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Sutures and shear zones in the Arabian-Nubian Shield

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Abstract—Deformational belts in the Arabian-Nubian Shield (ANS) are divided into: (1) those associated with sutures, both arc-arc and arc-continental; and (2) post-accretionary structures which include north trending shortening zones and northwest trending strike-slip faults. The arc-arc sutures manifest collision between arc terranes at ~800-700 Ma. They are orientated east to northeast in the northern part of the ANS and north to north-northeast in the south. North or south verging ophiolitic nappes are associated with the east to northeast trending sutures. These nappes were steepened by upright folds associated with the final stages of collision between terranes. East or west verging ophiolitic nappes are associated with the north to north-northeast trending sutures. These were deformed by upright folds and strike-slip faults related to oblique collision between terranes and/or post-accretionary deformations. The arc-continental sutures define the eastern and western boundaries of the ANS and are marked by north trending deformational belts which accompanied collision of the ANS with east and west Gondwana at ~750-650 Ma. The post-accretionary structures were developed between ~650-550 Ma due to continued shortening of the ANS. This produced north trending shortening zones which offset the east to northeast trending sutures in the northern part of the ANS but were superimposed as co-axial deformation on the north to north-northeast trending sutures in the south. The shortening deformation culminated with the development of northwest trending strike-slip faults and shear zones. Copyright © 1997 Elsevier Science Ltd. All rights reserved

Résumé—Les chaînes de déformation du Bouclier Arabo-Nubien (BAN) sont subdivisées en: (1) celles associées à des sutures, soit de type arc-arc, soit de type arc-continent et (2) des structures post-accrétion comprenant des zones de raccourcissement de direction septentrionale ainsi que des failles de décrochement de direction nord-ouest. Dans les sutures arc-arc, la collision entre différents "terranes" a eu lieu à ~800-700 Ma. Dans la partie septentrionale du BAN, les sutures sont orientées est à nord-est tandis qu'au sud elles passent à des directions nord à nord-est. Des nappes ophiolitiques à vergence nord ou sud sont associées aux sutures dirigées est à nord-est. Elles ont été redressées en plis droits, associés aux stades terminaux de la collision entre "terranes". Des nappes ophiolitiques à vergence est ou ouest sont associées aux sutures de direction nord à nord-nordest. Celles-ci ont été déformées par des plis droits et des failles de décrochement en relation avec une collision oblique entre "terranes" et/ou des déformations post-accrétion. Les sutures arc-continent définissent les limites orientales et occidentales du BAN et sont marquées par des chaînes de déformation de direction septentrionale, accompagnant la collision entre le BAN et le Gondwana Oriental et Occidental à ~750-650 Ma. Les structures post-accrétion se sont développées entre ~650-550 Ma et résultent du raccourcissement incessant du BAN. Il s'en suivit des zones de raccourcissement de direction septentrionale, décalant dans la partie nord du BAN les sutures de direction est à nord-est mais se superposant en tant que déformation co-axiale aux sutures de direction nord à nord - nord-est dans la partie sud. La déformation raccourcissante a culminé avec le développement de failles de décrochement et de couloirs de cisaillement de direction nord-ouest. Copyright © 1997 Elsevier Science Ltd. All rights reserved

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INTRODUCTION

The basement in northeast Africa and Eastern Arabia (Fig. 1) is referred to as the Arabian-Nubian Shield (ANS). This represents predominantly juvenile continental crust in that it was formed by differentiation of mantle melts largely without reworking of pre-existing continental crust (for summary of previous work; see Stern, 1994). The ANS represents the northern part of the East African Orogen, which formed by collision between east and west Gondwana at the end of a Wilson Cycle that encompassed most of the Neoproterozoic and defined the Pan-African Orogeny (Stern, 1994). The ANS is of global interest because it contains a complete record of the formation of juvenile continental crust and because the abundance of ophiolite rocks within it proves that processes indistinguishable from those at modern plate tectonic boundaries operated throughout the Neoproterozoic.

The ANS is composed of intra-oceanic island arc/back-arc basin complexes and micro-continents welded together along north to east trending sutures (Almond, 1982; Vail, 1983; 1985; Embleton *et al.*, 1984; Camp, 1984; Stoeser and Camp, 1985; Kröner *et al.*, 1987a, 1991; Pallister *et al.*, 1988; Stern and Kröner, 1993). The ANS collided with pre-Neoproterozoic continental blocks to the east and west at ~750-650 Ma (Stoeser and Stacey, 1988; Abdelsalam and Dawoud, 1991; Stern and Kröner, 1993; Stern, 1994). This collision deformed the ANS along north trending shortening zones (Stern *et al.*, 1989; 1990; Miller and Dixon, 1992; Abdelsalam, 1994) and major northwest trending, sinistral strike-slip faults (Delfour, 1979; Moore, 1979; Davies, 1984; Stern, 1985; Stacey and Agar, 1985; Agar, 1986, 1987; Berhe, 1986, 1990; Sultan *et al.*, 1986; Stoeser and Stacey, 1988; Bonavia and Chorowicz, 1993; Alene and Barker, 1993) and minor northeast trending, dextral (Berhe and Rothery, 1986; Nielsen *et al.*, 1988; Berhe, 1990; Abdelsalam, 1994).

Based on their structural styles, ages, and tectonic settings, the deformational belts (the term deformational belt is used here to refer to high-strain zones such as fold and thrust belts, fold belts, and strike-slip fault systems) in the ANS are divided into:

i) Sutures, including those separating individual arc terranes (arc-arc sutures), and those separating the ANS from the pre-Neoproterozoic continental blocks to the east and west (arc-continental sutures); and

ii) Post-accretionary structures including north trending shortening zones, and major northwest trending, sinistral and minor northeast trending, dextral strike-slip faults. Table 1 summarizes classification of major deformational belts in the ANS into sutures and post-accretionary structures.

The purpose of this contribution is to summarize the distinctive deformational styles of sutures and shear zones, and to discuss the tectonic significance of these belts in an attempt to establish a comprehensive model for the Neoproterozoic tectonic evolution of the ANS.

SUTURES

The term suture refers to zones along which oceans and back-arc basins have closed (Burke *et al.*, 1977). The closing of the oceanic basin is accompanied by a full range of structures, usually localized along linear zones of high-strain. The accreted fragments may be continents, micro-continents, or island arc/back-arc basin complexes. Terrane accretion in the ANS took place along arc-arc sutures (Fig. 1) developed between ~800-700 Ma (Stoeser and Camp, 1985; Pallister *et al.*, 1988; Ayalew *et al.*, 1990; Kröner *et al.*, 1992). The ANS was subsequently emplaced between the continental blocks of east and west Gondwana at ~750-650 Ma along arc-continental sutures (Fig. 1; Stern, 1994).

Arc-arc sutures

Many attempts have been made to link ophiolites in the ANS into major arc-arc sutures separating terranes of presumably different ages (Bakor *et al.*, 1976; Shackleton, 1979; Nassief *et al.*, 1984; Duyvermann, 1984; Vail, 1985; Berhe, 1990; Stern, 1993; Shackleton, 1994). The following alignment is adopted (Fig. 1):

i) The Allaqi-Heiani-Onib-Sol Hamed-Yanbu (YOSHGAH) suture;

ii) The Nakasib-Bir Umq suture;

iii) The Baraka-Tulu Dimtu suture; and

iv) The Adola-Moyale suture.

In addition to the above sutures, the Hafafit culmination will also be discussed as a possible structure associated with a suture in the Eastern Desert of Egypt. The belts above (with the exception of the Hafafit culmination) qualify as arc-arc sutures for the following reasons:

i) These belts are associated with zones of high-strain. Major structures such as fold and thrust belts and/or strike-slip fault system which

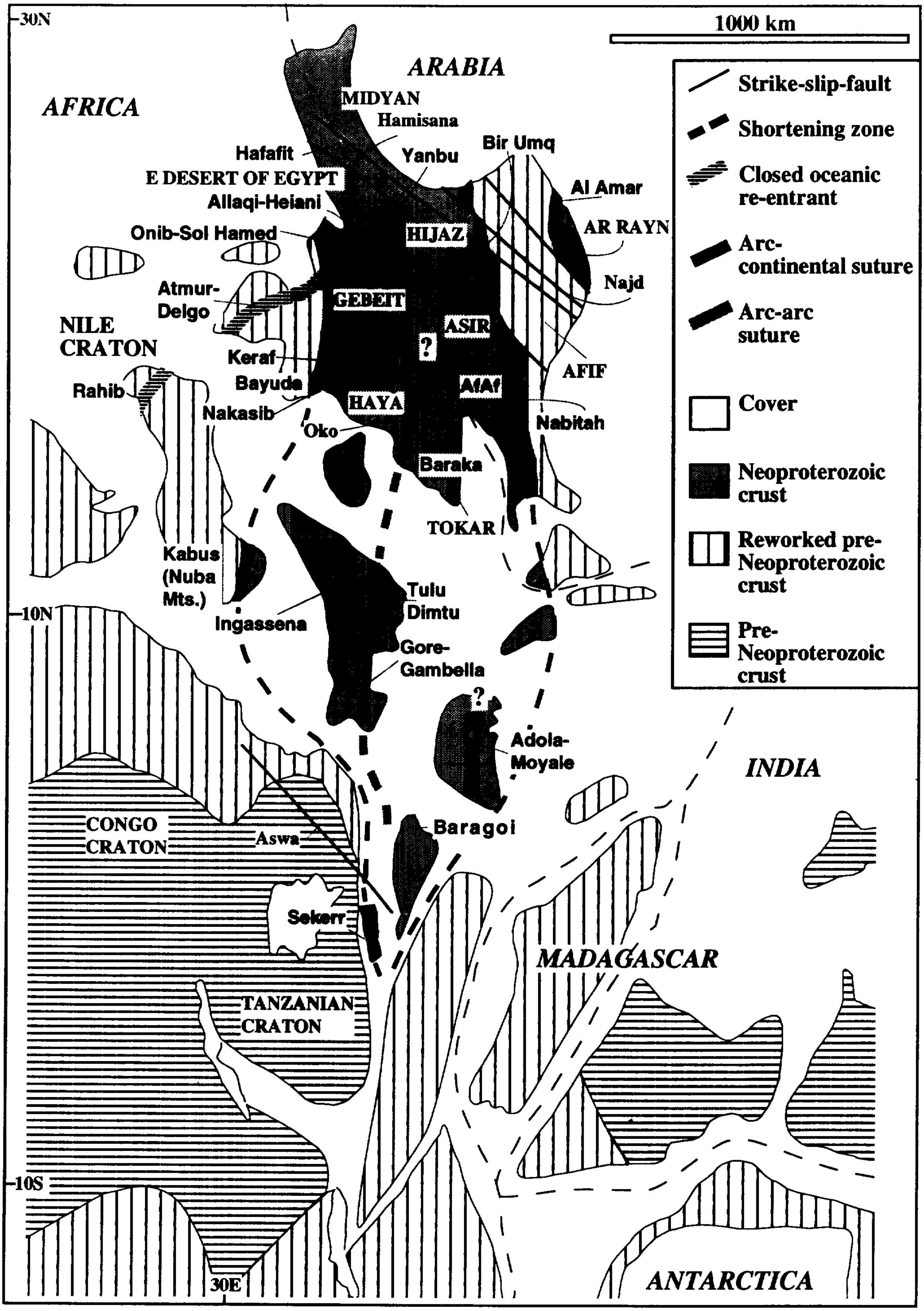

Figure 1. Sketch tectonic map of the ANS (Modified after Stern, 1994).

Table 1. Summary of the orientations, ages, and structural styles of major deformational belts in the ANS

		Deformational Belt	Orientation	Age of Deformation (Ma)	Structural Style
Sutures	Arc-Arc	YOSHGAH	E to NE	750 - 720	Early S- to SE-verging ophiolitic nappes. Late E- to NE-trending upright folds.
		Nakasib-Bir Umq	NE	800 - 750	Early SE-verging ophiolitic nappes. Late NE-trending upright folds.
		Baraka-Tulu Dimtu	N	820 - 760	N-trending sinistral transpression.
		Adola-Moyale	N	830 - 620*	Early E- or W-verging ophiolitic nappes. Late N-trending upright folds. or N-trending sinistral transpression.
	Arc-Continental	Keraf	N	700 - 610**	N-trending sinistral transpression.
		Kabus	NNE		E-verging ophiolitic nappe.
		Sekerr	N	820 - 620	W-verging nappes.
		Al Amar (?)	N	680 -640	Early E- or W-verging ophiolitic nappe. Late N-trending folds.
		Nabitah (?)	N	720 - 680	Early N-trending folds. Late E-verging thrusts. or N-trending sinistral transpression.
Post-Accretionary structures	Shortening Zones	Hamisana shear zone	N	660 - 610	Early N-trending upright folds. Late NE-trending dextral strike-slip faults
		Oko shear zone	N to NW	700 - 560	Early N-trending upright folds. Late NW-trending sinistral strike-slip faults.
	NW faults	Najd fault system	NW	630 - 530	Early dextral strike-slip faults & shear zones. Late sinistral strike-slip faults & shear zones.

* Based on correlating deformation of the Adola-Moyale suture with that of the Mazambique belt in northern Kenya.

** Based on regional constraint from dated deformation in the Atmur suture which is younger than the Keraf suture.

continue for hundreds of kilometres coincide with belts listed above as arc-arc sutures;

ii) Fragments of ophiolite rocks occur within these high-strain zones. These ophiolitic fragments, in most cases, represent eroded folded nappes which had travelled for distances from their corresponding sutures. Most of these ophiolitic fragments, however, lie within broad deformational belts which are the manifestation of collision between terranes; and

iii) These belts separate arc terranes with different pre-suturing history and, sometimes, with different ages as exemplified by the Nakasib suture which separates the 900-800 Ma Haya Terrane from the 830-720 Ma Gebeit Terrane (Fig. 1; Stern and Kröner, 1993).

The Allaqi-Heiani-Onib-Sol Hamed-Yanbu (YOSHGAH) suture

This east to northeast trending suture (Fig. 1) is defined by a deformational belt which encompasses the Allaqi-Heiani-Gerf (Kröner *et al.*, 1987a; Stern *et al.*, 1989, 1990) and the Onib-Sol Hamed (Fitches *et al.*, 1983; Hussein *et al.*, 1984) ophiolites in northeastern Sudan and southeastern Egypt, and the Jebel Ess (Shanti and Roobol, 1979) and the Jebel al Wask (Bakor *et al.*, 1976) ophiolites in northwestern Saudi Arabia. The suture separates the ~830-720 Ma Hijaz-Gebeit Terrane in the south from the Midyan-south Eastern Desert of Egypt Terrane to the north. The suture shows an apparent dextral offset by the north trending Hamisana

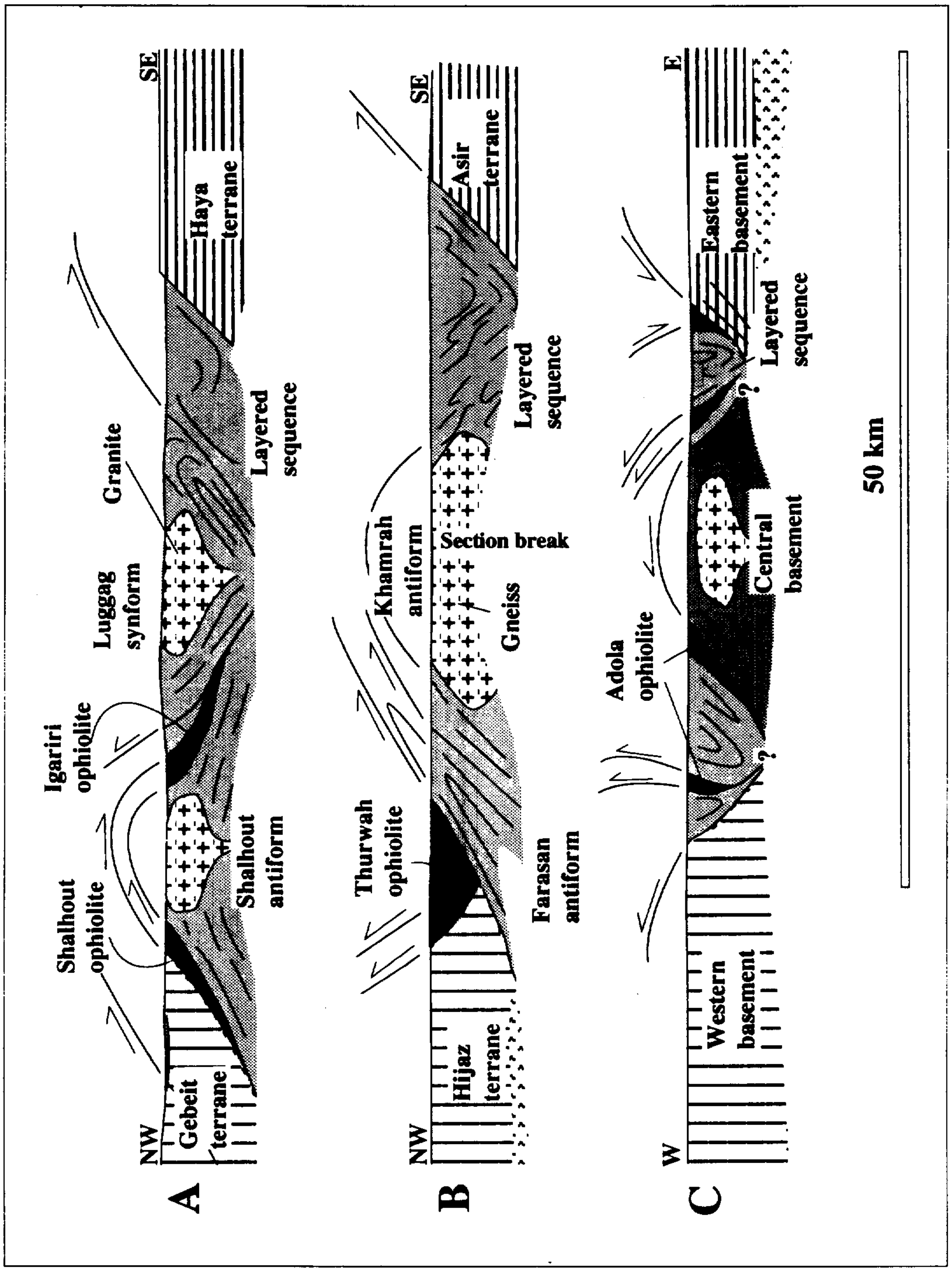

Figure 2. Geological sections across some arc-arc sutures in the ANS. (a) The Nakasib suture (after Abdelsalam and Stern, 1993a). (b) The Bir Umq suture (simplified after Ramsay, 1986). (c) The Adola-Moyale suture (simplified after Beraki et al., 1989).

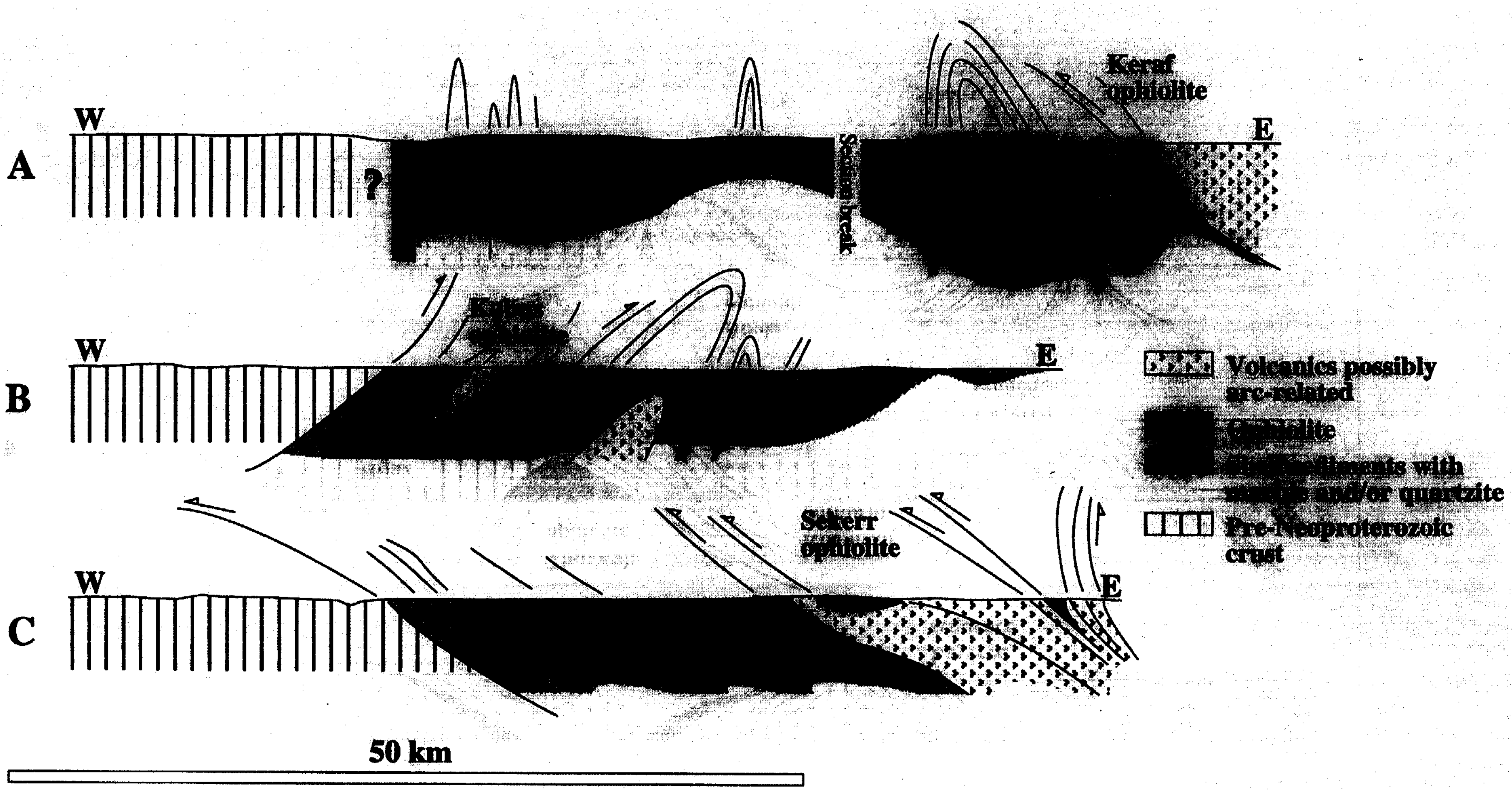

Figure 3. Geological sections across parts of the western boundary of the ANS. (a) The Kerraf suture (after Shackleton, 1986). (b) The Kabus suture (after Abdelsalam and Dawoud, 1991). (c) The Sekker suture. The cross-section steps to the south along section breaks. Distance between the section base lines in the western and central part is ~10 km. Distance between section base lines in the central and eastern part is ~50 km.

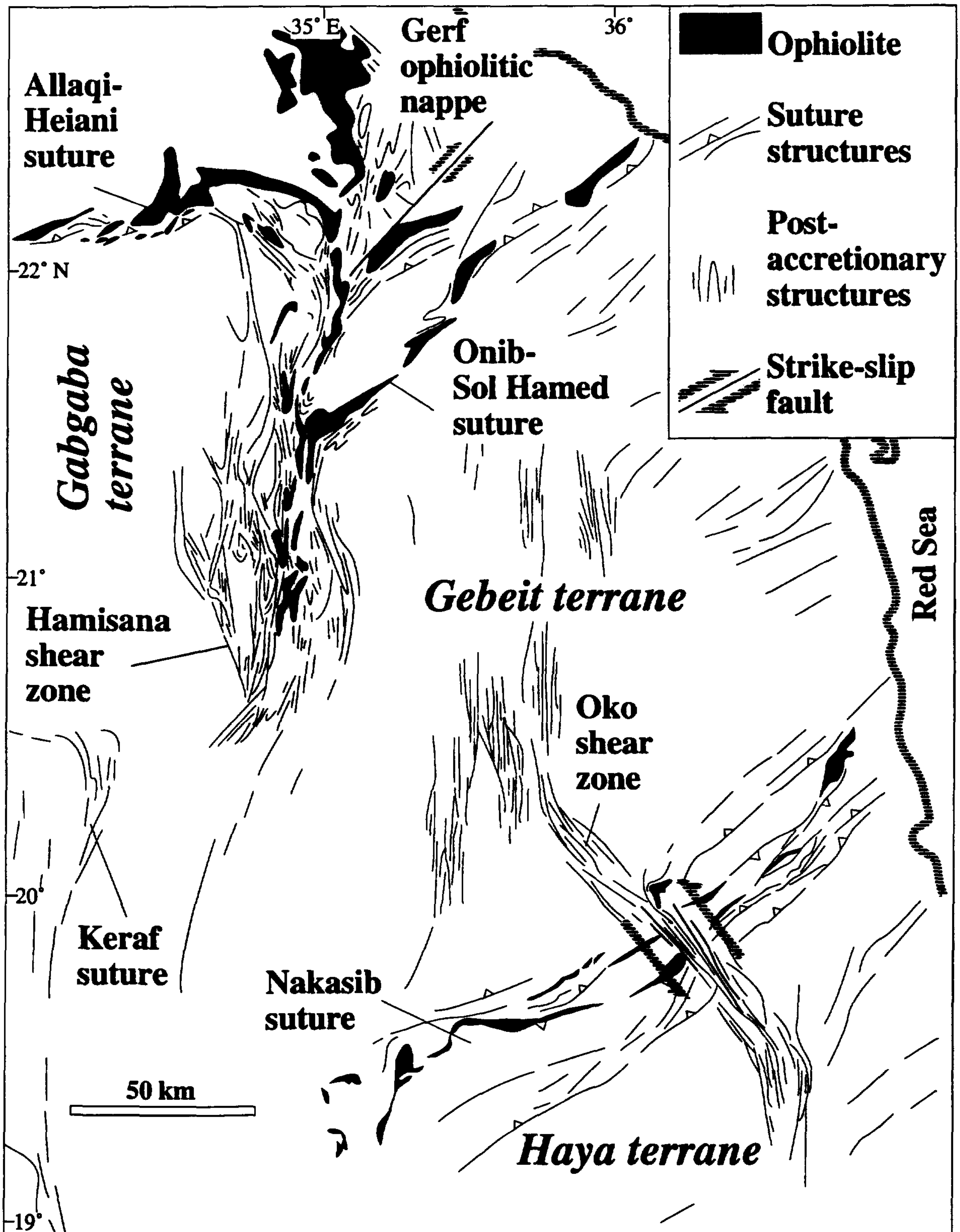

Figure 4. Structural map of the Hamisana and Oko Shear Zones (compiled from Stern et al., 1990 and Abdelsalam, 1994).

Shear Zone in the Sudan (Figs 1 and 4; Stern *et al.*, 1989; 1990; Miller and Dixon, 1992) and is sinistrally offset by the northwest trending Najd fault system in Saudi Arabia (Fig. 1; Stoeser and Camp, 1985).

The east trending Allaqi-Heiani ophiolite which is at high angle to the north trending front of the Nile Craton led to questioning of the interpretation of the YOSHGAH structures as a suture (Berhe, 1990). On the other hand, the transposition of the Onib-Sol Hamed ophiolite by the north trending ophiolite-decorated Hamisana Shear Zone had led to the proposition that the Onib-Sol Hamed and Hamisana ophiolites represent a suture which trend northeast in its northeastern part but follows a more northerly trend in the south (Vail, 1985; Berhe, 1990). Structural studies documented that the Hamisana Shear Zone was superimposed on a once coherent Allaqi-Heiani-Onib-Sol Hamed ophiolitic nappe in the form of upright folds which gave rise to the apparent dextral offset of the former (Stern *et al.*, 1990; Miller and Dixon, 1992).

The Sol Hamed ophiolite dips steeply to the southeast, and faces towards the southeast. This led Fitches *et al.* (1983) to suggest that the ophiolite was obducted over a southeast dipping subduction zone with the related arc volcanics unconformably overlying the ophiolites. Both the ophiolite and the surrounding arc volcanics were subsequently deformed by northeast plunging folds. Stern *et al.* (1990) proposed that the Allaqi-Heiani-Onib-Sol Hamed suture represent a south verging nappe which was refolded around a sub-horizontal, east trending axis to produce upright antiforms and late-stage southeast verging thrusts. Vergence of the ophiolite nappes is used to infer a north dipping subduction zone along the line of a suture which lies north of the Allaqi-Heiani-Onib-Sol Hamed ophiolite (Stern *et al.*, 1990).

The Jebel Ess ophiolite is a complete fault-bounded ophiolitic sequence separating a meta-sedimentary sequence of shale and polymict conglomerate in the south from a structurally and stratigraphically upper arc volcanics to the north (Shanti and Roobol, 1979). Shanti and Roobol (1979) concluded that the Jebel Ess ophiolite represent a nappe which has been folded into a northeast trending synform. To the northeast of the Jebel Ess ophiolite, Bakor *et al.* (1976) described the Jebel Al Wask ophiolite as a northeast trending dome with steeply dipping lithological contacts. Camp (1984) suggested that the Jebel Al Wask ophiolite constitutes part of an accretionary prism overlying a southeast dipping subduction zone, with the associated arc volcanics of the Hijaz Terrane to the southeast.

The Nakasib-Bir Umq suture

This northeast trending deformational belt extends from near the River Nile in the west to central Arabia (Fig. 1). The suture juxtaposes the ~900-800 Ma Asir-Haya Terrane in the south with the 830-720 Ma Hijaz-Gebeit Terrane to the north. Johnson (1994) explicitly correlated the stratigraphy and deformational history of the Nakasib and Bir Umq sutures. Ophiolite fragments defining the Nakasib-Bir Umq suture are remarkably aligned along, and structurally controlled by northeast trending structures. The northeastern part of the suture appear to terminate against the north trending Nabitah suture (Fig. 1). However, how the suture ends in the southeast is not obvious. Shackleton (1994) proposed that the Nakasib suture bends north at its southwestern end to follow the north trending Keraf suture (Fig. 4). The "Nakasib-Keraf Bend" would represent a closure of a major south-southwest plunging antiform, the axial trace of which coincides with the trend of the Hamisana Shear Zone (Fig. 1). However, structural and remote sensing data show that the Keraf suture continues south of where it should intersect with the Nakasib suture (Abdelsalam and Stern, 1996). In addition, these data reveal that the southern part of the Keraf suture is defined by north and north-northwest trending, sinistral strike-slip faults which everywhere truncate the northeast trending sutures, further indicating that the Nakasib suture terminates against the Keraf suture.

The Nakasib suture (Fig. 1) deforms ophiolite fragments defining the limbs of a northeast trending synform (Fig. 2a). The ophiolite belt in the northeastern part of the Nakasib suture separates rift volcanics and passive margin sediments in the south from arc volcanics and sediments to the north. This led Abdelsalam and Stern (1993a) to suggest a Wilson Cycle model to explain the evolution of the suture. This cycle ended with collision between the Haya and Gebeit Terranes at ~750 Ma after the consumption of an oceanic basin by a northwest dipping subduction zone (Abdelsalam and Stern, 1993b). Abdelsalam and Stern (1993c) demonstrated that the closure of the Nakasib oceanic basin gave rise to three phases of deformation. The two early phases are associated with emplacement of a southeast verging ophiolitic nappe across the passive margin sediments. The late phase manifests the final stage of collision between the Haya and Gebeit Terranes and refolded earlier structures into northeast trending, upright antiforms and synforms. This phase culminated with the development of northwest verging thrusts (Fig. 2a). Schandelmeier *et al.* (1994) investigated the southwestern part of the Nakasib suture and concluded that the "Nakasib oceanic basin" has been consumed at ~890-760 Ma by a south dipping subduction zone. The Bir Umq suture (Fig. 1) is marked by the Thurwah ophiolite in the southwest and the Bir Umq ophiolite to the northeast (Al Rehaili and Warden, 1980; Camp, 1984; Nassief *et al.*, 1984; Stoeser and Camp, 1985; Ramsay, 1986). The Thurwah ophiolite occurs as imbricate thrust sheets which were refolded about northeast trending synform (Nassief *et al.*, 1984; Fig. 2b). Ramsay *et al.* (1986) suggested that the thrusting of the Thurwah ophiolite was to the southeast. Al Rehaili and Warden (1980) described the Bir Umq ophiolite as a northeast trending arcuate belt which comprises three steeply north dipping allochthonous slices of ophiolitic rocks thrust over an autochthonous volcano-sedimentary sequence. Al Rehaili and Warden (1980) concluded that thrusting occurred originally at a lower angle but was steepened during a younger folding event associated with the closing of a back-arc basin.

The YOSHGAH and Nakasib-Bir Umq sutures share a common structural history in which north or south verging ophiolitic nappes were deformed about east to northeast trending upright folds. This caused steepening of the originally sub-horizontal structures and exposed the nappe remnants as imbricate thrusts with opposite apparent vergences. Hence, vergence of structures associated with these sutures might be misleading in deducing the subduction direction as will be discussed below.

The Baraka-Tulu Dimtu suture

This suture (Fig. 1) is composed of the north trending Baraka suture in northeastern Sudan and northern Eritrea (Drury and Berhe, 1993), the Tulu Dimtu ophiolite in western Ethiopia (Berhe, 1990), and further south the Gore-Gambella deformational belt in southwestern Ethiopia (Ayalew *et al.*, 1990). Berhe (1990) suggested linking the suture with the Sekerr ophiolite in northern Kenya (Fig. 1). Sultan *et al.* (1994) suggested that the suture continues to the north in Saudi Arabia as the Afaf deformational belt (Fig. 1).

The Baraka suture separates the ~900-800 Ma Haya Terrane in the west from the Tokar Terrane to the east (Fig. 1; Vail, 1983, 1985; Kröner *et al.*, 1987a). Drury and Berhe (1993) have shown that the Baraka suture comprises ophiolitic rocks and volcano-sedimentary sequences deformed by sinistral transpression. The Haya Terrane to the west is dominated by metasediments folded into complex basin and dome interference patterns. To the east of the Baraka suture lies the Tokar Terrane which is dominated by low-grade arc volcanics. Drury and Berhe (1993) concluded that the Baraka suture was the product of an oblique collision between the Haya and Tokar Terranes after the consumption of a back-arc basin.

The north trending Tulu Dimtu ophiolite belt in western Ethiopia (Fig. 1) separates a gneissic terrane in the east from volcanics to the west (Warden *et al.*, 1982). In the Gore-Gambella area to the south (Fig. 1), Ayalew *et al.* (1990) identified a north trending belt of low-grade arc volcanics and sediments sandwiched between high-grade gneissic terranes where the boundaries are steeply dipping shear zones. Ayalew *et al.* (1990) proposed that the Tulu-Dimtu ophiolite represents a stage of oceanic crust formation which was followed by subduction-related magmatism in the Gore-Gambella area at ~820 Ma. Closure of the oceanic basin occurred at ~760 Ma and was followed by the formation of major north trending transcurrent faults at ~635 Ma.

The Adola-Moyale suture

The north trending Adola-Moyale ophiolites (Figs 1, 2c) in southern Ethiopia and northern Kenya (Beraki *et al.*, 1987; Berhe, 1990; Tolessa *et al.*, 1991; Bonavia and Chorowicz, 1992, 1993; Alene and Barker, 1993) are interpreted as marking a suture separating high-grade gneissic terranes and thought to be the product of collision between the ANS and the Nile Craton (Bonavia and Chorowicz, 1993). Ages obtained by single zircon evaporation indicate that the high-grade gneisses on both sides of the Adola-Moyale suture are less than ~880 Ma in age (Teklay *et al.*, 1993) consistent with ages from other parts of the ANS (Kröner *et al.*, 1991). Moreover, geochemical data suggest that the protoliths of these gneisses were arc granitoids (Teklay *et al.*, 1993). These geochronological and geochemical data make it more acceptable to interpret the Adola-Moyale ophiolites as defining an arc-arc suture.

Beraki *et al.* (1987) mapped east and west dipping thrust faults separating the Adola ophiolite from the gneissic terranes to the east and west (Fig. 2c). Beraki *et al.* (1987) interpreted the opposite dipping of thrusts as due to refolding about north trending axes (Fig. 2c). However, Tolessa *et al.* (1991) explained this geometry in terms of a flower structure which was developed in response to a north trending, sinistral shear system. Bonavia and Chorowicz (1993) correlated the evolution of the Adola-Moyale suture with that of the Mozambique Belt in northern Kenya (Key *et al.*, 1989) and suggested that the structural history of the Adola-Moyale region started with collision-related deformation at ~830 Ma. This was followed by strike-slip faulting developed between ~620-530 Ma in the form of early north trending and late northwest trending shear zones. Bonavia and Chorowicz (1992) proposed that the north trending structures are the roots of northward expulsion of the ANS from the Mozambique Belt.

The Hafafit culmination

The presence of abundant ophiolitic rocks in the Central Eastern Desert of Egypt has led to the interpretation that there may be a suture. However, this zone differs from the well-defined YOSHGAH and Nakasib-Bir Umq sutures in not being an elongated belt defined by folds and thrusts separating two distinct terranes. Rather, the ophiolitic rocks in the Central Eastern Desert are scattered over a wide area situated between the Gerf or South Eastern Desert Terrane in the south and the younger North Eastern Desert Terrane to the north. The relationship between the North and Central Eastern Desert Terranes is intrusive, whereas a tectonic contact separates the Central Terrane from the South Eastern Desert Terrane (Stern and Hedge, 1985). The syntaxis of this boundary is defined by the Hafafit culmination (Fig. 1; El Ramly *et al.*, 1984).

The interpretation of the Central Eastern Desert ophiolites as defining a suture is further complicated by the uncertainties concerning their root zone. These ophiolitic rocks occur in tectonic melanges or as olistostromal debris (Shackleton *et al.*, 1980; Reis *et al.*, 1983; Church, 1988; El Gaby *et al.*, 1988). Shackleton (1994) argued that these fragments occur in three tectonic facies. In the south, near the YOSHGAH suture, ophiolitic rocks form intact thrust sheets and hence define a near-source tectonic facies. Further north, the ophiolitic rocks occur within tectonic melanges, interpreted as a medial tectonic facies, whereas farther north olistostromes with ophiolitic debris dominate indicating a distal tectonic facies. This interpretation implies that the South and Central Eastern Desert represent a far-travelled ophiolitic nappe, one that was emplaced up to 400 km away from its corresponding suture. However, this proposition awaits confirmation because of two considerations:

i) The transport direction inferred for the South and Central Eastern Desert nappe is to the north, opposite to what was inferred for the ophiolites of the YOSHGAH suture (Stern *et al.*, 1990); and

ii) There is evidence that ophiolitic melanges in the Central Eastern Desert were the product of deformation accompanied the post-accretionary Najd fault system and not suturing (Bennett and Mosely, 1984; Sultan *et al.*, 1992).

The Najd deformation is so profound that it is not clear that any fabrics preserve pre-Najd, suture-related deformation. In addition, the Central Eastern Desert ophiolitic nappes are interpreted by some workers as reflecting transpressive deformation associated with the Najd fault system (Wallbrecher *et al.*, 1993).

Regardless of the structural complexity discussed above, some workers proposed sutures in the Eastern Desert of Egypt. Structural studies around the Hafafit culmination led El Ramly *et al.* (1984) and El Bayoumi and Greiling (1984) to interpret this as the footwall of a suture resulting from collapse of a marginal basin and arc complex against an Andean margin to the west. Greiling *et al.* (1988, 1993, 1994) argue for northwest-southeast compression during collision which resulted in complex deformation in the Hafafit culmination.

It is concluded here that the Eastern Desert of Egypt may or may not preserve one or more sutures, and that the issue awaits resolution. It is certain that complex structures resulted from intensive superimposition of post-accretionary deformation on earlier structures, possibly associated with suturing. Hence, structures in the Eastern Desert of Egypt are not considered in discussing structural styles of deformation belts in the ANS due to the difficulty in distinguishing between accretionary and post-accretionary structures.

Arc-continental sutures

The Pan-African Orogeny in Arabia and northeast Africa is interpreted to have resulted from opening and closing of the Mozambique ocean which developed between east and west Gondwana (Stern, 1994). The arcs associated with this ocean are preserved as the ANS which is separated by tectonic boundaries from older crustal blocks to the east (Schmidt *et al.*, 1979; Stacey *et al.*, 1984; Stoeser and Stacey, 1988) and west (Vail, 1983, 1985, 1988; Abdelsalam and Dawoud, 1991). These boundaries will be referred to as arc-continental sutures as they juxtapose arc terranes with continental blocks (Fig. 1) after consumption of marginal oceanic basins.

The western boundary of the ANS

The high-grade gneissic terrane to the west of the ANS is thought to be pre-Neoproterozoic in age and referred to as the Nile Craton (Rocci, 1965), the Eastern Saharan Craton (Bertrand and Caby, 1978), the Sahara-Congo Craton (Kröner, 1977), or the Central Saharan Ghost Craton (Black and Liegeois, 1993). In this paper, the name Nile craton will be used. The presence of a pre-Neoproterozoic - yet highly reactivated during the Neoproterozoic - continental crust to the west of the ANS is based on U/Pb zircon ages (Wust *et al.*, 1987; Kröner *et al.*, 1987b; Sultan *et al.*, 1990, 1992, 1993; Stern *et al.*, 1994) and Pb, Sr, and Nd isotopic compositions (Harris *et al.*, 1984; Dixon and Golombek, 1988; Schandelmeier *et al.*, 1988; Harms *et al.*, 1990; Sultan *et al.*, 1992; Stern *et al.*, 1994).

Vail (1983) proposed that the western boundary of the ANS is marked by a deformed sedimentary prism overlying the high-grade rocks of the Nile Craton and can be traced from the Sekerr region in northern Kenya, through the Ingessana region in east-central Sudan, to the Eastern Bayuda Desert in northern Sudan. Abdelsalam and Dawoud (1991) argued that the boundary in central Sudan should be assigned to the Kabus ophiolitic melange which lies at ~500 km to the west of the Ingessana region. The contact between the ANS and the Nile Craton in northern Sudan was identified by Almond and Ahmed (1987) as the north trending, sub-vertical Keraf suture (Fig. 1). In the southern part of the Keraf suture, Abdel Rahman *et al.* (1993) interpreted a belt of dismembered ophiolite as indicating opening and closing of a back-arc basin between the Nile Craton and the ANS. The northern part of the Keraf suture is defined by north trending upright folds which deform passive margin carbonate belt (Fig. 3a; Schandelmeier *et al.*, 1993; Stern *et al.*, 1993; Abdelsalam *et al.*, 1995). In contrast to its northern part, the southern part of the Keraf suture is dominated by the development of north- and north-northwest trending, sinistral strike-slip faults (Abdelsalam and Stern, 1996). Older east to northeast trending structures of the Bayuda Desert are sharply truncated by the Keraf suture (Abdelsalam *et al.*, 1996). Abdelsalam *et al.* (1995, 1996) proposed that the deformation in the Keraf suture was due to sinistral transpression associated with oblique collision between East and West Gondwana.

The northeast trending Kabus ophiolitic melange in central Sudan (Figs 1 and 3b) separates a high-grade gneissic terrane in the west from a low-grade volcano-sedimentary sequence to the east. The zone is characterized by imbricated ophiolitic fragments, arc volcanic rocks, continental shelf conglomerates, and gneisses (Hirdes and Brinkmann, 1985; Brinkmann, 1986; Abdelsalam and Dawoud, 1991). Abdelsalam and Dawoud (1991) documented two phases of deformation in the rocks in the melange zone and the volcano-sedimentary sequence. These deformations were interpreted as due to closing of a basin developed between the Nile Craton and the ANS. The early deformation is characterized by the development of east verging isoclinal folds and regional schistosity. The late deformation produced tight, east verging folds within the volcano-sedimentary sequence and east verging imbricate thrusts within the Kabus ophiolitic melange (Fig. 3b).

The north trending Sekerr ophiolite in northern Kenya (Fig. 1) was tectonically imbricated with arc volcanics and shelf sediments and thrust from east to west over the eastern margin of the Tanzania Craton (Fig. 3c; Vearncombe, 1983; Shackleton, 1986; Ries *et al.*, 1992). Mosley (1993) proposed that the structures associated with the emplacement of the allochthonous ophiolite and the volcano-sedimentary sequences were modified by progressive shortening during collision between East and West Gondwana.

The Keraf, Kabus and Sekerr sutures show gross similarities in their tectonic setting, but have different structural styles. The Keraf suture is outlined by north trending upright folds in the north and north to north-northwest trending, sinistral, strike-slip faults to the south. The Kabus suture is defined by an east verging fold and thrust belt where the stacking order indicate pre-Neoproterozoic crust thrust across an ophiolitic melange which was thrust across the volcano-sedimentary sequences of the ANS. The Sekerr suture is defined by a west verging fold and thrust belt where the imbricated ophiolite and volcano-sedimentary rocks were tectonically emplaced from east to west across the Tanzania Craton margin. This difference in structural style along the western margin of the ANS may be due to an overall southeast-northwest compression which accompanied oblique collision between east and west Gondwana (Abdelsalam *et al.*, 1995). This non-orthogonal compression (i.e. maximum compression axis not at right angles to the orogen front) might have been resolved into north trending upright fold belt and north- to north-northwest trending, sinistral strike-slip faults in the north, and east or west verging nappes to the south.

The eastern margin of the ANS

This boundary is poorly defined. U/Pb zircon ages, and Pb and Sr isotopic data indicates that at least the southern part of the Afif Terrane (Fig. 1) includes pre-Neoproterozoic crust (Stacey *et al.*, 1980; Stacey and Stoeser, 1983; Stacey and Hedge, 1984). However, the presence of ~690-670 Ma arc volcanics of the Ar Rayn Terrane (Fig. 1) to the east of the Afif Terrane is problematic in that it indicates the presence of Neoproterozoic crust to the east of what is supposed to be the western margin of East Gondwana. To overcome this problem, the Ar Rayn Terrane is interpreted as the leading edge of a continent further east (Schmidt *et al.*, 1979; Fleck *et al.*, 1980; Davies, 1984) but isotopic studies by Calvez *et al.* (1984), Stacey and Stoeser (1983), and Stacey *et al.* (1984) indicate that the terrane is a Neoproterozoic magmatic arc lacking older basement. This led Stoeser and Stacey (1988) to suggest that the pre-Neoproterozoic basement exists further east in Oman and Yemen as demonstrated by isotopic data reported by Stacey *et al.* (1980) and Stacey and Stoeser (1983). In this paper, the evolution of the Al Amar and Nabitah deformational belts will be discussed as possible exposures of the eastern margin of the ANS on the basis that the Afif Terrane represents a micro-continent rifted off East Gondwana during the Neoproterozoic Pan-African Orogeny.

Some attempts have been made to define the eastern boundary of the ANS to the south of the Arabian peninsula. Berhe (1990) linked the Al Amar suture to the Adola-Moyale suture of southern Ethiopia (Fig. 1). Stern (1994) inferred the boundary in Yemen to be somewhere to the west of the Aden group which gave a <3.0 Ga TDM model Nd age (Stoeser *et al.*, 1991) and further south to the east of the Adola-Moyale and Baragoi ophiolites where it connects with the Mozambique Belt in northern Kenya (Fig. 1). Lenoir *et al.* (1994) concluded that the basement in northern Somalia is dominated by juvenile Neoproterozoic crust whereas southern Somalia is underlain by highly reworked pre-Neoproterozoic material with little addition of juvenile material. This is further supported by Haider and Berhe (1995) who indicated that - based on model ages - the margins of east Gondwana occur along the Burr massif in southern Somalia. The high-grade gneisses around the Adola-Moyale suture gave ages comparable to those in other part of the ANS (Teklay *et al.*, 1993). However, geochronological data for gneisses from eastern Ethiopia indicate involvement of pre-Neoproterozoic continental crust (Teklay *et al.*, 1993). These data suggest that the eastern boundary of the ANS lies somewhere in central Somalia and further south to the east of the Adola-Moyale suture.

The north trending Al Amar suture (Fig. 1) developed between ~680-640 Ma due to collision between the Afif Terrane in the west and the Ar Rayn Terrane to the east (Stoeser and Stacey, 1988). The suture is defined by two north trending discontinuous ophiolitic melange zones sandwiching the Abt schist belt (Al Shanti and Gass, 1983). Models which have been proposed to explain the relationships between the Afif Terrane, the Abt schist, the Al Amar suture, and the Ar Rayn Terrane agree in interpreting the Afif Terrane as a pre-Neoproterozoic micro-continent, and the Abt schist as an accretionary wedge on the leading edge of a major continent to the east (Al Shanti and Mitchell, 1976; Nawab, 1979; Schmidt *et al.*, 1979; Al Shanti and Gass, 1983; Stacey *et al.*, 1984; Stoeser and Stacey, 1988). However, views regarding the Ar Rayn Terrane vary between interpreting it as an Andean-type or intra-oceanic arc. Al Shanti and Gass (1983) identified two sets of co-axial north trending folds from the Abt schist. This led Al Shanti and Gass (1983) to conclude that the two ophiolitic melange zones marking the Al Amar suture initially occurred as a sheet-like layer underlying the Abt schist. The exposure of the ophiolitic melange to the east and west of the Abt schist is due to folding of the two units into a north trending synform.

The Nabitah suture (Fig. 1) is a north trending deformational belt extending for ~1000 km in central Arabia. The belt is marked by ophiolitic fragments. Early models interpreted the Nabitah belt as an arc-arc suture (Frisch and Al Shanti, 1977; Schmidt *et al.*, 1979). However, geochronological and isotopic data led Stoeser *et al.* (1984) and Stoeser and Stacey (1988) to suggest that the Nabitah suture has been the site of collision between arc terranes in the west (the Asir and Hijaz Terranes, Fig. 1) and a micro-continent to the east (the Afif Terrane, Fig. 1) at ~690-680 Ma. Agar (1985) and Stacey and Agar (1985) added that an Andean-type arc was developed on the western margin of the Afif Terrane between ~720-685 Ma. Structural data from the Nabitah suture were interpreted in two models:

i) Agar (1985) described the structures associated with the Nabitah suture as north trending, upright folds affecting a passive margin sedimentary group which lies unconformably on an older gneissic basement. Progressive deformation culminated in the development of east verging thrusts.

ii) Quick and Bosch (1989) and Quick (1991) interpreted the structures related to the Nabitah suture as resulting from sinistral transpression.

POST-ACCRETIONARY STRUCTURES

The ANS was affected by regional Neoproterozoic deformations younger than the collision between arcs, and distinct from collision between the ANS and Gondwana fragments. These younger deformations are typically localized along north- or northwest trending pure or simple shear zones. These structures are referred to as post-accretionary because they post-date the inferred arc-arc sutures in the ANS.

The north trending shortening zones

These deformational belts are characterized by the development of north trending, upright and tight folds developed between ~700-650 Ma (Stern, 1989, 1990; Abdelsalam, 1994). Two of these zones are exposed in northeast Sudan (Fig. 1): the Hamisana Shear Zone (Stern *et al.*, 1989, 1990; Miller and Dixon, 1992) and the Oko Shear Zone (Almond and Ahmed, 1987; Abdelsalam, 1994).

The ~660-610 Ma, north trending Hamisana Shear Zone (Figs 1 and 4) dextrally offsets the YOSHGAH suture (Stern *et al.*, 1989, 1990; Miller and Dixon, 1992). The shear zone is marked by tightly folded rocks and was previously thought to represent the continuation of the northeast trending Onib-Sol Hamed suture (Vail, 1983, 1985; Berhe, 1990). The apparent offset of the YOSHGAH suture by the Hamisana Shear Zone led to the proposition that the latter represents a dextral shear zone (Almond *et al.*, 1984; Almond and Ahmed, 1987; Kröner *et al.*, 1987a). Structural studies indicate that the belt is the product of east-west shortening (Stern *et al.*, 1990; Miller and Dixon, 1992). The alignment of ophiolitic fragments parallel to the Hamisana Shear Zone is due to deformation of the south verging YOSHGAH ophiolitic nappe by the north trending upright folds of the Hamisana Shear Zone (Stern *et al.*, 1990).

The north to northwest trending Oko Shear Zone (Fig. 1) sinistrally offsets the Nakasib suture (Almond *et al.*, 1987, 1989; Abdelsalam, 1994). The evolution of the Oko Shear Zone is poorly constrained between 700 and 560 Ma which is broadly contemporaneous with that of the Hamisana Shear Zone (Abdelsalam and Stern, 1993b). It developed through two phases of deformation (Abdelsalam, 1994). The early phase was characterized by the development of north-northwest trending, tight, upright folds. This was followed by the development of sub-vertical northwest trending, sinistral strike-slip faults which were initiated as a conjugate set of ductile shear zones.

The northwest trending fault zones

The most prominent of the northwest trending strike-slip fault zones in the ANS is the Najd fault system in Arabia and Egypt (Fig. 1; Delfour, 1979; Moore, 1979; Davies, 1984; Stacey and Agar, 1985; Agar, 1986, 1987; Stoeser and Stacey, 1988; Stern, 1985; Sultan *et al.*, 1986; El Gaby *et al.*, 1988). Other northwest trending strike-slip faults crop out in the Red Sea Hills of the Sudan (Abdelsalam, 1994), southern Ethiopia (Berhe, 1986, 1990; Bonavia and Chorowicz, 1993; Alene and Barker, 1993), and Kenya (Key *et al.*, 1989; Mosley, 1993).

The ~1200 km long, ~300 km wide Najd fault system (Fig. 1; More, 1979; Agar, 1987) is defined by northwest trending, sinistral strike-slip faults which offset the north trending Al Amar and Nabitah sutures and the northeast trending Bir Umq and Yanbu sutures (Stacey and Agar, 1985; Agar, 1986; Agar, 1987; Stoeser and Stacey, 1988). The cumulative displacement along the Najd fault system is ~240 km (Agar, 1987). The period of activity of the Najd fault system was thought to be ~580-530 Ma (Fleck *et al.*, 1980). However, Stacey and Agar (1985) have shown that the

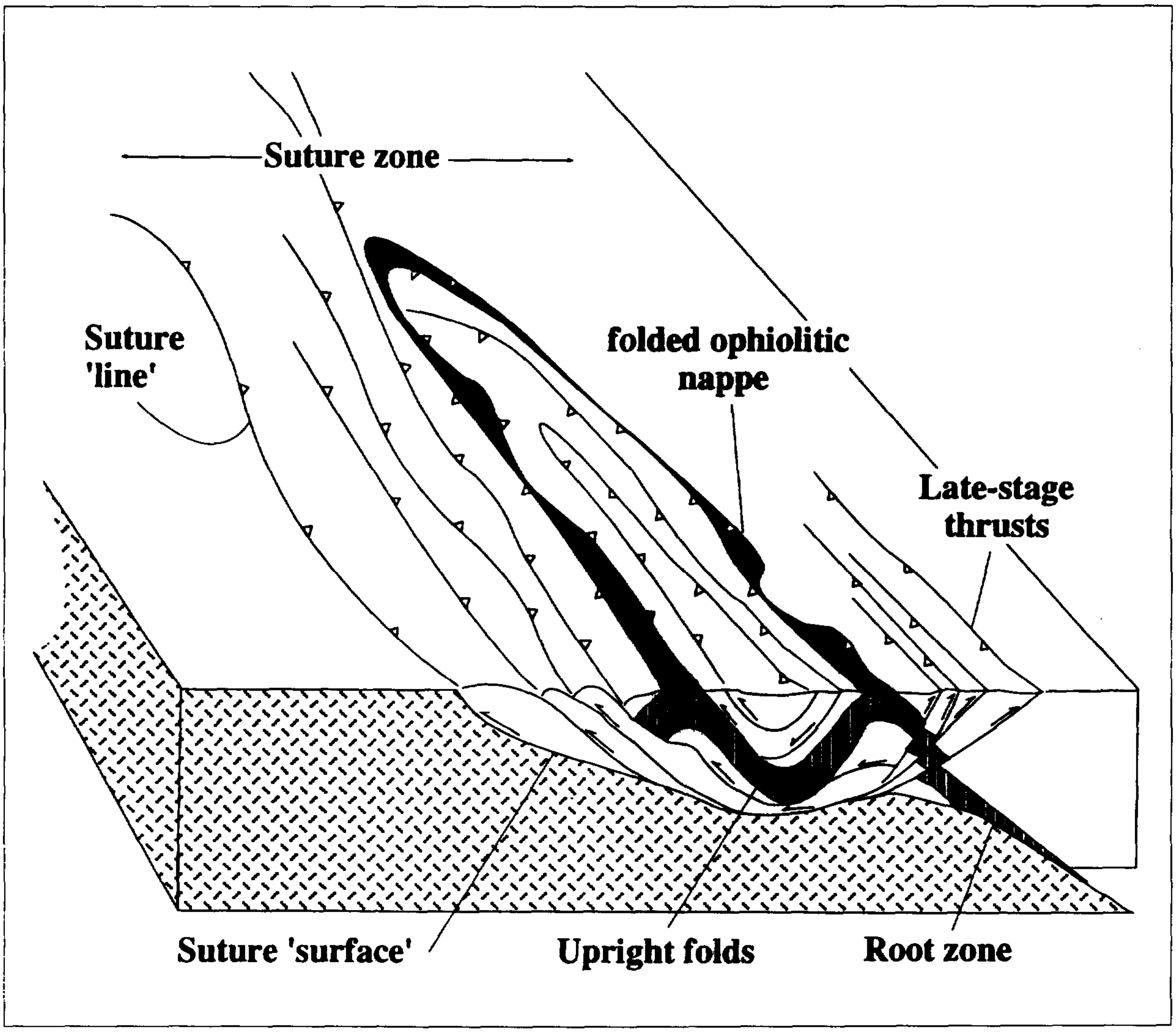

Figure 5. A three dimensional cartoon illustrating the geometrical features of a folded nappe defining a suture zone.

activity might have started as early as ~630 Ma. Stacey and Agar (1985) suggested that the Najd fault system was active between ~630-600 Ma as a dextral system and then as a sinistral system up to ~530 Ma.

Views vary regarding the tectonic significance of the northwest trending faults in the ANS:

i) Moore (1979) proposed that the Najd fault system was the product of deformation of a brittle cover overlying a basement comprising rigid blocks which were moving laterally relative to each other.

ii) Schmidt *et al.* (1979), Fleck *et al.* (1980), Davies (1984) and Agar (1987) proposed that the Najd fault system is related to collision between the ANS and a rigid indentor to the east of the Ar Amar suture. A similar model for the evolution of the Najd fault system and other northwest trending, strike-slip faults was proposed by Berhe (1990) who argued that these faults were the products of collision further south along the Mozambique Belt. Burke and Sengor (1986) explained the evolution of the northwest trending faults in the ANS in terms of escape tectonics which resulted in the formation of the Najd fault system and simultaneous extension in the northernmost ANS.

iii) Stern (1985) argued that the Najd fault system could not have been formed by continent-continent collision in eastern Arabia. Alternatively, Stern (1985) suggested that the Najd system represents a set of transform faults developed in response to a major episode of extension in the northwestern part of the ANS.

iv) Abdelsalam (1994) suggested that the northwest trending, sinistral strike-slip faults were developed by continuous east-west shortening deformation as zones of high shear

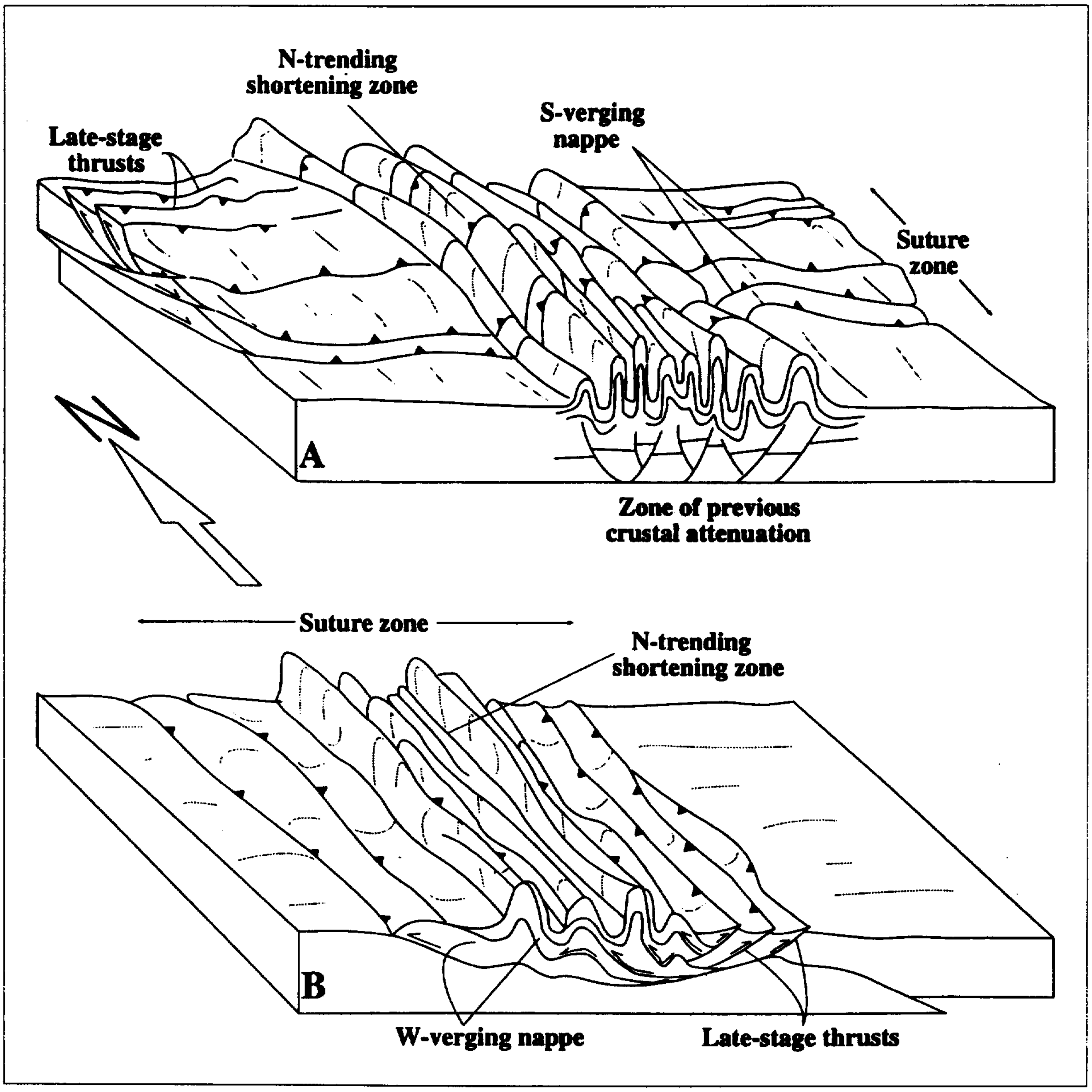

Figure 6. A three dimensional cartoon illustrating the geometrical relationships between intra-oceanic sutures and north trending shortening zones. (a) Superimposition of a north trending shortening zone on a suture zone defined by a south verging nappe. (b) Superimposition of a north trending shortening zone on a suture zone defined by east and west verging nappes.

strain when the ANS collided with the Nile Craton in the west and the Ar Rayn micro-plate to the east at ~670-610 Ma.

v) Stern (1994) suggested that the northwest trending faults were associated with escape tectonics due to collision between East and West Gondwana along the Mozambique Belt.

DISCUSSION

Reconstruction of deformational history of the ANS and the flanking tracts of East and West Gondwana had proven difficult. This is largely due to the fact that post-accretionary deformation is often confused with that resulting from suturing. The following discussion attempts to illuminate the structural history of the ANS by focussing on the following themes which are generalized from the review given above:

i) the structural styles of the ANS sutures;

ii) geometrical relationships between sutures and post-accretionary structures; and

iii) the genetic relationship between north trending shortening zones and northwest trending strike-slip faults.

The structural styles of sutures

It is clear from the foregoing review that some, but not all, of the ophiolite belts in the ANS mark suture zones. This point was eloquently made by Church (1988) and Shackleton (1988), who recognized that erosion of folded nappes would expose ophiolite trains that may be far removed from the corresponding sutures. This review confirms and expands upon this important result. The early phase of deformation in the ANS sutures (where these can be identified) indicates that the ophiolites were originally emplaced as thrust sheets travelling over low-angle decollements. In some cases, continued shortening (without reorientating the stress axes) deforms the initially sub-horizontal nappe structures about more upright folds. Erosion exposes the limbs of these folded ophiolitic nappes as steeply imbricated thrust sheets with apparent opposite vergence. In these instances, the ophiolitic nappes have not travelled far from the suture zone. This is the case for the YOSHGAH and Nakasib-Bir Umq ophiolitic nappes. These ophiolitic trains may not define the exact location of the suture line between colliding terranes; they do, however, lie within the broad deformation belts (suture zones) which are the manifestation of collision between terranes (Fig. 5). Hence, care must be taken not to interpret the ophiolite belt as marking the suture line itself, and not to interpret the vergence of associated structures as defining subduction polarity. In such structures, it is difficult to unequivocally identify the root zone of the suture zone. The Nakasib-Bir Umq suture may be the closest approximation, inasmuch as the ophiolite belt occupies a position between two distinctively different terranes. Even in this case, there are two parallel ophiolite belts (Fig. 2A), which represent the exposed limbs of the same, refolded ophiolitic nappe.

In many other instances, the position and trend of the ANS ophiolite belts are misleading criteria for defining the location of sutures and nature of plate collision. This often occurs when post-accretionary structures cross and entrain components of the ophiolitic nappes. Clear evidence of this is seen where younger, steep structures cross the older sub-horizontal structures at high angles. For example the ophiolite rocks exposed along the Hamisana Shear Zone were produced by refolding of the east trending YOSHGAH ophiolitic nappe along a north trending shortening zone. Similarly, northwest trending ophiolite belts have been produced by disruption of the northeast trending ophiolitic nappes by northwest trending Najd fault system (e.g. the original interpretation of sutures by Bakor *et al.*, 1976). As will be emphasised below, it is much more difficult to separate the effects of accretionary and post-accretionary deformations where the two are more nearly parallel, or where post-accretionary structures define broad rather than narrow zones.

The geometrical relationships between sutures and post-accretionary structures

In the northern part of the ANS, post-accretionary structures were generally superimposed at high angles to the orientation of ophiolitic nappes associated with arc-arc suture. The north trending shortening zones occur as discrete, linear belts of intense deformation, making it relatively straightforward to distinguish them from the suturing structures (Fig. 6A). Careful structural studies will have to unequivocally resolve accretionary and post-accretionary deformations. Deformation associated with the northwest trending fault system is more broadly distributed across the Arabian Shield, but the distinctive sinistral offsets associated with the Najd assists in separating the effects of this deformation from that related to suturing.

It is much more difficult to distinguish accretionary and post-accretionary deformation in the southern part of the ANS. This is the result of two factors:

i) Sutures in northern Kenya and Ethiopia and farther south appear to trend approximately north-south; and

ii) Post-accretionary structures - especially north trending shortening zones - become more closely spaced to the south as the Mozambique Belt is approached.

The north to northeast trending sutures in the southern part of the ANS display patterns in which east or west verging ophiolitic nappes were subsequently deformed by co-axial north trending folding events (Fig. 6B). Beraki *et al.* (1989) interpreted such structures in the Adola-Moyale suture in southern Ethiopia as due to a younger folding event which accompanied east-west shortening. In Kenya, Key *et al.* (1989) and Mosely (1993) identified north trending, sinistral shear zones which are younger than the nappe structures in the region. This suggests that the north trending shortening zones were superimposed on the north trending sutures in the southern part of the ANS as co-axial strain. Continuation of this east-west shortening deformation might have resulted in reactivation of some of these structures as north trending,

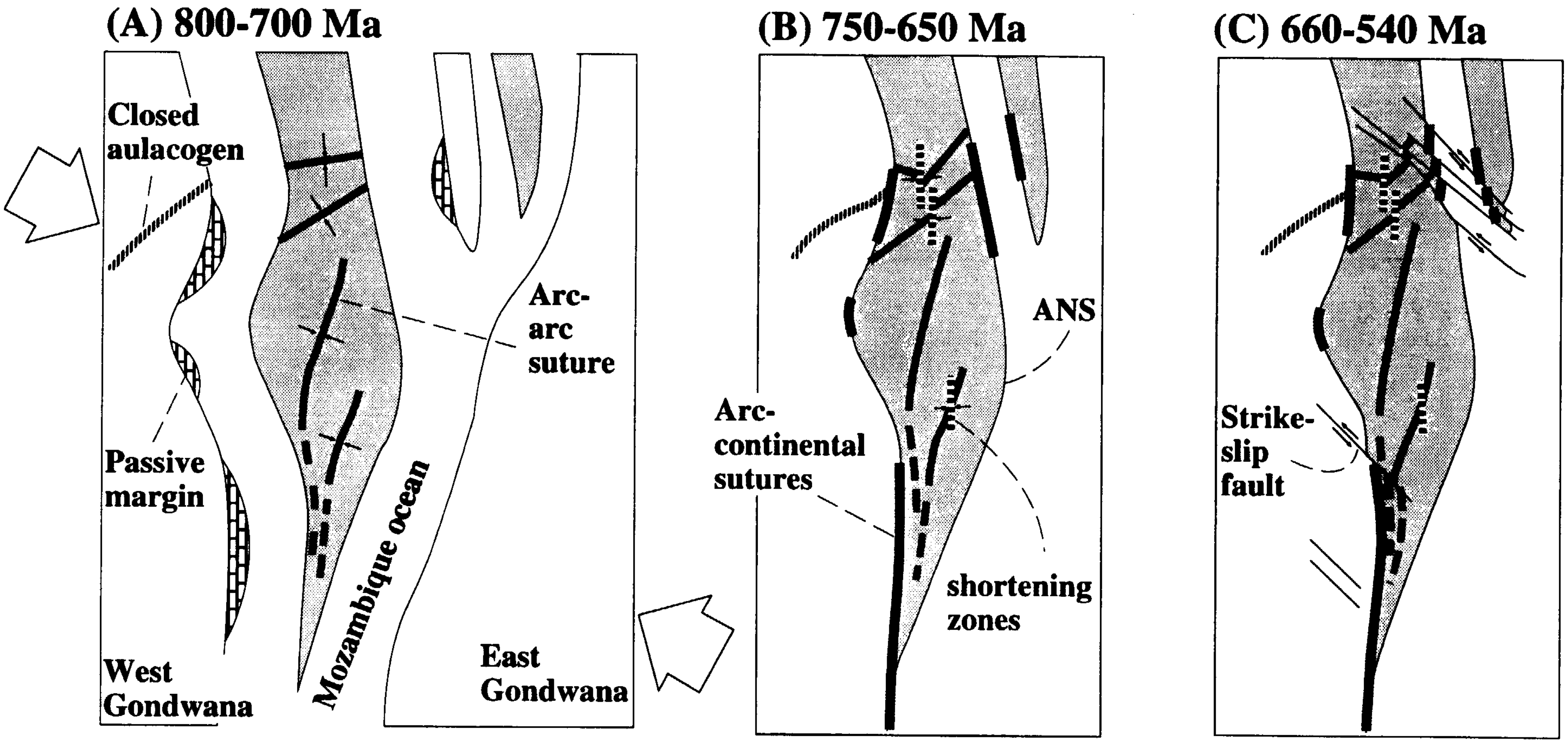

Figure 7. A three step, map-like cartoon outlining the tectonic evolution of deformational belts in the ANS. (a) Development of the ANS as a composite terrane made-up of accreted arcs. Development of arc-arc sutures between 800 and 700 Ma ago. (b) Closing of the Mozambique ocean between 750 and 650 Ma ago to produce arc-continental sutures and north trending shortening zones. (c) The culmination of the north trending shortening zones in the formation of northwest trending, sinistral strike-slip fault system.

sinistral strike-slip faults near the interface between the ANS and the Mozambique Belt.

The genetic relationship between the north trending shortening zones and the northwest trending strike-slip faults

Abdelsalam (1994) proposed that the north trending shortening zones were the product of shortening in the ANS due to its collision with East and West Gondwana at ~750-650 Ma (Stern and Kröner, 1993). On the other hand, the proposition that the northwest trending strike-slip faults in the ANS are collision-related was previously presented by Schmidt *et al.* (1979), Fleck *et al.* (1980), Davies (1984), Agar (1987), and Berhe (1990). Abdelsalam and Stern (1991) objected to this idea, arguing that the orientation of these faults is not in agreement with those expected to develop as a result of collision between East and West Gondwana (with East Gondwana acting as a rigid indentor). Stern (1994) argued that the northwest orientation of the sinistral faults in the ANS can be reconciled with collision along the Mozambique Belt if West Gondwana was the rigid indentor. Abdelsalam *et al.* (1993) suggested an alternative model which relates the north trending shortening zones to the northwest trending sinistral and northeast trending, dextral strike-slip faults. In this model, the east-west shortening culminated with the initiation of the strike-slip faults as zones of high shear strain.

Although this review adopts the explanation that the north trending shortening zones and the northwest trending strike-slip faults were the products of east-west shortening of the ANS between East and West Gondwana, the overall compression which produced such deformation might not have been east-west directed. Regional structural evidence indicates an overall northwest-southeast directed compression which was translated into east-west shortening and northwest wrenching deformational components:

i) The regionally significant stretching lineations in the ANS and the Mozambique Belt are northwest trending. These lineations are associated with nappe emplacement and were interpreted as indicating tectonic transport from the southeast or the northwest (Shackleton *et al.*, 1980; Ries *et al.*, 1983; Struchio *et al.*, 1984; Shackleton, 1986; Bennett and Mosley, 1987; Greiling *et al.*, 1988, 1993) and were further considered as indicating the direction of plate motion (Shackleton and Ries, 1984).

ii) The presence of sinistral transpression along parts of the eastern and western margins of the ANS (e.g. the Nabitah suture and the Keraf suture; Fig. 1) and along some of the north trending arc-arc sutures (e.g. the Baraka suture; Fig. 1). These transpressive deformations were interpreted as being due to oblique collision (Quick, 1989; Drury and Berhe, 1992).

CONCLUSIONS

In order to place the deformational history in the ANS within a regional tectonic framework, the following scenario is proposed:

i) Rifting of super-continent Rodinia at ~900-850 Ma led to formation of the Mozambique ocean. Intra-oceanic arc/back-arc basin complexes were accreted together to form the juvenile material in the ANS between ~870-690 Ma. Terrane accretion resulted in the formation of arc-arc sutures between ~800-700 Ma (Fig. 7a). These sutures are oriented east to northeast in the northern part of the shield and north to northeast in the south. The east to northeast trending sutures share a common structural scenario in which sub-horizontal ophiolitic nappe structures were steepened due to deformation by upright folds associated with collision between terranes. The north to northeast trending arc-arc sutures are marked by ophiolitic nappes which were sometimes overprinted by north trending upright folds and/or strike-slip faults. These faults are either developed as due to oblique collision between terranes or represent younger post-accretionary deformations.

ii) Between ~750-650 Ma, the closure of the Mozambique ocean led to the collision of the ANS with the rifted blocks of East and West Gondwana along north trending arc-continental sutures (Fig. 7b). The western boundary of the ANS is defined by north trending sutures marked by fold and thrust belts in the south and sinistral transpression in the north. The location of the eastern boundary of the ANS is uncertain. It is suggested here that the boundary is defined by two parallel sutures (the Al Amar and Nabitah, Fig. 1) with the Afif Terrane representing a micro-continent rifted off East Gondwana during the Neoproterozoic Pan-African Orogeny (Fig. 7b). Structures associated with the Al Amar suture (Fig. 1) are interpreted as a fold and thrust belt whereas those associated with the Nabitah suture (Fig. 1) is defined by a fold and thrust belt or a sinistral transpressive system.

iii) The continuation of convergence of East and West Gondwana resulted in crustal shortening in the ANS which was localised along north trending linear belts (Fig. 7b) which offset the east to northeast trending sutures in the northern part of the Shield and was superimposed as a co-axial deformations on the north to northeast trending sutures in the south.

iv) The shortening deformation culminated with the formation of northwest trending, sinistral and northeast trending, dextral strike-slip fault systems at ~640-540 Ma (Fig. 7c).

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REFERENCES

Abdelsalam, M. G. 1994. The Oko shear zone: post-accretionary deformations in the Arabian-Nubian Shield. *Journal Geological Society London* **151**, 767-776.

Abdelsalam, M. G. and Dawoud, A. S. 1991. The Kabus ophiolitic melange, Sudan, and its bearing on the west boundary of the Nubian Shield. *Journal Geological Society London* **148**, 83-92.

Abdelsalam, M. G. and Stern, R. J. 1991. Discussion of "Ophiolites in northeast and east Africa: implication for Proterozoic crustal growth". *Journal Geological Society London* **148**, 600-606.

Abdelsalam, M. G. and Stern, R. J. 1993a. Tectonic evolution of the Nakasib suture, Red Sea Hills, Sudan: evidence for a late Precambrian Wilson Cycle. *Journal Geological Society London* **150**, 393-404.

Abdelsalam, M. G. and Stern, R. J. 1993b. Timing of events along the Nakasib suture and the Oko shear zone, Sudan. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U. and Schandelmeier, H.), pp99-103. Balkema, Rotterdam.

Abdelsalam, M. G. and Stern, R. J. 1993c. Structure of the late Proterozoic Nakasib suture, Sudan. *Journal Geological Society London* **150**, 1065-1074.

Abdelsalam, M. G. and Stern, R. J. 1996. Mapping Precambrian structures in the Sahara Desert with SIR-C/X-SAR radar: the Neoproterozoic Keraf suture, NE Sudan. *Journal Geophysical Research* **101**(E10), 23, 63-23, 076

Abdelsalam, M. G., Stern, R. J. and Nielsen, K. C. 1993. The late Precambrian post-accretionary structures in the Arabian-Nubian Shield: zones of pure shear deformation. *GSA (S-Central Section) Meetings Abstracts* **25**, 1.

Abdelsalam, M. G. Stern, R. J. Schandelmeier, H. and Sultan, M. 1995. Deformational history of the Keraf Zone in northeast Sudan, revealed by Shuttle Imaging Radar. *Journal Geology* **103**, 475-491.

Abdel Rahman, E. M., Harms, U., Schandelmeier, H., Franz, G., Darbyshire, D. P. F., Horn, P., and Muller-Sohnius, D. 1990. A new ophiolite occurrence in northwest Sudan - Constraints on late Proterozoic tectonism. *Terra Nova* **2**, 363-376.

Abdel Rahman, E. M., Matheis, G., Schandelmeier, H., Karfis, M. A., Abdel Gadir, I. and El Khedir, M. 1993. Evolution of the Keraf back-arc basin: Constraints on the Nubian Shield margin. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U., and Schandelmeier, H.) pp93-98. Balkema, Rotterdam.

Agar, R. A. 1985. Stratigraphy and paleogeography of the Siham group: direct evidence for a late Proterozoic continental micro-plate and active continental margin in the Saudi Arabian Shield. *Journal Geological Society London* **142**, 1205-1220.

Agar, R. A. 1986. The Bani Ghayy Group: sedimentation and volcanism in pull-apart grabens of the Najd strike-slip orogen, Saudi Arabian Shield. *Precambrian Research* **31**, 259-274.

Agar, R. A. 1987. The Najd fault system revisited: a two way strike-slip orogen in the Saudi Arabian Shield. *Journal Structural Geology* **9**, 41-48.

Alene, M. and Barker, A. J. 1993. Tectono-metamorphic evolution of the Moyale region, south Ethiopia. *Precambrian Research* **62**, 271-283.

Almond, D. C. 1982. New ideas on the geological history of the basement complex of northeast Sudan. *Sudan Notes and Records* **59**, 106-136.

Almond, D. C. and Ahmed, F. 1987. Ductile shear zones on north Red Sea Hills, Sudan and their implication for crustal collision. *Geological Journal* **22**, 175-184.

Almond, D. C., Ahmed, F. and Dawoud, A. S. 1984. Tectonic, metamorphic and magmatic styles in the north Red Sea Hills of Sudan. *Faculty Earth Science Bulletin, King Abdulaziz University Jeddah* **6**, 449-458.

Almond, D. C., Darbyshire, D. P. F., and Ahmed, F. 1989. Age limit for major shearing episodes in the Nubian Shield of northeast Sudan. *Journal African Earth Sciences* **9**, 489-496.

Al Rehaili, M. H. and Warden, A. J. 1980. Comparison of the Bir Umq and Hamdah ultrabasic complexes, Saudi Arabia. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **4**, 143-156.

Al Shanti, A. M. S., and Mitchell, A. H. G. 1976. Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia. *Tectonophysics* **30**, 41-47.

Al Shanti, A. M. S., and Gass, I. G. 1983. The upper Proterozoic ophiolite melange zone of the easternmost Arabian Shield. *Journal Geological Society London* **140**, 867-876.

Ayalew, T., Bell, K., Moore, J. M. and Parrish, R. R. 1990. U-Pb and Rb-Sr geochronology of the west Ethiopian Shield. *Geological Society America Bulletin* **102**, 1309-1316.

Bakor, A. R., Gass, I. G. and Neary, C. R. 1976. Jebel al Wask, northwest Saudi Arabia: an Eocambrian back-arc ophiolite. *Earth Planet Science Letters* **30**, 1-9.

Bennett, J. D. and Mosely, P. N. 1987. Tiered-tectonics and evolution, Eastern Desert and Sinai, Egypt. In: *Current Research in African Earth Sciences* (Edited by Matheis, G., and Schandelmeier, H.) pp79-82. Balkema, Rotterdam.

Beraki, W. H., Bonavia, F. F., Getachew, T., Schmerold, R. and Tarekegn, T. 1989. The Adola fold and thrust Belt, south Ethiopia: a re-examination with implications for Pan-African evolution. *Geological Magazine* **126**, 647-657.

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

Berhe, S. M. 1990. Ophiolites in northeast and east Africa: implication for Proterozoic crustal growth. *Journal Geological Society London* **147**, 41-57.

Berhe, S. M. and Rothery, D. A. 1986. Interactive processing of satellite images for structural and lithological mapping in northeast Africa. *Geological Magazine* **123**, 393-403.

Bertrand, J. M. and Caby, R. 1978. Geodynamic evolution of the Pan-African orogenic belt: A new interpretation of the Hoggar Shield (Algerian Sahara). *Geologische Rundschau* **67**, 357-388.

Black, R. and Liegeois, J. P. 1993. Cratons, mobile belts, alkaline rocks and continental lithospheric mantle: the Pan-African testimony. *Journal Geological Society London* **150**, 89-98.

Bonavia, F. F. and Chorowicz, J. 1992. Northward expulsion of the Pan-African of northeast Africa guided by a reentrant zone of the Tanzania Craton. *Geology* **20**, 1023-1026.

Bonavia, F. F., and Chorowicz, J. 1993. Neoproterozoic structures in the Mozambique orogenic belt of south Ethiopia. *Precambrian Research* **62**, 307-322.

Brinkmann, K. 1986. Geology and mineralization of the basement complex in the northeast Nuba Mountains, Sudan. *Geologisches Jahrbuch* **64**, 3-34.

Burke, K. and Sengor, A. M. C. 1986. Tectonic escape in the evolution of the continental crust. *American Geophysical Union, Geodynamics Series* **14**, 41-53.

Burke, K., Dewey, J. F., and Kidd, W. S. F. 1977. World distribution of sutures - the site of former oceans. *Tectonophysics* **40**, 69-99.

Calvez, J. Z., Alsac, C., Delfour, J., Kemp, J. and Pellaton, C. 1984. Geologic evolution of west, central and east parts of the north Precambrian Shield, Kingdom of Saudi Arabia. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 24-48.

Camp, V. E. 1984 Island arcs and their role in the evolution of the west Arabian Shield. *Geological Society America Bulletin* **95**, 913-921.

Church, W. R. 1988. Ophiolites, sutures, and micro-plates of the Arabian-Nubian Shield: a critical comment. In: *The Pan-African belt of northeast Africa and adjacent areas* (Edited by El Gaby, S. and Greiling, R. O.) pp289-318. Friedr Vieweg and Sohn.

Church, W. R. 1991. Discussion of "Ophiolites in northeast and east Africa: implication for Proterozoic crustal growth". *Journal Geological Society London* **148**, 600-606.

Davies, B. F. 1984. Strain analysis of wrench faults and collision tectonics of the Arabian Shield. *Journal Geology* **82**, 37-53

Delfour, J. 1979. Upper Proterozoic volcanic activity in the northern Arabian Shield, Kingdom of Saudi Arabia. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **2**, 59-75.

Denkler, T., Franz, G., Schandelmeier, H., Harms, U., Darbyshire, D. P. F. and Pilot, J. 1993. Evolution of the SW part of the Atmur-Delgo suture. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U., and Schandelmeier, H.) pp87-89. Balkema, Rotterdam.

Dixon, T. H. 1981. Age and chemical characteristics of some pre-Pan-African rocks in the Egyptian Shield. *Precambrian Research* **14**, 119-133.

Dixon, T. H. and Golombek, M. P. 1988. Late Precambrian crustal accretion rates in northeast Africa and Arabia. *Geology* **16**, 991-994.

Drury, S. A. and Berhe, S. M. 1993. Accretion tectonics in northern Eritrea revealed by remotely sensed imagery. *Geological Magazine* **130**, 177-190.

Duyverman, H. J. 1984. Late Precambrian granitic and volcanic rocks and their relation to the cratonisation of the Arabian Shield. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 50-69.

El Bayoumi, R. M. A. and Greiling, R. O. 1984. Tectonic evolution of a Pan-African plate margin in southeastern Egypt - a suture zone overprinted by low angle thrusting? In: *African Geology* (Edited by Klerkx, J. and Michot, J.) pp47-56. Tervuren.

El Gaby, S., List, F. K., and Tehrani, R. 1988. Geology, evolution and Metallogenesis of the Pan-African Belt in Egypt. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S. and Greiling, R. O.) pp17-68. Friedr Vieweg and Sohn.

El Ramly, M. F., Greiling, R. O., Kröner, A. and Rashwan, A. A. 1984. On the tectonic evolution of the Wadi Hafafit area and environs, Eastern Desert of Egypt. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 113-126.

Embleton, J. C. B., Hughes, D. J., Klemenic, P. M., Poole, S. and Vail, J. R. 1984. A new approach to the stratigraphy and tectonic evolution of the Red Sea Hills, Sudan. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 113-126.

Fleck, R. J., Greenwood, W. R., Hadley, D. G., Anderson, R. E. and Schmidt, D. L. 1980. Age and evolution of the south part of the Arabian Shield. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **3**, 1-19.

Fitches, W. R., Graham, R. H., Hussein, I. M., Ries, A. C., Shackleton, R. M. and Price, R. C. 1983. The late Proterozoic ophiolite of Sol Hamed, northeast Sudan. *Precambrian Research* **19**, 385-411.

Frisch, W. and Al Shanti, A. M. S. 1977. Ophiolite belts and the collision of island arcs in the Arabian Shield. *Tectonophysics* **43**, 293-306.

Greiling, R. O., Kröner, A. and El Ramly, M. F. 1984. Structural interference patterns and their origin in the Pan-African basement of the south Eastern Desert of Egypt. In: *Precambrian tectonics illustrated* (Edited by Kröner, A. and Greiling, R. O), pp401-412. Schweizerbartsche Verlagsbuchhandlung.

Greiling, R. O., Kröner, A., El Ramly, M. F. and Rashwan, A. A. 1988. Structural relationships between the southern and central parts of the Eastern Desert of Egypt: Details of a fold and thrust belt. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S., and Greiling, R.O.) pp121-146. Friedr Vieweg and Sohn.

Greiling, R. O., El Ramly, M. F., Rashwan, A. A. and Kamal El Din, G. M. 1993. Towards a comprehensive structural synthesis of the (Proterozoic) Arabian-Nubian Shield in east. Egypt. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U. and Schandelmeier, H.) pp15-20. Balkema, Rotterdam.

Greiling, R. O., Abdeen, M. M., Darar, A. A., El Akhal, H., El Ramly, M. F., Kamal El Din, G. M., Osman, A. F., Rashwan, A. A., Rice, A. H. N., and Sadek, M. F. 1995. A structural synthesis of the Proterozoic Arabian-Nubian Shield in Egypt. *Geologische Rundschau* **83**, 484-501.

Haider, A. H. and Berhe, S. 1995. Crustal evolution in the Mozambique belt and implications for reconstruction of Gondwana. *Centennial Geocongress Abstracts Geological Society South Africa* **370**, 75p.

Harms, U., Schandelmeier, H., and Darbyshire, D. P. F. 1990. Pan-African reworked early/middle Proterozoic crust in northeast Africa west of the Nile: Sr and Nd isotope evidence. *Journal Geological Society London* **147**, 859-872.

Harris, N. B. W., Hawkesworth, C. J. and Ries, A. C. 1984. Crustal evolution in northeast and east Africa from model Nd ages. *Nature* **309**, 773-776.

Hirdes, W. and Brinkmann, K. 1985. The Kabus and Balula serpentinite and meta-gabbro complexes: a dismembered ophiolite in northeast Nuba Mountains, Sudan. *Geologische Jahrbuch* **58**, 3-43.

Hussein, I. M., Kröner, A. and Durr, St. 1984. Wadi Onib- a dismembered Pan-African ophiolite in the Red Sea Hills of Sudan. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 320-327.

Johnson, P. R. 1994. The Nakasib suture: a compilation of recent information about a Sudanese fold and thrust belt, and implications for the age, structure, and mineralization of the Bir Umq suture, Kingdom of Saudi Arabia. *Open-file report* **USGS-OF-94-6**. 44p.

Key, R. M., Charsley, T. J., Hackman, T. J., Wilkinson, A. F. and Rundle, C. C. 1989. Superimposed upper Proterozoic collision controlled orogenies in the Mozambique Orogenic belt of Kenya. *Precambrian Research* **44**, 197-225.

Kröner, A. 1977. The Precambrian geotectonic evolution of Africa: plate accretion vs. plate destruction. *Precambrian Research* **4**, 163-213.

Kröner, A., Greiling, R. O., Reischmann, T., Hussein, I. M., Stern, R. J., Durr, St., Kruger, J. and Zimmer, M. 1987a. Pan-African crustal evolution in northeast Africa. In: *Proterozoic Lithospheric Evolution. American Geophysical Union, Geodynamic Series* **17** (Edited by Kröner, A.) 235-257.

Kröner, A., Stern, R. J., Dawoud, A. S., Compston, W., and Reischmann, T. 1987b. The Pan-African continental margin in northeast Africa: evidence from a geochronological study of granulites at Sabaloka, Sudan. *Earth Planetary Science Letters* **85**, 91-104.

Kröner, A., Stern, R. J., Linnebacker, P., Manton, W., Reischmann, T. and Hussein, I. M. 1991. Evolution of Pan-African island arc assemblages in the south Red Sea Hills, Sudan, and in SW Arabia as exemplified by geochemistry and geochronology. *Precambrian Research* **53**, 99-118.

Kröner, A., Todt, W., Hussein, I. M., Mansour, M. and Rashwan, A. A. 1992. Dating of late Proterozoic ophiolites in Egypt and the Sudan using the single grain zircon evaporation technique. *Precambrian Research* **59**, 15-32.

Lenoir, J. L., Kuster, D., Liegeois, J. P., Utke, A., Haider, A. and Matheis, G. 1994. Origin and regional significance of late Precambrian and early Palaeozoic granitoids in the Pan-African belt of Somalia. *Geologische Rundschau* **83**, 624-641.

Miller, M. M. and Dixon, T. H. 1992. Late Proterozoic evolution of the north part of the Hamisana zone, northeast Sudan: constraints on Pan-African accretionary tectonics. *Journal Geological Society London* **149**, 743-750.

Moore, J. Mc. M. 1979. Tectonics of the Najd transcurrent fault system, Saudi Arabia. *Journal Geological Society London* **136**, 441-453.

Mosely, P. N. 1993. Geological evolution of the late Proterozoic "Mozambique Belt" of Kenya. *Tectonophysics* **221**, 223-250.

Nassief, M. O., MacDonald, R. and Gass, I. G. 1984. The Jebel Thurwah Upper Proterozoic ophiolite complex, west Saudi Arabia. *Journal Geological Society London* **141**, 537-546.

Nawab, Z. A. 1979. Geology of the Al Amar-Idsas region of the Arabian Shield. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **3**, 29-39.

Pallister, J. S., Stacy, J. S., Fischer, L. B. and Premo, W. R. 1989. Precambrian ophiolites of Arabia: Geologic settings, U-Pb geochronology, Pb-isotope characteristics, and implication for continental accretion. *Precambrian Research* **38**, 1-54.

Quick, J. E. 1991. Late Proterozoic transpression on the Nabitah fault system - implications for the assembly of the Arabian Shield. *Precambrian Research* **53**, 119-147.

Quick, J. E. and Bosch, P. S. 1989. Tectonic history of the north Nabitah fault zone, Arabian Shield, Kingdom of Saudi Arabia. Ministry of Petroleum and Mineral Resources, Jeddah, *Technical Report*. **USGS TR-08-2**, 87p.

Ramsay, C. R. 1986. Explanation notes to the geological map of the Rabigh quadrangle, sheet 22D, Kingdom of Saudi Arabia. *Ministry of Petroleum and Mineral Resources, Deputy Ministry for Mineral Resources, Geoscience map GM- 84C.*

Ries, A. C., Shackleton, R. M., Graham, R. H. and Fitches, W. R. 1983. Pan-African structures, ophiolites and melanges in the east Desert of Egypt: a traverse at 26° north. *Journal Geological Society London* **140**, 75-95.

Ries, A. C., Vearncombe, J. R., Price, R. C. and Shackleton, R. M. 1992. Geochronology and geochemistry of the rocks associated with a late Proterozoic ophiolite in West Pokot, northwest Kenya. *Journal African Earth Sciences* **14**, 25-36.

Rocci, G. 1965. Essai d'interpretation de mesures geochronologiques. La structure de l'Ouest africain. *Sciences Terre* **10**, 461-479.

Schmidt, D. L., Hadley, D. G. and Stoeser, D. B. 1979. Late Proterozoic crustal history of the Arabian Shield, south Najd province, Kingdom of Saudi Arabia. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **3**, 41-58.

Schandelmeier, H., Darbyshire, D. P. F., Harms, U., and Richter, A. 1988. The east Saharan craton: evidence for pre-Pan-African crust in northeast Africa west of the Nile. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S., and Greiling, R. O.), pp69-94. Friedr Vieweg and Sohn.

Schandelmeier, H., Kuster, D., Wipfler, E., Abdel Rahman, E. M., Stern, R. J., Abdelsalam, M. G., Sultan, M. 1993. Evidence for a new late Proterozoic suture in north Sudan. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U. and Schandelmeier, H.) pp83-85. Balkema, Rotterdam.

Schandelmeier, H., Abdel Rahman, E. M., Wipfler, E., Kuster, D., Utke, A. and Matheis, G. 1994. Late Proterozoic magmatism in the Nakasib suture, Red Sea Hills, Sudan. *Journal Geological Society London* **151**, 485-497.

Shackleton, R. M. 1979. Precambrian tectonics of northeast Africa. *Institute Applied Geology Bulletin, King Abdulaziz University, Jeddah* **3**, 1-6.

Shackleton, R. M. 1986. Precambrian collision tectonics in Africa. In: *Collision tectonics, Geological Society London Special Publication* **19** (Edited by Coward, M. P. and Ries, A. C.), 329-349.

Shackleton, R. M. 1988. Contrasting structural relationships of Proterozoic ophiolites in northeast and east Africa. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S. and Greiling, R. O.), pp183-193. Friedr Vieweg and Sohn.

Shackleton, R. M. 1994. Review of late Proterozoic sutures, ophiolitic melanges and tectonics of eastern Egypt and northeast Sudan. *Geologische Rundschau* **83**, 537-546.

Shackleton, R. M. and Ries, A. C. 1984. The relation between regionally consistent stretching lineations and plate motions. *Journal Structural Geology* **6**, 111-117.

Shackleton, R. M., Ries, A. C., Graham, R. H., and Fitches, W. R. 1980. Late Precambrian ophiolitic melange in the east Desert of Egypt. *Nature* **285**, 472-474.

Shanti, M. and Roobol, M. J. 1979. A late Proterozoic ophiolite complex at Jebel Ess in north Saudi Arabia. *Nature* **279**, 488-491.

Stacey, J. S. and Agar, R. A. 1985. U-Pb isotopic evidence for the accretion of a continental micro-plate in the Zalm region of the Saudi Arabian Shield. *Journal Geological Society London* **142**, 1189-1203

Stacey, J. S. and Hedge, C. E. 1984. Geochronology and isotopic evidence for early Proterozoic crust in the east Arabian Shield. *Geology* **12**, 310-313.

Stacey, J. S. and Stoeser, D. B. 1983. Distribution of oceanic and continental leads in the Arabian-Nubian Shield. *Contributions Mineralogy Petrology* **84**, 91-105.

Stacey, J. S. Delevaux, M. H., Gramlich, J. W., Doe, B. R. and Roberts, R. J. 1980. A lead isotopic study of mineralization in the Arabian Shield. *Contributions Mineralogy Petrology* **74**, 175-188.

Stacey, J. S., Stoeser, D. B., Greenwood, W. R., and Fischer, L. B. 1984. U-Pb geochronology and geologic evolution of the Halaban-Al Amar region of east Arabian Shield, Kingdom of Saudi Arabia. *Journal Geological Society London* **141**, 1043-1055.

Stern, R. J. 1985. The Najd fault system, Saudi Arabia and Egypt: A late Precambrian rift-related transform system? *Tectonics* **4**, 497-511.

Stern, R. J. 1994. Arc assembly and continental collision in the Neoproterozoic east African Orogen: implication for the consolidation of Gondwanaland. *Annual Review Earth Planetary Science* **22**, 319-351.

Stern, R. J. and Hedge, C. E. 1985. Geochronologic and isotopic constraints on late Precambrian crustal evolution in the Eastern Desert of Egypt. *American Journal Science* **285**, 97-127.

Stern, R. J. and Kröner, A. 1993. Geochronologic and isotopic constraints on the late Precambrian crustal evolution in northeast Sudan. *Journal Geology* **101**, 555-574.

Stern, R. J., Kröner, A., Manton, W. I., Reischmann, T., Mansour, M. and Hussein, I. M. 1989. Geochronology of the late Precambrian Hamisana shear zone, Red Sea Hills, Sudan and Egypt. *Journal Geological Society London* **146**, 1017-1030.

Stern, R. J., Nielsen, K. C., Best, E., Sultan, M., Arvidson, R. E. and Kröner, A. 1990. Orientation of late Precambrian sutures in the Arabian-Nubian Shield. *Geology* **18**, 1103-1106.

Stern, R. J., Abdelsalam, M. G., Schandelmeier, H. and Sultan, M. 1993. Carbonates of the Bailateb group, northeast Sudan: a Neoproterozoic (ca. 750 Ma) passive margin on the eastern flank of west Gondwanaland? *GSA Meetings Abstracts* **27**, 49.

Stern, R. J., Kröner, A., Reischmann, T., Bender, R. and Dawoud, A. S. 1994. Precambrian basement around Wadi Halfa: a new perspective on the evolution of the Central Saharan Ghost craton. *Geologische Rundschau* **83**, 564-577.

Stoeser, D. B. and Camp, V. E. 1985. Pan-African microplate accretion of the Arabian Shield. *Geological Society America Bulletin* **96**, 817-826.

Stoeser, D. B. and Stacey, J. S. 1988. Evolution, U-Pb geochronology, and isotope geology of the Pan-African Nabitah orogenic belt of the Saudi Arabian Shield. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S. and Greiling, R. O.) pp227-288. Friedr Vieweg and Sohn.

Stoeser, D. B., Fleck, R. J. and Stacey, J. S. 1984. Geochronology and origin of an early tonalite gneiss of the Wadi Tarib batholith and the formation of syn-tectonic gneiss complexes in the southeast Arabian Shield. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 351-364.

Stoeser, D. B., Whitehouse, M. J., Agar, R. A. and Stacey, J. S. 1991. Pan-African accretion and continental terranes of the Arabian Shield, Saudi Arabia and Yemen. *EOS Abstracts* **72**, 299.

Sturchio, N. C., Sultan, M., Sylvester, P., Batiza, R., Hedge, C., El Shazly, E. M. and Abdel-Maguid, A. 1984. Geology, age, and origin of Meatiq dome: implication for the Precambrian stratigraphy and tectonic evolution of the east Desert of Egypt. *Faculty Earth Science Bulletin, King Abdulaziz University, Jeddah* **6**, 127-143.

Sultan, M., Arvidson, R. E., and Sturchio, N. C. 1986. Mapping of serpentinites in the east Desert of Egypt by using Landsat thematic mapper data. *Geology* **14**, 995-999.

Sultan, M., Chamberlin, K. R., Bowring, S. A., Arvidson, R. E., Abuzied, H., and EL Kaliouby, B. 1990. Geochronologic and isotopic evidence for involvement of pre-Pan-African crust in the Nubian Shield, Egypt. *Geology* **18**, 761-764.

Sultan, M., Bickford, M. E., El Kaliouby, B. and Arvidson, R. E. 1992. Common Pb systematics of Precambrian granitic rocks of the Nubian Shield (Egypt) and tectonic implications. *Geological Society America Bulletin* **104**, 456-470.

Sultan, M., Tuckler, R. D., Gharbawi, R. I., Ragab, A. I. and El Alfy, Z. 1993. On the location of the boundary between the Nubian Shield and the old African continent: inferences from U-Pb (zircon) and common Pb data. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U., and Schandelmeier, H.), pp75-77. Balkema, Rotterdam.

Sultan, M., Becker, R., Arvidson, R. E., Shore, P., Stern, R. J., El Alfy, Z. and Attia, R. I. 1994. New constraints on the Red Sea rifting from correlations of Arabian and Nubian Neoproterozoic outcrops. *Tectonics* **12**, 1303-1319.

Teklay, M., Kröner, A. and Oberhansli, R. 1993. Reconnaissance Pb-Pb zircon ages from Precambrian rocks in eastern and southern Ethiopia and an attempt to define crustal provinces. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U. and Schandelmeier, H.). pp133-138. Balkema, Rotterdam.

Tolessa, S., Bonavia, F. F., Solomon, M., Haile-Meskel, A. and Teferra, E. 1991. Structural pattern of Pan-African rocks around Moyale, south Ethiopia. *Precambrian Research* **52**, 179-186.

Vail, J. R. 1983. Pan-African crustal accretion in northeast Africa. *Journal African Earth Sciences* **1**, 285-294.

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

Vail, J. R. 1988. Tectonics and evolution of the Proterozoic basement of northeast Africa. In: *The Pan-African belts of northeast Africa and Adjacent areas* (Edited by El Gaby, S. and Greiling, R. O.). pp185-226. Friedr Vieweg and Sohn.

Vearncombe, J. R. 1983. A proposed continental margin in the Precambrian of west Kenya. *Geologische Rundschau* **72**, 663-670.

Wallbrecher, E., Fritz, H., Khudeir, A. A. and Farahad, F. 1993. Kinematics of Pan-African thrusting and extension in Egypt. In: *Geoscientific Research in northeast Africa* (Edited by Thorweihe, U. and Schandelmeier, H.), pp27-30. Balkema, Rotterdam.

Warden, A. J., Kasmin, V., Kiesel, W. and Pohl, W. 1982. Some geochemical data of mafic-ultramafic complex at Tulu Dimtu, Ethiopia and their genetic significance. *Sitzungsberichte. Osterreichische Akademie der Wissenschaften Mathematisch Naturwissenschaftliche* **191**, 111-131.

Wust, H. J., Todt, W. and Kröner, A. 1987. Conventional and single grain zircon ages for meta-sediments and granitic clasts from the east Desert of Egypt: evidence for active continental margin evolution in Pan-African times. *Terra Cognita Abstracts* **7**, 333-334.