2

Geology of the Arabian Nubian Shield – An overview

2.1 Introduction

This chapter aims to provide an overview of the regional geology of the Arabian Nubian Shield (ANS) as published in the literature. The ANS extends from Jordan and southern Israel in the north to Eritrea and Ethiopia in the south and from Egypt in the west to Saudi Arabia and Oman in the east (Figure 2-1). The ANS consists of gneisses, granitoids, various (meta)volcanic and (meta)sedimentary rocks. Many authors interpret the early evolution of the ANS as the accretion of island arcs and of oceanic terranes (e.g. Vail 1985; Stoeser and Camp 1985; Harris et al., 1990; Samson and Patchet 1991; Abdelsalam and Stern 1996; Johnson and Kattan, 2001). The Afif and Ar Rayn Terranes in Saudi Arabia, both with a continental signature have also been included in the Arabian-Nubian Shield (Stoeser and Camp, 1985; Abdelsalam and Stern, 1996). Occasionally attention has been given to features that are generally associated with extension, such as dykes and sedimentary basins (e.g. Schürmann, 1966; Grothaus et al., 1979; Stern et al., 1984; Husseini 1989; Rice et al., 1991; Greiling et al., 1994; Blasband et al., 2000).

2.2 Relicts of oceanic crust

The ANS 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 2-1). Locally, complete ophiolitic sequences can be observed including peridotites, gabbros, sheeted dykes, pillow lavas and sedimentary rocks that reflect a deep-sea environment (Table 2-1). In many cases, the ophiolites have been dismembered and are now found in tectonic mélanges. The ophiolites were dated at approximately 870-740 Ma (Table 2-1; Stern et al., 2004 and Johnson et al., 2004). Geochemistry of a number of mafic schistose units throughout the ANS indicates a MORB provenance (Bentor 1985; El Gaby et al., 1984; El Din et al., 1991; Rashwan 1991). Some interpret the ophiolites to have been formed in back-arc basins and others believe that they were formed at mid oceanic spreading ridges (Bentor 1985; El Gaby et al., 1984; El Din et al., 1991; Rashwan 1991; Pallister et al., 1988). The ophiolites are thought to have been formed in the Mozambique Ocean that was formed upon rifting of Rodinia (Abdelsalam and Stern, 1996; Stern, 1994).

2.3 Island-arc remnants

Typical island-arc related rocks are found throughout the ANS (Table 2-2). Tonalites, gabbros, basalts, andesites and metavolcanics with a calc-alkaline island-arc geochemistry are common in the Eastern Desert and the Sinai, Egypt (Bentor 1985; El Gaby et al., 1984; El Din et al., 1991; Rashwan, 1991). Gabbro-diorite suites are typically observed in plutonic complexes in

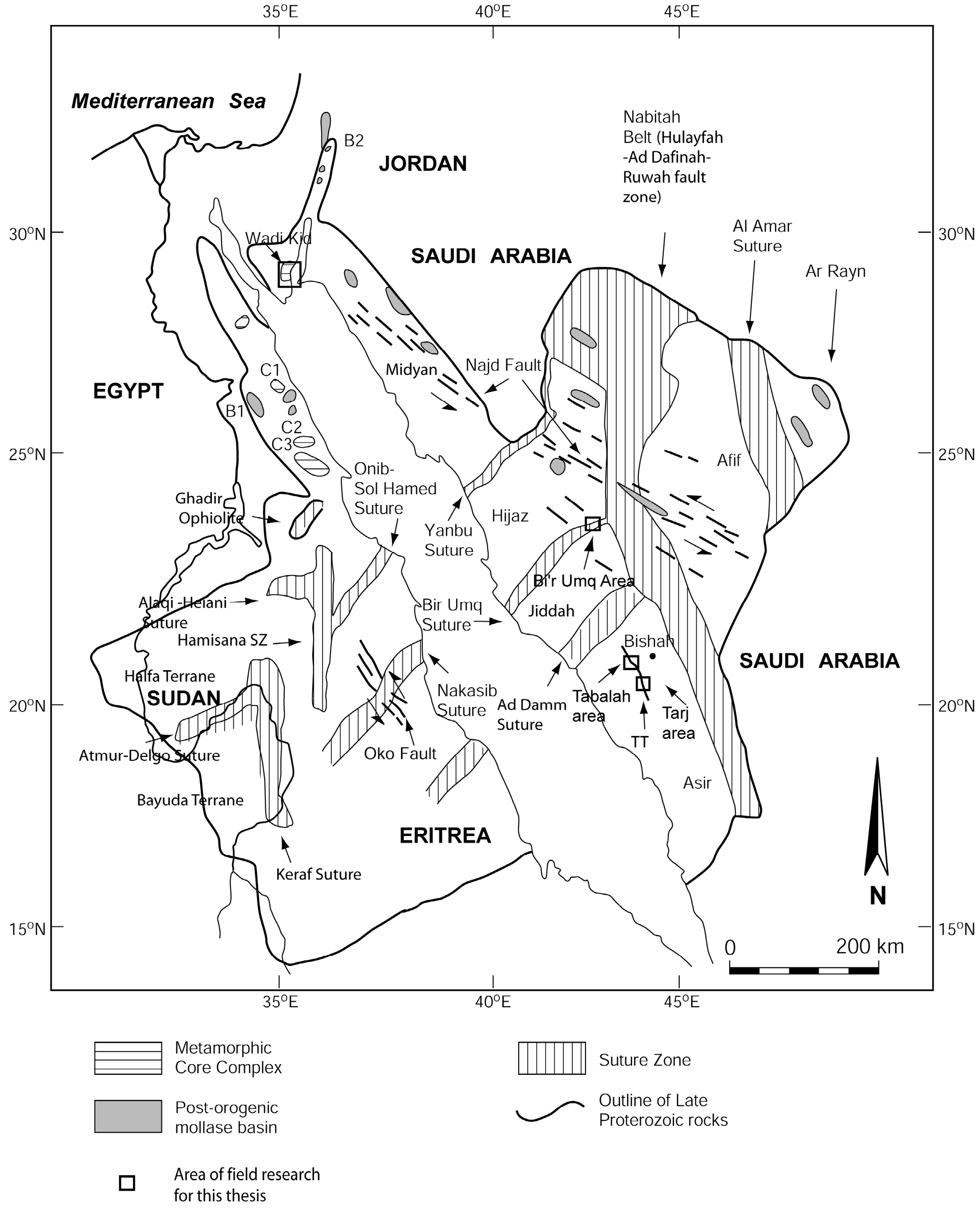

Figure 2-1 *A map showing the main Neoproterozoic features in the Arabian Nubian Shield. WK = Wadi Kid Complex, C1 = Meatiq Dome, C2 = El Sibai Dome, C3 = Wadi Ghadir Complex, C4 = Hafafit Dome, C5 = Taif area, C6 = Abha Complex, B1 = Basin with Hammamat sedimentary sequence, B2 = Basin with Saramuj Conglomerate. Compiled from maps by Vail (1985); Stoeser and Camp (1985); Brown et al., (1989) , Greiling et al., (1994) and Abdelsalam and Stern (1996).*

ancient island-arcs as the Umm Naggat Complex in the Eastern Desert of Egypt (Mohamed and Hassanen, 1996). 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 ca. 900-700 Ma (Table 2-2).

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 K tonalites, trondhjemites and andesites were formed during 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, as the ophiolites (Abdelsalam and Stern 1996).

2.4 Features related to arc-accretion

A number of deformed linear belts of ophiolitic rocks have been observed throughout the ANS (Table 2-3) and these were interpreted as sutures (e.g. Ries et al., 1983; Vail 1985; Abdelsalam and Stern 1996). The NE-SW trending Yanbu and Bi'r Umq Sutures represent examples of the ophiolitic linear belts in the Neoproterozoic shield of Saudi Arabia (Figure 2-1). 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 Rayn and Hijaz Domains (Figure 2-1) 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 overprint after the initial compressional phase (Quick 1991; Abdelsalam and Stern 1996; Johnson and Kattan 2001). Little reliable geochronological constrains are available for these NE-SW sutures, however interpretations of intrusives relations led Johnson et al. (2002) to date the suturing on the Bi'r Umq Suture at ca. 780-760 Ma. The deformation along the Yanbu Suture was estimated at 740-700 Ma (Johnson, 1999; Stoeser and Camp, 1985).

The two most easterly outcropping terranes in the ANS, the Ar Rayn and the Afif Terranes, have a continental signature as shown by their geochemical characteristics (Al-Salah and Boyle, 2001). The ophiolites of the Al-Amar suture, that separate these two terranes, is thought to have originated in a back-arc basin that was formed as a result of back-arc extension above the subduction zone (Al-Salah and Boyle, 2001). The formation of the back-arc took place at ca. 700 Ma and the closure of the back-arc, which is represented by the Al Amar Suture, took place at ca. 680 Ma (Al-Salah and Boyle, 2001).

The Nabitah Belt (referred to as Hulayfah-Ad Dafinah-Ruwah fault zone by Johnson and Kattan, 2001) in Saudi Arabia is the largest and most complicated feature that was formed during the arc-accretion phase in the ANS (Johnson and Kattan, 2001; Quick, 1991; Stoeser and Camp, 1985). It is some 1000 km long, up to 100 km wide and trends N-S. It forms the contact between the continental Afif Terrane and the juvenile Hijaz, Jiddah and Asir Terranes. Therefore, the Nabitah Belt also may represent the continental margin between the continental and the oceanic parts of the eastern ANS. The Nabitah Belt consists of ophiolites and sheared ophiolites in the form of N-S trending and steeply dipping mylonites and phyllonites (Quick 1991; Johnson and Kattan, 2001). These main structures were formed during a phase of left-lateral transpression from ca. 680 Ma (Quick 1991; Johnson and Kattan 2001). The closure of the oceanic basin between juvenile terranes and the Afif Terrane was completed by 630 Ma (Johnson and Kattan, 2001). The Siham Group in the Afif Terrane contains low-grade mixed sedimentary and volcanic sequences that were deposited on the high grade rocks which formed

Table 2-1 A review of lithologies and ages of rocks that are regarded as remnants of oceanic crust.

Oceanic crust (ophiolitic sequences)

Area	Lithology	Age (Ma)	Reference
Wadi Ghadir, Egypt	Serpentinites, layered gabbros, sheeted dykes, pillow lavas, black shales.	746±19 (Pb-Pb)	El Akhal, 1993; Kroner 1985;
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).	ca. 800	Ries et al., 1983; Kroner, 1985; El Gaby et al., 1984
Onib and Gerf, Sudan	Ultramafic cumulates, interlayered gabbros, sheeted dykes and pillow basalt.	ca. 840-740, e.g. 808±14 (Pb-Pb) 741±21 (Pb-Pb)	Stern et al., 1990; Kroner et al., 1987; Zimmer et al., 1995
Halaban Ophiolite, Al Amar Suture,	Ultramafics, gabbros, cherts. Gabbros indicate that ophiolites were formed in back-arc basin	Ca. 700	Al-Saleh et al., 1998
Ophiolites throughout Saudi Arabia	Peridotites, gabbros, sheeted dykes, pillow lavas, cherts, 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

the continental basement (Agar, 1985). Agar (1985) found these sedimentary sequences to be similar to those that were formed along the continental margins of western North and South America. This is confirmed by geochemical analyses of volcanic rocks of the Siham Group (Agar, 1985). Consequently Agar (1985) interpreted the Siham Group to have formed at the continental margin west of the Afif Terrane. The Nabitah Belt formed the relict of this continental margin (Agar, 1985).

Ophiolitic sutures have been observed in Sudan and Egypt (Table 2-3; Figure 2-1). The NE-SW trending Nakasib and Onib-Sol Hamed Sutures in Sudan are continuations of the Yanbu and Bi'r Umq sutures in Saudi Arabia (see Figure 2-1). These structures are interpreted to separate island-arcs terranes (Abdelsalam and Stern 1996). The Nakasib Suture displays relicts of an E-W compressional regime which represents the suturing phase. Strike-slip movement overprints the earlier structures and represents the later stages of arc-accretion (Abdelsalam and Stern 1996). The N-S trending Hamisana shear zone also contains ophiolitic remnants (Abdelsalam and Stern 1996). It recorded dextral strike-slip movement at 640-600 Ma and displaced Onib-Sol Hamid Suture (Abdelsalam et al., 2003). The N-S trending Keraf Suture in Sudan separates the continental Bayuda Terrane and the juvenile Gebeit Terrane and may thus be a relict of an active continental margin (Abdelsalam and Stern, 1996; Kuster and Liegeois, 2003). Structures in this terrane and the Keraf and Atmur-Delgo Sutures display evidence for closure of the ocean that is represented by the ophiolitic rocks of these sutures at ca. 700 Ma (Abdelsalam, 2003). N-S trending supra-subduction shear zones in Eritrea, which were related to arc-accretion, display HP metamorphism (Beyth et al., 2003; De Souza Filho and Drury, 1998). The collisional event that caused the HP-metamorphism ended before 650 Ma (De Souza Filho and Drury, 1998). Throughout the ANS, the N-S trending sutures postdate the NE-SW trending ophiolitic sutures.

Large NW-SE trending strike slip zones, such as the Najd Shear Zone in Saudi Arabia and the Oko Shear Zone in Sudan, represent another important structural feature in the ANS (e.g. Fleck et al., 1980; Stern 1985; Dixon et al., 1987). They cross-cut the NE-SW and N-S trending structures in the ANS (Stern 1985; Dixon et al., 1987). The Najd shear zone, the largest of the NW-SE strike-slip zones, started its activity around 680 Ma when it was formed during arc-accretion and collision (Stern, 1985; Johnson and Kattan, 1999). Its activity continued until 600 Ma or even later (Abdelsalam and Stern, 1996; Johnson and Kattan, 1999; Shalaby et al., 2005); however, no conclusive data are available for the age of its latest activity. NW-SE trending strike-slip faults are also observed next to the "gneissic domes" (Bregar et al., 2002; Fritz et al., 1996), which will be discussed late in this chapter.

I-type calc-alkaline magmas, which form, among others, granodiorites, tonalites and andesites, are igneous relicts of subduction at continental margins and of arc-accretion (Wilson, 1989). Also in the ANS, these rock-types were often associated with arc-accretion (Brown et al, 1989). For example, the tonalites and granodiorites from the El-Bula area in Central Eastern Desert in Egypt display geochemical characteristics of I-type intrusives that were formed at a continental margin (El-Shazly and El-Sayad, 2000). In the ANS, the I-type granitoids were generally interpreted to result from melting of an amphibolitic crust (e.g. Hassanen et al., 1996; Jarrar et al., 2003; Kuster and Liegeois, 2001) The I-type granitoids the ANS were dated at

Table 2-2 A review of lithologies and ages of rocks that are regarded as island-arc remnants.

Island-arc remnants

Area	Lithology	Age (Ma)	Reference
Wadi Hafafit, Egypt	Meta-andesites with an island-arc chemistry.	N/A	Rashwan, 1991
E. Desert, Egypt	Tonalites, trondjhemites, basalts, andesites. Volcanics with island-arc chemistry.	ca 900-700	Bentor, 1984; El Gaby et al., 1984; El Din, 1991; Rashwan, 1991
Umm Naggat, Egypt	Gabbro-diorite suite with island-arc geochemistry	N/A	Mohamed and Hassanen, 1996
Asir, Saudi Arabia	Basaltic to andesitic lavas and tuffs with calc alkaline to low K-chemistry.	ca. 900-800	Jackson and 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).	ca. 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
El-Aradiya area, Eastern Desert, Egypt	Gabbros and dolerites dykes display an island-arc geochemistry	NA	Abu El-Ela, 1999
Bayuda Desert, Sudan	Amphibolite schists with tholeiitic island-arc geochemistry	806 (Sm-Nd, WR)	Kuster and Liegeois, 2001
Nakfa Volcanics, Northern Erutra	Basalts and Rhyolites, deformed at greenschist grade with island-arc geochemistry	854±3 (U-Pb, SHRIMP)	Teklay et al, 2002

Table 2-3 A review of lithologies, metamorphism, structural data and ages of rocks that contain remnants of the arc-accretion phase.

Arc-accretion remnants

Area	Lithology	Metamorphism	Structural data	Age (Ma)	Reference
Idsas, Yanbu and Bir Umq sutures, Saudi Arabia	NW-SE trending linear ophiolitic belts.	Greenschist to lower amphibolite-grade	Folds, foliations, lineations, thrusts.	Ca. 780 -700	Johnson, 1999; Johnson et al., 2002
Alaqi-Heiani suture, Egypt	Ophiolites	Greenschist- to amphibolite grade	Early N- and S-dipping nappes and thrusts formed during N-dipping subduction followed by NW-striking folding phase due to NE-SW compression and N-striking folding phase due to E-W compression (Hamisana trend)	N-S compression: 770-730 NE-SW to E-W compression:	Abdelsalam et al., 2003a
Nakasib, Sudan	Ophiolitic suture, folded ophiolitic nappes, diorite	N/A	E-NE trending suture zone: Early (ca. 750Ma) SE-verging tight folds, overprinted by NE-trending upright folds (ca 700Ma),	ca. 840-760 arc-arc ca. 760-700 arc-continent	Abdelalam, 1994; Abdelsalam and Stern, 1996; Schandelmeier et
Onib-Sol Hamed, Sudan	Ophiolitic suture. Granodiorite with I-type geochemistry	Greenschist to amphibolite-grade	Suture zone: Early S-to SE verging ophiolitic nappes, late E-NE-trending	ca. 750-720	Stern et al., 1990; Abdelsalam and

Continuation Table 2-3 A review of lithologies, metamorphism, structural data and ages of rocks that contain remnants of the arc-accretion phase.

Throughout Saudi Arabia	Synorogenic diorites and granodiorites.	N/A	Syn-kinematic	ca. 763-660	Stoeser, 1986; Brown et al., 1989
Nabitah Belt/ Hulayfah-Ad Dafinah-Ruwah fault zone, Saudi Arabia	N-S trending ophiolites and sheared ophiolites, phyllonites and mylonitest juxtaposes terranes with different petrological characteristics. Intruded by quartz diorites. .	Non-metamorphosed to amphibilite	Open folds with NE-SW trending fold axes and subvertical axial planes, overprinted by N-S trending steeply dipping mylonites (Nabitah trend). Steeply NE-dipping foliation, lineation and folds. Sinistral shear indicators.	Quartz diorite: 710 Sinistral strike – slip: 680-630	Quick, 1991 Johnson and Kattan, 2001
Halaban ophiolite, Al Amar suture, Saudi Arabia	N-S trending linear ophiolitic belt.	Amphibolite-grade	Ophiolitic sutures	679±6 (Ar-Ar)	Al-Saleh et al, 1998; Al-Salah and Boyle, 2001
El-Bula area	Tonalites and granodiorites with an I-type geochemistry	N/A	N/A	NA	El-Shazly and El-Sayad, 2000
Dineibit/El-Quleib, South Eastern Desert, Egypt	Calc-alkaline granite with I-type geochemistry	Non-metamorphosed	Undeformed	NA	El-Sayed and El-Nisr, 1999
El Sibai Dome	Deformed tonalites and granodiorites with an I-type geochemistry	Amphibolite	North-west directed thrusting	680	Bregar et al., 2002;El Din, 1991
Gabal Igla Ahmar, Eastern Desert, Egypt	Diorites and granodiorites with I-type geochemistry. Interpreted to have been formed through melting of amphibolitic crust	NA	Undeformed	NA	Hassanen et al, 1996

Continuation Table 2-3 A review of lithologies, metamorphism, structural data and ages of rocks that contain remnants of the arc-accretion phase.

Quseir-Marsa Alam, Egypt	Ophiolitic melanges.	Greenschist	Suture zone: mylonites interpreted as thrusts dipping NE, and folds.	N/A	Ries et al., 1983
Hamisana shear zone	Ophiolites	NA	Different folding phases. E-W shortening followed by dextral strike-slip movement	640-600	Abdelsalamn and Stern, 1996; Abdelsalam et al., 2003a
Aqaba, Jordan	Tonalites and granodiorites. Geochemistry indicates that they resulted from melting of an amphibolitic crust above a subduction zone	NA	NA	640	Jarrar et al., 2003
Roded Area, Israel	Diorites with I-type geochemistry. Formed through melting of amphibolite crust	Non-metamorphosed	Undeformed	NA	Bogoch et al, 2002
Keraf Suture, Sudan	Ophiolitic suture, diorites, granodiorites and gneiss. Diorites and granodiorites intruded at active continental margin as indicated by geochemistry	Upper amphibilite	N-S striking thrusts. Main deformation-phase resulted from E-W shortening	730 for diorites and granodiorites	Abdelsalam and Stern, 1996 Kuster and Liegeois, 2001
Bayuda Terrane	Gneiss and volcano-sedimentary sequences (interpreted as continental terrane). A-type granites	NA	Phase 1: S-verging thrusts; Phase 2: N-trending folds; Phase 3: N-S trending sinistral strike slip; Phase 4: W-dipping normal faults	Phase 1: 700 Phase 2: 659-650 Phase 3: 590-550 Phase 4: <550	Abdelsalam et al., 2003b
Nacfu and Ghedem Terranes, Eritrea	Meta-volcanics and meta-sediments.	Amphibolite (HP-HT)	Steep S1-foliation and F1-folds (D1)	650 Ma	Ghebreab, 1999; Beyth et al., 2003

approximately 760-650 Ma (e.g. Bregar et al., 2002; Jarrar et al., 2003; Kuster and Liegeois, 2003).

From the scarcely available geochronological data, it appears that deformation on the NE-SW trending ophiolitic belts took place at ca. 780-700 Ma (e.g. Abdelsalam and Stern, 1996; Johnson et al., 2002; Pallister et al., 1989). The deformation on the N-S trending faults took place at ca. 700-620 Ma (e.g. Abdelsalam and Stern, 1996; Quick, 1991; De Souza Filho and Drury, 1998).

2.5 Gneissic domes

A number of gneissic domes have been described in the Eastern Desert, Egypt (Table 2-4). The Meatiq, Hafifit, Gebel El Sibai and Wadi Kid areas (Figure 2-1) 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 lower-crustal units comprise deformed tonalites, diorites and granodiorites, and metasedimentary, metavolcanic and meta-ophiolitic schists. The schists have been generally metamorphosed at amphibolite-grade 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. Many of the gneissic domes are bordered at their NE- and SW-margins by NW-SE trending strike-slip faults (Bregar et al., 2002; Fritz et al., 1996).

The Meatiq Dome is one of the most studied gneissic domes in the ANS. It consists of a lower-crustal unit of gneiss and amphibolite-schists and an upper-crustal unit of ophiolitic mélanges, low-grade island-arc related rocks and other volcano-sedimentary rocks (Loizenbauer et al., 2001; Sturchio et al., 1983). The lower- and upper-crustal units are separated by a cataclasite (Habib et al., 1985). The foliation in the lower crustal rocks is mainly subhorizontal to moderately dipping (Loizenbauer et al., 2001; Sturchio et al., 1983). A NW-SE trending mineral lineation is developed on the foliation (Loizenbauer et al., 2001; Sturchio et al., 1983). Evidence for non-coaxial strain was observed in the schists in the form of S-C fabrics, asymmetric porphyroclasts and asymmetric boudins (Loizenbauer et al., 2001; 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). HT/LP metamorphism took place during the final stages of formation when the Meatiq Dome received its domal structure (Loizenbauer et al., 2001). The low-angle shear zone of the Meatiq Dome was dated at 590 Ma (Fritz et al., 2002). Late anorogenic granites are associated with the doming of the complexes (Greiling et al., 1994). The lower-crustal mylonitic shear zones of the gneissic domes in the ANS were formed at approximately 620-580 Ma (Table 2-4).

2.6 Other late orogenic features

A number of geological features, namely dykes, sedimentary basins and alkaline granites, have been formed at the latest stages of the Neoproterozoic development of the ANS (Table 2-5 and

Table 2-6). These features were formed simultaneously to, or slightly after the low-angle shear zones in the “gneissic domes” (Tables 2-4, 2-5 and Table 2-6).

The Hammamat Group in the Eastern Desert, Egypt contains one of the best preserved clastic sedimentary sequences found in this part of the ANS. Grothaus et al., (1979) have described this sequence in detail. The sedimentary rocks of the Hammamat Gp. uncomformably overlie metamorphic rocks 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 structures 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 Neoproterozoic 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 syn-sedimentary 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, Neoproterozoic post-orogenic molasse sequences, deposited in environments similar to the Hammamat and Saramuj Conglomerate Groups, overlie basement rocks (e.g. Jackson and Ramsay 1980; Hadley and Schmidt 1980; Brown et al., 1989). Evaporitic and clastic basins in Oman, formed at 620-580 Ma, were bordered by NE-SW trending faults Husseini (1989).

Widespread intrusions of mostly undeformed alkaline granites into the lower-crustal sequences in the ANS were dated at ~620-530 Ma (e.g. Schmidt et al., 1980; Habib et al., 1985; El Din et al., 1991; Greiling et al., 1994; Harms and Kuster, 1998). On the basis of geochemical studies, these granitoids have been interpreted as A-type granites that were derived from mantle magmas (Beyth et al., 1994; Kessel et al., 1998; Kuster and Harms, 1998; Moghazi, 2003).

Reconnaissance maps by Schürmann (1966) and Eyal and 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 ca. 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 striking NE-SW were described (Dodge 1979; Clark 1985). Jarrar et al., (2003) and Kessel et al., (1998) showed that these late mafic and felsic dykes were formed from mantle-derived magmas, similar to the A-type granites.

Throughout the ANS, undeformed basalts and rhyolites overlie the lower- and upper crustal metamorphic sequences. The Dohkan Volcanics, in the central part of the Eastern Desert of Egypt, consist of basalts and rhyolites (Moghazi, 2003). Detailed geochemical studies show that the volcanics originate from mantle derived magmas that were extruded from a thinned and extending crust (Moghazi, 2003).

Table 2-4 A review of lithologies, metamorphism, structural data and ages of rocks associated with the "gneissic domes".

"Gneissic domes"

Area	Lithology	Metamorphism	Structural data	Age (Ma)	Reference
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.	596±0.5 and 588±0.3 (Ar-Ar)	Sturchio et al., 1983; El Gaby et al., 1984; Greiling et al., 1994; Fritz et al., 1996; Loizenbauer et al., 2001; Fritz et al., 2002
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.	585	Greiling et al., 1984; Greiling et al., 1994; Fritz et al., 2002
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.	615	El Din, 1991; Bregar et al., 2002; ; Fritz et al., 2002

Continuation Table 2-4 A review of lithologies, metamorphism, structural data and ages of rocks associated with the "gneissic domes".

Um Had area, Egypt	Core: Gneiss and schists; "Overthrusted units": ophiolitic mélange, volcanics and clastic sediments	Core: M1 – upper amphibolite; M2 – greenschist; M3 – amphibolite; "Overthrusted units": non-metamorphosed to	Core: Sub-horizontal foliation and NW-SE sub-horizontal stretching lineation. "Overthrusted units": Folding, SW- and NE-dipping thrusts. NW-SE striking sinistral strike-slip.	NA	Fowler and Osman, 2001
Nacfu and Ghedem Terranes, Eritrea	Meta-volcanics and meta-sediments	Upper-amphibolite	Sub-horizontal shear zones with flat-lying S2-foliation	640	Ghebreab, 1999
East Eritrea and northern Ethiopia	Deformed granodiorites and diorites, undeformed granites, (meta)volcanics, (meta)sediments, (cap-)carbonates In Eritrea; Gneiss and schist in Ethiopia	Greenschist-amphibolite	W-dipping low-angle ductile shear zones with top-to-W shear indicators, overprinted by low-angle cataclasites	590-545	Beyth et al., 2003

2.7 Proposed models for the Neoproterozoic in the ANS

It is generally thought that the ophiolitic rocks and island-arc related rocks of the ANS, described in Table 2-1 and Table 2-2, were formed in the Mozambique Ocean which was formed upon the rifting of Rodinia (e.g. Abdelsalam and Stern, 1996; Rogers et al, 1995; Shackleton, 1996; Unrug, 1996). The rifting of Rodinia and the formation of the Mozambique Ocean started at ~900 Ma (e.g. Abdelsalam and Stern, 1996; Rogers et al, 1995; Shackleton, 1996; Unrug, 1996). The formation of oceanic crust continued until ca. 740 Ma. Meanwhile, intra-oceanic subduction in the Mozambique Ocean formed the island-arcs (e.g. Abdelsalam and Stern, 1996; Bentor, 1985; Brown et al., 1989; Greiling et al., 1994). The relicts of these island-arcs are found in the form of the juvenile terranes of the ANS, as the Asir, Jiddah and Hijaz Terranes in Saudi Arabia (e.g. Brown et al., 1989; Harris et al., 1990; Johnson et al., 1987; Stoeser and Camp, 1985). The island-arcs were formed at ~900-780 Ma (see Table 2-2).

The ophiolites, described above, are found in strongly deformed linear belts which trend NE-SW or N-S (see Figure 2-1 and Table 2-3). They mark the borders between the terranes (e.g. Abdelsalam and Stern, 1996; Johnson et al., 1987; Stoeser and Camp, 1985). They are thought to represent the zones of closure of the oceanic basins between the juvenile terranes and between the juvenile terranes and the continental terranes (e.g. Abdelsalam and Stern, 1996; Stoeser and Camp, 1985). The closure took place along subduction zones and so these ophiolitic sutures are thought to represent relicts of ancient subduction zones (Abdelsalam and Stern, 1996; Shackleton, 1996; Stoeser and Camp, 1985). Consequently arc-accretion is regarded as the process responsible for the assemblage of the different terranes in the ANS (Pallister et al., 1988; Harris et al., 1990; Samson and Patchet 1991). The accretion-phase was accompanied by the intrusion of I-type plutons (Brown et al., 1989; Kuster and Liegeois, 2001; Stoeser 1986). It took place at 780-630 Ma (see Figure 2-2 and Table 2-3). The earliest evidence for arc-accretion was found in the NE-SW trending Bi'r Umq Suture where suturing was dated at 780-760Ma (Johnson et al., 2002). The Nabitah Belt, the contact between the juvenile terranes in Saudi Arabia and the continental Afif Terrane, is believed to represent the active continental margin of East Gondwanaland (Abdelsalam and Stern, 1996; Al-Salah and Boyle, 2001). The activity along the Nabitah Belt is thought to have started at 700 Ma however this date is not regarded as robust (Johnson and Kattan, 2001). The Keraf Suture is part of the continental margin at the southwestern side of the ANS and should thus be the continental margin of Western Gondwanaland (Abdelsalam at al., 2003b; Abdelsalam and Stern, 1996; Unrug, 1996). Calc-alkaline magmatism in the Saharan craton, which contains the relicts of western Gondwanaland, indicated that subduction started at 730 Ma (Bailo et al., 2003). From the limited available geochronological data on arc-accretion, it appears that the NE-SW trending sutures pre-date the N-S trending sutures.

Some authors regard the NW-SE trending Najd sinistral strike-slip shear zone as the major structure in the later development of the ANS (e.g. Stern, 1985; Sultan et al., 1988) however recent research indicates that the faults that represent the Najd shear zone may not form the major system as initially thought (Johnson and Kattan, 1999; Shalaby et al., 2005). Abdelsalam and Stern (1996) and Stern (1994) believe that the Najd shear zone formed due to

Table 2-5 A review of geological lithologies, structural data and ages of rocks associated with "late orogenic"sedimentary basins.

"late orogenic" sedimentary basins

Area	Feature/Lithology	Structural data	Age (Ma)	Reference
Hammamat Egypt	Hammamat Gr.; 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.	ca. 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	ca. 600-550 Dyke at 545±13 (K-Ar)	Jarrar et al., 1991; Jarrar et al., 1992
Saudi Arabia	Sedimentary basins; Fatima, Murdama, Jibalah and Shammar Groups: conglomerates, sandstones, deposited in shallow water, high-energy environments.	N/A	ca. 620-540	Jackson and Ramsay, 1980; Hadley and Schmidt, 1980; Brown et al., 1989; Kemp, 1996; Johnson, 2003
Oman	Salt basins	Basins bounded by NE-SW striking normal faults.	ca. 620-540	Husseini, 1989

Table 2-6 A review of lithologies, structural data and ages of "late orogenic" igneous rocks. .

"late orogenic" igneous rocks

Area	Feature/Lithology	Structural data	Age (Ma)	Reference
E. Desert Egypt	Dykes: bimodal, mafic and felsic	Dykes trend NE-SW	ca. 620-550	Schürmann, 1966; Stern and 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.	ca. 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
Dokhan Volcanics	Basalts and rhyolites	Undeformd	N/A	Moghazi, 2003
Sudan, Eritrea	Potassic and metaluminous granites that are interpreted as A-type granites	Undeformed	580-470	Küster and Harms, 1998
Araba, Southeastern	A-type granites, mafic and felsic volcanics . Geochemistry indicates that derived from	Undeformed	600-540	Jarrar et al., 2003

Continuation Table 2-6 A review of lithologies, structural data and ages of "late orogenic" igneous rocks. .

Shalatin-Halaib, south Eastern Desert, Egypt	Granites with A-type geochemistry	Undeformed	NA	El-Nisr et al, 2001
Elat, Southern Israel	Granites with A-type geochemistry. Mafic and felsic dykes. All were derived from a mantle derived magma	Undeformed	NA	Beyth et al., 1994; Kessel et al., 1998
Entire Shield	Alkaline granites: A-type granite geochemistry, intruded in thinned and extending crust.	None to slightly lineated.	ca. 600-540 Granite at 594±4 (Rb-Sr) and granite at 544 (Rb-Sr)	Stern and Hedge 1985; Husseini, 1989; Beyth et al., 1994; Greiling et al., 1994; Brown et al., 1989; Hassanen , 1997

continuing collision of East- and West-Gondwanaland after the closure of the oceanic basins and after the end of the actual arc-accretion.

The formation of the gneissic domes postdates the arc-accretion and is the latest Neoproterozoic features that was formed in the ANS (Blasband et al., 2000; Greiling et al., 1994). Most authors interpret the "gneissic domes" as core complexes (e.g. Blasband et al., 2000; Bregar et al., 2002; Greiling et al., 1994; Loizenbauer et al., 2001). Disagreement exists, however, about their mode of formation. Some believe that the low-angle shear zones of the core complexes are thrusts (Fowler and Osman, 2001; Habib et al., 1985). Others interpret the core complexes in the ANS as expressions of local extension in the NW-SE strike-slip shear zones as the Najd shear zone (e.g. Bregar et al., 2002; Fritz et al., 2002; Loizenbauer et al., 2001). For this model, the NW-SE strike-slip shear zones were thought to have been formed during the later stages of collision in the ANS (e.g. Bregar et al., 2002; Fritz et al., 2002; Loizenbauer et al., 2001). Recently, a number of authors have interpreted the core complexes as structures that were formed during regional extension throughout the ANS at the latest stages of its development (Blasband et al., 2000; Greiling et al., 1994). The core complexes were formed when the collision had ceased completely (Beyth et al., 2003; Blasband et al., 2000). Consequently, these core complexes were thought to have been formed in similar way as the Cordilleran core complexes in western North America (Blasband et al., 2000). Thick low-angle high-grade shear zones in Eritrea and Ethiopia, similar to those in core complexes, were also related to regional extension during the latest stages of the development of the ANS (Beyth et al., 2003; Ghebreab, 1999). The "gneissic domes" or core complexes were formed at ca. 620-580 Ma (see Table 2-4).

Granitoid intrusions, dykes, and sedimentary basins represent other notable geological features that were formed simultaneously with the gneissic domes. Alkaline granites are found throughout the ANS. On the basis of their geochemistry, they are generally thought have been derived from mantle and to have intruded in an extending and thinned crust (e.g. Beyth et al., 1994; Jarrar et al., 2003; Kessel et al, 1998; Kuster and Harms, 1998).

Undeformed felsic and mafic dykes, and undeformed rhyolites and basalts, dated at ~620-550 Ma (see also Table 2-6), were also interpreted to have been formed in a thinned and extending crust (Jarrar et al., 2003; Kessel et al., 1998). These dykes trend generally NE-SW and this led Blasband et al., (2000) and Jarrar et al., (1992) to postulate that they were intruded during NW-SE extension.

Little to undeformed sedimentary basins were interpreted to have been formed at ca. 620-540 Ma (see Table 2-5). These basins contain many different types of clastic sequences. Salt and carbonates fill the Neoproterozoic basins in Oman (Husseini, 1989). Some sedimentary basins were formed during extension in a NW-SE extension (Jarrar et al., 1991; Grothaus et al., 1979; Husseini, 1989). Other "late orogenic" basins were interpreted as pull-apart basins that were related to the NW-SE strike-slip shear zones (Fritz et al., 1996; Johnson, 2003).

A number of authors state that compression and collision continued until the end of the Neoproterozoic in the ANS (e.g. Abdelsalam and Stern, 1996, Bregar et al., 2002; Shackleton, 1996; Stern, 1999). Alternatively, those who relate the "gneissic domes" and the other "late orogenic" geological features to extension, state that the transition from arc-accretion and

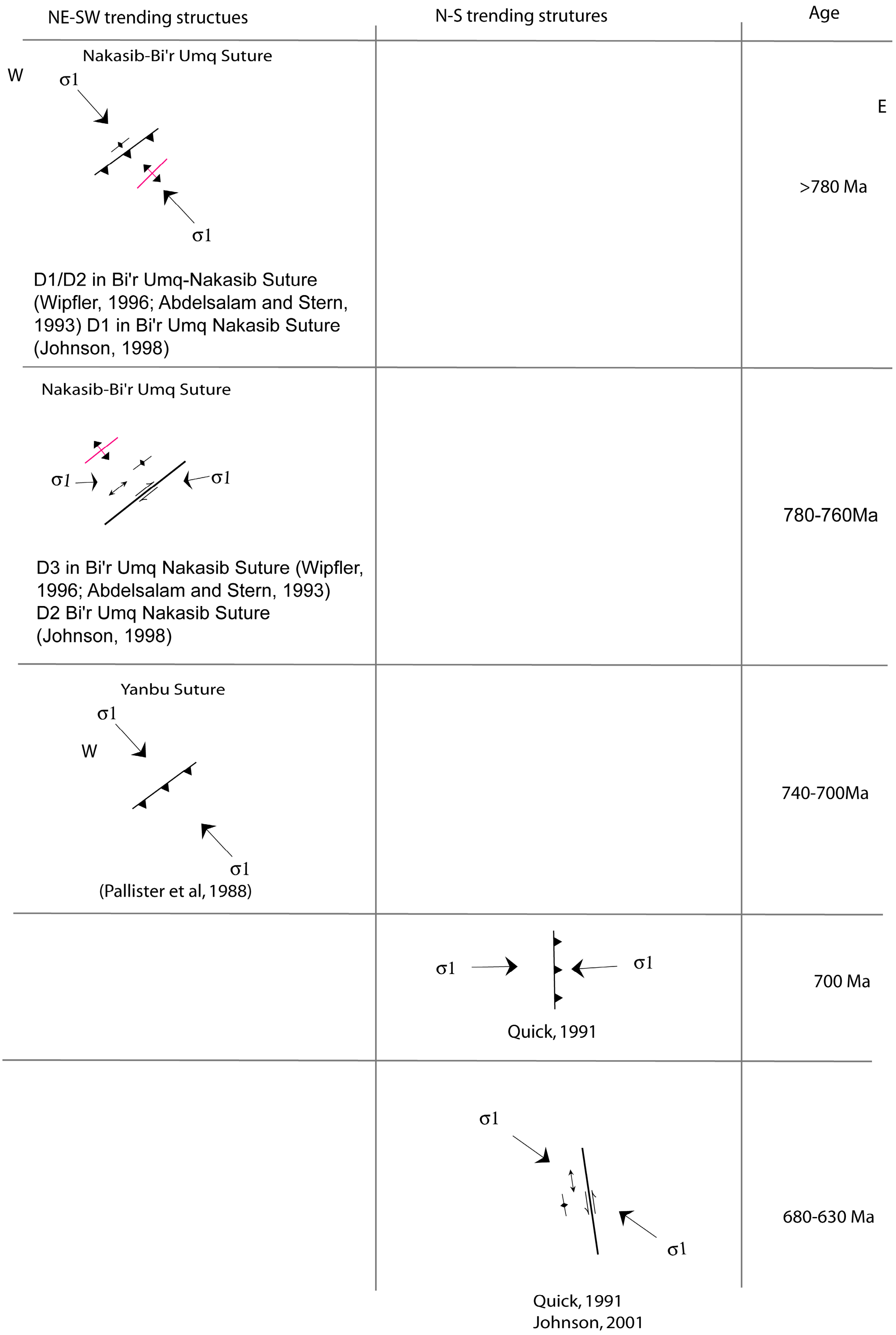

Figure 2-2 Sketch table of major structures that are related to arc-accretion in the Arabian-Nubian Shield as described in literature.

Note: the ages in the right column are not according to a scale.

collision towards extension was caused by gravitational collapse (e.g. Abdelsalam et al., 2003b; Beyth et al., 2003; Blasband et al., 2000; Kessel et al., 1998; Moghazi, 2003).