Journal of the Geological Society, *London*, Vol. **157,** 2000, pp. 615–628. Printed in Great Britain.

Late Proterozoic extensional collapse in the Arabian–Nubian Shield

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Abstract: A structural and petrological study of the Late Proterozoic rocks in the Wadi Kid area, Sinai, Egypt indicates the presence of an extensional metamorphic core complex in the northern Arabian–Nubian Shield. Gneissic domes throughout the Arabian–Nubian Shield resemble the core complex of the Wadi Kid area and as a result, they are interpreted as extensional metamorphic core complexes. The presence of a widespread phase of extension at the end of the Pan-African period in the Arabian–Nubian Shield requires a new interpretation of the tectonic history of this shield. Three main tectonic phases are recognized in the Late Proterozoic of the Arabian–Nubian Shield. Ophiolites and island-arc remnants are relicts of an oceanic phase, the oldest one. This phase was followed by arc-accretion, well established in the Arabian–Nubian Shield from the presence of individual terranes bordered by sutures, which was responsible for lithospheric thickening. The Late Proterozoic ended with widespread NW–SE extension. The metamorphic core complexes, late-orogenic extensional basins and large strike slip zones were formed during this phase. Similarity of the tectonic evolution of the Arabian–Nubian Shield with the Mesozoic and Early Cenozoic evolution of western North America lead us to conclude that gravitational instability at the final stages of the arc-accretion phase caused the collapse and resulted in extension at the latest stages of the Pan-African orogeny in the Arabian–Nubian Shield.

Keywords: Arabian–Nubian Shield, Wadi Kid area, Pan-African Orogeny, metamorphic core complexes, extension.

The Arabian–Nubian Shield extends from Jordan and southern Israel in the north to Eritrea in the south and from Egypt in the west to Saudi Arabia and Oman in the east (Fig. 1). The Arabian–Nubian Shield consists of gneisses, granitoids, various (meta)volcanic and (meta)sedimentary rocks. Many authors interpret its early evolution as the accretion of island arcs and of oceanic terranes (e.g. Vail 1985; Stoeser & Camp 1985; Harris *et al.* 1990; Samson & Patchet 1991; Abdelsalam & Stern 1996). Occasionally attention has been given to features that are generally associated with extension (e.g. Schürmann 1966; Grothaus *et al.* 1979; Stern *et al.* 1984; Husseini 1989; Rice *et al.* 1991; Greiling *et al.* 1994). Recent research demonstrates the presence of a metamorphic core complex, developed in an extensional regime, in the Sinai of Egypt, as the result of extensional collapse (Blasband *et al.* 1997).

In this paper, we evaluate whether extensional collapse took place throughout the Arabian–Nubian Shield. For this purpose, published geological data from other parts of the Arabian–Nubian Shield were reviewed and compared to recently published (Blasband *et al.* 1997) and new data, presented here, from the Wadi Kid area, Sinai. We conclude that extensional collapse took place throughout the entire Arabian–Nubian Shield during the later stages of the Pan-African orogeny and that the late Proterozoic tectonic development of the Arabian–Nubian Shield is similar to that of the Mesozoic and early Cenozoic evolution of western North America where arc accretion and related crustal thickening were followed by extension and the development of core complexes (e.g. Coney & Harms 1984; Malavieille 1987; Dewey 1988).

Outline of the Late Proterozoic geology of the Arabian–Nubian Shield

Relicts of oceanic crust

The Arabian–Nubian Shield contains many remnants of oceanic crust, in the form of ophiolites. Typical ophiolite sequences are found in the Eastern Desert, Egypt, in Sudan and in western Saudi Arabia (Table 1). Locally, complete ophiolitic sequences can be observed including peridotites, gabbros, sheeted dykes, pillow lavas and sedimentary rocks that reflect a deep-sea environment (Table 1). In many cases, the ophiolites have been dismembered and are now found in tectonic melanges. The ophiolites were dated at approximately 900–740 Ma (Table 1). Geochemistry of a number mafic schistose units throughout the Arabian–Nubian Shield indicate a MORB provenance (Bentor 1985; El Gaby *et al.* 1984; El Din *et al.* 1991; Rashwan 1991). Some of the ophiolites were interpreted to have been formed in back-arc basins (Pallister *et al.* 1988).

Overall, the ophiolites of the Arabian–Nubian Shield are thought to represent the oceanic crust of the Mozambique Ocean which was formed upon the rifting of Rodinia (Abdelsalam & Stern 1996).

Island-arc remnants

Typical island-arc related rocks are found in the Arabian–Nubian Shield (Table 2). Tonalites, gabbros, basalts, andesites and metavolcanics with a calc-alkaline island-arc geochemistry

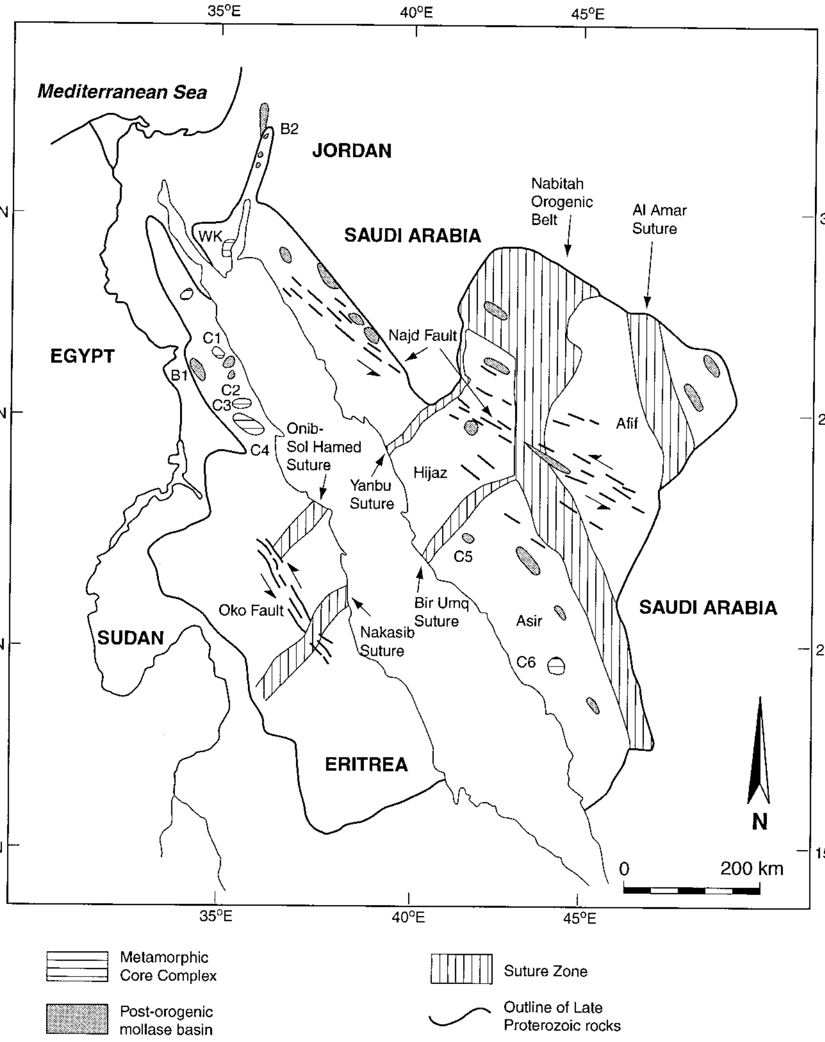

Fig. 1. Map showing the main Late Proterozoic features in the Arabian Nubian Shield. WK, Wadi Kid Complex; C1, Meatiq Dome; C2, El Sibai Dome; C3, Wadi Ghadir Complex; C4, Hafafit Dome; C5, Taif area; C6, Abha Complex; B1, Basin with Hammamat sedimentary sequence; B2, Basin with Saramuj Conglomerate. Compiled from maps by Vail (1985); Stoeser & Camp (1985); Brown *et al.* (1989), Greiling *et al.* (1994) and Abdelsalam & Stern (1996).

Table 1. *A review of geological features that are indicative of an oceanic crust*

Area	Lithology	Age (Ma)	References
Wadi Ghadir, Egypt	Layered gabbros, sheeted dykes, pillow lavas, black shales	746 ± 19 (Pb–Pb)	El Akhal (1993); Kröner (1985); Kröner *et al.* (1992)
Qift-Quseir, Egypt	The Eastern Desert Ophiolitic Melange Group/Abu Ziran Supergroup: Dunites, peridotites, layered gabbros, sheeted dykes, pillow lavas and deep sea sediments (red pelites)	*c.* 800	Ries *et al.* (1983); Kröner (1985); El Gaby *et al.* (1984)
Onib and Gerf, Sudan	Ultramafic cumulates, interlayered gabbros, sheeted dykes and pillow basalt	*c.* 840–740, e.g. 808 ± 14 (Pb–Pb), 741 ± 21 (Pb–Pb)	Stern *et al.* (1990); Kröner *et al.* (1987)
Ophiolites throughout Saudi Arabia	Peridotites, gabbros, sheeted dykes, pillow lavas, chert, pelagic metasediments and marble	882 ± 12 (U–Pb) to 743 ± 24 (Sm–Nd)	Brown *et al.* (1989); Kemp *et al.* (1980); Claeson *et al.* (1984); Pallister *et al.* (1988)

are common in the Eastern Desert and the Sinai, Egypt (Bentor 1985; El Gaby *et al.* 1984; El Din *et al.* 1991; Rashwan 1991). Many amphibolites throughout the Eastern Desert, Egypt have island-arc protoliths (Bentor 1985; El Din 1993). The formation of the island-arc rocks has been dated at approximately 900–700 Ma (Table 2).

The oldest island-arc remnants in Saudi Arabia (900–850 Ma) consist of tholeiitic andesites (Jackson 1986; Brown *et al.* 1989) and are thought to represent young immature island arcs (Jackson 1986). Thickening and melting of the immature tholeiitic crust caused the formation of more mature island arcs with rocks of calc-alkaline character. Low- to high

Table 2. *A review of geological features that represent the development of island arcs*

Area	Lithology	Age (Ma)	References
Wadi Hafafit, Egypt	Meta-andesites with an island-arc chemistry	N/A	Rashwan (1991)
Eastern Desert, Egypt	Tonalites, trondjhemites, basalts, andesites. Volcanics with island-arc chemistry	*c.* 900–700	Bentor (1985); El Gaby *et al.* (1984); El Din (1991); Rashwan (1991)
Asir, Saudi Arabia	Basaltic to andesitic lavas and tuffs with calc alkaline to low K-chemistry	*c.* 900–800	Jackson & Ramsay (1980); Jackson (1986)
Throughout Saudi Arabia	Tholeiitic andesites and basalts, andesites, pillow basalts, tonalites and trondhjemites. Chert, marble, graywackes (no sedimentary structures), turbedites, claystone, siltstone (sediments were in part deposited in back-arcs), back-arc basins trend NE (perpendicular to principal direction of compression)	*c.* 900–780, e.g. 912 ± 76 (Rb–Sr), 785 ± 96 (Rb–Sr)	Hadley and Schmidt (1980); Brown *et al.* (1989); Schmidt *et al.* (1980); Johnson *et al.* (1987)

K tonalites, trondhjemites and andesites were formed at this phase and have been dated at 825–730 Ma (Schmidt *et al.* 1980; Jackson 1986; Brown *et al.* 1989).

Many of the island-arc related rocks are also thought to have been formed in the Mozambique Ocean (Abdelsalam & Stern 1996).

Features related to arc accretion

Throughout the Arabian–Nubian Shield a number of deformed linear belts of ophiolitic rocks have been observed (Table 3) and these were interpreted as sutures (e.g. Ries *et al.* 1983; Vail 1985; Abdelsalam & Stern 1996). The Al Amar, Yanbu and Bir Umq Belts represent examples of the ophiolitic linear belts in the Late Proterozoic shield of Saudi Arabia (Fig. 1). These belts separate little deformed domains that are distinguished from each other on the basis of different petrology, geochemistry and ages. This led several authors to interpret the Asir, Midyan, Afif, Ar Ryan and Hijaz Domains (Fig. 1) as accreted terranes and helped to identify the linear belts as ophiolitic sutures (Vail 1985; Stoeser 1986; Johnson *et al.* 1987). A number of sutures display significant strike-slip movement (Quick 1991; Abdelsalam & Stern 1996; Johnson & Kattan in press), which appears to postdate the initial stages of the suturing (see below). Granodioritic intrusions were associated with the arc-accretion phase (e.g. Stoeser & Camp 1985; Stoeser 1986; Quick 1991).

The Nabitah Belt (Fig. 1) in Saudi Arabia is the largest and most complicated feature that was formed during the arc-accretion phase in the Arabian–Nubian Shield. It is some 1200 km long, 100–200 km wide and trends north–south. The Nabitah Belt consists of ophiolites and sheared ophiolites in the form of steeply dipping mylonites and phyllonites (Quick 1991). The oldest folding phase in this belt indicates WNW–ENE to NW–SE compression (Quick 1991). This phase is overprinted by a phase of left-lateral transpression along north–south trending strike slip faults which were active at 700–650 Ma (Quick 1991).

Similar features have been observed in Sudan and Egypt (Table 3). The NE–SW trending Nakasib Suture in Sudan separates island-arc terranes in the east from a pre-Neoproterozoic continental terrane in the west (Abdelsalam & Stern 1996). The Nakasib Suture displays relicts of a east–west compressional regime which represents the suturing phase. Strike-slip movement overprints the earlier structures and represents the later stages of arc accretion (Abdelsalam & Stern 1996). The activity on the sutures took place at *c.* 750–650 Ma (Table 3). The strike-slip movement, related to the later stages of the arc-accretion event, started at *c.* 670 Ma (Abdelsalam & Stern 1996).

Gneissic domes

A number of ‘gneissic domes’ have been described in the Eastern Desert, Egypt (Table 4). Recently some of these structures have been compared to the metamorphic core complexes in Western North America (Sturchio *et al.* 1983; Greiling *et al.* 1994; Fritz *et al.* 1996; Blasband *et al.* 1997). The Meatiq, Hafifit, Gebel El Sibai and Wadi Kid areas (Fig. 1) contain the most studied of these ‘gneissic domes’, which show a broad similarity in structure. The ‘gneissic domes’ have lower- and upper-crustal units. The former consists of deformed tonalites, diorites and granodiorites, and of meta-sedimentary, metavolcanic and meta-ophiolitic schists. The schists have been generally metamorphosed at amphibolite grade-high-temperature–low-pressure (HT–LP) conditions. The upper crustal unit consists of folded and thrusted island-arc volcanics, island-arc related sedimentary sequences and ophiolites. This unit displays low-grade metamorphism. In the Meatiq Dome, the two units are separated by a cataclasite (Habib *et al.* 1985). The foliation in the lower crustal rocks is mainly subhorizontal to moderately dipping. A NW–SE-trending mineral lineation is developed on the foliation. Evidence for non-coaxial strain was observed in the schists in the form of S–C fabrics, asymmetric porphyroclasts and asymmetric boudins (Sturchio *et al.* 1983; El Din 1993). Consequently, the schists were interpreted as low-angle mylonitic shear zones that formed under lower-crustal conditions (Greiling *et al.* 1994; Fritz *et al.* 1996). Late anorogenic granites are associated with the doming of the complexes (Greiling *et al.* 1994).

Gneissic domes are present in Saudi Arabia (Okrusch & Jamal-Allil 1979; Schmidt *et al.* 1980; Brown *et al.* 1989), but have not been described in detail. Nasseef & Gass (1977) describe complexes of gneissic rocks with amphibolite grade schists concordantly overlying them in the Taif area, Hijaz, Saudi Arabia. The Abha Complex in SW Saudi Arabia consists of a core of sillimanite-bearing gneisses which is overlain by biotite schists (Okrush & Jamal-Allil 1979). The sillimanite-bearing gneisses are indicative of HT–LP conditions. The schists are overlain by low-grade volcanics (Okrush & Jamal-Allil 1979). The core of the Al Qarah Dome, southern Najd,

Table 3. *A review of geological features that represent the arc-accretion phase*

Area	Lithology	Metamorphism	Structures	Age (Ma)	References
Nabitah Belt, Saudi Arabia	North–south-trending ophiolites and sheared ophiolites, phyllonites. Nabitah Belt juxtaposes terranes with different petrological characteristics	N/A	Open folds with NE–SW-trending fold axes and subvertical axial planes, overprinted by north–south-trending steeply dipping mylonites (Nabitah trend). Steeply dipping foliation, lineation and folds	*c.* 710–680	Quick (1991)
Idsas, Yanbu and Bir Umq sutures, Saudi Arabia	Linear ophiolitic belts	Greenschist to lower amphibolite grade	Ophiolitic sutures	*c.* 715–650	Vail (1985); Stoeser & Camp (1985)
Al Amar suture, Saudi Arabia	Halaban ophiolitic belt	Amphibolite grade	Ophiolitic sutures	679 ± 6 (Ar–Ar)	Al-Saleh *et al.* (1998)
Saudi Arabia	Synorogenic diorites and granodiorites	N/A	Syn-kinematic	*c.* 763–660	Stoeser (1986); Brown *et al.* (1989)
Quseir-Marsa Alam, Egypt	Ophiolitic melanges	Greenschist	Suture zone: mylonites interpreted as thrusts dipping NE, and folds	N/A	Ries *et al.* (1983)
Allaqi-Heiani and Onib-Sol Hamed, Sudan	Ophiolitic suture, granodiorite	Greenschist to amphibolite grade	Suture zone: Early South- to SE-verging ophiolitic nappes, late East- to NE-trending upright folds	*c.* 750–720	Stern *et al.* (1990); Abdelsalam & Stern (1996)
Nakasib, Sudan	Ophiolitic suture, folded ophiolitic nappes, diorite	N/A	East- to NE-trending suture zone: Early (*c.* 750 Ma) SE-verging tight folds, overprinted by NE-trending upright folds (*c.* 700 Ma)	*c.* 840–760 arc–arc, *c.* 760–700 arc–continent	Abdelalam (1994); Abdelsalam & Stern (1996); Schandelmeier *et al.* (1994)

Table 4. *A review of geological features that were associated with the gneissic domes*

Area	Lithology	Metamorphism	Structures	Age (Ma)	References
Meatiq, Egypt	Supracrustal: folded ophiolites, cataclasites; Infracrustal: amphibolite schists, tonalitic and dioritic gneisses, late A-type granites	Greenshist to upper-amphibolite grade (LP) and relicts of HP	Subhorizontal to moderately dipping foliation interpreted as thick mylonite, NW–SE stretching lineation, cataclasites	595.9 ± 0.5 and 588.2 ± 0.3 (Ar–Ar)	Sturchio *et al.* (1983); El Gaby *et al.* (1984); Greiling *et al.* (1994); Fritz *et al.* (1996)
Wadi Hafafit, Egypt	Supracrustal: ophiolites, cataclasites; Infracrustal: metavolcanic and metasedimentary schists, gneisses, late A-type granites	High grade (HP)overprinted by amphibolite grade (LP)	NE–SW folds at upper crustal levels, large mylonitic shearzones with NW–SE stretching lineation, cataclasites	N/A	Greiling *et al.* (1984, 1994)
Gebel El Sibai, Egypt	Gneisses, migmatites overlain by amphibolite schists, overlain by low grade metavavolcanics and metasediments	Upper amphibolite grade	Sub-horizontal foliation with NW–SE-trending lineation and shear indicators. This structure was interpreted as a low-angle shear zone by Greiling *et al.* (1994). Cataclasites	N/A	El Din *et al.* (1991)
Taif, Saudi Arabia	Quartzo-feldspathic gneisses, amphibolites, both intruded by slightly to non-deformed granites	Amphibolite grade	Foliated	595 ± 20 to 525 ± 20 (Rb–Sr, granite emplacement)	Nasseef & Gass (1977)
Abha Saudi Arabia	Gneisses, migmatites, metavolcanics (tholeiites) and metasediments intruded) by granites	Upper amphibolite grade (LP)	Foliated	622–588 (K–Ar, last heating phase of gneiss)	Okrush & Jamal-Allil (1979)
Al Qarah Saudi Arabia	Granodioritic and tonalitic gneiss, migmatites and schists, all intruded by post-tectonic granites	N/A	Subhorizontal foliation	*c.* 600	Schmidt *et al.* (1980)

Table 5. *A review of geological features that interpreted to be related to extension*

Area	Feature/lithology	Structures	Age (Ma)	References
Eastern Desert Egypt	Dykes: bimodal, mafic and felsic	Dykes trend NE–SW	*c.* 620–550	Schürmann (1966); Stern & Gottfried (1986); Greiling *et al.* (1994)
Midyan Saudi Arabia	Dykes: bimodal, mafic and felsic; silicic volcanics and pyroclasts	Dykes trend NE–SW, volcanics and pyroclasts in fault basins	*c.* 625–575	Clark (1985); Agar (1986)
Wadi Araba	Dykes: bimodal, mafic and felsic	Dykes trend NE–SW	550 ± 13 (K–Ar)	Jarrar *et al.* (1991)
Hammamat Egypt	Hammamat GP; Basin-and-Range-type molasse: sandstones, conglomerates with debris flows, channel fills	Syn-sedimentary normal faults forming NE–SW-trending basins	585 ± 15 (Rb–Sr)	Grothaus *et al.* (1979); Willis *et al.* (1988)
Wadi Igla, Wadi Hafafit, Egypt	Post-orogenic molasse: basal conglomerates overlain by volcanics and pyroclastics	NE–SW-striking normal faults	*c.* 595–575	Greiling *et al.* (1994)
Wadi Araba Jordan	Saramuj Conglomerate; post-orogenic molasse: sandstones, conglomerates with debris flows, channel fills; bimodal dykes	NE–SW-striking normal faults NE–SW-trending dykes	*c.* 600–550. Dyke at 545 ± 13 (K–Ar)	Jarrar *et al.* (1991, 1992)
Saudi Arabia	Sedimentary basins; Fatima, Murdama, Jibalah and Shammar Groups: conglomerates, sandstones, deposited in shallow water, high-energy environments	N/A	*c.* 620–540	Jackson & Ramsay (1980); Hadley & Schmidt (1980); Brown *et al.* (1989); Kemp (1996)
Oman	Salt basins	Basins bounded by NE–SW-striking normal faults	*c.* 620–540	Husseini (1989)
Entire Shield	Anorogenic granites: alkali-feldspar granites, intruded in thinned and extending crust	None to slightly lineated	*c.* 600–540. Granite at 594 ± 4 (Rb–Sr) and granite at 544 (Rb–Sr)	Stern & Hedge (1985); Husseini (1989); Beyth *et al.* (1994); Greiling *et al.* (1994); Brown *et al.* (1989)

Saudi Arabia, consists of gneissic tonalites and granodiorites. These gneisses are overlain by schists with a subhorizontal foliation (Schmidt *et al.* 1980).

The lower-crustal mylonitic shear zones in the Arabian–Nubian Shield have been dated at approximately 620–580 Ma (Table 4).

Late extensional features

A number of geological features, namely dykes, sedimentary basins and post-orogenic A-type granites, were interpreted to have been formed in an extending crust (Table 5). These features were formed at the same time or slightly after the low-angle shear zones of the core complexes (Tables 4 and 5).

Reconnaissance maps by Schürmann (1966) and Eyal & Eyal (1987) show the presence of NE–SW-striking Precambrian dykes in large parts of the Eastern Desert, Egypt. The bimodal mafic and felsic dykes in the Eastern Desert were dated at *c.* 620–550 Ma (Stern *et al.* 1984). In the Midyan region of northwestern Saudi Arabia and the Uyaijah area of central Saudi Arabia, mafic to intermediate and felsic dykes also strike NE–SW (Dodge 1979; Clark 1985). Generally, little tectonic importance has been attributed to these dykes. Only Stern *et al.* (1984) has used them as an indicator for NW–SE extension.

Studies of sedimentation and basin-structures also present helpful tools for the interpretation of the regional tectonics (Ingersoll & Busby 1995). The Hammamat Group in the Eastern Desert, Egypt contains one of the best preserved clastic sedimentary sequences found in this part of the Arabian–Nubian Shield. Grothaus *et al.* (1979) have described this sequence in detail. The sedimentary rocks of the Hammamat Gp uncomformably overlie the metamorphic sequences and consist of thick sequences of unsorted to well-sorted conglomerates, sandstones and siltstones (Grothaus *et al.* 1979). The sequence contains several types of sedimentary features such as debris flows, alluvial fans and channel fills (Grothaus *et al.* 1979). Grothaus *et al.* 1979 believed syn-sedimentary normal faulting to be necessary to explain the sedimentary sequence of the Hammamat Gp. Other Late Proterozoic sedimentary basins in the Eastern Desert were interpreted as molasse-type basins (Fritz *et al.* 1996). They are bordered by major NE–SW-striking normal faults and display internal synsedimentary normal faulting (Fritz *et al.* 1996).

The Saramuj Conglomerate Gp, Wadi Araba, SW Jordan, dated at 600–550 Ma, is similar to the Hammamat Group (Jarrar *et al.* 1991). It consists of a post-orogenic molasse-type basin with poorly sorted conglomerates and sandstones. Sedimentary structures include alluvial fans, channel fills and debris flows. The Saramuj Conglomerate Gp was deposited in a fan-type depositional system in grabens that were formed during NW–SE extension (Jarrar *et al.* 1991). NE–SW-striking dykes cross-cut this sequence. Throughout Saudi Arabia, late Proterozoic post-orogenic molasse sequences, deposited in environments similar to the Hammamat and Saramuj Conglomerate Groups, overlie basement rocks (e.g. Jackson & Ramsay 1980; Hadley & Schmidt 1980; Brown *et al.* 1989). Evaporitic and clastic basins in Oman, bordered by

NE–SW-trending faults led Husseini (1989) to conclude that a NW–SE extension occurred in this part of the Shield between 620 and 580 Ma. From the above discussion and Table 5, we conclude that widespread extension occurred within the Arabian–Nubian Shield at *c.* 620–530 Ma.

A widespread intrusion of anorogenic, potassium-rich, granites into the lower-crustal sequences of the 'gneissic domes' occurred at *c.* 620–530 Ma (e.g. Schmidt *et al.* 1980; Habib *et al.* 1985; El Din *et al.* 1991; Greiling *et al.* 1994) and was synchronous with, or postdated, the extensional features. According to Beyth *et al.* (1994) and Greiling *et al.* (1994) these A-type anorogenic granites were mantle-derived and intruded in a thinned crust.

Large strike slip zones, such as the Najd Shear Zone in Saudi Arabia and the Oko Shear Zone in Sudan, represent another important feature in the Arabian–Nubian Shield (e.g. Fleck *et al.* 1980; Stern 1985; Dixon *et al.* 1987). They were active in the period 620–540 Ma (Stern 1985) and were thus synchronous with the low-angle shear zones and the NW–SE extension. These brittle to greenschist-grade strike-slip shear zones trend NW–SE (Moore 1979; Sultan *et al.* 1988).

The Late Proterozoic of the Wadi Kid area, Sinai, Egypt

Geological background

The sequence of geological features described above and presented in Tables 1–5, reveals a complex tectonic history for the Arabian–Nubian Shield. We have chosen the Wadi Kid area, Sinai, Egypt to study this history in detail, especially because the lower crustal rocks are well represented in this area. The geology of this area is influenced by rifting of the Gulf of Aqaba which started in the Miocene and continues until today.

The Wadi Kid area consists mainly of lower-crustal metavolcanic and metasedimentary schists of amphibolite grade (Fig. 2). The total thickness of this sequence is approximately 1–1.5 km. In addition, foliated and gneissic diorites, tonalites and granodiorites also represent lower-crustal rocks. The lower-crustal rocks are overlain by weakly metamorphosed (lower-greenschist grade) to non-metamorphosed sedimentary and volcanic units. The upper-crustal rocks, only found in the SE part of the Wadi Kid area (Fig. 2), include sandstones, claystones, conglomerates, andesites, basalts and agglomerates. Some of the sedimentary sequences are typical trench turbidites.

Locally, 50–100 m thick bands of chlorite- and biotite-schists, striking NE–SW, were observed within the low-grade metamorphic rocks. These schists are foliated equivalents of their neighbouring rocks, the low-grade metavolcanics and metasediments (Figs 2 and 5a). The contact between the lower- and upper-crustal rocks is marked by a brittle cataclastic layer (*c.* 0.5 m thick), overlying a chlorite schist, at the southeastern contact of these units, and a post-Oligocene brittle fault at the northeastern contact of these two units. Undeformed and non-metamorphosed rhyolites and ignimbrites overlie all other low-grade rocks.

The upper crustal rocks were deposited/extruded at 770–650 Ma (H. N. A. Priem unpubl. data). Two phases of metamorphism (M1 and M2) are recognized. During the M1 metamorphic phase, dated at 720–650 Ma (Priem *et al.* 1984), all the rocks were deformed at greenschist-grade under Barrovian conditions. M1 was followed by an M2 LP–HT phase, when the structurally deeper rocks were metamorphosed at intermediate- to upper-amphibolite-grade conditions. The rocks representing this phase were dated at *c.* 620–580 Ma (Bielski 1982). Major- and trace-element studies by Furnes *et al.* (1985) indicate that the protoliths of the amphibolite-grade schists consist of tholeiitic and calc-alkaline basalts formed in an island-arc setting and in an arc-accretion setting. The amphibolite-grade schists are intruded by post-orogenic A-type alkali-granites dated at 590–530 Ma (Bielski 1982) and a gabbro–diorite complex in the north, dated at 580–570 Ma (Moghazi *et al.* 1998). Furthermore, mafic, felsic and composite dykes intrude the upper- and lower-crustal units in the Wadi Kid area. Similar dykes, near the Wadi Kid area, were dated at 620–560 Ma (Stern & Manton 1987). Jarrar *et al.* (1992) dated felsic and mafic dyke-systems in the nearby Wadi Araba, southwest Jordan, at 550–540 Ma (Jarrar *et al.* 1992). From intrusive and structural relations, the undeformed rhyolite–ignimbrite body appears to be younger than any of the other sedimentary and volcanic sequences. Rhyolites in SW Jordan were dated at 553 Ma (Jarrar *et al.* 1992).

Structural geology

The oldest deformation phase (D1) in the Wadi Kid area is represented by an S1 foliation that was formed in the greenschist-grade metasedimentary rocks of the southern Wadi Kid area, during M1. This foliation is axial planar to isoclinal F1 folds with NNE–SSW- to NE–SW-trending fold axes (see Figs 2 and 4a). The D1-deformational phase, responsible for the formation of S1 and F1, indicates WNW–ESE to NW–SE compression. Features related to this phase were dated at approximately 720–650 Ma (Priem *et al.* 1984; H. N. A. Priem unpubl. data). In view of the tectonic development of other parts of the Arabian–Nubian Shield and the parallelism of the compressional phase in the Wadi Kid area to the compressional regime in the Late Proterozoic rocks of NW Saudi Arabia (Stoeser & Camp 1985; Quick 1991), this phase is attributed to arc-accretion with a WNW–ENE to NW–SE compressional stress field.

The D2 phase is mainly represented by the deformation features in the lower-crustal rocks. The S2-foliation is subhorizontal (Fig. 3a) and best developed in the amphibolite-grade schists. A mineral and stretching lineation is developed on the S2 foliation. This L2 lineation trends uniformly NW–SE (Fig. 3b). A large variety of indicators of non-coaxial strain such as rotated clasts, extensional crenulation cleavages and asymmetric quartz *c*-axis fabrics are evidence of dominantly simple shear and indicate that the S2 foliation is of mylonitic origin (see also Blasband *et al.* 1997). Finite-strain indicators such as deformed xenoliths and conglomerates, together with the majority of local shear indicators, show a top-to-the-NW movement (Blasband *et al.* 1997). A minority of the local shear sense indicators throughout the schistose sequence display a shear reversal (Blasband *et al.* 1997). The thin chlorite- and biotite-schists that cross-cut the upper-crustal greenschist-grade rocks represent D2 features in the upper-crustal section (see Figs 2 and 5a). Asymmetric features as extensional crenulation cleavages (Fig. 4b), indicate that these moderately NW dipping mylonitic zones (Fig. 3c), with a NW plunging lineation (Fig. 3d), all display a top-to-the-NW movement.

The Wadi Kid area is cross-cut by NE-SW trending mafic, felsic and composite dykes. The mineral and stretching lineations are orthogonal to the strike of the dykes and the fact

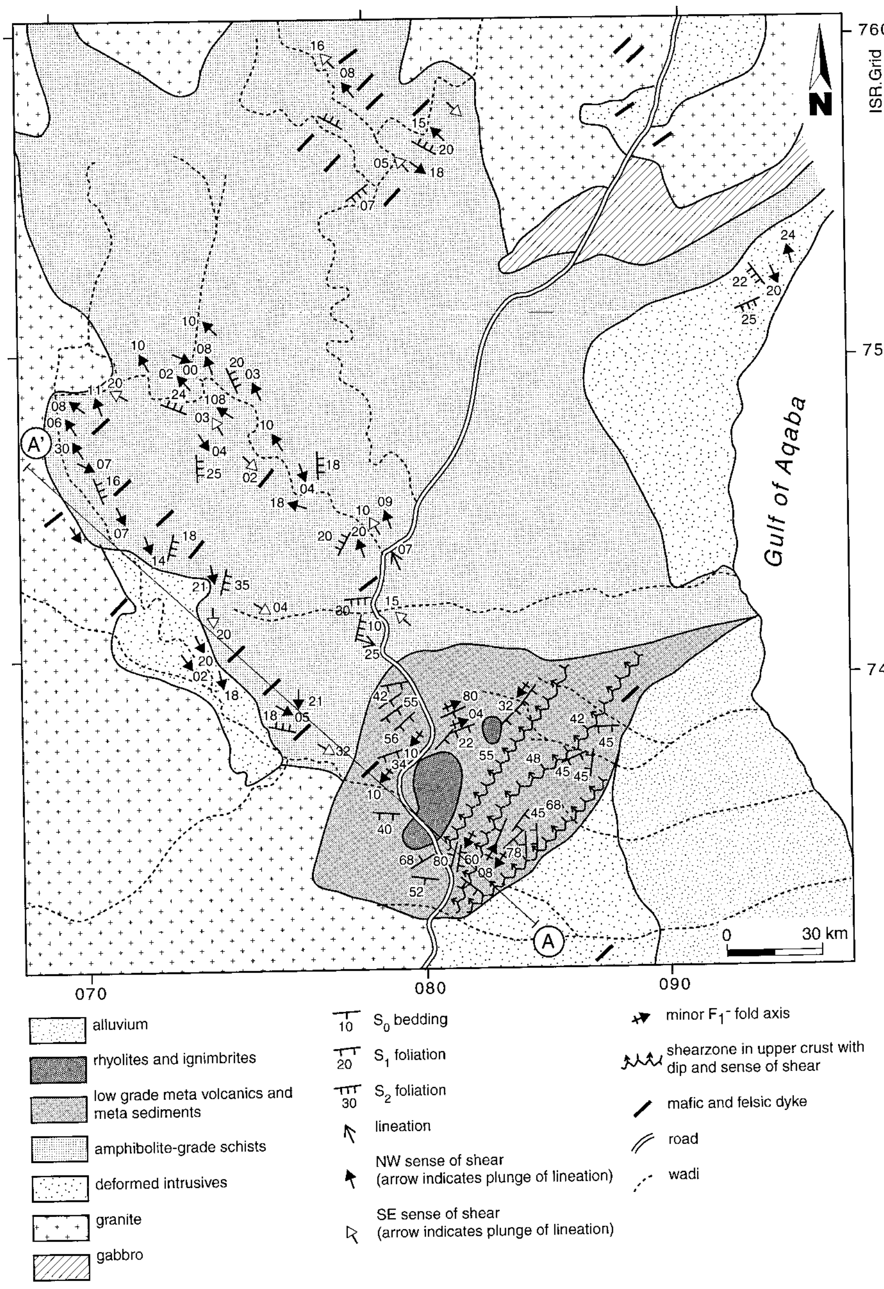

Fig. 2. Geological map of the Wadi Kid area, Sinai, displaying the main lithological units and structures.

that these two features are synchronous, indicate NW–SE extension (Blasband *et al.* 1997). The D2 deformation phase took place under HT–LP metamorphic conditions (M2).

A tectonic model for the Wadi Kid area, Sinai

A section across the Wadi Kid area is shown in Fig. 5a and an interpretation is presented in Fig. 5b. In this interpretation it is seen that upper-crustal rocks, metavolcanics and metasediments, display the compressional features that are indicative of the of the D1 deformation phase. These rocks structurally overlie lower-crustal rocks, mainly mylonites, in the form of amphibolites and metaplutonic rocks, which were formed in an NW–SE extensional regime during the D2 deformation phase. The NE–SW-striking shear zones in the upper-crustal metamorphic rocks are interpreted as original splays off the deeper shear and were also formed during the extensional D2 phase. The lower- and upper-crustal rocks are separated by a brittle shear. Late anorogenic granites intruded the lower-crustal mylonitic sequence. Blasband *et al.* (1997) suggested that the SE-sense of movement in the lower-crustal mylonitic sequence postdated the NW-sense of movement and that this reversal was a result of doming. A cataclasite separates the lower- and upper-crustal units. The undeformed rhyolites and ignimbrites overlie the upper-crustal deformed rocks.

The sequence consisting of deformed plutons, of thick subhorizontal amphibolite-grade schists with uniformly trending lineations, and which were formed at HT–LP conditions in an extensional regime, overlain by rocks displaying relicts of older compressional phases, with a cataclasite separating the two sequences, closely resembles the metamorphic core

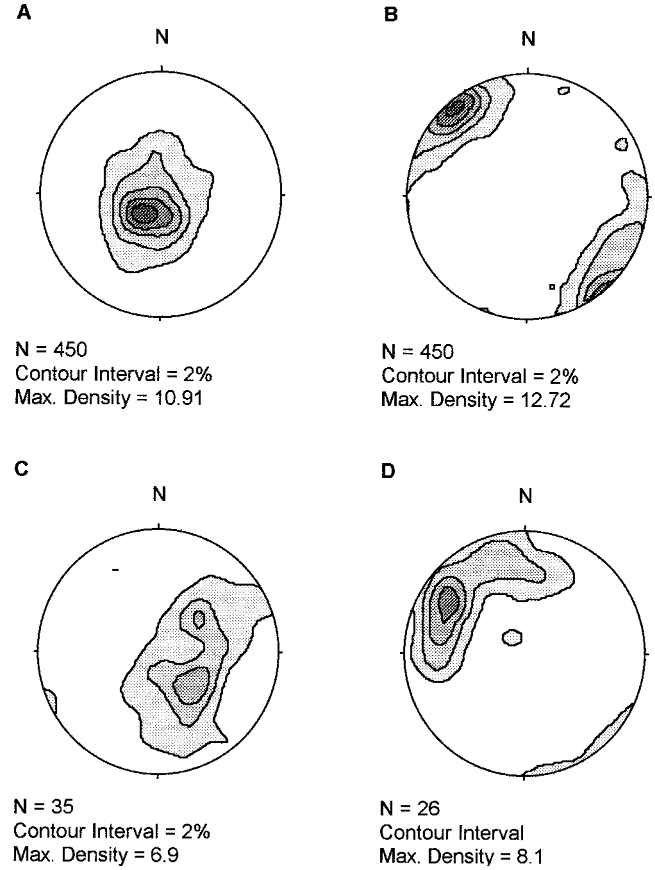

Fig. 3. (**a**) Contoured stereographic plot (equal area) of the poles to the S2 foliation in lower-crustal rocks. (**b**) Contoured stereographic plot (equal area) of the poles to the L2 lineation in lower-crustal rocks, showing maxima at NW–SE. (**c**) Contoured stereographic plot (equal area) of the poles to the S2 foliation in the upper-crustal rocks. (**d**) Contoured stereographic plot (equal area) of the poles to the L2 lineation in upper-crustal rocks, showing maximum at NW.

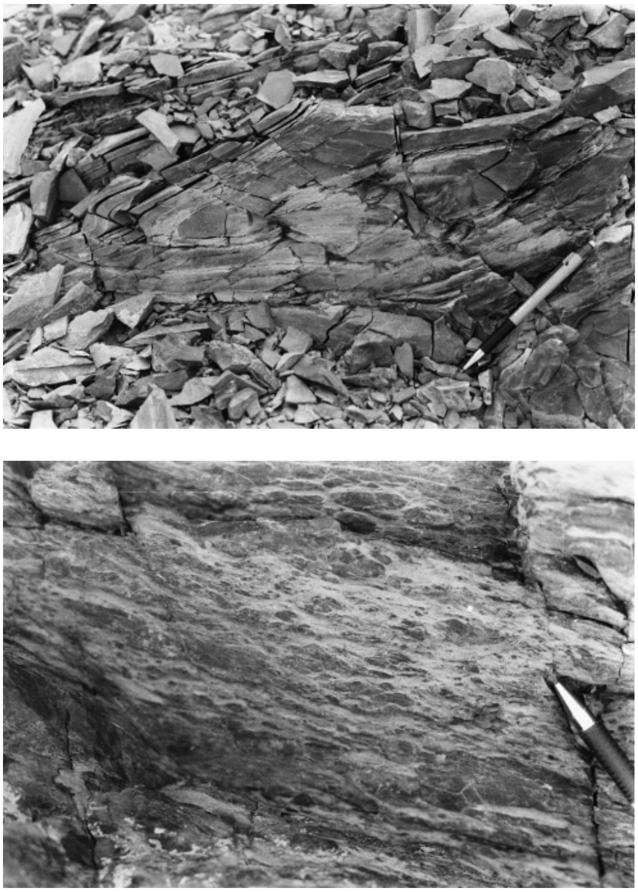

Fig. 4. (**a**) F1 folds, folding S0 bedding, and S1 foliation in the low-grade metasediments of the SE Wadi Kid area. (**b**) NE–SW-striking chlorite-schist in the SE Wadi Kid, representing splays off the deeper shear in the upper-crustal rocks. Extensional crenulation cleavages indicate dextral movement (in this case top-to-the-NW).

complexes of western North America. The foliated mylonitic rocks which form the amphibolite-grade schists and metaplutonic mylonitic sequence represent the lower-crustal part of a crustal-scale extensional shear zone system (detachment) with a top-to-the-NW movement. The upper-crustal schistose shear zones in the SE part of the Wadi Kid area represent upper-crustal splays off this. The cataclasites represent a detachment fault that was responsible for the final juxtaposition of the lower-and upper crustal sections during the last stages of the extension. Quartz *c*-axis textural studies from some of the younger A-type granites show that these were also deformed at the D2 regime (Blasband *et al.* 1997). This and the intrusion of NE–SW dykes into these granites, dated by Bielski (1982) at 580–530 Ma, indicate that the extensional phase continued into the early Cambrian.

On the basis of data presented above and data presented by Blasband *et al.* (1997), we propose the following model for the tectonic development of the Late Proterozoic in the Sinai (Fig. 6). An era of extensive magmatism in an island-arc environment started the Pan-African of the Sinai, prior to 720 Ma, and was responsible for the intrusion of tonalites, extrusion of different types of volcanics and deposition of clastics, all typical of such a setting. Arc accretion followed this phase with WNW–ESE to NW–SE compression. D1 structures and (grano)dioritic plutons are typical of this phase. This compressional phase was followed by a phase of NW–SE-trending extension which caused the formation of a crustal-scale normal shear zone system with both lower- and upper-crustal detachments. A-type mantle-derived granites and composite dykes were intruded into a thinned crust at the end of the Late Proterozoic in the Sinai. Tectonic denudation by the detachment and isostatic rebound, as observed in the metamorphic core complexes of the Basin and Range, western USA (Wernicke & Axen 1988), together with the intrusion of the granites caused the formation of a metamorphic core complex. Felsic dykes are the feeders to the rhyolites and ignimbrites.

The transition from a compressional arc-accretion setting to an extensional regime is best explained by extensional collapse (Dewey 1988; Platt & England 1993). Arc accretion caused lithospheric thickening. Extensional collapse then initiated normal faulting and core complex development. Syntectonic granodiorites intrude at the initial stages of the collapse (Anderson & Cullers 1990; Barton 1990). Post-orogenic A-type granites intruded at the later stages of the extensional collapse (Anderson & Cullers 1990; Barton 1990). The undeformed rhyolites and ignimbrites are typical volcanic features of the extensional phase (Coney 1989).

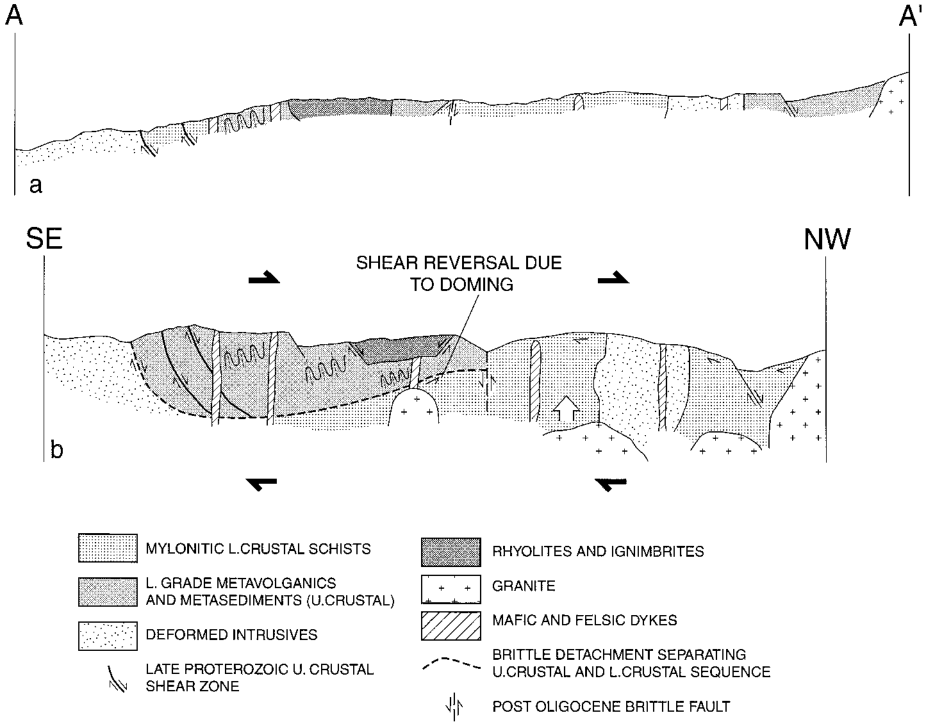

Fig. 5. (**a**) Schematic cross-section through the Wadi Kid area (section A–A′ of Fig. 2). (**b**) Interpreted cross-section of the metamorphic core complex in the Wadi Kid area based on (a).

Discussion

Extensional core complexes in the Arabian–Nubian Shield

Being similar to the Wadi Kid Complex, we interpret the ‘gneissic domes’ of the Arabian–Nubian Shield as metamorphic core complexes (Table 4). These ‘gneissic domes’ were formerly interpreted to have been formed in a compressional setting where the high-strain zones represent thrusts (e.g., Ries *et al.* 1983; Greiling *et al.* 1988; Fritz *et al.* 1996). However, Greiling *et al.* (1994) speculated that the El Sibai end Meatiq domes may have been formed in an extensional regime. Contemporaneity and parallelism of the stretching lineations and the NW–SE extension (Table 4 and 5) lead us to interpret the schistose sequences, overlying the gneissic cores, as low-angle extensional detachment faults of the type envisaged by Wernicke (1985) and which caused considerable crustal thinning. Isostatic rebound together with the intrusion of granites lead to doming of the lower crust. The doming was responsible for the formation of typical extensional core complexes similar to those formed in the Mesozoic and Early Cenozoic of western North America (e.g. Coney & Harms 1984; Davis & Lister 1989).

Western North American Mesozoic and Early Cenozoic development as an analogue for the Arabian–Nubian Shield

Extensional metamorphic core complexes can be formed within back-arcs (e.g. Jolivet *et al* 1994; Lips 1998) or as the result of extensional collapse (Dewey 1988; Platt & England 1993). In the case of the Arabian–Nubian Shield, the compressional (arc-accretion) event completely predated the extensional event (Tables 3, 4 and 5) and extensional collapse appears thus to be the most likely cause of extension.

The different terranes in the Arabian–Nubian Shield, bordered by ophiolitic sutures, consisting of juvenile crust and large amounts of arc-related igneous rocks, led a number of authors to compare the terrane assemblages of the Arabian–Nubian Shield to the Cordillera of western North America (Pallister *et al.* 1988; Harris *et al.* 1990; Samson & Patchet 1991; Stern 1994). As in the North American Cordillera, the terranes of the Arabian–Nubian Shield consist of juvenile crust and are separated by ophiolitic sutures. Juxtaposition of the terranes in the North American Cordillera resulted from multiple arc-accretion events (Coney 1989). The multiple arc-accretion took place at an active continental plate margin, causing fast growth of the continental crust and lithospheric thickening in Western North America during the Mesozoic (Coney & Harms 1984; Livacarri 1991; Platt & England 1993). Large transpressional strike slip zones were associated with the arc accretion and developed in the later stages of the terrane assemblage (Potter 1986; Coney 1989). Similar transpressional zones are seen in the Arabian–Nubian Shield.

Multiple arc accretion is regarded as the process responsible for the assemblage of the different terranes in the Arabian–Nubian Shield (Pallister *et al.* 1988; Harris *et al.* 1990; Samson & Patchet 1991). The accretion phase in the Arabian–Nubian Shield was accompanied by the intrusion of I-type plutons (Stoeser 1986). We agree with many authors (e.g. Stoeser & Camp 1985; Samson & Patchet 1991) who state that this compressional phase caused fast crustal growth, and we believe that this phase was responsible for lithospheric thickening in the Arabian–Nubian Shield from 750 Ma to 650 Ma ago, similar to the crustal thickening in Western North America during the Mesozoic (Livacarri 1991; Platt & England 1993). The Nabitah orogenic belt represents a large transpressional strike slip zone associated with the arc accretion in the Arabian–Nubian Shield. The pre-Neoproterozoic continental terranes in the western parts of the Arabian–Nubian Shield in

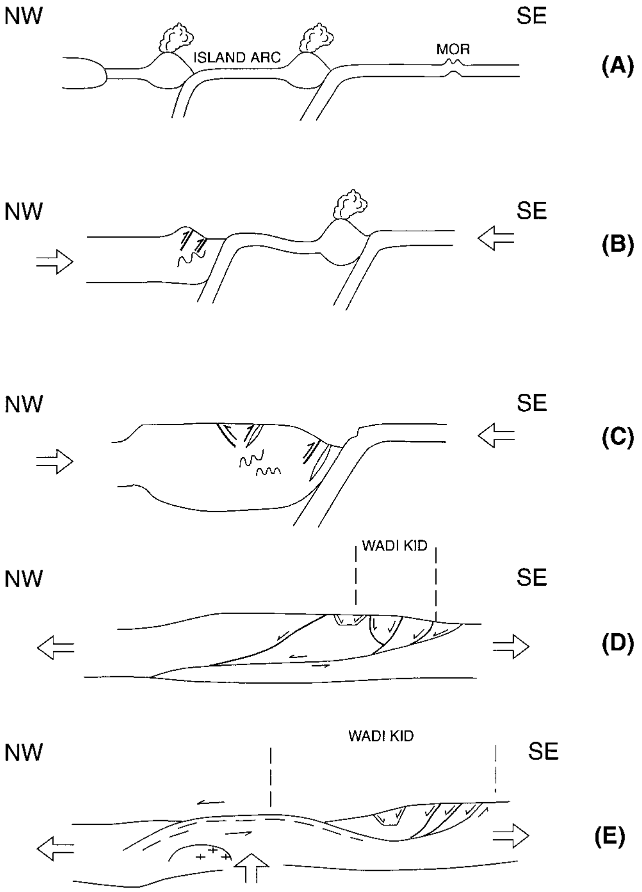

Fig. 6. A cartoon displaying the different stages of the evolution of the Arabian Nubian Shield with special reference to the Wadi Kid area, Sinai, Egypt. The oceanic phase is shown in (**a**), with island arcs developing in the Mozambique Ocean. Remnants of a continental block, representing the western margin of this ocean, were found Sudan and western Egypt. Volcanics formed in an island-arc setting are remnants of this phase in the Wadi Kid area. At stage (**b**), multiple arcs accreted upon the continental block in Sudan and western Egypt. At (**c**), multiple arc-accretion led to lithospheric thickening. The D1 structures in the Wadi Kid area are relicts of this phase. When convergence slowed down, thermal re-equilibration caused slow thinning of the thickened lithosphere and the conductive heating of the lithospheric root decreased the strength of the crust. Stages (**d**) and (**e**) refer to the tectonic development of the Wadi Kid area in more detail and a smaller scale with the start of extension in stage (**d**) and the development of a metamorphic core complex in (**e**). At stage (**d**) the crust became gravitationally unstable and collapsed which led to extension and thinning of the crust through crustal-scale shear zones. At (**e**), tectonic denudation by the main detachment, together with isostatic rebound and the intrusion of A-type granites resulted in the development of metamorphic core complexes.

Sudan and in Egypt represent the continents where arc–continent collision took place and where the arcs accreted onto a continental block (Abdelsalam & Stern 1996).

We have argued that the gneissic domes throughout the Arabian–Nubian Shield represent extensional metamorphic core complexes similar to the core complexes that were formed during the Mesozoic and early Cenozoic in Western North America. Other extensional features in the Arabian–Nubian Shield also display a high similarity with Mesozoic and Early Cenozoic features in western North America. Agar (1986) argued that the composite dykes and associated volcanism in the Arabian–Nubian Shield was comparable to volcanism in a continental rifting environments such as western North America. The sediments in the extensional basins of the Arabian–Nubian Shield were deposited in areas of major tectonic instability characterized by high relief and strong hydrodynamic energy (Grothaus *et al.* 1979; Jarrar *et al.* 1991). The sedimentation has been viewed in a framework of an alluvial fan-braided stream model, comparable to the sedimentation in a continental extensional regime such as the Basin and Range of western Northern America (Grothaus *et al.* 1979) and is indeed very similar to the sedimentation in the highly extending continental crust of the Basin and Range province as described in case studies by Beard (1996) and Lucchita & Suneson (1996). The A-type anorogenic granites were mantle derived and intruded in a thinned crust (Beyth *et al.* 1994; Greiling *et al.* 1994) and correspond to granites in the Basin and Range province (Smith *et al.* 1990).

Most authors have related the strike-slip zones of the Arabian–Nubian Shield to indentor tectonics as in the Indo-Asian collision system (Schmidt *et al.* 1980; Fleck *et al.* 1980; Burke & Şengör 1986; Stern 1994), and regard them as crucial for the interpretation of the tectonics in the Arabian–Nubian Shield. We relate the strike-slip faults to the extensional phase. According to the data presented in Tables 4 and 5 there was widespread extension throughout the shield during this period (*c.* 620–530 Ma). Large strike-slip zones, sub-parallel to the main direction of tectonic transport, are typical features in extensional regimes with crustal-scale normal faults (Lister *et al.* 1986; Faulds & Varga 1998). They represent zones where the dip of the detachment fault changes rapidly (Lister *et al.* 1986), or represent transfer zones linking adjacent normal faults and which transfer strain between different systems of normal faults (see papers in Faulds & Stewart 1998).

A synthesis of the features described above, justifies, we believe, the comparison with the Mesozoic and Early Cenozoic development of western North America. Consequently, we propose a tectonic scenario for the Arabian–Nubian Shield (see Fig. 6) similar to the one that was proposed for the Mesozoic and Early Cenozoic development of western North America by Platt & England (1993). Island arcs were formed in the Mozambique Ocean (Fig. 6a). Terranes with different geological characteristics were accreted onto a continental margin, represented by a continental terrane west of the Nakasib–Bir Umq suture in Sudan and possibly by a continental block in western Egypt (Fig. 6b). The arc accretion led to substantial lithospheric thickening (Fig. 6c). A reduction in the rate of convergence with thermal re-equilibration caused slow thinning of the thickened lithosphere. At this stage, conductive heating of the lithospheric root decreased the strength of the crust. The thickened crust became gravitationally unstable and collapsed, which, in turn, led to extension (Fig. 6d). Crustal thinning, through large low-angle normal shear zones, allowed the intrusion of A-type granites. The isostaic rebound and the intrusion of these granites contributed to the doming of the lower crust and the development of metamorphic core complexes such as the Wadi Kid complex, and the El Sibai and Meatiq domes (Fig. 6e). Sedimentary basins, bordered by normal faults, were formed at upper crustal levels as a response to the extension and allowed the deposition of post orogenic molasse sequences as the Hammamat Gp and the Saramuj Conglomerate Gp.

Conclusions

In this paper we have argued that the Late Proterozoic tectonic evolution of the Arabian–Nubian Shield is very similar to that of the Mesozoic and Early Cenozoic of western North America. The Pan-African in the Arabian–Nubian Shield included early oceanic features and intra-oceanic subduction. This phase was followed by arc accretion and lithospheric thickening. The thickened lithosphere eventually collapsed and NW–SE-trending extension took place throughout the Shield.

We present the following model for the Late Proterozoic development of the Arabian Nubian Shield.

(1) Rifting of Rodinia led to the formation of the Mozambique ocean. Intra-oceanic subduction led to the development of island arcs. Ophiolites and island-arcs remnants, dated at approximately 900–750 Ma, are relicts of this period.

(2) Subduction at continental margins in western Sudan and possibly western Egypt led to accretion of the remnants of island arcs and of oceanic crust at these margins. The arc accretion took place between 750 and 650 Ma. The arc accretion marked the closure of the Mozambique ocean as Gondwanaland formed and was responsible for fast continental crustal growth and lithospheric thickening. The terrane assemblages in Saudi Arabia and Sudan are remnants of this stage.

(3) The thickened lithosphere collapsed and extension started. Normal faults and shear zones, forming an extensional detachment system, were formed at *c.* 600–560 Ma. The core complexes in the Arabian–Nubian Shield are relicts of this process. Late orogenic extensional basins throughout the Arabian–Nubian Shield and NE–SW-trending dykes also indicate NW–SE extension. During the latest stage, A-type mantle-derived granites intruded the thinned extended crust. The extension in the Arabian–Nubian Shield continued until approximately 530 Ma. This phase of extension appears to be lengthy, however the uniform NW–SE structural trend indicates a single protracted event, as indicated by the presently available geochronological data.

This research was supported by the Dr. Schurmann Foundation for Precambrian Research, grants nos. 1994/06 and 1997/04. We thank H. N. A. Priem for his support during all the stages of this project. We thank H. Kisch for useful discussions in the field and during the preparation of this manuscript. We appreciate the help of I. Shalaby. B.B., P.B. and W.V thank Halliburton SDL, Ijmuiden, the Netherlands. R. O. Greiling and Y. Dilek are thanked for constructive reviews which greatly improved the paper.

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Received 28 May 1999; revised typescript accepted 8 October 1999.
Scientific editing by Alex Maltman.