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The Neoprotorozoic Keraf Suture in NE Sudan: Sinistral Transpression along the Eastern Margin of West Gondwana

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The Neoproterozoic Keraf Suture in NE Sudan: Sinistral Transpression along the Eastern Margin of West Gondwana[1]

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ABSTRACT

The Keraf Suture, formed during the Neoproterozoic consolidation of Gondwana, is a ~500 km long, ~50 km wide, N-trending suture between the Neoproterozoic Arabian-Nubian Shield in the east and the older Nile Craton to the west. The Keraf Suture is superimposed on E- and NE-trending structures on both sides. The northern part of the suture is dominated by N-trending, upright folds, whereas the southern part is characterized by N- and NNW-trending, sinistral, strike-slip faults. A major antiform defines a structural divide between the northern and southern parts of the suture. $^{40}Ar/^{39}Ar$ ages on biotite and hornblendes separated from a deformed granitic body indicate that the sinistral movement along the N- and NNW-trending faults took place at ~580 Ma. The difference in structural styles along strike is due to formation of the Keraf Suture by sinistral transpression, which accompanied early NW-SE oblique collision between East and West Gondwana at ~650–600 Ma and terminal collision at ~580 Ma.

Introduction

The supercontinent of Greater Gondwana formed by collision between East and West Gondwana (figure 1a) at ~650–600 Ma after consumption of the Neoproterozoic ''Mozambique Ocean'' (Stern 1994). This resulted in the formation of the ~5000 km long East African Orogen, which comprises the Arabian-Nubian Shield (figure 1b) in the north and the Mozambique Belt to the south (Stern 1994). Continental collision occurred in the south along the Mozambique Belt, whereas remnants of the ancient Mozambique Ocean were preserved in the north as intra-oceanic island arc/back-arc/ophiolite assemblages that now define the Arabian-Nubian Shield (Burke and Sengor 1986).

The Neoproterozoic crust in the Arabian-Nubian Shield consists of ~900–550 Ma arc volcanics and calc-alkaline batholithic granitoids, which comprise terranes welded together along E- and NE-trending, ophiolite-decorated arc-arc sutures (figure 1b; for summary see Stern 1994 and Abdelsalam and Stern 1996a). This Neoproterozoic crust is sandwiched between older continental fragments of East and West Gondwana (figure 1a). West Gondwana in NE Africa is represented by the Paleoproterozoic and Mesoproterozoic crust of the Nile Craton (figure 1b; Harris et al. 1984; Schandelmeier et al. 1988; Harms et al. 1990; Sultan et al. 1993). However, the Nile Craton was pervasively reset during the Neoproterozoic through metamorphism and granitic emplacement (Ries et al. 1985; Stern et al. 1994), or opening and closing of aulacogen-like oceanic reentrants as exemplified by the Atmur-Delgo Suture (figure 1c; Abdel-Rahman et al. 1990; Schandelmeier et al. 1993; Denkler et al. 1994; Harms et al. 1994; Stern et al. 1994).

The location, nature and deformation history of the boundary between the Arabian-Nubian Shield and the Nile Craton are controversial topics. Previous attempts to define this boundary were made largely on the basis of lithological or isotopic differences (Vail 1983; 1985; Almond and Ahmed 1987; Schandelmeier et al. 1988; Dixon and Golombek 1988; Sultan et al. 1990, 1992, 1994; Abdelsalam and Dawoud 1991). The tectonic evolution of this boundary in northern Sudan remains poorly understood because of its partial burial under the sand sheets of the Nubian Desert. Almond and Ahmed (1987) identified a N-S trending, subvertical shear

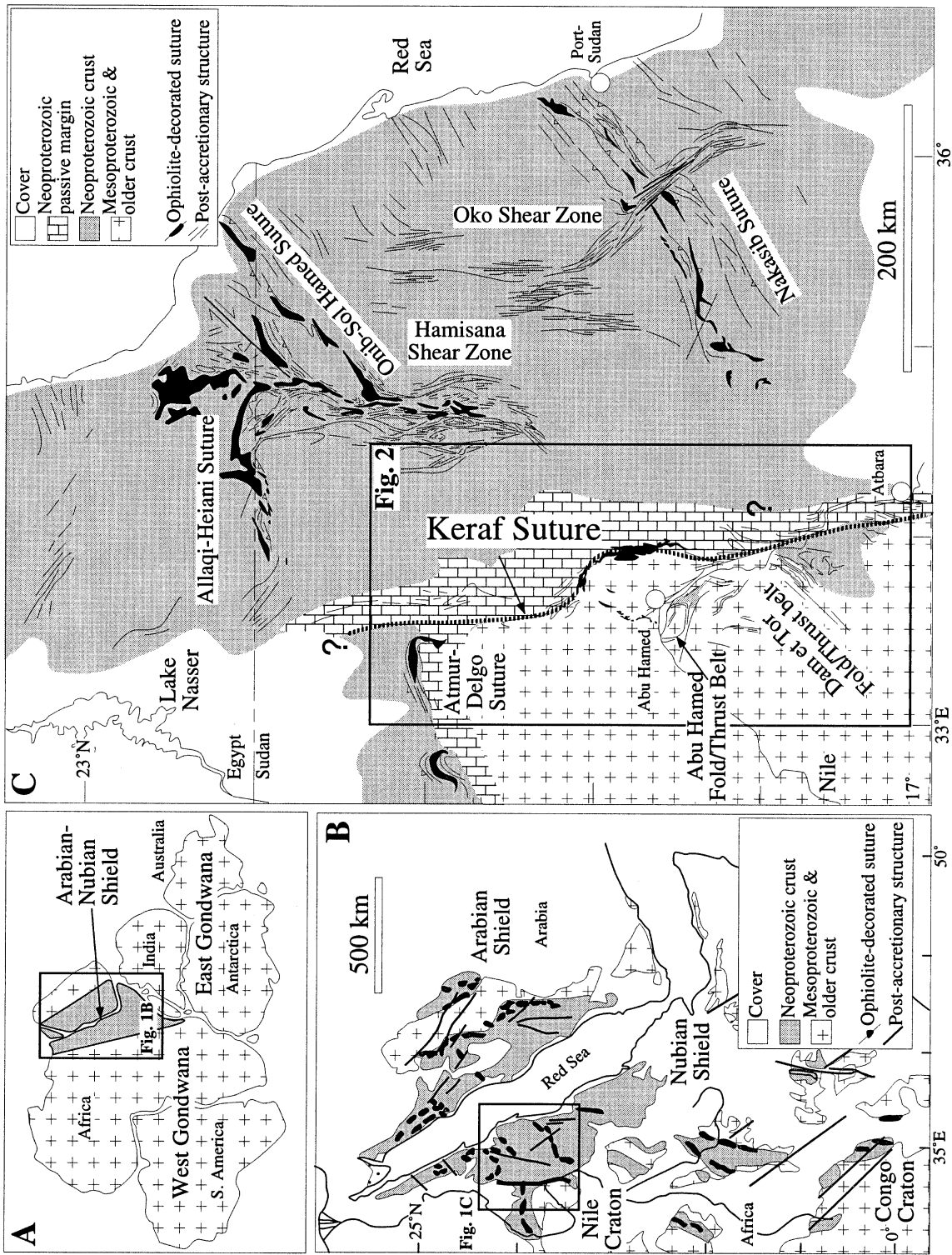**Figure 1.** (*a*) Location of the Arabian-Nubian Shield between East and West Gondwana, simplified after Unrug (1997). (*b*) The Arabian Nubian Shield and parts of continental fragments of East and West Gondwana, simplified after Stern (1994). (*c*) Structural features in the western part of the Arabian-Nubian Shield and the eastern part of the Nile Craton. Note the location of the Keraf Suture between the two crustal blocks.

zone near Abu Hamed (figure 1b) and named it the Keraf Zone. They noted that this shear zone is decorated with small lenses of ultramafic rocks and separates high-grade rocks in the west from low-grade rocks in east (figure 1c). Further identification of ophiolitic rocks along the eastern flank of the Keraf Zone (figure 2; Abdel-Rahman et al. 1993) led to the proposition that it marks an arc-continental suture termed the Keraf Suture (KS) (Stern 1994; Abdelsalam and Stern 1996a). Shuttle Imaging Radar data enabled tracing structures in the KS for ~550 km from the Sudanese/Egyptian border south to the vicinity of Atbara, where the structure is lost beneath Phanerozoic sediments (Abdelsalam et al. 1995; Abdelsalam and Stern 1996b). These radar images provided base maps for our structural studies in the KS. The northern continuation of the suture is buried under Cretaceous sandstone, which crops out around the Sudanese/Egyptian border (figure 1c).

This work presents structural and geochronological results from the KS and adjacent areas. These results are based on interpretation of Shuttle Imaging Radar (SIR) C/X Synthetic Aperture Radar (SAR) data, ground investigation, and $^{40}Ar/^{39}Ar$ dating on biotite and hornblende separated from a deformed granite located within the KS. Results from the northern part of the KS have been published previously by Schandelmeier et al. (1994) and Abdelsalam et al. (1995). Techniques used to map major structures in the KS based on SIR-C/X-SAR imagery acquired during two flights of the NASA shuttle Endeavor are outlined in Abdelsalam and Stern (1996b). The present work builds on an earlier study of the northern KS (Abdelsalam et al. 1995) and aims at: (1) understanding the structural evolution and age of deformation of the KS, and (2) interpreting its significance for the nature of the Neoproterozoic collision between East and West Gondwana.

Tectonic Setting of the Keraf Suture

The KS is a ~550 km long, ~50 km wide deformational belt between Neoproterozoic juvenile crust of the Arabian-Nubian Shield in the east and Paleoproterozoic and Mesoproterozoic crust of the Nile Craton to the west (figure 2). The KS is dominated by N-trending structures that truncate older E- and NE-trending structures in the Nile Craton. To the east, the E-trending Allaqi-Heiani Suture and the NE-trending Nakasib Suture approach the KS at almost right angles (figure 1c), but relationships between these structures are not exposed.

The eastern and western limits of the northern part of the KS are confined to a ~50 km wide, weakly metamorphosed (greenschist facies) belt of carbonate-rich turbidites (figure 2; Stern et al. 1993; Abdelsalam et al. 1995). These carbonates represent a slope facies reflecting development of a passive margin on the eastern flank of the Nile Craton about 800 Ma (Stern et al. 1993; Schandelmeier et al. 1994). The southern KS is dominated by intercalation of medium-grade (amphibolite facies) supracrustal rocks that include paragneisses (~55%), marbles (~40%), and amphibolite (~5%). The western boundary of the southern KS is marked by N- and NNW-trending, sinistral, strike-slip faults (figure 2), but the exact location of the eastern limit of the southern KS is not apparent due to poor exposure. Lithological differences along strike of the KS might reflect variation in sedimentation: carbonate sediments dominate in the northern part whereas both carbonates and clastic sediments are found in the south. Differential metamorphism or erosion has exposed greenschist facies assemblages in the north and amphibolite facies assemblages in the south.

Structural Features

In addition to the lithologic and metamorphic differences, structural styles vary significantly along strike in the KS. Structures in the north are dominated by N-trending, upright folds (Abdelsalam et al. 1995), whereas deformation in the south is characterized by N- and NNW-trending, sinistral strike-slip faults and shear zones. The Abu Hamed Antiform (figure 2) defines the transition between the northern and southern parts of the KS. Because of differences in structural styles along strike, the KS is divided into northern, central, and southern segments. In spite of these along-strike differences, the N-trending structure of the KS is everywhere younger than the E- and NE-trending structures of the Nile Craton to the west (figure 2). For this reason, structures in the region are divided into pre-Keraf and Keraf structures.

Pre-Keraf Structures. Pre-Keraf structures are best preserved in the Nubian and Bayuda Deserts to the west of the KS. This region is dominated by medium- to high-grade gneisses of Paleoproterozoic and Mesoproterozoic age and associated metasedimentary and metavolcanic cover. In the Nubian Desert, the Atmur-Delgo Suture crops out as a discrete ENE-trending, ophiolite-decorated structure and is oriented at a high angle to the N-trending KS (Schandelmeier et al. 1994). Medium- to high-grade gneisses and supracrustal rocks of the Bayuda Desert are dominated by E- to NE-trending structures,
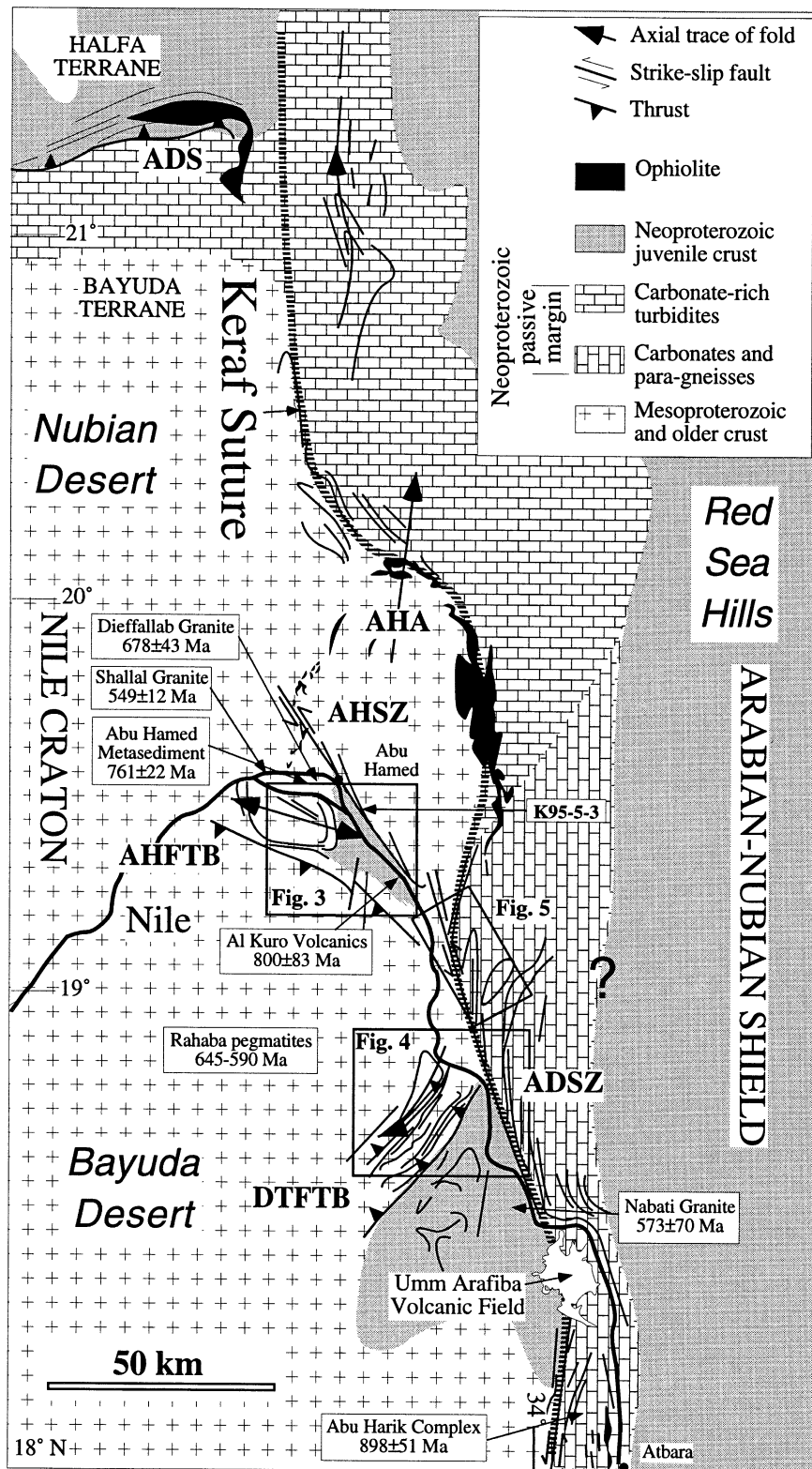
Figure 2. The main structural features in the Keraf Suture and surrounding areas. ADS = Atmur-Delgo Suture; AHA = Abu Hamed Antiform; AHSZ = Abu Hamed Shear Zone; AHFTB = Abu Hamed Fold/Thrust Belt; ADSZ = Abu Dis Shear Zone; and DTFTB = Dam et Tor Fold/Thrust Belt. Areas of detailed structural work are outlined by boxes. Geochronological data are also shown (see text for references). The western limit of deformation related to the Keraf Suture is shown by heavy dashed line. Structures related to the suture are confined to a ~50 km wide zone which mostly coincides with the carbonate-rich turbidite and carbonate and paragneisses belt. The Abu Hamed Antiform (AHA) approximates a structural divide between the northern and southern Keraf Suture.

as exemplified by the Abu Hamed and Dam et Tor Fold/Thrust Belts (figure 2).

The Atmur-Delgo Suture. The evolution of the Atmur-Delgo Suture and its structural relationship with the KS are outlined by Schandelmeier et al. (1994) and Abdelsalam et al. (1995). This suture separates the Halfa terrane in the north from the Bayuda terrane to the south and is defined by ophiolitic remnants (figure 2) that extend in a WSW-direction for at least 100 km (Schandelmeier et al. 1994). Ophiolitic remnants occur as S-verging nappes dominated by ophiolitic melanges (Schandelmeier et al. 1994). These nappes structurally overly carbonate-rich turbidites to the south (Stern et al. 1993; Schandelmeier et al. 1994).

Early structures of the Atmur-Delgo Suture reflect the development of the S-verging ophiolitic nappes (Schandelmeier et al. 1994). Associated with these nappes are small-scale, tight to isoclinal folds, the axial surfaces of which trend ENE and generally dip shallowly to the NNW. These folds are locally steepened or overturned by younger co-axial upright folds. Both fold sets are strongly developed in the ophiolitic nappes, become less well developed in the turbidite-rich carbonates to the south, and finally disappear by about 20°30′N. Superimposition of co-axial deformation suggests that nappes and upright folds reflect progressive changes in deformational style, resulting from the same tectonic pulse. Schandelmeier et al. (1994) proposed that the early structures in the Atmur-Delgo Suture are related to early thrust movement in a N-dipping subduction zone, whereas the late folds are related to terminal collision between the Halfa and Bayuda terranes (figure 2).

The Abu Hamed Fold/Thrust Belt. This structure lies in the northeastern part of the Bayuda Desert (figure 2), and is defined by a biotite-hornblende gneissic core surrounded by layered supracrustal rocks, including mica and graphite schist with marble and quartzite bands (figure 3a; Ries et al. 1985; Meinhold 1979). The central part of the belt is a dome developed by superimposition of a N-trending antiform on a E-trending antiform. The dome is bounded to the south by a N-verging thrust (figure 3a, b), decorated by talc-carbonate schist. This thrust juxtaposes quartzofeldspathic gneisses of the Bayuda Desert with supracrustal rocks of the Abu Hamed Fold/Thrust Belt. To the east, the rocks of the Abu Hamed Fold/Thrust Belt are bounded by a triangular body of low-grade greenschist facies volcanosedimentary rocks (figure 3a). The eastern boundary of these low-grade rocks is defined by the Abu Hamed Shear Zone of the KS (figures 2 and 3a, c).

The dominant structure in the Abu Hamed Fold/Thrust Belt is a subhorizontal E-trending antiform (figure 3a). The eastern part of the antiform plunges ~2° to the east (figure 3d). The E-trending antiform deforms foliations and intrafolial folds. These have various trends depending on their positions with respect to the antiform. Complex interference folds developed when the older intrafolial folds were refolded by second- and third-order folds associated with the E-trending antiform. A younger set of N- and S-plunging cross-folds deforms older foliation and axial planar cleavage associated with the E-trending antiform. These cross-folds are related to the N-trending antiform that was superimposed on the E-trending antiform to produce the domical structure, and almost certainly represent Keraf structures.

The Dam et Tor Fold/Thrust Belt. This structure occupies the east-central part of the Bayuda Desert where it extends NE-SW for >40 km (figures 2 and 4a). Vail (1971) first mapped the region that we call the Az Zuma Interference Fold and recognized at least three phases of deformation. The Dam Et Tor Fold/Thrust Belt is defined by high-grade supracrustal rocks (Vail 1971) dominated by garnet- and kyanite-bearing schists thrust SE over low-grade, greenschist facies volcanosedimentary rocks (figure 4a). This thrust is partially decorated by talc-carbonate schist. The northern boundary of the Dam et Tor Fold/Thrust Belt is defined by another SE-verging thrust within the high-grade sequence (figure 4a). This thrust is also partially decorated by talc-carbonate schist. The Az Zuma Interference Fold is a mushroom structure that plunges ~20° to the SW (figure 4c); it reflects the superimposition of a NE-trending antiform on an older NNW-trending synform.

The central part of the Dam et Tor Fold/Thrust Belt is occupied by a NE-trending synform, the northeastern part of which plunges to the SW (figure 4a, d) and shows a hinge zone with a rounded closure (figure 4a). The southwestern closure of the synform plunges NW and is defined by N- and NE-trending hinge zones (figure 4a, e). This structure reflects superimposition of a NNW-trending fold of probable Keraf age on a NE-trending pre-Keraf synform.

The Dam et Tor Fold/Thrust Belt extends NE for ~5 km east of the Nile before it is truncated by the Abu Dis Shear Zone (figure 4a), the most prominent structure in the KS (figure 2). The southern part of the Abu Dis Shear Zone also defines the eastern boundary of the volcanosedimentary domain south of the Dam et Tor Fold/Thrust Belt (figure 4a). N-plunging tight folds (figure 4a, f)
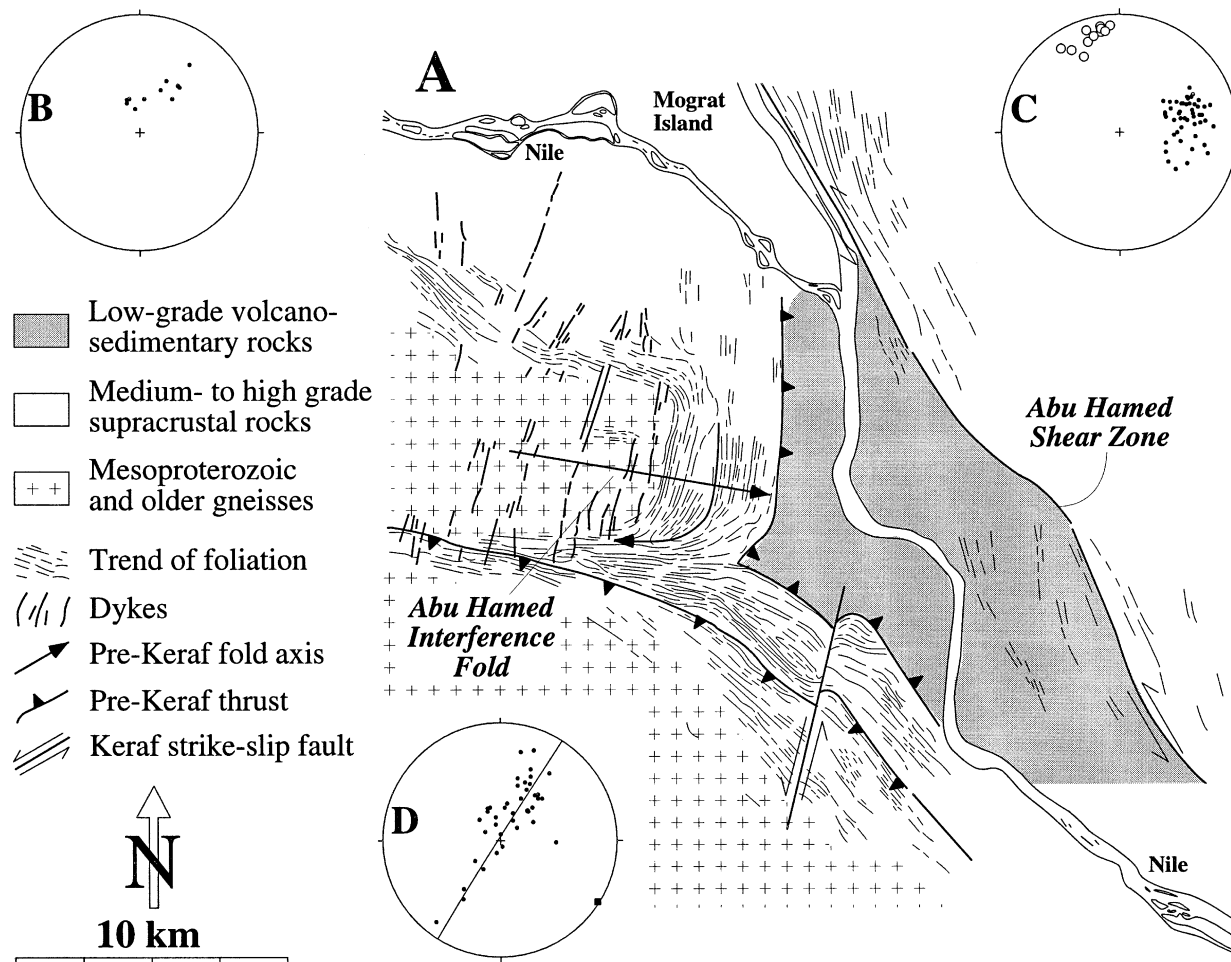
Figure 3. (a) The Abu Hamed Fold/Thrust Belt. (b) Plot of poles to foliation from along the thrust that separates the supracrustal rocks of the Abu Hamed Fold/Thrust Belt from the Paleoproterozoic and Mesoproterozoic gneissic terrane to the south. (c) Plot of poles to mylonite fabric and associated stretching lineation from along the Abu Hamed Shear Zone. (d) π-diagram of poles to foliation from the eastern part of the fold at the core of the Abu Hamed Fold/Thrust Belt. Plots are in equal-area stereonet. Poles to foliation are shown as solid circles, stretching lineation as open circles, and π-axes as solid squares.

probably induced by sinistral shear along the Abu Dis Shear Zone (discussed below), deform the low-grade volcanosedimentary rocks.

Keraf Structures. The northern KS is dominated by upright N-S folds (Abdelsalam et al. 1995), whereas deformation in the southern KS is dominated by N- and NNW-trending, sinistral, strike-slip faults and shear zones (figure 2). The Abu Hamed Antiform (figure 2) forms a structural divide between the northern and southern KS.

The northern Keraf Suture. Well-developed N-trending folds and associated axial planar cleavage represent the early stage in the evolution of the northern KS. These were refolded by co-axial, but not co-planar, W-verging tight folds. Both N-S fold

sets are refolded along axes that plunge steeply to the E and ENE (Abdelsalam et al. 1995). The last phase of deformation in the northern KS is in the form of conjugate sets of mesoscopic NE-trending dextral and NW-trending sinistral strike-slip faults. Some shear zones, however, are N-trending and contain kinematic indicators (bookshelf sliding of broken boudins and rotated pressure fringes) for both dextral and sinistral strike-slip movement. Cumulative displacement along these shear zones might have resulted in a minor sinistral displacement along the northern KS.

The central Keraf Suture. The Abu Hamed Antiform is a broad dome NNE of the town of Abu Hamed (figure 2) where it occupies an area of
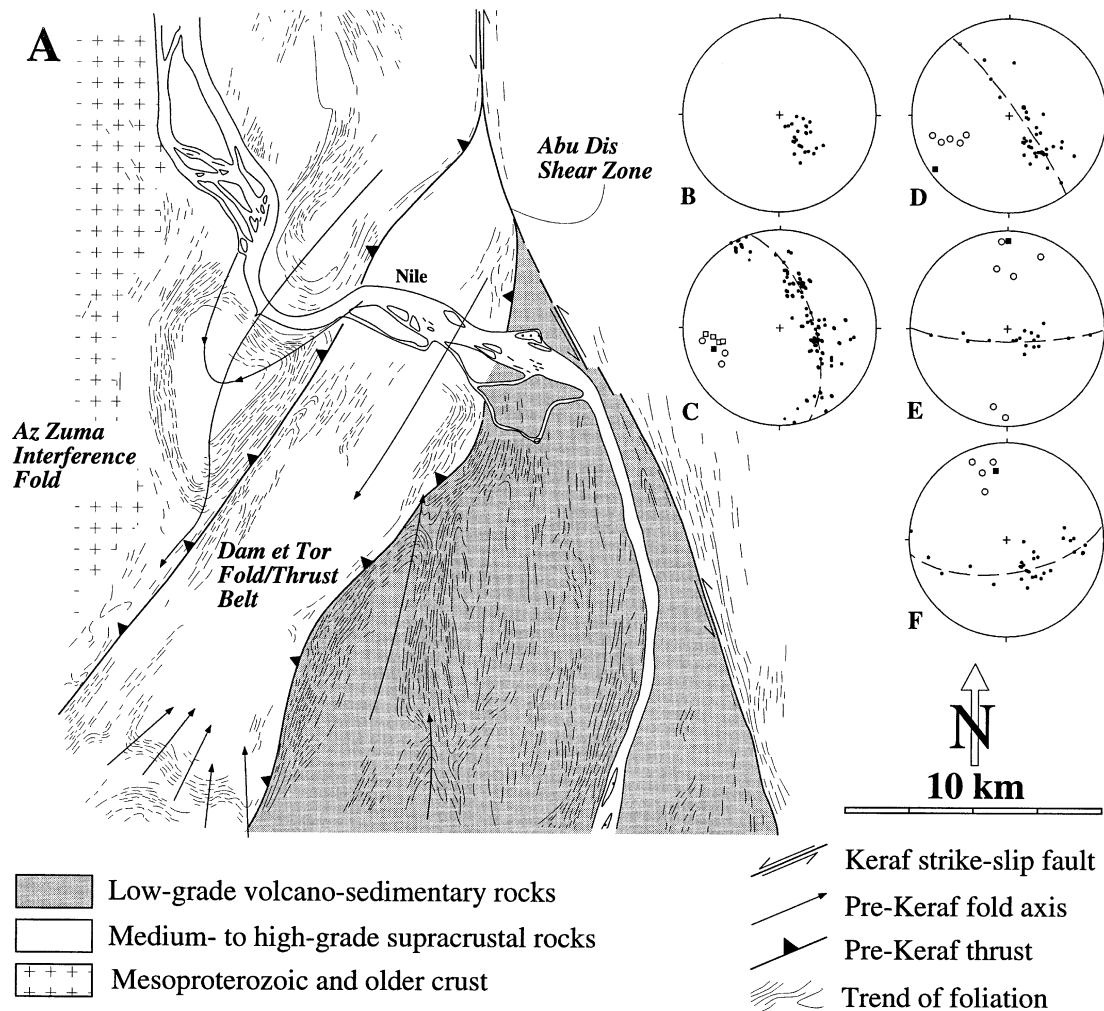
Figure 4. (*a*) The Dam et Tor Fold/Thrust Belt. (*b*) Plot of poles to foliation from along the thrust which separates the high-grade supracrustal rocks of the Dam et Tor Fold/Thrust Belt from the low-grade volcanosedimentary rocks to the south. (*c*) π-diagram of poles to foliation from the Az Zuma Interference Fold. (*d*) π-diagram of poles to foliation from the northeastern part of the synformal structural basin in the center of the Dam et Tor Fold/Thrust Belt. (*e*) π-diagram of poles to foliation from the southwestern part of the synformal structural basin in the center of the Dam et Tor Fold/Thrust Belt. (*f*) π-diagram of poles to foliation from the low-grade volcanosedimentary rocks to the south of the Dam et Tor Fold/Thrust Belt. Plots are in equal-area stereonet. Poles to foliation are shown as solid circles, minor fold axes as open circles, intersection lineation as open squares, and π-axes as solid squares.

~3500 km². The antiform forms a lithologic, metamorphic, and structural divide, separating the greenschist-facies carbonate-rich turbidites of the northern KS from the amphibolite-facies paragneisses and marbles of the southern KS.

The Abu Hamed Antiform plunges moderately (~40°) to the north and verges to the W. The core of the antiform is dominated by medium- to high-grade quartzofeldspathic gneisses and foliated granites. These are rimmed by low-grade, greenschist facies metamorphic rocks, including immature vol-

canogenic sediments such as polymict conglomerates and highly sheared and carbonated serpentinites of inferred ophiolitic origin (Abdel-Rahman et al. 1993). The ophiolite and low-grade assemblages were thrust from the east over the quartzofeldspathic gneisses before being deformed with them about the N-plunging antiform.

The southern Keraf Suture. Deformation in the southern KS is dominated by N- and NNW-trending faults. Kinematic indicators (S-C fabric, rotated feldspar crystals, and bookshelf sliding of broken

boudins) along these shear zones indicate dominant sinistral strike-slip movement. In oriented thin sections the sinistral sense of shearing is indicated by microscopic S-folds and mica-fish structures in biotite grains. Marble bands within the shear zones show reclined S-folds and tensional gashes indicative of sinistral sense of shearing. However, due to the absence of marker beds, it was not possible to constrain the magnitude of strike-slip displacements along these faults. The two most important of these are the Abu Hamed and Abu Dis Shear Zones (figure 2). These two strands of a single sinistral shear system together can be traced for over 200 km from north of Abu Hamed south to the vicinity of Atbara.

The Abu Hamed Shear Zone is a ~70 km long, NNW-trending, sinistral shear system that lies immediately to the east of the Nile (figure 2). The central part of the shear zone is dominated by brittle deformation. However, the northern part of the shear zone ductily transposes the western limb of the Abu Hamed Antiform (figure 2). How the shear zone ends in the north is obscured by Quaternary deposits. Part of the Abu Hamed Shear Zone is defined by a narrow zone (~50 m) of well-developed mylonite fabric that dips steeply to the west (figure 3c). The foliation planes contain subhorizontal stretching lineation (figure 3c). The eastern edge of the shear zone is defined by planar fabric folded about N-trending axes. These folds are interpreted as flattening zones developed due to secondary E-W-shortening, which accompanied the sinistral strike-slip movement. The Abu Hamed shear zone widens to the south, where it is defined by a ~500 m wide mylonitic zone that bends east before it translates into a complex set of folds and mesoscopic shear zones as it approaches the Abu Dis Shear Zone (figures 2 and 5a).

The Abu Dis Shear Shear Zone is a N-trending, ~150 km long, sinistral shear system (figures 2 and 5a). The northern part of the shear zone truncates the eastern limb of the Abu Hamed Antiform. Farther north, the transcurrent movement in the Abu Dis Shear Zone might have been accommodated by complex folding observed within the quartzofeldspathic core of the Abu Hamed Antiform. The southern end of the shear zone crosses the Nile and disappears under the Umm Arafiba volcanic field (figure 2). A NNE-trending sinistral shear zone extends south of the Umm Arafiba volcanic field and almost certainly represents the continuation of the Abu Dis Shear Zone (figure 2). The major part of the Abu Dis Shear Zone is defined by a narrow (~50 m wide) band of highly mylonitized, pink granite that extends along strike for >25 km. The mylonite

fabric dips consistently to the west and contains subhorizontal stretching lineation (figure 5b). Locally, the mylonite fabric contains down-dip lineation younger than the subhorizontal lineation. The down-dip foliation is defined by growth of fibrous quartz on foliation plane. We interpret the subhorizontal lineation as related to the sinistral movement along the Abu Dis Shear Zone, whereas the down-dip lineation may be associated with subsidence in the Amaki pull-apart basin (discussed below).

The mylonite fabric in the granite is defined by alternation of pink bands dominated by K-feldspar and quartz and darker bands rich in biotite and hornblende. Under the microscope, the pink bands are noticeably finer-grained compared to the darker bands, and feldspar and quartz crystals are free of internal deformation, suggesting complete dynamic recrystallization. Larger quartz and feldspar crystals in the darker bands are surrounded by dynamically recrystallized neocrystals, which rim relic grains. Mafic minerals are free of internal deformation, which suggests that they have been completely recrystallized. In some samples, however, mafic minerals define well-developed S-C fabric and microscopic S-folds, which indicate a sinistral sense of shearing. The consistent definition of the Abu Dis Shear Zone by the highly deformed pink granite suggests that the granite was emplaced during deformation, and that emplacement was controlled by the shear zone.

The region east of the Abu Dis shear zone is dominated by NNE-trending antiforms and synforms (figure 5a). The northernmost synform plunges steeply to the NNW and verges to the west (figure 5c). The southernmost fold is a doubly plunging synform (figure 6a). A major antiform dominates the region between these synforms (figure 5a). The axial planes of these folds trend ~30° to 40° from the trend of the Abu Dis Shear Zone. This suggests domination of NW-SE shortening during the evolution of the shear zone; hence these folds can be interpreted as due to NW-SE compressional stress associated with sinistral movement along the Abu Dis Shear Zone.

Folded but unmetamorphosed sediments referred to as the Amaki Series (Dawoud 1980) crop out west of the Abu Dis Shear Zone, where they define a NNE-elongated, ~30 km long and ~5 km wide basin (figure 5a). The Amaki Series comprises immature and poorly sorted lithic wackes and conglomerates. Most of the conglomeratic clasts (90%) are derived from the mylonite granite defining the Abu Dis Shear Zone.

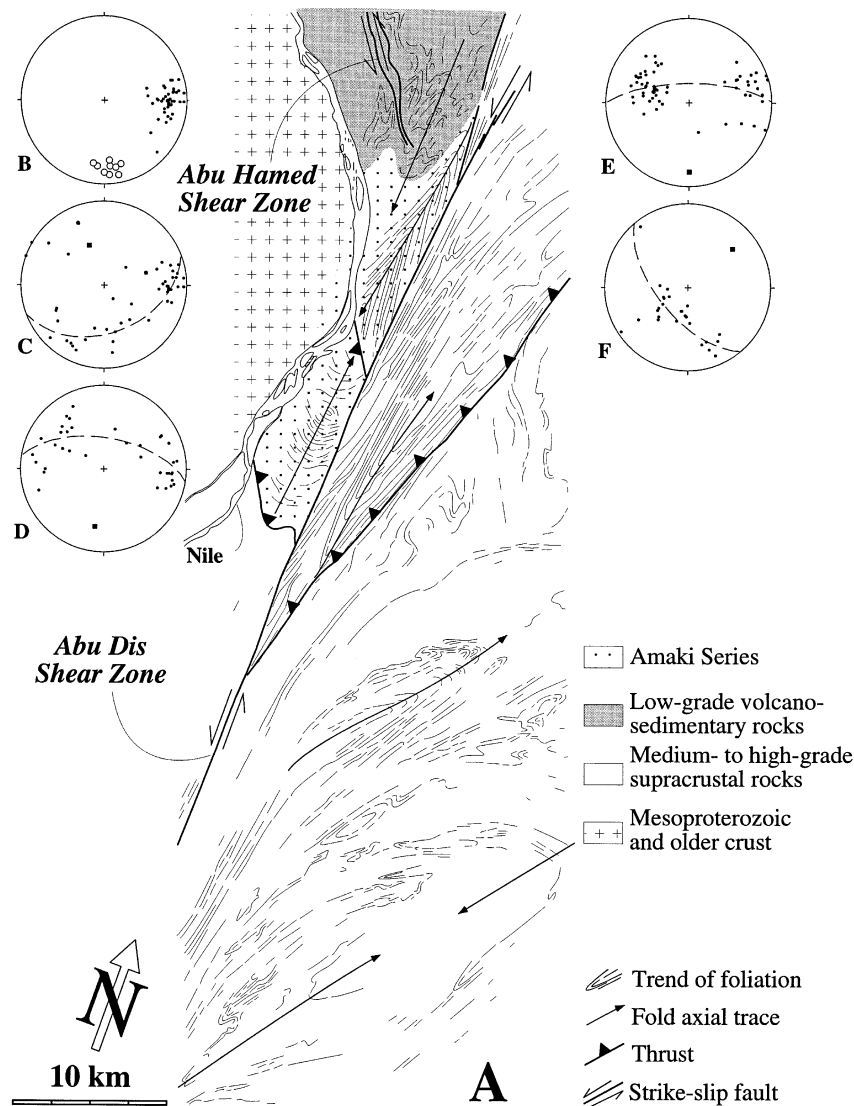The Amaki basin is bounded by a S-verging

Figure 5. (*a*) The Abu Dis Shear Zone. (*b*) Plot of poles to mylonite fabric and associated stretching lineation from along the Abu Dis Shear Zone. (*c*) π-diagram of poles to foliation from the area to the east of the Abu Dis Shear Zone. The folds plunge at ~40° to the NNW, different from the NNE-trend defined by the axial traces of the folds in *a*. This difference indicates that the folds verge to the NW. (*d*) π-diagram of poles to foliation from the area occupied by the low-grade volcanosedimentary rocks at the northern part of *a*. (*e*) π-diagram of poles to bedding planes from the northern part of the Amaki Series. The fold plunges at ~10° to the S. (*f*) π-diagram of poles to bedding planes from the southern part of the Amaki Series. Plots are in equal-area stereonet. Poles to foliation are shown as solid circles, stretching lineation as open circles, and π-axes as solid squares.

thrust in the south and a folded unconformity to the north (figure 5*a*). The S-verging thrust in the south is a tectonic contact between Amaki sediments and amphibolites and gneisses. The folded unconformity in the north suggests deposition of the Amaki Series on top of a low-grade volcanosedimentary sequence dominated by tourmaline-biotite schist. The foliation in these low-grade rocks is deformed into S-plunging folds (figure 5*d*) similar to the northern part of the Amaki Series, where a S-plunging, chevron-type synform deforms the bedding planes (figure 5*e*). The southern part of the Amaki Series is deformed into NE-trending, open, basin-dome interference folds (figure 5*a*, *f*). The boundary between the northern and southern parts is a NE-verging thrust (figure 5*a*).

The Amaki basin is interpreted to have devel-oped in response to a transtensional strain induced by sinistral strike-slip movement along the Abu Dis Shear Zone, for the following reasons: (1) The Amaki basin is bounded by the Abu Dis Shear Zone, and conglomerate is dominated by clasts derived from the mylonite granites of the Abu Dis Shear Zone. (2) Amaki sediments witnessed only one phase of deformation, whereas underlying and adjacent rocks are polydeformed. This suggests that these sediments were deposited after deformation started and witnessed the youngest event of it. (3) The northerly trend of fold axes in the Amaki sediments is in agreement with those expected to develop as a response to compression imposed by an overall NW-SE transpressive regime that accompanied a late stage in the kinematic evolution of the shear zone system. (4) The late, down-dip linea-

tion in the mylonite granite is consistent with subsidence in the region to the west of the Abu Dis Shear Zone.

Geochronology

Hornblende and biotite separated from a highly deformed granite located within the Abu Hamed Shear Zone were analyzed by the $^{40}Ar/^{39}Ar$ method (McDougall and Harrison 1988). Location of the sample (K95-5-3) is shown in figure 2. This gray granite (35% quartz, 35% K-feldspar, 10% albite, 10% biotite, and 10% hornblende) contains a well-developed, N-trending mylonitic fabric dipping moderately (50°) to the west. We interpret this fabric as having developed during the sinistral movement along the Abu Hamed Shear Zone, as discussed earlier. The biotite and hornblende crystals in sample K95-5-3 are free of internal deformation, which suggests that they were dynamically recrystallized. Electron microprobe analysis of the hornblende shows it to be edenitic in composition with moderate amounts (1.08 to 1.54%, $n = 20$) of K_2O. K_2O in biotite ranges from 8.6 to 9.5%.

$^{40}Ar/^{39}Ar$ analyses were performed at the University of Houston. The samples were heated using a double-vacuum resistance furnace, and the evolved gas measured with a Mass Analyzer Products 215-50 rare gas mass spectrometer. Two size fractions of biotite (125–250 μm and 75–125 μm) and one fraction of hornblende (75–125 μm) were analyzed. Results are presented in table 1 and figure 6. Table 1 can be obtained from *The Journal of Geology* upon request, free of charge. The hornblende yielded an age spectrum with an initial step with an age of 465 Ma followed by the remaining 89.1% of the ^{39}Ar released in 18 steps, having similar ages and an average age of 577 ± 2 Ma (figure 6a). Except for the first step on the fine-grained fraction, the two biotite analyses yielded essentially identical results with the final 86.9% of the gas of the fine fraction giving an average age of 577 ± 2 Ma and the final 92.2% of the gas of the coarse fraction giving an average age of 577 ± 5 Ma (figure 6b, c).

These identical ages for the hornblende and the biotite indicate that this sample cooled very rapidly from ~525 to 325°C, the approximate closure temperature of the hornblende and biotite, respectively, for fast cooling rates (Harrison 1981; Harrison et al. 1985). These results indicate that ductile deformation ceased in the Abu Hamed Shear Zone by ~577 Ma.

Discussion

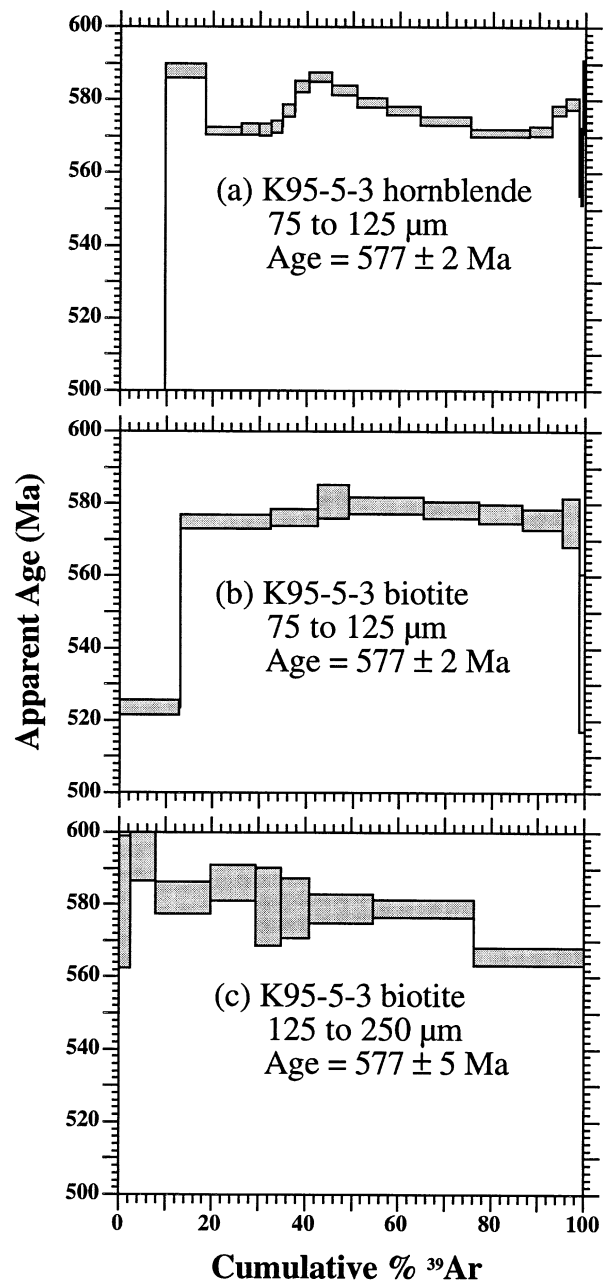The KS is interpreted as a major arc-continental suture defining the eastern margin of West Gondwana

Figure 6. $^{40}Ar/^{39}Ar$ plateau ages for hornblende and biotite from sample K-95-3-3.

(Almond and Ahmed 1987; Stern 1994; Abdelsalam et al. 1995; Abdelsalam and Stern 1996b) for the following reasons: (1) The KS is a major structural feature in NE Africa, which separates crustal blocks with distinctly different geochronological and isotopic characteristics (Stern and Kröner 1993; Stern et al. 1994). (2) Strain localization along the KS indicates an E-W crustal shortening related to collision between the Arabian-Nubian Shield and the Nile Craton (Abdelsalam et al. 1995; Abdelsalam and

Stern 1996b). (3) The presence of dismembered ophiolites thrust westward over the passive margin sequence indicates that a tract of oceanic lithosphere existed between the Arabian-Nubian Shield and the Nile Craton (Abdel-Rahman et al. 1993). Continued shortening resulted in overprinting of the suture by sinistral shear zones. In the following, we integrate our data with previously published results to discuss: (1) the significance of structural styles along the KS; (2) age of deformation in the KS; and (3) tectonic evolution of the KS and adjacent areas.

Significance of Structural Styles. Northern and southern KS have different structural styles. The northern KS is dominated by N-trending upright folds consistent with contraction, whereas the southern KS is characterized by strike-slip faults indicating a transcurrent shear regime. These differences might be due to oblique collision between the Arabian-Nubian Shield and the Nile Craton. The collision imposed an overall NW-SE compression manifested as sinistral transpression. In the northern KS, the sinistral transpressive regime was partitioned into major E-W shortening followed by minor NE-trending, dextral and NW-trending, sinistral strike-slip faults (Abdelsalam et al. 1995). The presence of thick carbonates in the north might have enabled accommodation of strain as ductile deformation (Abdelsalam et al. 1995). In the southern KS, however, strike-slip ductile shear zones might be due to the presence of paragneisses, which are more competent than the carbonates to the north.

The proposition that NW-SE oblique collision is responsible for the formation of the KS agrees with conclusions of other studies on the East African Orogen (Shackleton 1986; Drury and Berhe 1993; Wallbrecker et al. 1993). Oblique collision also explains the evolution of E- and NE-trending structures on both sides of the KS as fold/thrust belts, without the need to call for changing the orientation of the principal axes of regional stress exerted by plate convergence. This is because such oblique collision would translate into NW-SE compression which, in turn, produces orthogonal shortening across E- and NE-trending zones. Hence, the NW-SE oblique convergence between East and West Gondwana could be responsible for the evolution of older E- and NE-trending structures as fold/thrust belts and the younger KS as a sinistral transpression zone.

Age of Deformation. Cross-cutting relationships indicate that the KS post-dates older structures in the Nubian and Bayuda Deserts (figure 2). Previous geochronologic data include: (1) a two-point Rb-Sr whole-rock isochron age of 573 ± 70 Ma (r_i =

0.7043 ± 17) for the post-tectonic Nabati ring complex (figure 2; Barth et al. 1983), a 549 ± 12 Ma Rb-Sr "errorchron" for the post-tectonic Shalul granite, and a 678 ± 43 Ma Rb-Sr isochron age from the syn-tectonic Dieffallab granite west of Abu Hamed (figure 2; Ries et al. 1985); and (2) Rb-Sr errorchron ages of about 900, 800, and 760 Ma for supracrustal rocks including gneisses, volcanics, and metasediments from the Abu Hamed area (figure 2; Ries et al. 1985). These ages bracket both pre-Keraf and Keraf deformation to sometime between 800 and 550 Ma. The post-tectonic Rahaba pegmatites located between the Abu Hamed and the Dam et Tor Fold/Thrust Belts gave K/Ar ages between 645 and 590 Ma (figure 2; Vail and Rex 1970). In the Nubian Desert, a whole-rock Sm/Nd isochron of 752 ± 48 Ma for metagabbro of the Delgo ophiolite provides a lower age limit for deformation along the Atmur-Delgo suture (Harms et al. 1994). The peak metamorphism associated with emplacement of the Atmur-Delgo ophiolite is dated at 702 ± 27 Ma, using the Sm-Nd technique on calc-silicates (Harms et al. 1994). The above summary suggests that pre-Keraf deformation in the Bayuda and Nubian Deserts took place between 750 and 640 Ma.

Although cross-cutting relationship between the KS and the E- and NE-trending structures associated with arc-arc sutures to the east are not exposed, regional considerations indicate that the KS evolved after consolidation of arc terranes in the Arabian-Nubian Shield. E- and NE-trending, arc-arc sutures in the Arabian-Nubian Shield formed between 800 and 700 Ma (Stoeser and Camp 1985; Kröner et al. 1992; Stern and Kröner 1993; Stern 1994).

N-trending shear zones such as the Hamisana Shear Zone superimposed on arc-arc sutures are constrained to have formed between 640 and 600 Ma (Stern et al. 1989). These are interpreted as due to shortening of the Arabian-Nubian Shield during collision between East and West Gondwana (Stern 1994; Abdelsalam and Stern 1996a) and should be similar in age to the KS. Our $^{40}Ar/^{39}Ar$ ages indicate that the last stage of Keraf deformation ended by ~577 Ma, a time consistent with regional activity of Najd strike-slip deformation (540 to 620 Ma; Stern 1984); hence Keraf deformation might have started as early as 640 Ma and ended by ~580 Ma. Our results also indicate that the Amaki sediments were deposited about 580 Ma.

Tectonic Evolution. The tectonic evolution of the region around the Keraf Suture can be summarized as follows:

1) Paleoproterozoic and Mesoproterozoic continental crust of the Nile Craton and juvenile Neoproterozoic crust of the Arabian-Nubian Shield
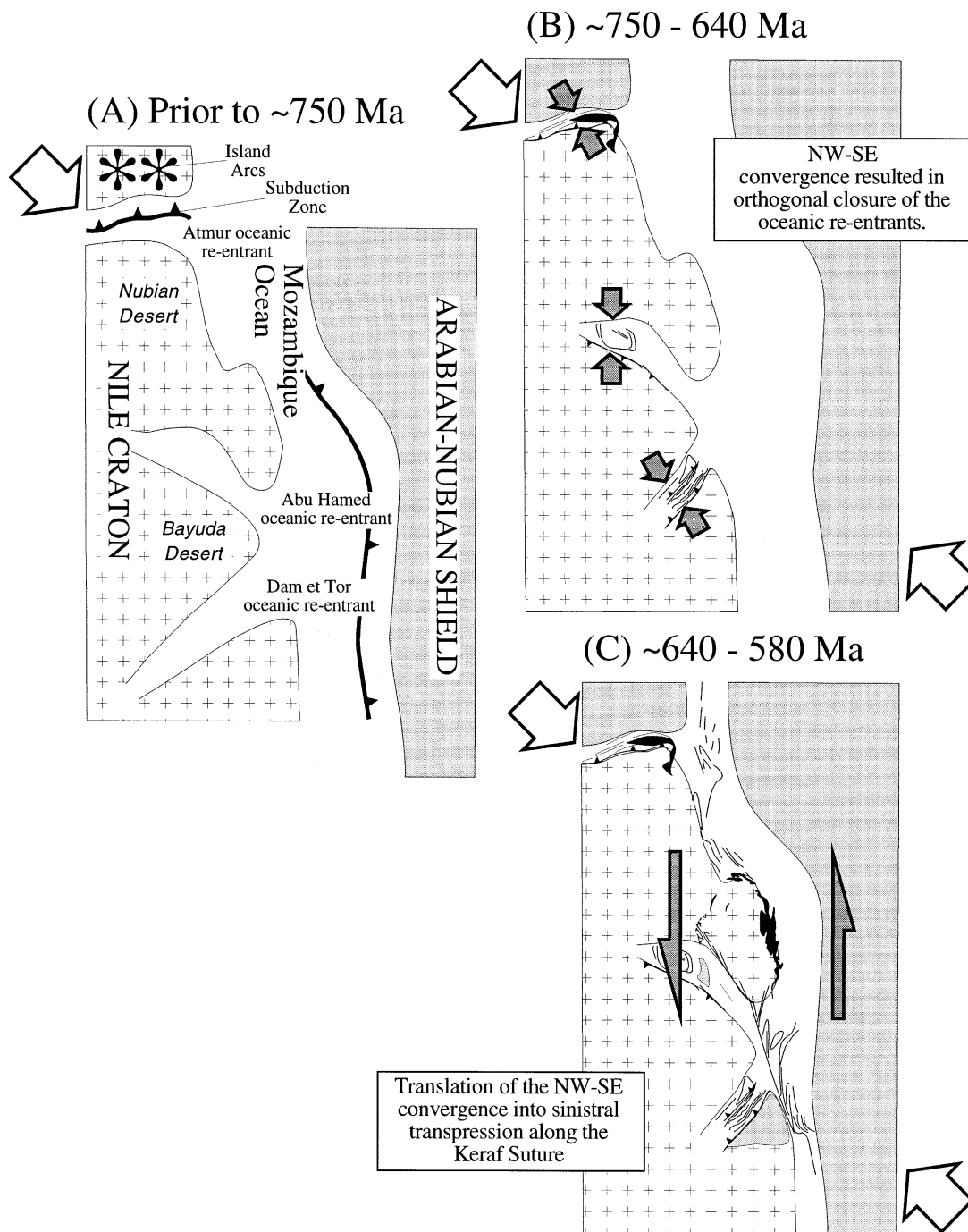
Figure 7. A three-step, map-like model illustrating the tectonic evolution of the pre-Keraf and Keraf structures as products of oblique collision between the Arabian-Nubian Shield and the Nile Craton. (*a*) Pre-collision configuration of the Arabian-Nubian Shield and the Nile Craton with part of the Mozambique Ocean between them. Note the presence of oceanic reentrants along the present extent of the Atmur-Delgo Suture and the Abu Hamed and Dam et Tor Fold/Thrust Belts. The Atmur-Delgo reentrant is different from the Abu Hamed and Dam et Tor reentrants in that it is associated with a N-dipping subduction zone. (*b*) Closure of the oceanic reentrants due to oblique convergence. (*c*) Closure of the oceanic basin between the Arabian-Nubian Shield and the Nile Craton. The NW-SE convergence was translated into sinistral transpression along the Keraf Suture.

were deformed prior to Keraf deformation. By ~700 Ma, the Arabian-Nubian Shield had emerged as a super-terrane composed of intra-oceanic arc systems. These formed within the Mozambique Ocean, which developed between East and West Gondwana (Stern 1994). The eastern forelands of West Gondwana were close to the present location of the Nile Valley (Stern 1994).

Localization of strain along E- and NE-trending belts in the Arabian-Nubian Shield reflects collision between intra-oceanic arc terranes (for summary see Stern 1994; Abdelsalam and Stern 1996a). However, localization of strain along E- and NE-trending belts in the Nile Craton is not fully understood. Schandelmeier et al. (1994) proposed that the E-trending Atmur-Delgo Suture (figure 2) manifests closing of an aulacogen-like oceanic reentrant that extended from the Mozambique Ocean into the interior of the Nile Craton. It remains to be explained why strain was localized along the Abu Hamed and the Dam et Tor Fold/Thrust Belts. It is possible that oceanic reentrants similar to that responsible for the Atmur-Delgo Suture existed along the present trend of the Abu Hamed and the Dam et Tor Fold/Thrust Belts (figure 7a). In contrast to the Atmur-Delgo Suture, defined by unequivocal ophiolitic nappes, the Abu Hamed and the Dam et Tor Fold/Thrust Belts are decorated by scraps of talc-carbonate schist which may or may not be derived from ophiolitic protolith. Shortening across the E- and NE-trending structures on both sides of the KS was accommodated in the form of thrust stacking and development of E-trending folds (figure 7b). We interpret this shortening as due to NW-SE oblique convergence between East and West Gondwana (figure 7b). Oblique convergence produced orthogonal shortening across E- and NE-oriented zones but was partitioned into sinistral transpression along the N-trending KS (figure 7c).

2) An oceanic basin existed between the Arabian-Nubian Shield super-terrane and the Nile Craton (figure 7a) and became the site for accumulation of carbonate and clastic sediments. Carbonate-rich turbidites dominated the northern part of the basin, whereas interbedded sequences of carbonate and clastic sediments accumulated in the south. Metamorphism induced during collision between the Arabian-Nubian Shield and the Nile Craton yielded paragneisses and marbles in the south and the weakly metamorphosed carbonate-rich turbidites to the north. NW-SE oblique collision between the Arabian-Nubian Shield and the Nile Craton at ~580 Ma gave rise to the formation of the KS as an arc-continental suture involving sinistral transpression (figure 7c). This produced N-trending, upright folds in the north and N- and NNW-trending, sinistral, strike-slip faults in the south (figure 7c).

The sinistral strike-slip movement in the KS was accompanied by local transpressional and transtensional tectonic regimes. Transpression resulted in the formation of secondary E-W to NW-SE shortening that produced N- to NE-trending folds on both sides of the faults. These were superimposed on the earlier E- to NE-trending folds to the west of the KS and produced interference folds along the western margin of the KS. A local transtensional tectonic regime produced the Amaki pull-apart basin. Syntectonic sediments derived mainly from along the Abu Dis Shear Zone accumulated in this basin. Continued deformation folded the Amaki sediments about N- and NE-trending fold axes.

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