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The Bi'r Umq-Nakasib Suture Zone in the Arabian-Nubian Shield: A Key to Understanding Crustal Growth in the East African Orogen

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Abstract

The Bi'r Umq-Nakasib suture zone, 5–65 km wide and over 600 km long, consists of highly deformed ophiolite nappes and metavolcanic, metasedimentary, and intrusive rocks contained in one of the longest ophiolite-decorated shear zones in the Arabian-Nubian Shield. The rocks originated in a variety of juvenile oceanic environments and include assemblages formed in mid-ocean-ridge, subduction-zone, passive-margin, and continental-slope settings. Dating of the ophiolites, volcanic rocks, and pre- and syntectonic plutons indicates that oceanic magmatism in the region was active ~870–830 Ma whereas suturing occurred ~780–760 Ma. This chronology suggests that suturing involved the closure of a relatively long-lived oceanic basin and makes the Bi'r Umq-Nakasib shear zone the oldest accretionary structure known among the juvenile Neoproterozoic rocks of the northern East African Orogen. Creation of the shear zone dates the onset of arc-arc convergence in what eventually became the Arabian-Nubian shield, and marks the beginning of the complex, heterogeneous process of terrane amalgamation and continental accretion that led to the eventual accretion of East and West Gondwana.

Key words: Arabian-Nubian shield, Neoproterozoic, suture, terrane amalgamation, ophiolite.

Introduction

The northern exposures of the East African Orogen (EAO) preserved in the Arabian-Nubian Shield (ANS) include amalgamated terranes of Tonian (1000–850 Ma) and Cryogenian (850–650 Ma) volcanic and plutonic rocks. Sutures have been postulated between the terranes since the mid 1970s (Al-Shanti and Mitchell, 1976) on the basis of ophiolite- and serpentinite-decorated shear zones, although the timing, structure and kinematics of individual putative suture zones are important current topics of research because the identification of shear zones as sutures on the basis of the presence of mafic-ultramafic rocks alone yields ambiguous results (Church, 1988). Obviously, the presence of ophiolites is a primary consideration in establishing whether a shear zone is a suture or not, but equally important are other criteria including (1) chemical and isotopic evidence of juvenile oceanic environments; (2) indications of high strain; (3) contrasting geologic histories in flanking tectonostratigraphic terranes; (4) the presence of rocks deposited at the margins of buoyant crustal blocks, such as volcanic-arc units and continental-rise and shelf limestone and quartzite; (5) evidence of complex thrusting and progressive deformation suggestive of oblique transpression and (6) indications that the suspected suture is a structure of regional scale, extending hundreds of kilometers along strike (Johnson et al., 2002).

The purpose of this paper is to summarize the geologic features of the Bi'r Umq-Nakasib shear zone and to show that it convincingly satisfies the criteria of being a suture (Johnson et al., 2002). The suture zone is 5–65 km wide and can be traced for more than 600 km from the central part of the Arabian Shield across the Nubian Shield almost to the Nile (Fig. 1). It constitutes a major belt of VMS (Cu, Zn) and epithermal gold mineralization, as shown by the line of deposits indicated on figure 1; it is one of the longest shear zones recognized in the northern part of the EAO, and in terms of its age and location is critical to our understanding of the initial process of crustal accretion in the ANS.

Evidence for Suturing

Ophiolites

With regard to the primary consideration of the presence of ophiolites, it is well known that the Bi'r Umq-Nakasib

shear zone contains an abundance of ophiolitic complexes (Fig. 1) composed of serpentinized ultramafic rocks, basalt, minor chert and large amounts of tectonic ultramafic mélange intercalated with metavolcanic and metasedimentary rocks (Al-Rehaili, 1980; Abdel Rahman, 1993; Abdelsalam and Stern, 1993a, b; Schandelmeier et al., 1994; Nassief et al., 1984; Pallister et al., 1988). The ophiolites include the Bi'r Umq (Fig. 2) and Tharwah (Fig. 3) complexes in Saudi Arabia; and the Arbaat, Shalhout, Oshib, and other complexes in Sudan (Fig. 4). Individual ophiolitic bodies are as much as 130 km long, 20 km wide and more than 2 km thick. The rocks are strongly deformed but typical ophiolite rock units can be recognized including: (1) basal mantle-tectonite harzburgite and dunite with podiform and disseminated chromite; (2) cumulate-layered peridotite, pyroxenite, and gabbro; (3) massive isotropic gabbro and dolerite dike complexes and (4) pillow basalt, sheeted dykes, and chert (Abdel Rahman, 1993). Previous studies of their whole-rock and chromite geochemistry concluded that the ophiolites variably originated in mid-ocean-ridge spreading centers, intraoceanic convergent margins, fore-arc suprasubduction zones and back-arc basins (Abdel Rahman, 1993; Schandelmeier et al., 1994; Nassief et al., 1984; Pallister et al., 1988; Le Metour et al., 1982). However, the Mg-rich character of the some of the ophiolite rocks (Fo 89.5-94.4 in Tharwah harzburgite olivine: Nassief et al., 1984; MgO 38.32-42.59 percent in Nakasib serpentinized dunite-harzburgite: Abdel Rahman, 1993) is similar to that of peridotites recovered from forearcs. This suggests that the ultramafic rocks are residual after extensive melting, consistent with the high Cr# (≥60) of the Nakasib ophiolites (Abdel Rahman, 1993). On the evidence of a near-concordant three-point U-Pb zircon model age of 838±10 Ma obtained from diorite close to the southern margin (Pallister et al., 1988) (Fig. 2) and a composite Sm-Nd isochron of 828±47 Ma obtained from trondhjemite and pyroxene from a nearby gabbro (Dunlop et al., 1986), the Bi'r Umq ophiolite is inferred to be about 830 Ma, whereas a near-concordant U-Pb zircon model age of 870±11 Ma obtained from gabbro (Fig. 3) suggests that the Tharwah ophiolite is older. These results are not robust, and the Thawrah data may be skewed by the effect of inheritance, but if they approximate crystallization ages the results suggest a prolonged, 870–830 Ma period of ocean-floor magmatism. A maximum age for ophiolite obduction at Bi'r Umq is given by single-point zircon model ages of 764±3 Ma and 783±5 Ma obtained from plagiogranite that intrudes already serpentinized and carbonated peridotite (Pallister et al., 1988).

Crustal margin assemblages

Supporting evidence for convergence and suturing along the Bi'r Umq-Nakasib suture zone is the presence of rocks that originated in a variety of tectonic settings but are now juxtaposed by faulting and folding in a narrow

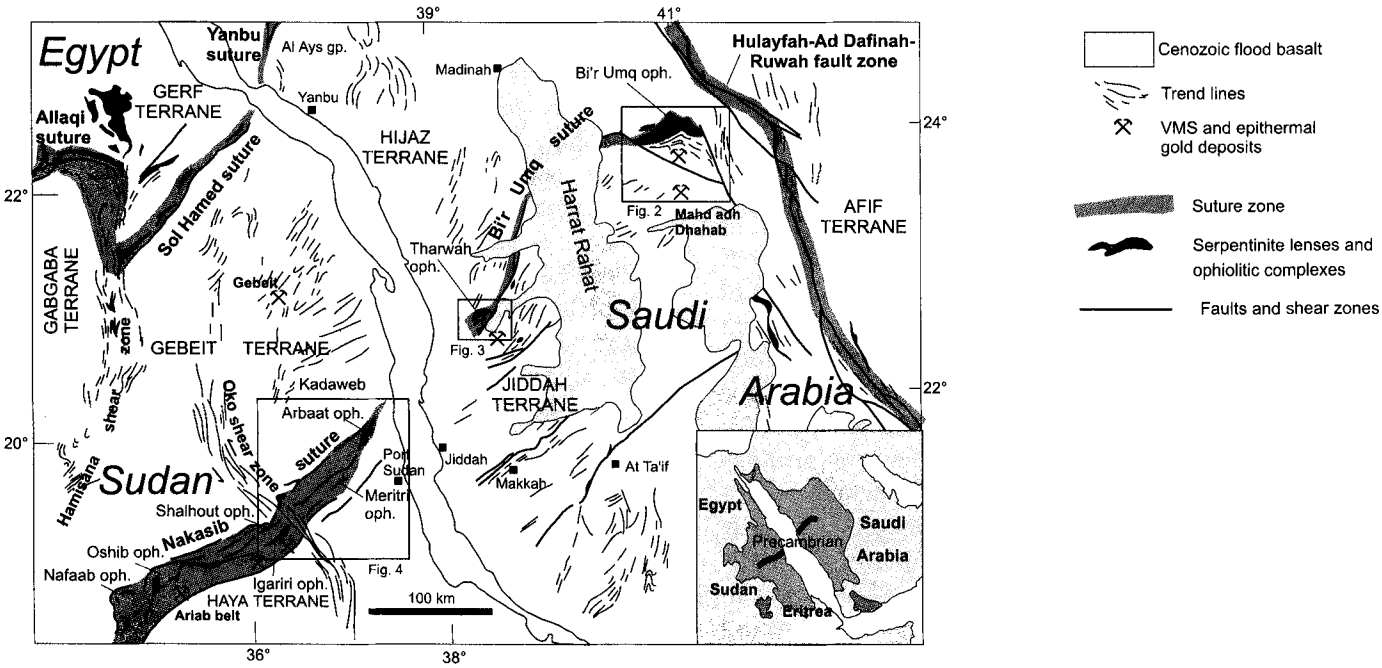

Fig. 1. The Bi'r Umq-Nakasib shear zone and associated structures in the central part of the Arabian-Nubian shield, plotted on a pre-Red Sea-opening palinspastic compilation. Inset shows regional extent of Precambrian exposure. Boxes outline locations of figures 2, 3 and 4. (After Johnson et al., 2002).

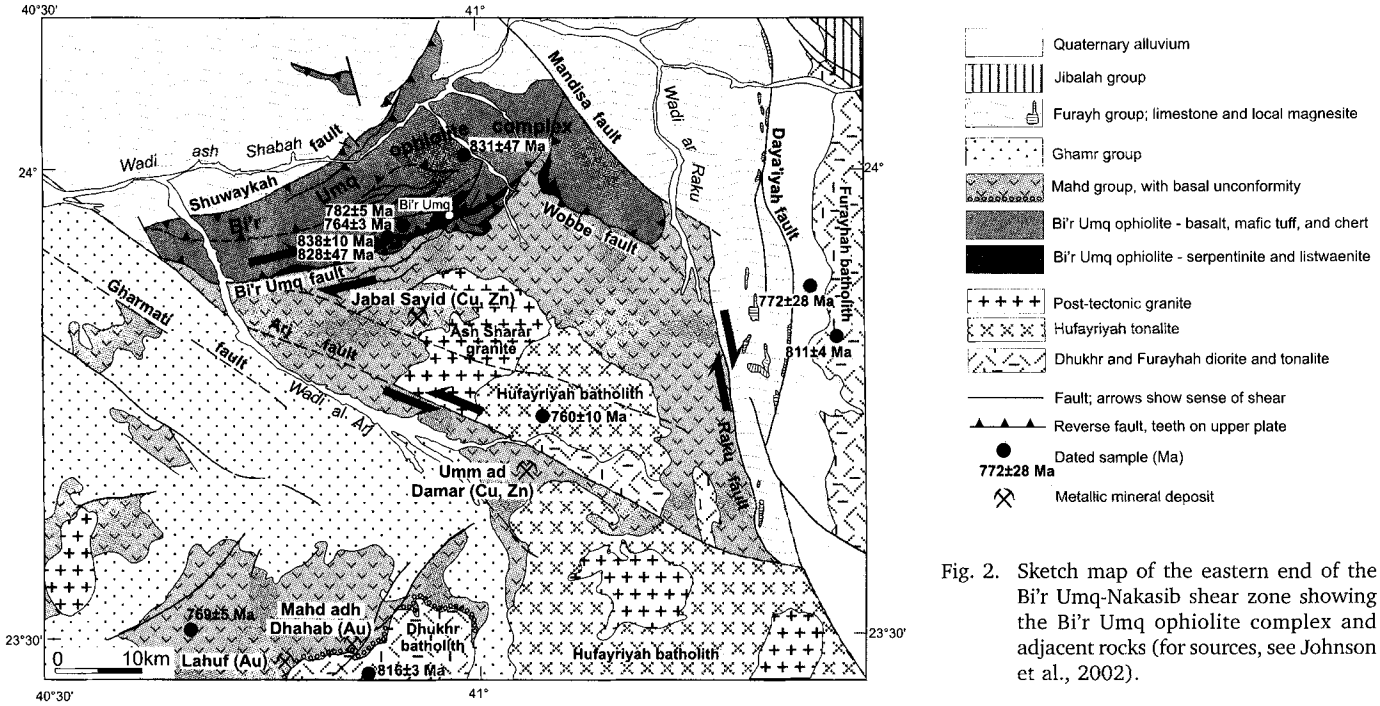

Fig. 2. Sketch map of the eastern end of the Bi'r Umq-Nakasib shear zone showing the Bi'r Umq ophiolite complex and adjacent rocks (for sources, see Johnson et al., 2002).

shear zone. The rocks include island-arc and extensional-basin deposits, ocean-basin to continental-slope deposits, and subduction-related intrusive rocks characteristic of the types formed at the margins of crustal blocks. The Ariab series (in the Ariab Belt; Fig. 1) (Aye et al., 1985; Bakheit, 1991; Schandelmeier et al., 1994) includes tholeiitic to calc-alkaline basalt to rhyolite that resemble present-day intraoceanic island arcs. The Mahd group (~810–770 Ma; Calvez and Kemp, 1982) (Fig. 2) is a volcanic-volcaniclastic sequence more than 5 km thick containing tholeiitic to calc-alkalic basalt, basaltic andesite, andesite, dacite and rhyolite that have Cr/Y and Ti/Zr ratios characteristic of rift or intraplate and arc environments (Johnson et al., 2002) and have some characteristics of local extensional basins (Afifi, 1989). Tholeiitic to calc-alkalic basalt, basaltic-andesite, and rhyolite in the Samran group south of the suture zone in Saudi Arabia (Fig. 3) yield weak geochemical indications of arc, within-plate, and MORB settings (Ramsay, 1986). The chemical characteristics of the bimodal sub-alkaline, tholeiitic to calc-alkalic, locally pillowed, basalt, basaltic-andesite, and subordinate silica-rich rhyolite of the Arbaat group (~790 Ma) strongly suggest MORB and within-plate settings (Abdelsalam and Stern, 1993a).

Basalt, chert, marble and quartzite in the Labunah formation (Fig. 3) and possibly correlative felsic lava, felsic tuff, graywacke, conglomerate, quartzite and marble in the Salatib and Meritri groups (Fig. 4) likely formed in continental-slope environments along the suture zone. The Labunah formation (Ramsay, 1986) was deposited in a transitional deep-ocean to continental-shelf environment. The Salatib and Meritri groups were deposited distal to the volcanic rocks of the Ariab series (Schandelmeier et al., 1994) or at fault scarps against a passive margin (Abdelsalam and Stern, 1993a).

Active margins in the region are indicated by subduction-related pretectonic dioritoid and granitoid intrusions (816–810 Ma) represented by the Dhukhr and Furayhah batholiths in Saudi Arabia (Fig. 2) and the Adaiamet and Tala plutons in Sudan (Fig. 4), and by syntectonic plutons (780–760 Ma) such as the Hufayriyah batholith in Saudi Arabia and the Arbaat, Luggag and Shalhout plutons in Sudan (Calvez and Kemp, 1982; Stern and Abdelsalam, 1998; Schandelmeier et al., 1994). Rocks in the Sudanese plutons have a calc-alkaline, low-K, "M-type" and medium- to high-K, "I-type" chemistry characteristic of magmatic rocks formed in a suprasubduction intraoceanic island-arc setting (Schandelmeier et al., 1994; Stern and Abdelsalam, 1998). Post-tectonic intrusions in Sudan (Fig. 4) are mainly leucocratic, K-feldspar rich metaluminous to slightly peraluminous evolved "I-type" and partly "A-type" granitoids resembling plutons that result from melting of island-arc rocks during arc-collision or intra-arc extension (Schandelmeier et al., 1994).

Isotopes

Further support of suturing is provided by the isotope

systematics of the rocks along and flanking the Bi'r Umq-Nakasib shear zone. These include: (1) low initial-strontium values (Sr_i = 0.7021–0.7033) similar to those expected for mantle-derived MORB and OIB melts (Dunlop et al., 1986; Schandelmeier et al., 1994; Stern and Abdelsalam, 1998), (2) restricted ratios of $^{206}Pb/^{204}Pb$ (17.50–17.62), $^{207}Pb/^{204}Pb$ (15.46–15.51), and $^{208}Pb/^{204}Pb$ (36.95–37.15) (Stern and Abdelsalam, 1998) that plot at or below the orogene growth curve for lead, and (3) positive $\varepsilon Nd_{(t)}$ values (+5.97–+6.1) and T_{DM} model ages that approximate crystallization ages. The data are strong evidence that the rocks formed in juvenile oceanic environments and were derived from depleted magma sources that lacked input from older continental crust. Sr_i values of 0.7024-0.7029 and $\varepsilon Nd_{(t)}$ values of +5.8 to +8.4 (Fleck, 1985; Kröner et al., 1991; Reischmann et al., 1992; Stern and Kröner, 1993; Reischmann and Kröner, 1994) are evidence that similar juvenile depleted environments existed in the regions flanking the suture zone.

Adjacent crustal blocks—tectonostratigraphic terranes

Interpretation of a given shear zone as a suture is also strengthened by evidence that the rocks on either side of the suspected suture belong to distinct tectonostratigraphic terranes. In the case of the Bi'r Umq-Nakasib suture zone, robust geochronologic data are relatively sparse, but the known stratigraphic, geochronologic, and isotopic differences are evidence that the flanking regions constitute separate Tonian-Cryogenian terranes (Stern and Kröner, 1993). In the literature, these regions are referred to as the Gebeit and Haya terranes in Sudan, and the Hijaz and Jiddah terranes in Saudi Arabia (Fig. 1). The Gebeit terrane includes ~830–813 Ma volcanic assemblages in the northeast (Gaskell, 1985; Reischmann and Kröner, 1994; Stern and Kröner, 1993) derived from very depleted magma sources ($\varepsilon Nd_{(t)}$ values of +6.5 to +8.4), younger, 780–760 Ma, volcanic/magmatic rocks farther north and northwest (Stern and Kröner, 1993), and volcanic rocks of uncertain age in the south, in the Kadaweb area. The Hijaz terrane comprises arc-related volcanosedimentary rocks of the Birak group (>807 Ma) close to the suture zone and the Al Ays group (?740–720 Ma) farther north (Fig. 1), overlain by younger volcanosedimentary sequences assigned to the Furayh and Hadiyah groups.

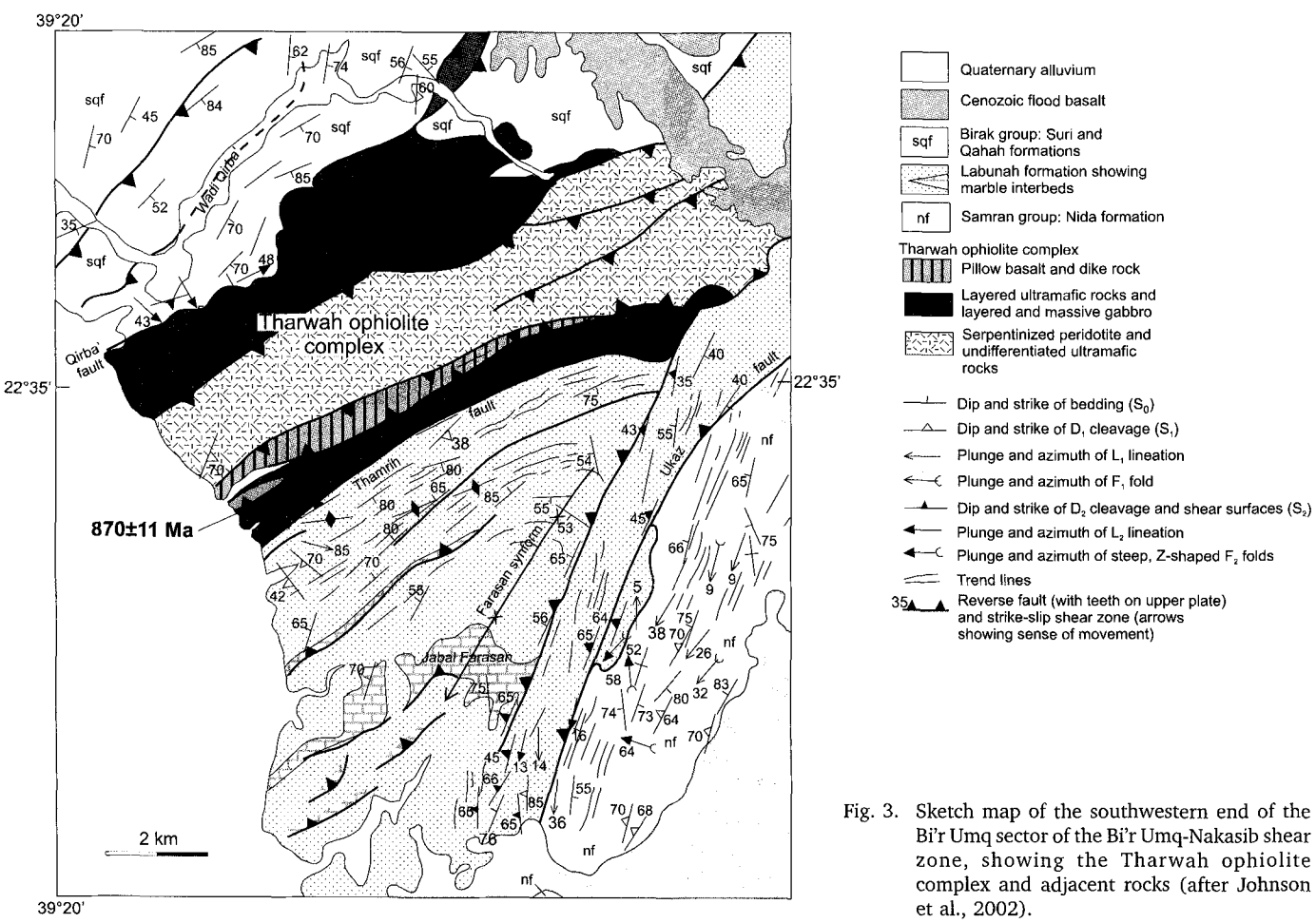

Fig. 3. Sketch map of the southwestern end of the Bi'r Umq sector of the Bi'r Umq-Nakasib shear zone, showing the Tharwah ophiolite complex and adjacent rocks (after Johnson et al., 2002).

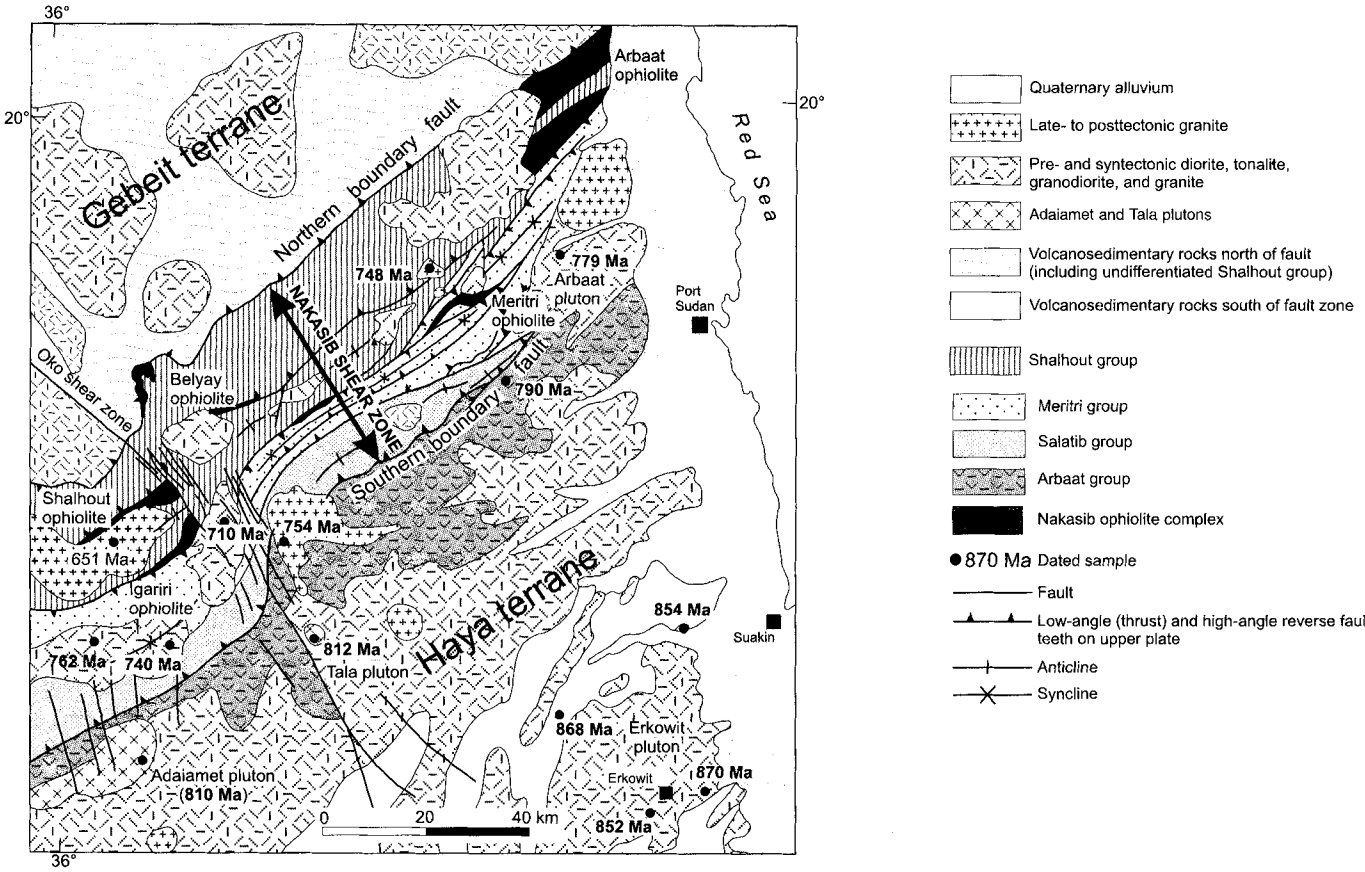

Fig. 4. Eastern part of the Nakasib sector of the Bi'r Umq-Nakasib shear zone (after Abdelsalam and Stern, 1993a, b).

In contrast, the Haya terrane (Fig. 4) includes volcanic, sedimentary and intrusive rocks that are considerably older (870–850 Ma) than those in the Gebeit terrane and are derived from less depleted magma sources ($\varepsilon Nd_{(t)}$ values of +5.95 to +6.05) (Embleton et al., 1984; Klemenic, 1985; Kröner et al., 1991; Reischmann et al., 1992). These rocks are centered about 80 km south of the suture zone and pass north into 812–810 Ma diorite and granodiorite (Adaiamet and Talal plutons) (Schandelmeier et al., 1994) and, adjacent to the suture zone, into autochthonous 790 Ma bimodal volcanic rocks (Arbaat group) (Abdelsalam and Stern, 1993a). The Jiddah terrane includes a similar assemblage of gabbro, norite, diorite and tonalite, which passes north into 816–811 Ma quartz diorite, tonalite, trondhjemite and granodiorite intrusions of the Dhukhr (816±3 Ma) and Furayhah batholiths (811±4 Ma) (Calvez and Kemp, 1982; Stoeser and Stacey, 1988) and, toward the shear zone, passes into volcanic rocks of the autochthonous Mahd group (~810–770 Ma) (Fig. 2) and the para-autochthonous Samran group (Fig. 3).

Thrusting and shearing

Structures along the Bi'r Umq-Nakasib shear zone include (1) early folds, thrusts, and strike-slip shears, (2) later cross-cutting brittle-ductile shear zones such as the Raku shear zone in Saudi Arabia (Fig. 2) and the Oko shear zone in Sudan (Abdelsalam, 1994) (Fig. 4), (3) Neoproterozoic III sinistral strike-slip faults of the Najd fault system and (4) Cenozoic faults associated with Red Sea spreading. The early structures are the focus of this section because they show the effects of progressive and(or) combined shortening orthogonal to the trend of the shear zone and horizontal shear along the shear zone. The southwestern limit of the Bi'r Umq-Nakasib shear zone (southwest of the area shown in Fig. 4) is concealed by sand although the shear zone appears to bend toward and may be truncated by a north-trending shear zone in the vicinity of the Nile referred to as the Keraf suture, which is interpreted as one of the youngest (~650–600 Ma) sutures in the ANS (Abdelsalam et al., 1998). East of Bi'r Umq, the Bi'r Umq-Nakasib shear zone is truncated by the Raku and Mandisa faults (Fig. 2), which are part of the complex ~680–650 Ma Hulayfah-Ad Dafinah-Ruwah suture zone (Johnson and Kattan, 2001).

At its southwestern end (west of the area shown in Fig. 4), the northern boundary fault of the Nakasib shear

zone is a northwest-vergent thrust dipping 40°–50° to the southeast; the southern margin is a subvertical dextral shear zone; and the axial part is a flower structure composed of thrusts and synforms and antiforms (Bakeit, 1991; Schandelmeier et al., 1994). As demonstrated by Wipfler (1996), D_1 thrusts and tight to isoclinal, northeast- and southwest-plunging folds were steepened and refolded about co-axial northeast- and southwest-plunging folds during D_2, and were dextrally sheared during D_3, at which time the southern margin of the shear zone became subvertical.

East of the Oko shear zone (Fig. 4), the Nakasib shear zone is bounded by a northwest-dipping thrust on the north and steeply (70°E) northwest-dipping reverse shear zones on the south and its southeastern half has an asymmetric flower-type structure created by the combination of the steeply dipping southern boundary shear zone and moderately dipping (45°) northwest-vergent ophiolitic nappes (Abdelsalam and Stern, 1993b). Non-coaxial shear fabrics are not conspicuous and structures in this section of the shear zone are largely interpreted to be the result of orthogonal shortening and thrusting. It is inferred that the steep reverse faults at the southern margin of the shear zone originated during early (D_1) thrusting as gently northwest-dipping shears and mylonite zones that were rotated and steepened during D_3 (Abdelsalam and Stern, 1993b). F_1 folds, where preserved, are tight to isoclinal, verge to the southeast, and plunge gently southwest. Together with lineations on shear surfaces in the southern boundary fault zone, the fold limbs have down-dip stretching lineations consistent with a phase of early thrusting. D_2 created upright, NE- and SW-plunging F_2 folds that are broadly coaxial with F_1 folds. Continuation of thrusting into D_2 imbricated the ophiolite complexes in the northeastern part of the shear zone and created a tectonic mélange and mylonite. D_3 deformation rotated and steepened D_1/D_2 thrusts at the southern boundary of the shear zone (Abdelsalam and Stern, 1993b) and created gently dipping thrusts in the north.

In the Tharwah area (Fig. 3), the Bi'r Umq shear zone is bounded by steeply dipping shears and thrusts and is inferred to have a flower structure (Johnson, 1998). The most conspicuous regional-scale fold is the southwest plunging (40°–50°) Farasan synform, which has a steeply dipping northwest limb and a more gently dipping southeastern limb truncated by a southeast-vergent thrust along the southern flank of Jabal Farasan. These structures resulted from two phases of progressive deformation involving a large component of non-coaxial strain (Genna, 1995; Bellivier et al., 1997; Johnson, 1998). D_1 caused northeast- and southwest-trending tight to isoclinal F_1 folding and the development of bedding-parallel shear surfaces and moderately dipping thrusts. Folding during D_2 created the Farasan synform, and folded and steepened F_1 folds, thrusts, and shear surfaces about steeply plunging axes. Non-coaxial dextral shear, indicated by S/C fabrics, asymmetrical extensional shear bands, rotated porphyroclasts, and quartz-mosaic ribbons, affected the rocks during both D_1 and D_2 (Johnson, 1998). The Qirba' fault, at the northern margin of the Tharwah ophiolite, records the effect of sinistral and dextral horizontal as well as top-to-the-northwest reverse-slip movements; the Ukaz fault, at the southern margin of the Bi'r Umq shear zone, shows the effect of reverse-slip and dextral horizontal movements.

In the Bi'r Umq area (Fig. 2), the Bi'r Umq shear zone is bounded by steeply dipping shear zones. Along the southern margin, the Bi'r Umq fault dips 50°–70° to the north and is interpreted to be a steeply north-dipping reverse fault; the Wobbe fault is a moderately (40–50°) southwest-dipping reverse fault. The Shuwaykah fault, along the northern margin, is believed to be a high-angle southeast-dipping reverse fault (Johnson et al., 2002). Shear fabrics and stretching lineations indicate D_1 top-to the south reverse dip-slip movement followed by dextral and sinistral D_2 horizontal movement on the Bi'r Umq fault (B. Blasband, written communication, 2001); the kinematics of the Wobbe and Shuwaykah faults are unknown.

Tectonic Implications

In terms of the available geologic information and criteria described above, it is strongly evident that the Bi'r Umq-Nakasib shear zone is a suture. The shear zone includes multiply deformed, greenschist- and locally amphibolite-grade metavolcanic, metasedimentary, and ophiolitic rocks intruded by pre-, syn-, and post-tectonic plutonic rocks, arranged in a distinctive unifying spatial pattern of rock types and structures. Allochthonous ophiolite fragments marking the collapse of an oceanic basin(s) are located along the axis of the shear zone and its northwestern side; allochthonous to para-allochthonous volcanic and intrusive assemblages indicative of active subduction crop out on its southeastern side; and continental-rise deposits are present along its axis. Structurally, the shear zone records the effects of progressive folding, refolding, thrusting, and non-coaxial shearing, and has the characteristics of a shear zone developed during oblique transpression.

The inferred suture extends over 600 km along strike and is one of the longest shear zones in the ANS. As implied by the presence of 780–760 Ma syntectonic plutons, it is also one of the oldest. The approximately 50-million year difference between the age of formation of the oceanic and volcanic rocks along the shear zone

and the age of syntectonic plutonism suggests that terrane convergence and suturing significantly postdated creation of ocean floor in the region and is evidence that terrane convergence and suturing entailed the subduction of relatively old ocean floor rather than closure of a short-lived ocean basin. Undoubtedly some parts of the active margin system along the suture zone underwent extension, as evidenced by the Arbaat group, but it appears that much of the system involved arc convergence rather than back-arc spreading.

Although shear-zone kinematics do not necessarily directly extrapolate to far-field trajectories, the common dextral sense of movement on the Bi'r Umq-Nakasib shear zone suggests a pattern of plate movements in which the Gebeit-Hijaz terrane obliquely converged with the Haya-Jiddah terrane from the northwest (present-day coordinates), at an angle to the orogen front. The 3-dimensional geometry of the suture is unknown because subsurface geophysical information is unavailable, but the length, broadly linear trend, and prevalent steep dip of the shear zone implies that it is a subvertical lithospheric-scale structure. Southerly dips on nappes and shears at its northern margin and northerly dips at its southern margin are consistent with a flower structure (Bakheit, 1991), which, if true, means that the suture zone is rooted between the flanking terranes (Johnson et al., 2002).

On the basis of the relatively old age of the Bi'r Umq-Nakasib shear zone, its location in the core of the ANS, and structural relations with other sutures and terranes, it is inferred that the shear zone and the flanking Gebeit-Hijaz and Haya-Jiddah terranes formed a nucleus around which younger terranes in the ANS amalgamated. This is evidenced by the manner in which the Bi'r Umq-Nakasib suture is perpendicularly truncated by the younger Hulayfah-Ad Dafinah-Ruwah suture on the east (Fig. 1) (Johnson and Kattan, 2001), and possibly by the younger Keraf suture, on the west (Abdelsalam et al., 1998). As a result, the composite terrane created by amalgamation of the Gebeit-Hijaz and Haya-Jiddah terranes along the Bi'r Umq-Nakasib suture is discordantly surrounded by other terranes. The crosscutting orientations of the younger sutures imply, moreoever, that the trajectory of subduction during the process of terrane amalgamation varied with time and that younger terranes possibly converged from different directions than the Gebeit-Hijaz and Haya-Jiddah terranes.

On the regional scale, the Bi'r Umq-Nakasib suture is an important structural element in the ANS and marks the onset of arc-arc collision and the beginning of Neoproterozoic terrane convergence in the northern part of the EAO (Johnson and Woldehaimanot, 2003). On the global scale, it is arguably the best-exposed Neoproterozoic suture in the world. It provides clear evidence for plate-tectonic processes during the late Precambrian, and warrants detailed study as a type Neoproterozoic suture. One general outcome of such study already known is that the Bi'r Umq-Nakasib suture and other sutures in the ANS are part of a ~250-million year period of multiple crustal accretions (Johnson and Woldehaimanot, 2003) and a component of a tectonic history that included concurrent phases of deformation, metamorphism, uplift and extension as well as subduction. Establishing the details of this tectonic history is the focus of ongoing research by geoscientists in both Arabian and Nubian sectors of the ANS, and many issues of structure, geochronology and tectonic setting remain unresolved. Beginning with the recognition of the nuclear position of the Bi'r Umq-Nakasib suture in the ANS, it is likely that further work will demonstrate that the ANS is not the product of a simple Wilson cycle of oceanic opening and closing, but reflects the complex accretion of multiple crustal blocks. Complex, multiple accretions are indicated, for example, by paleomagnetic studies in the blocks that make up East Gondwana (Meert, 2002). Similar multiple accretions may likewise be an explanation for the variations in convergence trajectories noted here, creating a heterogeneous strain field that would account for the observed structural discordances, in contrast to the more homogeneous strain field expected to result from the convergence of large, already amalgamated, continental-scale crustal blocks of East and West Gondwana as envisaged in most existing models of ANS accretion.

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