structurally upwards to S_2 kink band in the schists at intermediate levels in the escarpment (Fig. 4e). At still higher structural levels S_2 is represented by subhorizontal arrays of en-échelon quartz veins in the greenschist facies rocks of the Bizen domain (Fig. 4f).

F_2 recumbent folds vary in scale from microscopic to a nappe with limbs about 5 km long at We'a. Most F_2 mesoscopic folds are sharp-hinged isoclinal recumbent folds. Low-angle PAD2 shear zones are characterised by asymmetric folds associated with geometrically compatible stretching lineations, rotated clasts and boudins and locally well-developed mesoscopic sheath folds. Recumbent folds in these shear zones show west-southwestward or east-northeastward vergence in different places, probably because they are on different limbs of major recumbent folds. The *s*-asymmetry of the We'a nappe looking north (profile Fig. 2) indicates westward vergence. Recumbent mesoscopic *z*-folds looking NW in northern Ghedem verge north-eastward. L_2 intersection lineations between S_1 and S_2 and F_2 fold hinges, generally trending NNW–NNE, are well developed throughout the Ghedem domain. Top-to-the-northeast high angle (~45°) ductile to semi-ductile thrust and extensional (collapse) shear zones are also attributed to a late stages of PAD2 while metamorphism was still at amphibolite facies.

3.3. PAD3 deformation

PAD3 deformation resulted in comparatively rare, open to gentle NNW- and N-trending F_3 upright folds (Fig. 2) that locally steepened and refolded F_2 recumbent folds. S_3 commonly occurs as mesoscopic spaced cleavage and brittle and semi-brittle strike-slip shear zones and empty or vein-filled fractures, which locally reactivated the steep S_1 foliation. Major strike-slip shear zones in the area (Fig. 2) trend N–S to NNE–SSW and NW–SE. Bizen granitoid rocks (Fig. 2) were probably emplaced contemporaneous with these shear zones during PAD3.

The phases of deformation described above are related to lateral compression during convergence (PAD1 and early PAD2) followed by isostatic orogenic root recovery from depth during gravitational collapse at surficial levels (late PAD2) and lateral escape associated with strike-slip shear zones during PAD3 (Ghebreab, 1999).

4. Cenozoic tectonics

In Eritrea the extension which subsequently led to the opening of the Red Sea is divisible into at least three main phases, designated RSE1, RSE2 and RSE3 (Fig. 5). Prominent strain markers are Pan-African pegmatites, amphibolite layers and Oligo-Miocene basaltic flows, sills and dykes (Ghebreab, 1998). Fault gouge and cataclasites with associated slickenlines are well developed only locally.

4.1. RSE1 extension

RSE1 structures consist of normal faults at various scales with low to moderate basinward dips (≤35°) above semi-brittle top-to-basin RSE1 subhorizontal detachments occurring at the lowest levels of erosion (Fig. 5 stereograms). Most RSE1 low-angle detachments (and dolerite sills along them) are marked by altered and/or hydrated minerals and calcite and generally exploit PAD2 subhorizontal ductile shear zones and fabrics (Fig. 6a–f), although some cross cut the PAD2 structures at <20° by exploiting PAD1 fabric (e.g. Fig. 6f).

Block tilting is generally landward (e.g. Fig. 6a). Cenozoic mafic and felsic sills locally follow the low-angle detachments that exploited PAD2 subhorizontal mylonitic foliation (Fig. 6d). Such sills have a weak cataclastic foliation. In places, RSE1 detachments displaced steep mesoscopic PAD3 fabrics by exploiting the PAD2 fabric (e.g. Fig. 6e). Subhorizontal displacements along RSE1 detachments are probably in the order of at least hundreds of metres because some of the detachments (Fig. 6a–d) are exposed for tens of kilometres around four gentle domes at Damas, Ghedem, SSW of Ghedem (We'a) and Buri (Fig. 5). We

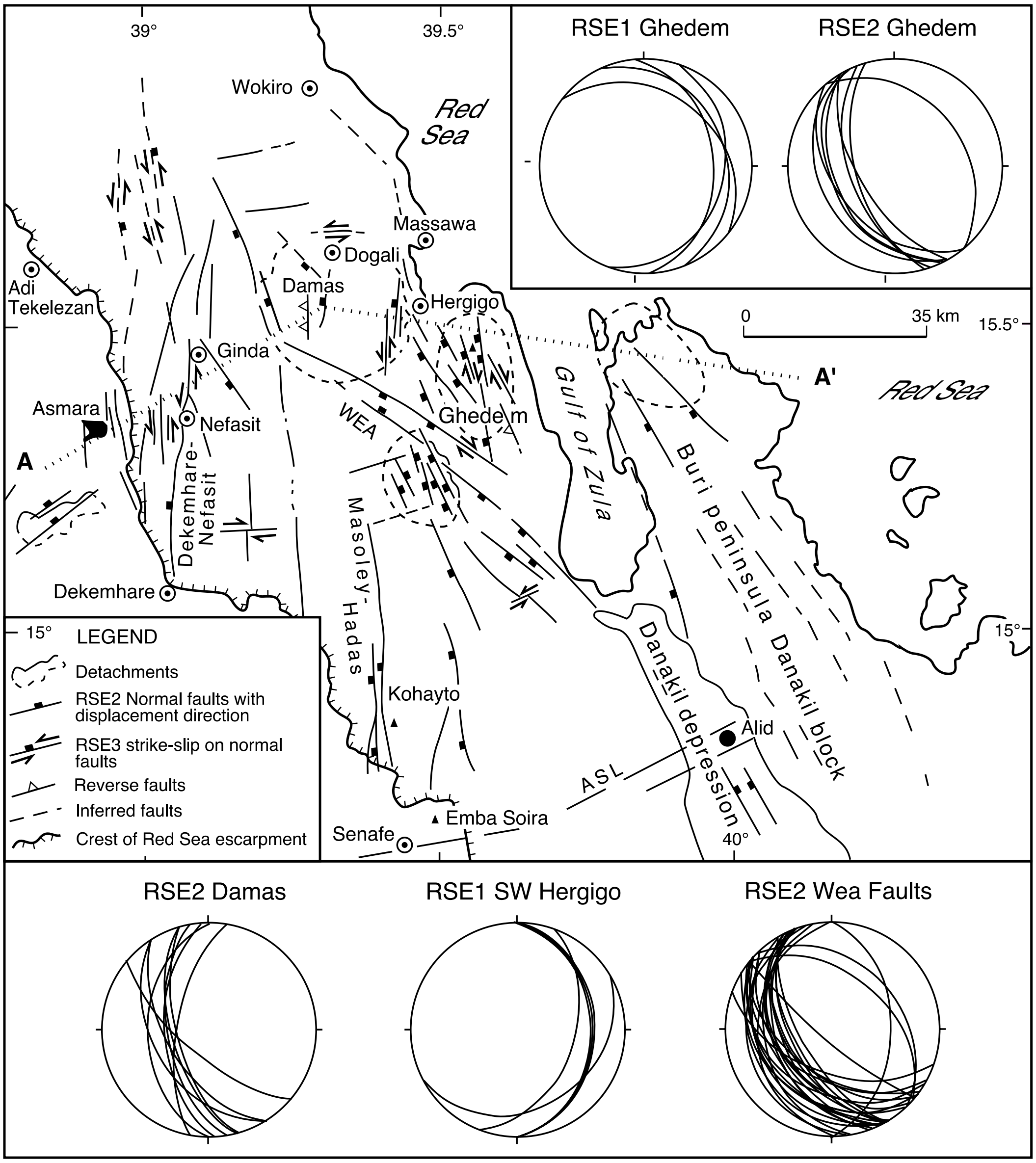

Fig. 5. Map showing distribution of representative Red Sea low angle detachments outlining domes or extensional core complexes and normal, reverse and strike-slip/oblique-slip faults in eastern Eritrea. Fault spacing varies from tens to hundreds of metres and there are many more than shown on the map. Lower hemisphere stereographic projections show a few RSE1 and RSE2 faults. ASL = Allid–Senafe lineament.

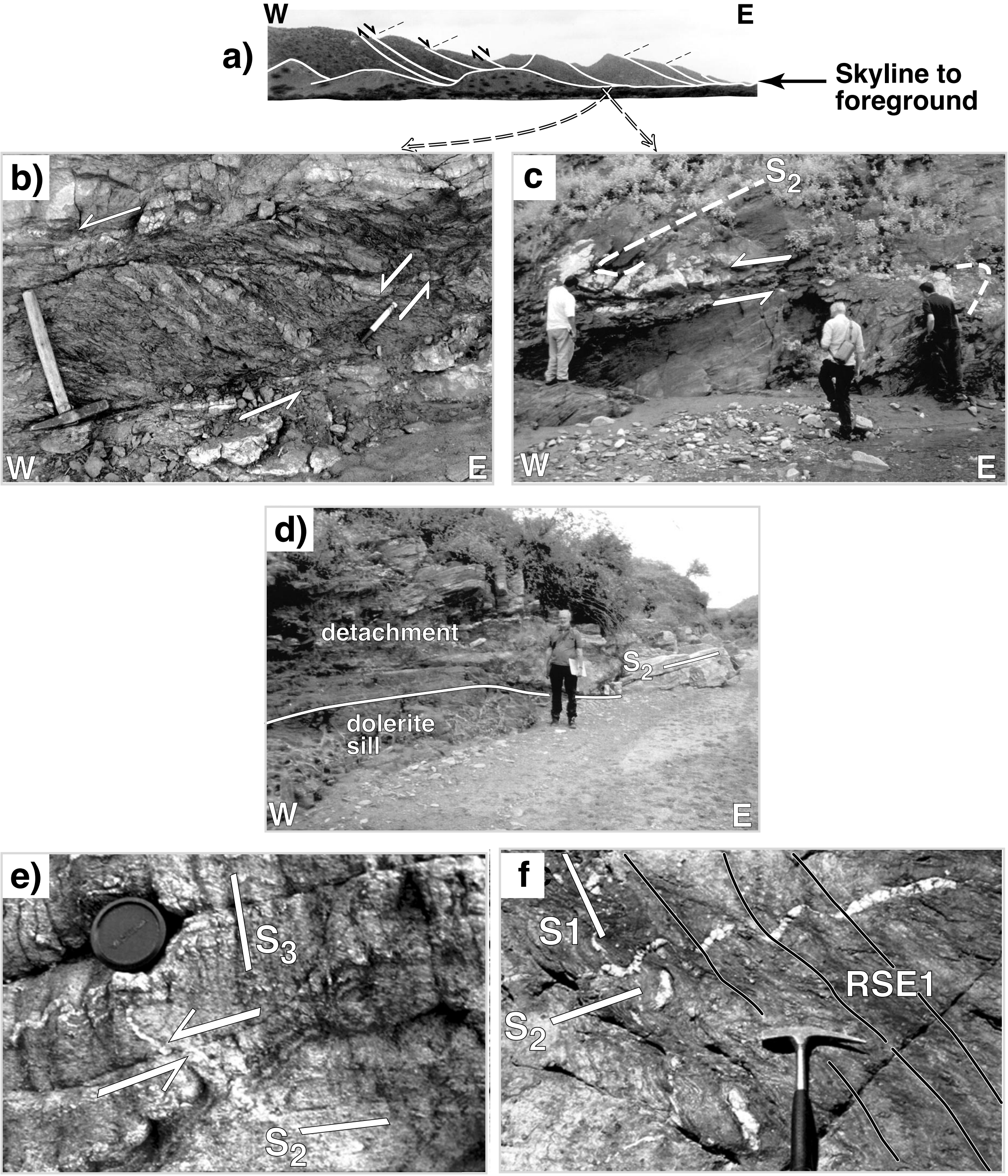

Fig. 6. RSE1 structures. (a) Kilometre-scale basinward dipping RSE1 semi-brittle low-angle detachments SW of Hergigo looking NW, white lines represent normal faults behind foreground skyline and black dashes approximate landward tilted blocks. (b, c) Details within the detachments looking SE. (b) Shear band duplexes within the detachment showing top-to-basin sense of shear and synthetic minor normal faults within the duplexes. (c) RSE1 detachment that truncated the short limb of a Pan-African fold in a quartz vein pinched in PAD1 and folded in PAD2. (d) Cenozoic doleritic sill that exploited RSE1 detachment along PAD2 fabric in marble within the transition zone south of Damas. (e) Looking south at minor RSE1 Red Sea low-angle detachment with top-to-basin sense of shear offsetting steep PAD3 fabric, lens cap = 5.5 cm across. (f) Looking north at RSE1 semi-brittle extensional shear zone (subparallel to head of hammer 30 cm long) offsetting subhorizontal quartz vein folded by PAD1 and steep vein boudinaged by PAD1 and folded by PAD2 with local reactivation of PAD1 fabric (black lines) in pelite west of Gulf of Zula.

consider these gentle domes to be either extensional core complexes or the crests of crustal scale boudins (see later, Fig. 8a).

RSE1 structures were not seen affecting the Oligocene Dogali Formation suggesting that this formation was deposited in asymmetric basins between the domes formed during RSE1 extension. RSE1 extension is related to the first extension episode that probably began its activity in the region during late Eocene (e.g. Hempton, 1987).

4.2. RSE2 extension

RSE2 structures are characteristically moderate to steep (40°) landward-dipping, domino-style normal faults (Fig. 5 stereograms and Fig. 7) most with strikes parallel to the NNW–SSE-trending coast but some with N–S and NE–SW strikes. These faults are accompanied by reverse faults that locally displace basalts within the Dogali Formation. The RSE2 coast-parallel normal faults define half-graben along the flanks of Damas, Ghedem and Buri asymmetric domes. RSE2 structures displace the older RSE1 detachments and the syn-rift and post-rift volcano-sedimentary rocks. Block tilting of 20–40° seaward is characteristic in the lowlands (Fig. 7). Steep offsets locally reach ~200 m. Some of the RSE2 normal faults are along highly strained and altered dykes. This indicates that steep faults exploited most of the altered vertical dykes and that they were then rotated together to dips about 50° landward above late RSE2 younger detachment(s) that we infer exist beneath exposure levels in the lowlands (Fig. 7b–c). A few steep dykes along other faults with NW–SE strikes are fresh and unsheared. The age relationships between dykes and RSE2 normal faults are therefore not consistent for nearby dykes and appear to both pre-date and post-date normal faults. We therefore interpret episodes of essentially contemporaneous faulting and dyking.

On the plateau, south-southeast of Asmara, NNE–SSW-trending dykes cut both the lateritised uppermost basement and the overlying Oligocene basalts. These dykes are in turn displaced by top-to-basin late RSE2 subhorizontal detachments, which are along weak lateritic soils beneath the basalts (Fig. 7d). In contrast to the semi-brittle extension in the lowlands, the RSE2 subhorizontal detachments in the plateau did not rotate the dykes. In the escarpment, short top-to-basin low-angle detachments displace steep Pan-African quartz veins in isotropic or weakly deformed granitoid rocks. The orientation of most dykes and normal faults in the rocks of the Bizen domain, particularly south of Asmara parallel and reactivate steep NE-trending Pan-African shear zones (Fig. 7e).

Brittle RSE2 normal fault zones with NW strikes (e.g. those of We'a) include red–brown cataclastic zones containing irregular and angular ferrugenous rock fragments and complex networks of quartz veinlets and are clearly along altered mafic dykes. These cataclastic zones display well-developed cataclastic foliation with down-dip slickenlines and abruptly offset the older subhorizontal Pan-African fabric. The NNE–SSW-trending Masoley–Hadas, Nefasit–Dekemhare lineaments with N–S trends are probably major normal faults with westward displacement (Fig. 5) that exploited steep PAD3 structures. RSE2 structures are related to the first episode of opening of the Red Sea with the local creation of ocean floor between 23.5–16 Ma (e.g. Girdler et al., 1980).

4.3. RSE3 extension

RSE3 extension is dominated by strike-slip and oblique-slip faults ranging in trend between NW–SE and NNE–SSW. These faults displace prominent strain markers (e.g. Fig. 7f) and are well developed with local slickenlines on chilled dyke margins and adjacent rocks. The most obvious N–S strike-slip faults concentrate along particular zones in the escarpment near Nefasit and SW of Hergigo and most show left-lateral sense of displacement. In Ghedem, however, dextral strike-slip displacements dominate (Fig. 5). Dextral offsets of geomorphologic features across these strike-slip faults are generally a little over 500 m. A series of small NE-trending steep strike-slip faults of this phase offset structures in the basement and basaltic dykes in the Oligocene lavas on the plateau also. A steep landward-dipping oblique-slip fault with NNW–SSE strike offsets NW-trending doleritic dykes (N Silike) dextrally along the western side of the Hergigo half-graben (Fig. 7f). N70°E left-lateral strike-slip faults and mafic dykes with N60–70°E trends are also evident locally (Ghebreab, 1998). Satellite imagery and limited field studies also reveal a ~60-km-long E–W-trending lineament termed here the Alid–Senafe lineament along which prominent volcanic plugs (Alid–Senafe–Tequile) are roughly aligned (Fig. 5). Major faults in the Danakil depression south of this lineament appear to dip seaward. Strike-slip and oblique-slip faults appear to be younger than, at least, the oldest set of RSE1 normal faults and dykes. Many faults in the region that initiated as RSE2 normal faults appear to have been subsequently reactivated as strike-slip or oblique-slip faults. The age of RSE3 strike-slip and oblique-slip faults is probably < 5 Ma.

The triple phase NE–SW extension history of the Red Sea escarpment in eastern Eritrea is related to dilatation by dyking and extension by faulting. However, on-land crustal dilation by dyke injection during RSE2 was hardly significant even locally. It was most intense within the dyke swarm at Nefasit (Fig. 3) where about 50 dykes, centimetres thick, indicate only

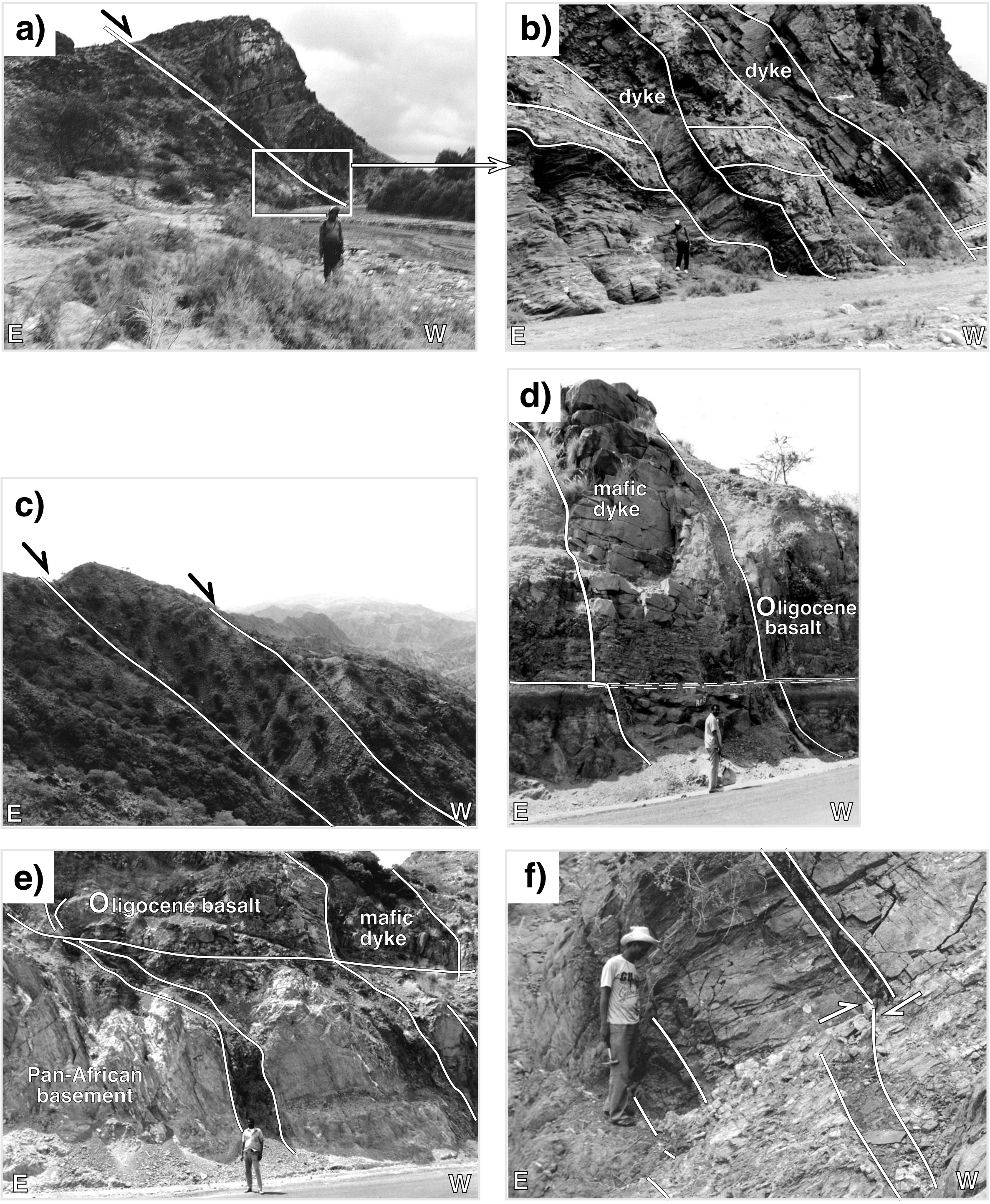

Fig. 7. RSE2 landward dipping faults and dykes looking south-southeast. (a) Normal fault blocks tilting Pan-African mylonitised semipelites about 25° basinward. (b) Landward-dipping normal fault along one of the sheared dykes. All dykes near here were intruded vertically, but were rotated to landward dips byRSE2. (c) Landward-dipping normal faults along dykes in Ghedem. (d) Late stage RSE2 low-angle detachment along paleosols of basement beneath Oligocene basalts on plateau south of Asmara. Here the dykes are displaced almost along their strikes but remained steep. (e) Dykes along steep PAD3 shear zones in the plateau south of Asmara. (f) NW-trending dolerite dyke offset by NNW-trending oblique-slip fault SW of Silike (Lahazin).

1.4% lateral extension across a zone only 36 m wide. By contrast synthetic minor RSE2 normal domino-faults bounding the Zula, Hergigo and Damas half-graben are about 50–100 m apart and indicate a percentage of lateral extension estimated at 60% (Talbot and Ghebreab, 1997) for the western side of the Zula half-graben. Such significant extension distinguishes half-graben from full-graben, which are more likely to have lower (<20%) lateral extension (Morley, 1995). In general, the percentage of lateral extension in eastern Eritrea by dyke injection is insignificant compared to mechanical extension along the domino-faults, which rotated above low-angle detachments. The spacing of faults decreases basinward from a few kilometres in the plateau to tens of metres across the escarpment to tens of metres in the lowlands.

5. Discussion

5.1. Red Sea escarpment in Eritrea: a monoclinal flexure

The Red Sea escarpment in Eritrea differs from classic rifts in a number of ways: (1) there is no obvious major basinward dipping normal fault along the eastern margin of the plateau, (2) all major RSE2 normal faults dip steeply landward on the plateau and lowlands and less steeply in the escarpment in between, (3) dykes are vertical in the plateau and parts of the lowlands; but dip landward near the foot of the escarpment, (4) subvertical Pan-African fabrics on the plateau have moderate landward dips near the foot of the escarpment, (5) small low-angle detachments are numerous, and (6) a few reverse faults occur in the lowlands.

We attribute all these features to the rift shoulder in the area we studied being flexed in the Eritrean monocline which is (1) where the northern end of the Danakil block is still hinged to the African plate (see Fig. 1b inset), (2) where the spreading axes of the Red Sea and the Afar may lead to a future transform in line with N60–70°E-trending incipient dykes west and southwest of Ghedem (Fig. 3), and (3) where Pan-African PAD2 subhorizontal fabrics and shear zones dominate along the transition zone between the Ghedem and Bizen domains.

The lateral extension began with RSE1 landward rotation of domino-faults dipping basinward above low-angle semi-brittle detachments at ~40 Ma (Fig. 8a). This was followed at ~23 Ma by RSE2 high-angle basinward rotation of domino-style normal faults dipping landward over deeper detachments. RSE2 was accompanied by uplift of the flood basalts on the Eritrean plateau from sea level to about 3 km as continental crust of normal thickness beneath the plateau thinned drastically in the lowland where asymmetric half-graben developed between domes or half-horsts. We therefore interpret the escarpment of Eritrea as an eroded monoclinal flexure on the shoulder, ~35 km thick. A crust beneath the plateau is joined into a coastal zone thinned to ~10–14 km with the domes being the crests of small boudins outlined by exposed RSE1 detachments (Fig. 8b). This accounts for (1) the base of the volcanics originally extruded over lateritised basement at sea level, that are now ~3 km above sea level on the plateau and (on basement stripped of its laterites) at or below sea level in the lowlands and (2) the fanning of dykes in the escarpment that are vertical on the plateau and part of the lowland.

The short brittle detachments without precursor in the isotropic granitoid rocks exposed in the escarpment and the brittle low-angle detachment along the lateritised basement near the edge of the plateau (e.g. Fig. 7d) are attributed to flexural slip on new fractures and along pre-existing weak zones in the outer upper arc of the monoclinal flexure. Similarly, the reverse movements on some RSE2 domino-faults in the lowlands are attributed to flexural shortening in the inner arc of the lower hinge of the monocline. The consistent away-from-basin dip of the RSE2 domino faults and dykes outside the flexure in the still thinning crust is probably due to further isostatic rise of the asthenosphere offshore. The low-angle planar anisotropy of the Pan-African crust both facilitated potential concentric slip surfaces in the flexure and inhibited steep normal faults. The monocline may have developed because low-angle RSE1 detachments that had reactivated PAD2 fabrics and shear zones provided potential slip surfaces. Uplift associated with monoclinal flexure and low-angle detachments on the plateau post dates Oligocene (28–30 Ma) flood basalts and most on-land dykes. Timing and rate of uplift of some of the RSE2 hanging walls in the lowlands will be constrained by apatite fission track data (work in progress).

The youngest RSE3 extension involving significant dextral strike-slip and oblique-slip faulting, particularly in Mt Ghedem (Fig. 5), is attributed to the counter-clockwise rotation in the hinge of the Danakil block where it was rotated by incipient ocean-floor spreading in the Afar depression during the last million years (Fig. 1b inset).

5.2. Cenozoic extension along low-angle detachments and high-angle normal faults

There has been considerable controversy as to whether low-angle detachments are steep as they form and deactivate as they rotate to low angles (Buck, 1988) or whether they can originate with low angles (e.g. Rehring and Reynolds, 1980; Allmedinger et al., 1983). The fact that the dykes on the plateau (Fig. 8b) and quartz veins in the escarpment remain steep above and below short detachments emphasises that the detachments in Eritrea must have initiated at their current low-angles. Miocene detachment has been recognised in the Gulf of Suez (Bosworth, 1995) and may be obscured by complex structures in the Amber salt in offshore Eritrea. The rotation of originally vertical RSE2 faults and Miocene dykes in Eritrea dips to about 50–60° along subsurface detachments and implies significant ductile flow below exposure levels on a regional scale.

Thick-skinned crust extension leading to the opening of the Red Sea involved multiple phases of simple shear along domino-style parallel faults in the brittle upper crust accommodated by synthetic shear in the

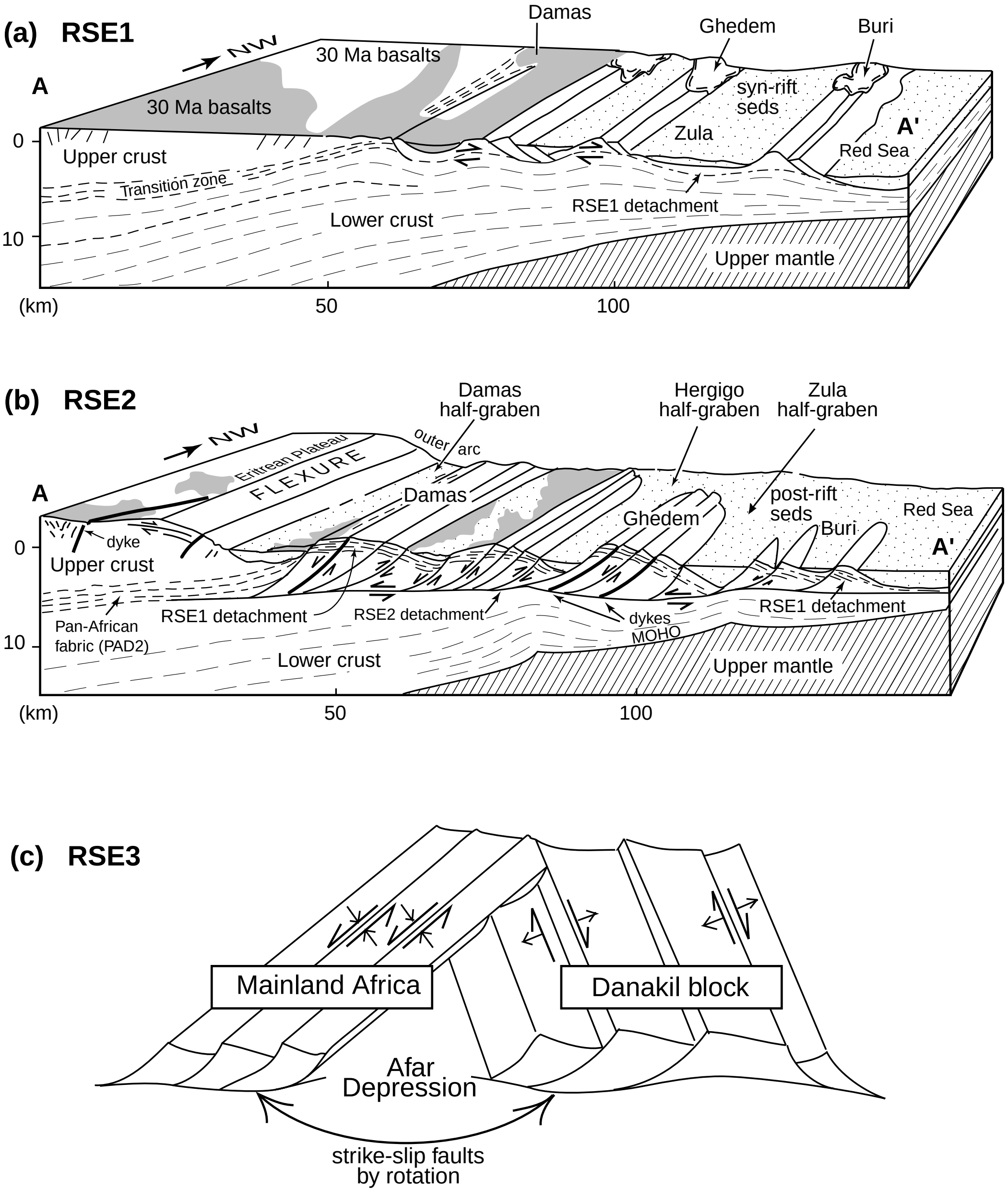

Fig. 8. Tectonic models based on schematic profile AA′ on Fig. 5. (a) Top-to-basin domino-faults over low-angle detachments outlining core complexes at exposure levels. (b) RSE2 dominoes dipping landward above a contemporaneous low-angle detachment(s) inferred to be at intermediate crustal depth (or Moho?). Short RSE2 brittle detachments in the outer-arc of the flexure of the Eritrean Monocline offset steep dykes intruding Oligocene basalts on the plateau and steep Pan-African quartz veins in the escarpment. Notice rotation of Pan-African fabrics and steep RSE2 dykes in the plateau to gentler dips in the flexed Eritrean Monocline. (c) RSE3 structures due to counterclockwise rotation of the Danakil block. Gray shade represents Oligocene basalts. Dots indicate syn-rift sediments in (a) and post-rift sediments and flows in (b).

ductile lower crust, between the interface of the upper and lower crust (Lister and Davis, 1989), or along the Moho (Lowell and Genik, 1972), or even along heterogeneities as unconformities (e.g. Fig. 7d) and low-angle PAD2 shear zones within the crust. Along such extended continental margins, basinward-dipping normal faults with landward-titled blocks like those above RSE1 detachments in eastern Eritrea (Fig. 6a) are commonly accepted as revealing basinward shear of the brittle upper crust over the ductile lower crust (Fig. 8a). However, the seaward-dipping RSE1 detachments are bound by a systematic array of younger landward-dipping RSE2 normal faults with a synthetic sense of shear in the ductile lower crust or the Moho (Fig. 8b). Consistent seaward dips of the Dogali–Desset Formations of eastern Eritrea (Section 2.4) could represent the seaward dipping reflectors characteristic of other continental margins elsewhere. Marginal blocks tilted seaward by landward-dipping normal faults in west Greenland have been interpreted as analogues of seaward-dipping reflectors elsewhere with thicknesses comparable to displacements across the faults (Geoffroy et al., 1998).

There are similarities in structural styles between the continental margin of the Red Sea and the Basin and Range Province (Bosworth, 1989). However, the Basin and Range developed in hot continental crust overthickened by a thrust belt not long before. The Red Sea was formed sufficiently long after the preceding Pan-African orogeny for the crust to have cooled and returned to a normal thickness of 35 km. Eritrean crust was weakened when the Red Sea extension began, but this weakening was due to heat provided by the Afar mantle plume and its magmatic derivatives (Talbot and Ghebreab, 1997). The Wernicke model suggested that steep brittle faults in the Red Sea sole out to narrow top-to-basin low-angle ductile shear zones that traverse much or all of the crust. Our observation supports this scenario for the RSE1 structures now locally at the exposure levels. However, the deep low-angle ductile RSE2 detachment, along which we infer the exposed steep RSE2 faults sole out, has an opposed sense of shear (Fig. 8b).

5.3. Influence of the Pan-African tectonic grain on the cenozoic Red Sea extension

All the Pan-African structures and fabrics that have previously been shown to influence rifts in and around Africa have been steep. Thus the Masoley–Hadas and Nefasit–Dekemhare lineaments (Fig. 5) are parallel and similar to the steep Barka normal fault with east side up (e.g. Mohr, 1979; Fig. 1b) which reactivated the Pan-African Barka strike-slip shear zone in Miocene. Steep Pan-African structures influenced Red Sea extension in Egypt (Greiling et al., 1988) and in Eritrea (Mohr, 1979; Berhe, 1986; Drury et al., 1994). However, our work shows that it is not only the steep Pan-African structures, but also that the flat-lying shear zones and fabrics that dominate the coastal areas of eastern Eritrea, that influenced the Red Sea extension. Reactivation of low-angle pre-existing features, like the PAD2, are known to control the location of subsequent extension elsewhere (e.g. Price, 1967; Coward, 1988). This is because old structures such as PAD2 shear zones are characterised by substantially reduced frictional strength (Etheridge, 1986; Ivins et al., 1990) and are geometrically viable in terms of size and orientation (e.g. Dixon et al., 1987) to be reactivated during later Red Sea extension. PAD2 fabrics and structures exploited by RSE1 thus define the roofs of exposed and subsurface domes or extensional core complexes (Fig. 8a). Later high angle RSE2 normal faults displaced the low-angle PAD2 structures, but exploited steeper late PAD2 thrusts and PAD3 strike-slip shear zones along the escarpment and in the plateau (e.g. Fig. 7f).

6. Conclusions

In eastern Eritrea, steep and low-angle Pan-African tectonic grain influenced Red Sea extension. The first phase, RSE1 extension, exploited low-angle PAD2 fabrics and structures, which are dominant in the lowlands. The normal faults of the second phase of extension, RSE2, are often along steep strike-slip shear zones of PAD3 deformation in the plateau, but at high-angles to the PAD2 tectonic grain in the lowlands. However, they rotated over an inferred deep detachment that exploited tectonic grain imparted by PAD2 long before.

The Red Sea escarpment in eastern Eritrea is closer to a monoclinal flexure than to a rift.

The geographical link between the Eritrean monocline and the Red Sea detachments along low-angle PAD2 tectonic grains, which are potential concentric slip surfaces, raises the possibility that other monoclinal flexures along continental margins occur where the crust is characterised by inherited low-angle anisotropies.

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References

Allmedinger, R.W., Sharp, J.W., Tish, D.V., Serpa, L., Brown, L., Kaufinan, S., Oliver, J., Smith, R.B., 1983. Cenozoic–Mesozoic structure of the eastern Basin and Range province, Utah, from COCORP seismic reflection data. Geology 11, 532–536.

Baker, B., Mohr, P.A., Williams, L.A.J., 1972. Geology of the Eastern Rift System of Africa. Geological Society of America Special Paper 136, 67.

Bakor, A.R, Gass, I.G., Neary, C.R., 1976. Jabal Wask, NW Saudi Arabia, An Eocambrian back arc ophiolite. Earth and Planetary Science Letters 30, 1–9.

Berhe, S.M., 1986. Geologic and geochronologic constraints on the evolution of the Red Sea—Gulf of Aden and Afar Depression. Journal of African Earth Sciences 5, 101–117.

Berhe, S.M., 1990. Ophiolites in Northeast and East Africa—Implication for Proterozoic crustal growth. Journal of the Geological Society of London 147, 41–57.

Bohannon, R.G., 1986. Tectonic configuration of the western Arabian continental margin, Southern Red Sea. Tectonics 5, 477–499.

Bohannon, R.G., 1989. Style of extensional tectonism during rifting. Journal of African Earth Sciences 8, 589–602.

Bonati, E., 1985. Punctiform initiation of sea-floor spreading in the Red Sea during transition from a continental to oceanic rift. Nature 316, 33–37.

Bosworth, W., 1995. A high-strain rift model for the southern Gulf of Suez (Egypt). In: Lambiase, L.L. (Ed.), Hydrocarbon Habitat in Rift Basins, Geological Society Special Publication, 80, pp. 75–102.

Bosworth, W., 1989. Basin and Range style tectonics in East Africa. Journal of African Earth Sciences 8, 191–201.

Buck, W.R., 1988. Flexural rotation of normal faults. Tectonics 7, 959–973.

Cochran, J.R., 1981. The Gulf of Aden, structure and evolution of a young ocean basin and continental basin. Journal of Geophysical Research 86, 263–288.

Cochran, J.R., Martinez, F., 1988. Evidence from the northern Red Sea on the transition from continental to oceanic rifting. Tectonophysics 153, 25–53.

Coward, M., 1988. The Moine thrust and the Scottish Caledonides. In: Mitra, G., Wojtal, S. (Eds.), Geometries and Mechanics of Thrusting with Special Reference to the Appalachians, Geological Society of America Special Paper, 222, pp. 1–16.

Dainelli, G., 1943. Goelogia del'Africa Orientale, 2. Reale Academia, d'Italia, Centro studi, per l'Africa Orientale Italiana, Rome.

Dixon, T.H., Stern, R.J., Hussein, I.M., 1987. Control of Red Sea geometry by Precambrian structures. Tectonics 6, 551–571.

Drury, S.A., Kelley, S.P., Berhe, S.M., Collier, R.E., Abraha, M., 1994. Structures related to Red Sea evolution in northern Eritrea. Tectonics 13, 1371–1380.

Etheridge, M.A., 1986. On the reactivation of extensional fault systems. Philosophical Transactions of the Royal Society of London Series A317, 179–194.

Frazier, S.B., 1970. Adjacent structures of Ethiopia, that portion of the Red Sea coast including Dahlak Kebir Island and Gulf of Zula. Philosophical Transactions of the Royal Society of London Series A267, 131–141.

Gass, J.G., 1981. Pan-African (Upper Proterozoic) plate tectonic of the Arabian–Nubian Shield. In: Kröner, A. (Ed.), Precambrian Plate Tectonics, pp. 387–403.

Geoffroy, L., Gelard, J.P., Lepvrier, C., Olivier, P., 1998. The coastal flexure of Disko (West Greenland), onshore expression of the 'oblique reflectors'. Journal of the Geological Society of London 155, 463–473.

Ghebreab, W., 1998. Tectonics of the Red Sea region reassessed. Earth Science Reviews 45, 1–44.

Ghebreab, W., 1999. Tectono-metamorphic history of Neoproterozoic rocks in eastern Eritrea. Precambrian Research 98, 83–105.

Gherardi, D., 1951. Preliminary geological survey of Eritrea. The Mining Magazine 84, 265–276.

Girdler, R.W., Styles, P., 1978. Sea-floor spreading in the western Gulf of Aden. Nature 271, 615–617.

Girdler, R.W., Brown, F., Noy, D.J.M., Styles, P., 1980. A geophysical survey of the westernmost Gulf of Aden. Philosophical Transections the Royal Society of London Series A 298, 1–45.

Girdler, R.W., 1991. The Afro-Arabian Rift System: An overview. Tectonophysics 197, 139–153.

Greiling, R.O., El-Ramly, M.P., El-Akhal, H., Stern, R.J., 1988. Tectonic evolution of the northern Red Sea margin as related to the basement structure. Tectonophysics 153, 179–191.

Hempton, M.R., 1987. Constraints on Arabian plate motion and extensional history of the Red Sea. Tectonics 6, 687–705.

Hobbs, B.E., Means, D.W., Williams, P.F., 1976. An Outline of Structural Geology. John Wiley & Sons, New York.

Ivins, E.R., Dixon, T.H., Golombek, M.P., 1990. Extensional reactivation of abandoned thrust: a bound on shallowing in the brittle regime. Journal of Structural Geology 12, 303–314.

LaBreque, J.L., Zitellini, N., 1985. Continuous sea-floor spreading in Red Sea. An alternative interpretation of magnetic anomaly pattern. American Association of Petroleum Geologists Bulletin 69, 513–524.

Lister, G.S., Davis, G.A., 1989. The origin of metamorphic gneiss domes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, USA. Journal of Structural Geology 7, 65–93.

Lowell, J.D., Genik, G.J., 1972. Sea-floor spreading and structural evolution of the Southern Red Sea. American Association of Petroleum Geologists Bulletin 56, 247–259.

McConnell, R.B., 1972. Geological development of the rift system of Eastern Africa. Geological Society of America Bulletin 83, 2549–2572.

McKenzie, D.P., 1978. Some remarks on the development of sedimentary basins. Earth and Science Planetary Letters 60, 25–32.

Merla, G., Abbate, E., Ganuti, P., Sargi, M., Tacconi, P., 1979. Geological Map of Ethiopia and Somalia, Scale 1:2 million. Consiglio Nazionale Delle Ricerche, Italy.

Mohr, P.A., 1979. Lithology and structure of the Precambrian rocks of Eritrea. In: Tahoun, S.A. (Ed.), Evolution and Mineralization of the Arabian–Nubian Shield, pp. 7–15.

Mohr, P.A., 1987. Structure style of continental rifting in Ethiopia. Reverse decollements. EOS Transactions American Geophysical Union 68, 721–730.

Morley, C.K., 1995. Developments in the structural geology of rifts over the last decade and their impact on hydrocarbon exploration. In: Lambiase, J.J. (Ed.), Hydrocarbon Habitat in Rift Basins, Geological Society Special Publication, 80, pp. 1–32.

Moustafa, A.R., 1997. Controls on the development and evolution of transfer zones: the influence of basement structure and sedimentary thickness in the Suez rift and Red Sea. Journal of Structural Geology 19, 755–768.

Rehring, W.A., Reynolds, S.J., 1980. Geologic and geochronologic reconnaissance of a north-west trending zone of metamorphic gneiss domes in southern Arizona. Geological Society of America Memoir 153, 131–158.

Rogers, J.J.W., Miller, J.S., Climents, S.A., 1995. A Pan-African zone linking East and West Gondwana. Memoir of the Geological Society of India 34, 11–23.

Price, R.A., 1967. The tectonic significance of mesoscopic subfabrics in the southern Rocky mountains of Alberta and British Colombia. Canadian Journal of Earth Sciences 4, 39–70.

Savoyat, E., Shiferaw, A., Balcha, T., 1989. Petroleum exploration in the Ethiopian Red Sea. Journal of Petroleum Geology 12, 187–204.

Stein, M., Goldstein, S.L., 1996. From plume head to continental lithosphere in the Arabian–Nubian Shield. Nature 382, 773–778.

Stern, R.J., 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen—Implications for the consolidation of Gondwanaland. Annual Review of Earth and Planetary Sciences 22, 319–351.

Shackleton, R.M., 1996. The final collision zone between East and West Gondwana: Where is it? Journal of African Earth Sciences 23, 271–287.

Souriot, T., Brun, J.P., 1992. Faulting and block rotation in the Afar triangle, East Africa: the Danakil 'crank arm' model. Geology 20, 911–914.

Talbot, C.J., Ghebreab, W., 1997. Red Sea detachment and basement core complexes in Eritrea. Geology 25, 655–658.

Vail, J.R., 1985. Pan-African (Late Precambrian) tectonic Domains and the reconstruction of the Arabian–Nubian Shield. Geology 13, 839–842.

Voggenreiter, W., Hotzl, H., Jado, A.R., 1988. Red Sea related history of extension and magmatism in the Jizan area (SW Saudi Arabia): Implications for simple shear during early Red Sea rifting. Geologische Rundshau 77, 257–274.

Wernicke, B., 1985. Uniform-sense normal simple shear of the continental lithosphere. Canadian Journal of Earth Sciences 22, 108–125.

White, R., McKenzie, D., 1989. Magmatism at rift zones; the generation of volcanic continental margins and flood basalts. Journal of Geophysical Research 94, 7685–7729.

Wright, I.A., Troxel, B.W., 1973. Shallow-fault interpretation of Basin and Range structure, southwestern Great Basin. In: De Jong, K.A., Scholten, R. (Eds.), Gravity and Tectonics, pp. 397–407.