6

A new geodynamic model for the Neoproterozoic of the Arabian-Nubian Shield

6.1 Introduction

In the framework of this study, research was performed in a number of areas of the ANS that are thought to represent examples of the typical tectonic stages in its Neoproterozoic development: 1) the oceanic stage, which includes mainly remnants of intra-oceanic subduction, 2) the arc-accretion stage and 3) a late extensional stage which is still controversial (see chapter 2). The main goal of this chapter is to integrate the data from the different areas in this thesis, together with relevant data from literature, and to create an updated tectonic model for the Neoproterozoic evolution of the ANS.

6.2 Summary of newly obtained data for the three main tectonic phases in the Arabian-Nubian Shield

6.2.1 Introduction

The most important data that were obtained in the framework of this study include kinematic data for the Bi'r Umq Complex and kinematic and geochronological data for the Tabalah and Tarj Complex and the Wadi Kid Complex. Their results are summarized in Figure 6-1. Also included in Figure 6-1, are similar published data for the Nabitah Belt. The location of the studied areas and key structures in the ANS is shown in Figure 6-2.

6.2.2 The Bi'r Umq Complex: Relicts of the oceanic stage and the arc-accretion stage

Research was performed in the framework of this thesis in the Bi'r Umq Complex in Saudi Arabia (Figure 6-2) because it is thought to contain relicts of two of the three main tectonic phases in the ANS, namely the oceanic stage and arc-accretion stage. The Bi'r Umq Complex is part of the Nakasib-Bi'r Umq suture and is described in detail in chapter 3. The study focused on the detailed structural/kinematic analysis of the key structure in the area, the Bi'r Umq Shear Zone (BUSZ).

The Bi'r Umq Complex consists of a lithological sequence with ultramafics, basalts and cherts. In other parts of the Nakasib-Bi'r Umq suture, complete ophiolitic sequences were found (e.g. Johnson et al., 2002) and therefore the Bi'r Umq Complex (BUC) is assumed to be a dismembered ophiolite. In Chapter 3, it was interpreted as a suprasubduction ophiolite that was formed in a fore-arc or a back-arc because it contains a mixed MORB/OIB geochemistry and is located close to the island-arc relicts of the Jiddah Terrane and Hijaz Terrane. This is in agreement with the interpretations of Johnson et al. (2002) and Dilek and Ahmed (2003) and it was thus formed at an intra-oceanic subduction environment. The ophiolite was thought to have been formed at ~830 Ma (Pallister et al., 1988).

The detailed structural/kinematic research, described in Chapter 3, focused on the WSW-ENE trending BUSZ. In this shear zone, three phases of deformation were identified. D1-structures include sub-vertical WSW-ENE trending foliations, steeply NW plunging lineations and shear sense indicators that indicate top-to-SE movement. On the basis of these structural observations, it was concluded that the D1-phase resulted in SE-vergent thrusting on the BUSZ. Thrusting was also observed on other WSW-ESE to SW-NE trending shear zones in the BUC and the surrounding areas. Therefore, it was concluded that the D1-structures formed during NW-SE to NNW-SSE compression (Figure 6-1). The emplacement of the Bi'r Umq ophiolite took place during the NW-SE compressional regime of D1 which happened at an intra-oceanic subduction zone. D2-structures, only observed in the central part of the WSW-ENE-trending BUSZ, included sub-horizontal WSW trending lineations that were formed on the S1-foliation, and dextral shear sense indicators. These structures indicated dextral strike-slip with a minor transpressional component. The D2-structures resulted from WNW-ESE compression. The D3-structures, like the D2-structures, were only observed in the BUSZ. They consist of sinistral shear sense indicators. These were developed along the sub-horizontal WSW lineations that were initially formed during D2. Consequently, these structures indicated sinistral strike-slip shear reversal on the BUSZ and were interpreted to result from NNE-SSW compression.

D1, D2 and D3 all took place after 820 Ma and before 760 Ma however no constraining dates are available for each of these phases independently. During this period, arc-accretion along the NE-SW trending ophiolitic sutures was the prevailing tectonic process in the ANS (see Chapter 2). This, combined with the fact that the Bi'r Umq Complex contains features that are typical for ophiolitic sutures that were formed during arc-accretion, implies that the deformation that was observed for D1, D2 and D3 resulted from a process that involved accretion of terranes at a subduction zone. The arc-accretion resulted in the compression that was observed during the deformation phases in the Bi'r Umq Complex. This sequence of events is summarized in Figure 6-1. In Chapter 3, it was proposed that the changes in the directions of compression of the different deformation phases were caused by the change of the direction of plate motion of subducting plates during arc-accretion. The reasons for the changes in the directions of compression will be discussed in more detail below.

6.2.3 The Tabalah and Wadi Tarj Complex: Relicts of the oceanic stage and the arc-accretion stage

The Tabalah and Wadi Tarj Complex in Saudi Arabia (Figure 6-2) was chosen as a research area because it contains relicts of two of the three main tectonic phases of the ANS, namely, the oceanic/island-arc phase and the arc-accretion phase. The Tabalah and Wadi Tarj Complex is in the central part of the Asir Terrane and its geology will thus reflect intra-terrane relicts of the oceanic phase and the arc-accretion phase, opposed to the Bi'r Umq Complex which contains features that were formed at a plate margin. The geology of this area is described in detail in chapter 4.

The Tabalah and Tarj Complex contains amphibolites, gabbros, quartz-diorites, diorites, tonalites and granodiorites. Geochemical analyses that were presented in chapter 4 show that the gabbros and quartz-diorites were formed in an island-arc environment. Tonalites and granodiorites display geochemical characteristics of rocks that intruded at an active continental margin. The island-arc related rocks were formed at an intra-oceanic subduction environment and were interpreted to be older than ca. 780 Ma. The granodiorite was dated at ca. 761 Ma.

The detailed structural/kinematic analysis in the Tabalah and Tarj Complex focused on the 5-10 km wide NNW-SSE to NW-SE trending Tabalah/Ta'al Shear Zone. Two Neoproterozoic deformation phases were observed on this shear zone. The D1-phase was responsible for the formation of steep NNW-SSE to NW-SE trending foliations, E- to ESE-plunging lineations and top-to-W shear sense indicators. These structures indicate thrusting that was caused by E-W to WNW-ESE compression (Figure 6-1). Geochronological analyses that were performed in the framework of this thesis showed that this phase took place at ca. 779Ma. The D2-phase displayed dextral strike slip, as indicated by NNW-SSE trending lineations and shear sense indicators. These structures were formed by NNE-SSW compression. The $^{40}Ar/^{39}Ar$-analyses showed that this event took place at ca. 765 Ma. These two deformation phases took place in a period when arc-accretion and (oblique) subduction along the NE-SW sutures were the prevailing tectonic processes (see also Chapter 2). The structures of the Tabalah and Tarj Complex are thus intra-terrane responses to arc-accretion at the terrane margins. The changes in the directions of compression of the deformation phases were ascribed to the change of plate motion of subducting plates during arc-accretion.

6.2.4 The Wadi Kid Complex: A core complex

In the framework of the research for this thesis, a mainly structural based research was performed in the Wadi Kid Complex in Egypt (Figure 6-2). These results of this study are described in Chapter 5 and Appendix 1. In the Wadi Kid Complex, a sequence of thick sub-horizontal amphibolite HT/LP grade schists was interpreted as a low-angle normal shear zones and was associated with upper-crustal normal shear zones which displayed top-to-the-NW movement. The high-grade schists are overlain by slightly to non-metamorphosed sediments and volcanics (Chapter 5 and Appendix 1). The high-grade and low-grade sequences are separated by a clear metamorphic break (Appendix 1). Undeformed granites intruded the lower-crustal sequence of the Wadi Kid Complex. Geochemical analyses showed that these granites are similar to the A-type granites found in other parts of the ANS which are interpreted to be related to extension. The intrusion of NE-SW trending dykes, perpendicular and synchronous to the movement on the shear zone, indicated that the shear zones were formed in a NW-SE extensional regime (Figure 6-1). $^{40}Ar/^{39}Ar$-analyses in this thesis showed that the deformation on the low-angle shear zone took place at ca. 595 Ma. In Chapter 5 and Appendix 1 it is demonstrated that the geological features observed in the Wadi Kid area justify its interpretation as a core complex that was formed during NW-SE extension.

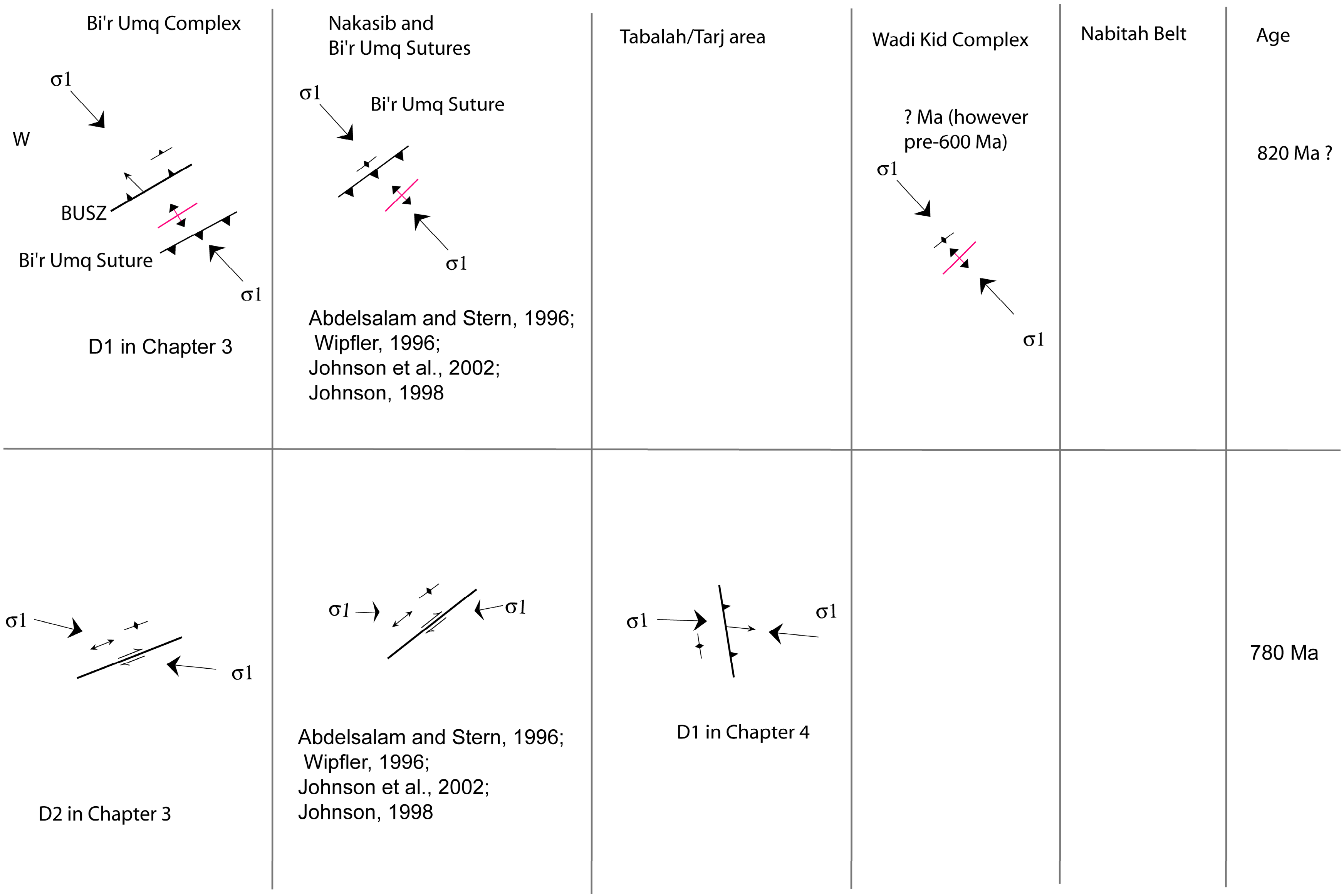
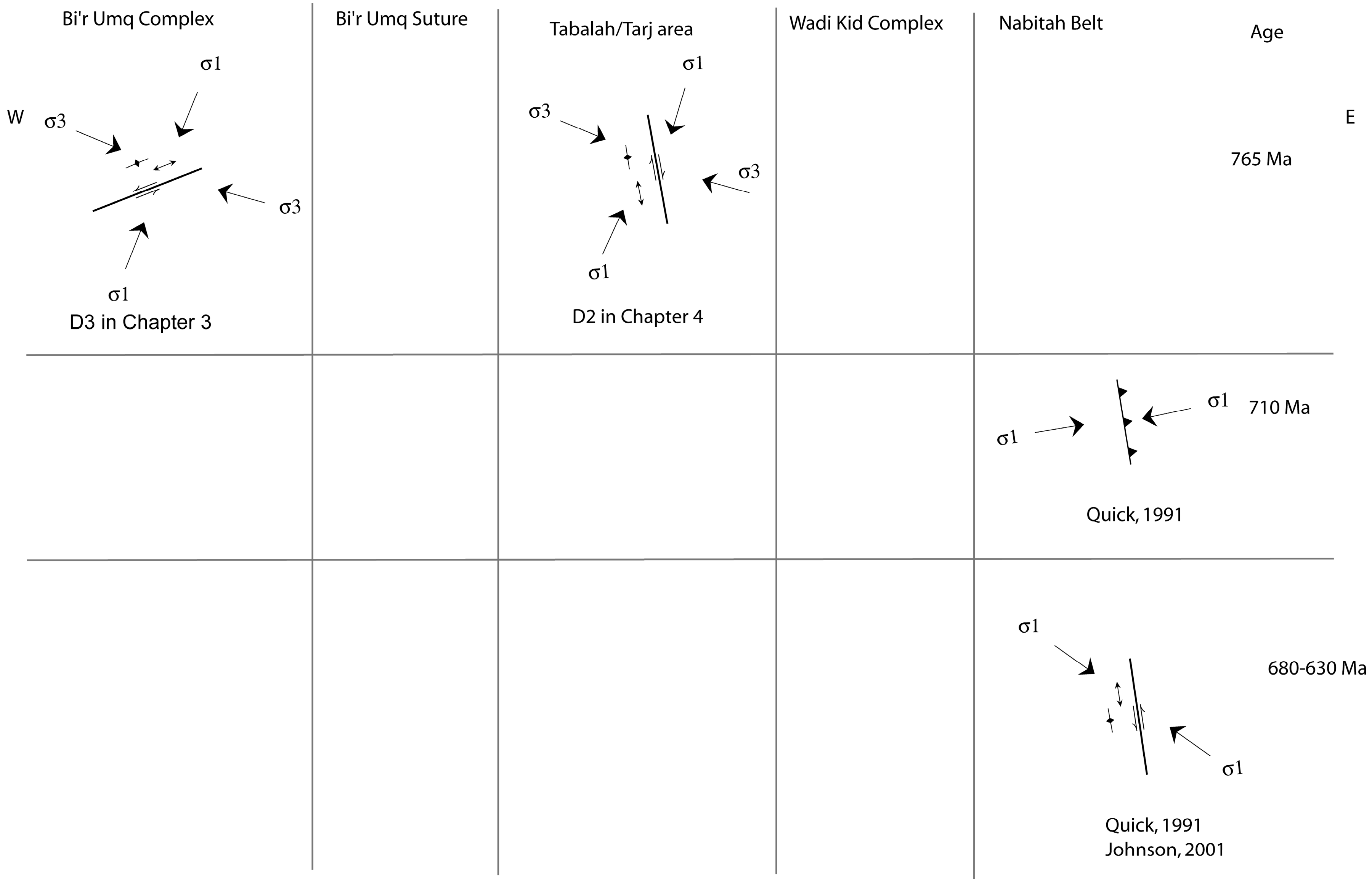
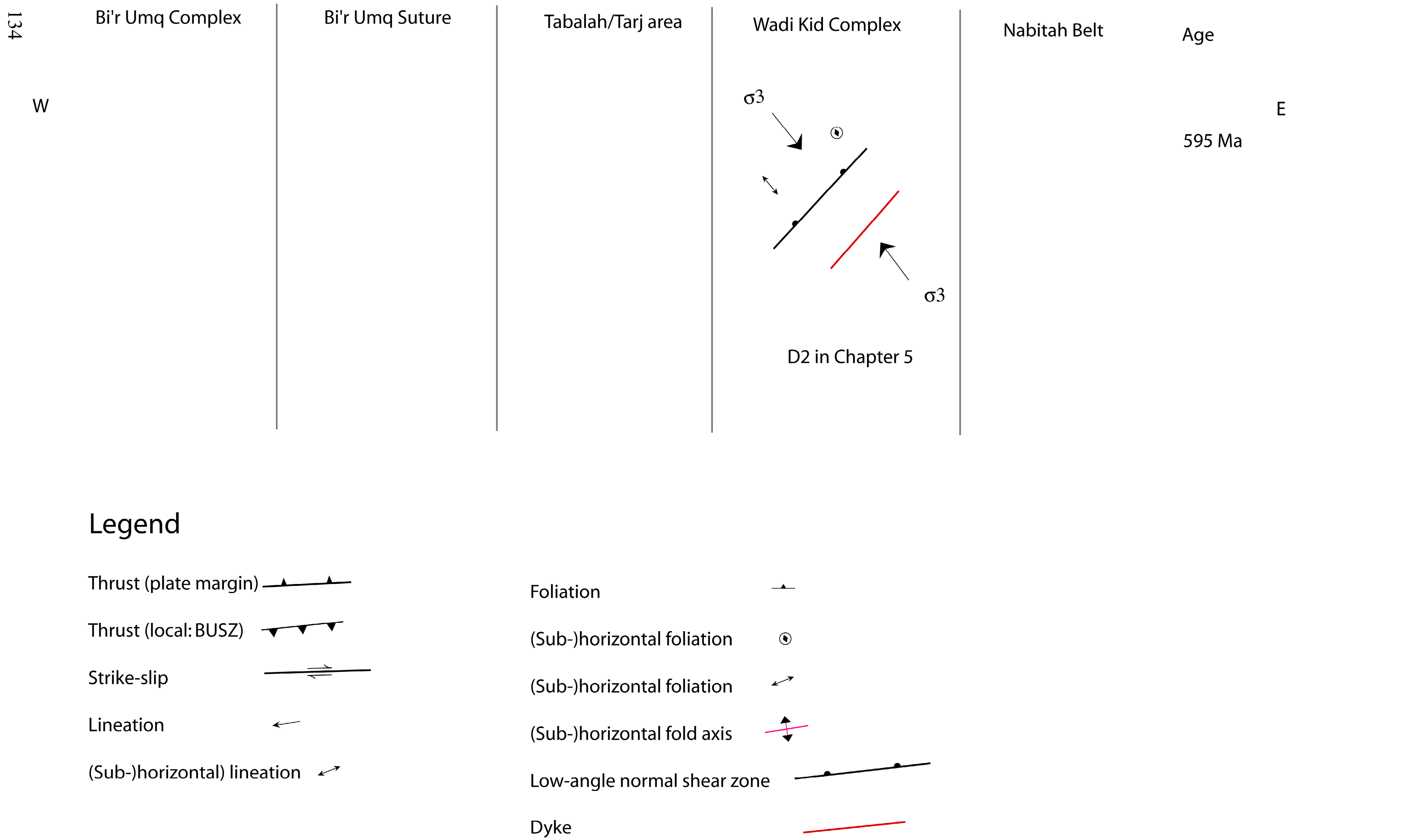


Figure 6-1 Sketch table of the major deformation phases in the Arabian-Nubian Shield. The major deformation phases are drawn for each of the areas that were studied in detail within the framework of this thesis.



Continuation Figure 6-1 Sketch table of the major deformation phases in the Arabian-Nubian Shield. The major deformation phases are drawn for each of the areas that were studied in detail within the framework of this thesis.



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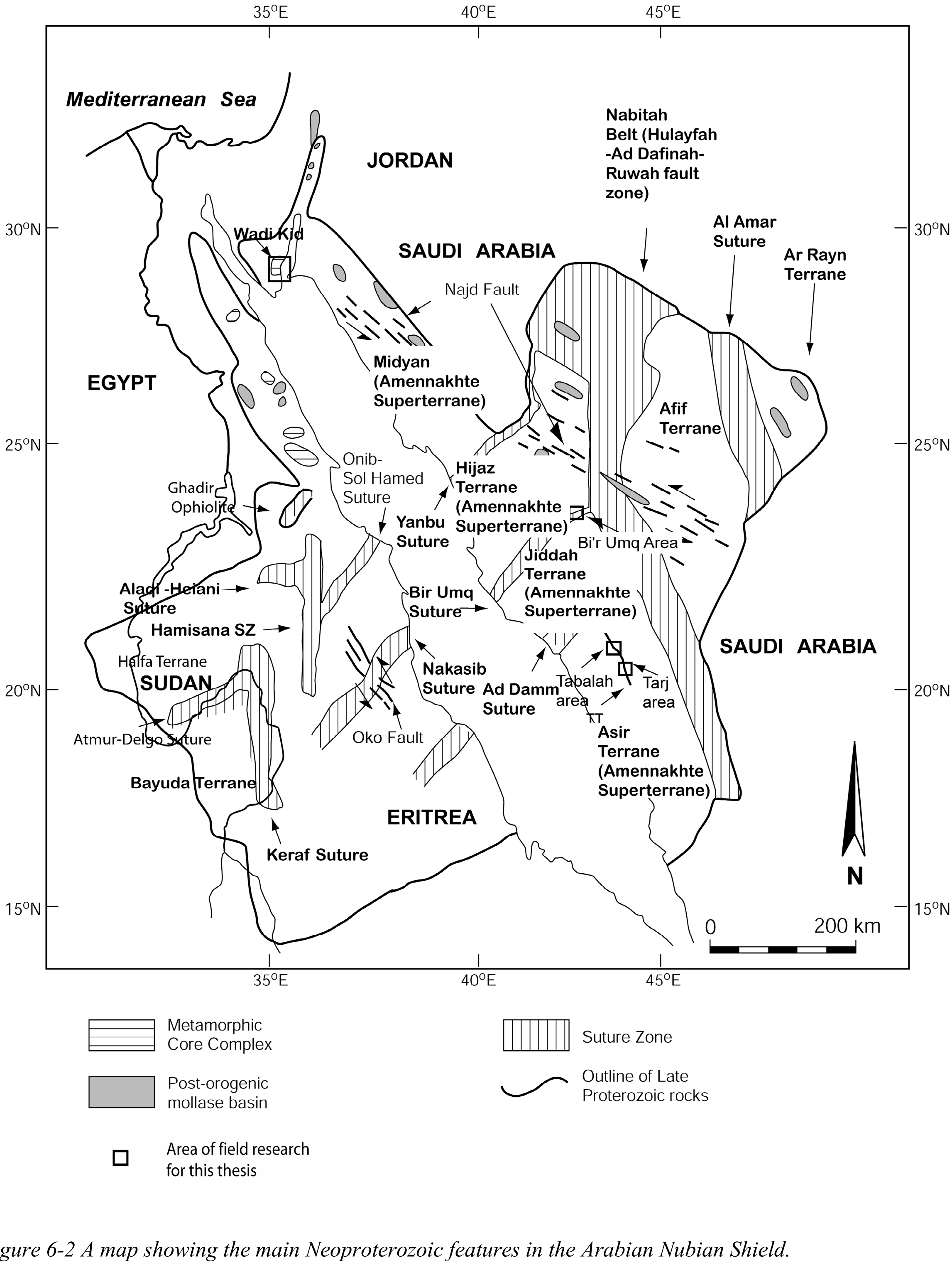


Figure 6-2 A map showing the main Neoproterozoic features in the Arabian Nubian Shield.

6.3 A synthesis of the newly obtained data from the Bi'r Umq area, the Tabalah and Wadi Tarj area and the Wadi Kid area

In the framework of this thesis a number of key areas were chosen in order compile a geodynamic model for the Neoproterozoic development of the ANS. The areas were chosen in order to represent the three main tectonic phases: 1) the oceanic subduction stage, which is reflected by remnants of intra-oceanic subduction, 2) the arc-accretion stage and 3) a late extensional stage which is still controversial (see chapter 2). The oldest Neoproterozoic relict that was observed in any of the areas in the framework of this study was the Bi'r Umq ophiolite. It was dated at ca. 830 Ma by Pallister et al. (1989) and was formed in an intra-oceanic suprasubduction setting. Another relict of the intra-oceanic subduction phase was represented by the island-arc related gabbro-diorite suite that was observed in the Tabalah and Wadi Tarj Complex. No ages are available for these intrusives however structural relations indicate this suite intruded before ca. 780 Ma. In chapter 3, the three phases of deformation that were observed in the Bi'r Umq Complex, were related to arc-accretion along the SE-NW trending sutures. The two deformation phases that were observed in the Tabalah and Wadi Tarj Complex were also related to arc-accretion (see Chapter 4).

No age constraints are available for the separate deformation phases in the Bi'r Umq Complex however dates from literature (e.g. Johnson et al., 2002; Pallister et al., 1989) indicate the D1-D3 took place at ca. 820-760 Ma. The two deformation phases at the Tabalah and Tarj Complex were dated in the framework of this study: D1 was dated at ca. 779 Ma and D2 was dated at ca. 765 Ma. The earliest deformation phase in the Bi'r Umq Complex resulted from NW-SE compression (Figure 6-1). During D2 in the Bi'r Umq Complex, WNW-ESE compression caused dextral strike-slip along the WSW-ENE trending BUSZ (Figure 6-1). A NNE-SSW compressional phase was responsible for shear reversal during D3 at the Bi'r Umq Suture (Figure 6-1). The D1-phase in the Tabalah and Tarj Complex caused top-to-the-W thrusting on a NNW-SSE trending shear zone (Figure 6-1). This deformation phase resulted from an approximately E-W to WNW-ESE compression and was dated at ca. 779 Ma. The youngest deformation phase in the Tabalah and Tarj area was dated at ca. 765 Ma and resulted from NNE-SSW compression.

Since the deformation phases of both the Bi'r Umq Complex and the Tabalah and Tarj Complex took place at the same timeframes, it is justified to relate them to each other (it should be noted that the deformation at the Bi'r Umq Complex started earlier than the deformation at the Tabalah and Tarj Complex however it ended approximately simultaneously at both complexes). The direction of compression of D2 for the Bi'r Umq Complex is sub-parallel to the direction of compression of the D1 phase of the Tabalah and Tarj Complex (Figure 6-1). From an Andersonian perspective (Anderson, 1951), $\sigma3$ is vertical for thrusts and horizontal during strike-slip deformation and therefore the trends of $\sigma3$ for D2 in the Bi'r Umq Complex and for D1 in the Tabalah and Tarj Complex should not be the same. However, this Andersonian framework is only valid for newly formed shear zones. Strike-slip faults often take advantage of pre-existing zones of weakness (e.g. Davis, 1984) and so upon a change of a compressional regime, a strike-slip fault may form at a re-activated older structure even though the stress regime may not require it to form. This may explain the apparent difference in orientation of σ2 and σ3 for D2 in the Bi'r Umq Complex and for D1 in the Tabalah and Tarj Complex. It should be noted that the re-activation of thrusts as strike-slip shear zones in accretionary orogens takes place when the new orientation of compression is at an angle of 30º-45º with the sense of shear of the new strike–slip shear zone (Ellis and Watkinson, 1987).

As noted in Chapter 3, many examples have been recorded for strike-slip shear during arc-accretion and oblique subduction. These examples include the Cretaceous strike-slip shear zones that were formed during arc-accretion along the continental margin of western North America (e.g. Oldow et al., 1989; Cole et al., 1999; Wolf and Saleeby, 1992) and neotectonic strike-slip faults as observed in El Salvador, Central America (Corti et al., 2005).

The co-existence of strike-slip shear zones along plate margins, and thrusts within terranes, is also observed during the Late Cretaceous arc-accretion in western North America. Bergh (2002) described intra-terrane thrusting for the San Juan fault system at the Cascades Orogen, western USA (Figure 6-3). These thrusts were related to oblique subduction along a sinistral strike-slip fault (Bergh, 2002). Cole et al (1999) described the co-existence of strike-slip shear zones and thrusts during arc-accretion during the Late Cretaceous in central Alaska (Figure 6-3). Also in this area, oblique subduction along a strike-slip shear zone led to intra-terrane thrusting (Cole et al., 1999).

On the basis of the above, it can be assumed that the dextral strike-slip deformation of the D2-phase in the Bi'r Umq Complex and the thrusting of the D1 in the Tabalah and Tarj Complex belong to the same regional WNW-ESE to E-W compressional regime which took place at ca 779 Ma. The D1-phase in the Tabalah and Tarj Complex was thus the intra-terrane response to the D2-event at the BUSZ.

The D3-phase in the Bi'r Umq Complex resulted from a NNE-SSE compressional regime (Figure 6-1). This is parallel to the compressional regime that caused the dextral strike-slip along the NNW-SSE Tabalah/Ta'al shear zone during D2 (Figure 6-1). Consequently, the Tabalah/Ta'al Shear Zone was conjugate to the BUSZ in this period (Figure 6-1). Since these shear zones form a conjugate set, it may be assumed that σ3 is horizontal and trends WNW-ESE (Figure 6-1). The D2-deformation in the Tabalah and Tarj Complex was dated at ca.765 Ma and therefore this should also be the approximate age for D3 in the Bi'r Umq Complex. The timing of the NNE-SSE compressional regime in both areas indicates that it was related to the arc-accretion along the NE-SW trending sutures. The structures in the Tabalah and Tarj Complex were thus the intra-terrane response to the deformation at the BUSZ.

It was postulated in Chapter 3 and 4 that the changes in the sense of shear between the different deformation phases resulted from the changes in plate motion of a subducting plate at a plate margin. Approximately 90º of anti-clockwise movement was observed for the shift from the WNW-ESE compression in the D1-phase of Tabalah and Tarj Complex and D2-phase in Bi'r Umq Complex, towards the NNE-SSW compression for the D2-phase of Tabalah and Tarj Complex and D3-phase in Bi'r Umq Complex. This anti-clockwise shift occurred within 15 Ma. It may appear a short time for such large rotations however similar large scale rapid rotations have been described in the geological record. Wolf and Saleeby (1992) assumed a rotation of plate motion of up to 90º for the Proto-Pacific plate during the Jurassic accretion at the Cordillera which took place in a time span of 15-20 Ma. Wallace et al. (1989) assumed a rotation of plate motion of up to 90º at the margin of Alaska during the Cretaceous in a time span of 15-20 Ma. Also in present-day tectonics, rapid plate rotations have been observed. Wallace et al. (2005) describe such rotations for microplates in the southeastern Pacific where the South Bismarck microplate rotates at ~ 9º/m.y.

The earliest deformation phase in the Wadi Kid Complex was only observed in its upper-crustal rocks and resulted from NW-SE compression. No dates are available to relate this phase to the deformation phases in the Bi'r Umq Complex and the Tabalah and Tarj Complex. Its trend however indicates that it could have been related to the arc-accretion.

D2 is the main phase of deformation in the Wadi Kid Complex (see Chapter 5 and Appendix 1). During this phase, a low-angle normal shear zone was developed in a NW-SE extensional regime (Figure 6-1). Continuing extension and thinning of the crust led to the intrusion of late orogenic granites and the formation of core complex. The main activity on the shear zone of the Wadi Kid Complex was dated at ca. 595 Ma (see Chapter 5 and Appendix 1). In Chapter 5, it was postulated that the extension in the Wadi Kid Complex resulted from gravitational collapse. This form of collapse requires to be preceded by a lithospheric thickening (e.g. Dewey, 1988; Platt and England, 1993). The arc-accretion observed in the Bi'r Umq Complex and in the Tabalah and Tarj Complex could have caused lithospheric thickening that could lead to gravitational collapse. The 'arc-accretion related deformation' in these areas ceased however at ca. 760 Ma and so it is not likely that this phase of arc-accretion led to the gravitational collapse. Later in this chapter, it will be investigated if other arc-accretion phases in the ANS have been described in literature that could lead to lithospheric thickening and gravitational collapse.

6.4 A model for the tectonic evolution of the Arabian-Nubian Shield based on the Bi'r Umq Complex, the Tabalah and Tarj Complex and the Wadi Kid area

6.4.1 The oceanic/island-arc phase in the ANS

The ANS contains numerous relicts of the oceanic phase in the form of ophiolites and remnants of island-arcs (see chapter 2). In Chapter 3, the Bi'r Umq ophiolite was interpreted as a suprasubduction ophiolite. It is generally accepted that other ophiolitic sequences in the ANS also were formed in oceanic environment (e.g. Stern, 1994, Pallister et al., 1989). Some of the ophiolites in the ANS, like the Bi'r Umq Complex, are thought to have originated in an intra-oceanic suprasubduction environment (Al-Salah and Boyle, 2001; El-Sayed and El-Nisr, 1999; Zimmer et al., 1995).

Island-arc remnants are very common in the ANS (see also chapter 2) and they form the core of the main Neoporoterozoic terranes as the Asir, the Hijaz, the Jiddah and the Midyan terranes in Saudi Arabia (see Figure 6-2 for locations) (Jackson 1986; Brown et al., 1989). The mixed gabbro-diorite suite in the Tabalah and Wadi Tarj area shows geochemical characteristics of island-arcs. Island-arcs form important parts of many of the Neoproterozoic complexes in Egypt and Sudan (e.g. Bentor 1985; El Gaby et al., 1984; El Din et al., 1991;

Rashwan, 1991).

The geochemical studies that were performed in the framework of this thesis in the Bi'r Umq Complex and the Tabalah and Wadi Tarj areas confirm the presence of rocks with oceanic/intra-oceanic subduction origin in the ANS.

Many of the ophiolites and island-arcs in the ANS are generally believed to have originated in intra-oceanic subduction environments in the Mozambique Ocean, that was formed upon rifting of Rodinia at ~900Ma (e.g. Abdelsalam and Stern, 1996; Pallister et al., 1988; Rogers et al, 1995; Shackleton, 1996; Unrug, 1996).

6.4.2 Arc-accretion phase in the ANS

Most of the ophiolitic belts in the ANS are strongly deformed and trend SW-NE and N-S (see Figure 6-2). The ophiolites mark the borders between the different 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 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).

The Bi'r Umq Complex, at the NW-margin of the Bi'r Umq-Nakasib Suture is an example of area that displays evidence for arc-accretion at the border of two terranes, namely the Hijaz Terrane and the Jiddah Terrane. The detailed structural research in Chapter 3 showed three phases of deformation on the main structure in the area, the Bi'r Umq Shear Zone.

It is generally thought that the initial movement on the Bi'r Umq Suture and the Nakasib Suture (the continuation of the Bi'r Umq Suture in Sudan, see Figure 6-2 for location) was related to NW- or SE-vergent thrusting that resulted from NW-SE compression (e.g. Abdelsalam and Stern, 1993; Abdelsalam and Stern, 1996; Wipfler, 1996; Johnson et al., 2002) like D1 in the Bi'r Umq Suture. Most studies of the Nakasib and Bi'r Umq Sutures also indicate that the earlier thrusting was followed by a major phase of dextral transpression (e.g. Abdelsalam and Stern, 1996; Wipfler, 1996; Johnson et al., 2002) as observed for the D2-phase in the Bi'r Umq area.

The three deformation phases in the Bi'r Umq Complex, described in Chapter 3, recorded the deformation that was responsible for the juxtaposition of the Jiddah Terrane and the Hijaz Terrane. Consequently, the deformation in Bi'r Umq Complex was related to the arc-accretion. The deformation in the Bi'r Umq Complex took place at ca. 820-760 Ma, an era when arc-accretion along NE-SW trending sutures was the main "tectonic driver" in the ANS.

The main structure in the Tabalah and Tarj areas is the Tabalah/Ta'al Shear Zone. It displays two phases of deformation. This shear zone lies in the central part of the Asir terrane and is thus an intra-terrane structure. The timing of the Tabalah/Ta'al Shear Zone, ca. 780-760 Ma (see Chapter 4), indicates that it was active in the same period as the Bi'r Umq Shear Zone. As shown above, it can be assumed that D1 and D2 in the Tabalah and Tarj Complex were formed during the same trend of compression as D2 and D3 in the Bi'r Umq Complex. The deformation in Tabalah and Tarj Complex was thus interpreted to represent intra-terrane response to arc-accretion along the NE-SW trending sutures.

From chapter 2, it can be concluded that subduction at the N-S trending active continental margins, as the Nabitah Belt, started not earlier than 700 Ma, after the arc-accretion along the NE-SW trending sutures had ceased. Therefore, the juxtaposition of the island-arcs of the Jiddah Terrane and Hijaz Terrane, as reflected by the deformation along the Bi'r Umq Shear zone, was arc-arc collision. Typically, arc-arc collision can only take place when both island-arcs would have had a mature (> 20 m.y.) and thicker crust with a relatively low density (Cloos, 1993). The subduction zone at the Jiddah island-arc, which was also responsible for the emplacement of the Bi'r Umq ophiolite, would have been the place where the actual arc-accretion of the Hijaz Terrane upon the Jiddah Terrane took place (see Figure 6-2 for locations of Terranes). The Hijaz island-arc would have collided on the Jiddah Terrane after its back-arc basin or fore-arc had been subducted at the Jiddah island-arc, which happened during the D1-phase and which was recorded as such at the Bi'r Umq Complex. It is thus very possible that the Bi'r Umq ophiolite itself was a part of the back-arc or the fore-arc of the Hijaz island-arc. The Hijaz Terrane and the Jiddah Terrane formed thus a superterrane at 820-760 Ma.

The Asir Terrane (see Figure 6-2 for its location) was formed at 900-800 Ma and probably represents the oldest island-arc in the Arabian part of the ANS (Brown et al., 1989; Jackson, 1986; Stoeser and Camp, 1985). Structural data from the Asir terrane were recorded in the Tabalah SZ and the Wadi Ta'al SZ of the Tabalah/Tarj Complex. As demonstrated above, it may be assumed that D2 in the Bi'r Umq Complex and D1 in the Tabalah and Tarj Complex formed simultaneously. Furthermore, it was concluded that D3 in the Bi'r Umq Suture formed parallel to the direction of compression during D2 in the Tabalah and Tarj Complex. These facts may indicate that the Jiddah Terrane and the Asir Terrane underwent the same deformation history from D1 and D2 at the Tabalah and Wadi Tarj Complex and from D2 and D3 at the Bi'r Umq Complex and that the two terranes formed one "superterrane" before the start of D1 in the Tabalah/Wadi Tarj Complex. Johnson (1999) postulated that the amalgamation of the Asir Terrane and the Jiddah Terrane took place around 790 Ma and this is in accordance with the data from this thesis.

The amalgamation of the Hijaz Terrane and its northerly neighbor, took place along the Yanbu Suture (see Figure 6-2 for its location). The formation of the ophiolitic rocks of the Yanbu Suture itself was dated at ~740 Ma (Claeson et al., 1984; Pallister et al., 1988). No solid age data are available for this suturing event, however it was estimated at 740-696 Ma (Johnson, 1999; Stoeser and Camp, 1985). The Onib-Sol Hamed Suture is the extension of the Yanbu Suture into the Nubian part of the ANS. The subduction at this suture was estimated at 740-690 Ma (Abdelsalam and Stern, 1996; Shackleton, 1994). Consequently, no arc-accretion took yet place north of the BUSZ within the ANS while the deformation took place at the Bi'r Umq SZ. The Bi'r Umq SZ represented thus the most northerly subduction zone of the ANS until after its D3-deformation phase. The D1-, D2- and D3- deformation phases at the BUSZ display thus different phases of arc-accretion at the subduction of which the Bi'r Umq Suture is a remnant. Since no other deformation was observed to have impacted the Asir Terrane at 820-760 Ma, the D1- and D2-deformation phase at the Tabalah/Wadi Tarj Complex represent intra-terrane deformation during the D3-deformation phases at the Bi'r Umq SZ.

Geochemical studies indicate that the undeformed granodiorite of the Tabalah and Tarj

Complex was intruded at a continental margin at ca. 761 Ma. This is before the start of subduction at the "real" active continental margins of East and West Gondwanaland. However, the granodiorite formed within the superterrane consisting of the Asir Terrane and Jiddah Terrane, which, by 761 Ma, could be treated as a microcontinent, which will be referred to as the Amennakhte Superterrane (named after the Theban scribe who is thought to have prepared the pharaonic map of the Wadi Mammamat area) (Figure 6-2). It had an amphibolite crust that was relatively stable from an "island-arc magmatic" point of view (pure island-arc magmatism at the Asir Terrane ceased before 800 Ma). Continental sedimentary processes were active and the crust contained large volumes of island-arc plutons. The latest stages of subduction at the Bi'r Umq suture could have led to the partial melting of a lithosphere that had been thickened by the accretion of the Midyan and Hijaz Terranes up on the Asir/Jiddah Superterrane. The partial melting of a thickened amphibolite crust with continental affinity would have led to the formation of granodiorites such as those in the Wadi Tarj area.

In chapters 3 and 4, it is shown that both the BUSZ and the Tabalah/Ta'al SZ initiate as thrusts. Both shear zones display later phases of deformation, strike-slip shearing, that result from changes in plate motion. Little detailed structural studies are available for ophiolitic sutures in the ANS however a study by Johnson et al. (2002) indicated that along the entire the Bi'r Umq-Nakasib Suture thrusting was followed by strike-slip movement.

As argued already in chapter 3 and 4, the emplacement of ophiolites and accretion of terranes shows similarity with the arc-accretion in western North America. Like in the ANS, thrusting and strike-slip faults were related to the different phases of arc-accretion in the Cordilleran of western North America (e.g. Oldow, 1989; Stewart and Crowell, 1992). The strike-slip faults in western North America were related to oblique subduction (Stewart and Crowell, 1992) or to intra-terrane response to deformation at plate boundaries (Chardon et al., 1999). These strike-slip faults often showed shear-reversal (Cole et al., 1999; Stewart and Crowell, 1992). The transition from convergence to oblique subduction at the plate boundaries in western North America was related to a change in the direction of plate motion of the subducting plate (e.g. Cole et al., 1999; Oldow et al., 1989; Stewart and Crowell, 1992). Shear reversal on strike-slip faults was also related to changes in the directions of plate motions (e.g. Cole et al., 1999; Oldow et al., 1989; Stewart and Crowell, 1992). The transition from convergence to strike-slip faulting and the strike-slip shear reversal as observed in the study of the Bi'r Umq SZ and the Tabalah/Ta'al SZ is interpreted to be a result of changes in the directions in plate motion of the subduction plate.

The accretion of island-arcs and composite island-arc terranes upon continental margins was not recorded in any of the areas that were studied during this research. From Chapter 2 and references within, it can be concluded that arc-continent collision, subduction at the active continental margin at the western boundary of the ANS started at ca. 730 Ma along the Keraf Suture and the Kabus Suture (Abdelsalam and Stern, 1996; Bailo et al., 2003). Here, the oceanic basin between continental Bayuda Terrane and the island-arc terranes of the ANS was closed during the arc-continent collision. HP-metamorphism at supra-subduction N-S trending shear zones in Eritrea, were formed before 650 Ma (De Souza Filho and Drury, 1998). No other reliable constraints exist on the end of the subduction at the western margin of the ANS, and no features that are typically associated with the arc-accretion at the western margin of the ANS, post-date 650 Ma.

The arc-continent collision at the eastern margin of the ANS took place along the N-S trending Nabitah Belt (Agar, 1985; Abdelsalam and Stern, 1996). This structure is bordered at its western margin by the Hijaz, Jiddah and Asir Terranes, which are part of the Amennakhte Superterrane. Subduction at this active continental margin started ca. 700 (Abdelsalam and Stern, 1996; Johnson and Kattan, 1999; Quick, 1991). By ca. 650 Ma activity along the Nabitah Belt ended (Abdelsalam and Stern, 1996), and so the accretion of the Amennakhte Superterrane upon the continental Afif Terrane was completed. The Nabitah Belt contains ophiolites and their obduction was related to the closure of a fore-arc at a subduction zone (Quick, 1991). The Nabitah Belt is interpreted to be the feature where the final closure of the Mozambique Ocean and the island-arcs that were formed within this ocean, took place (Shackleton, 1996) and so the end of activity on the Nabitah Belt marks the end of arc-accretion at the ANS. Miller and Dixon (1992) proposed that the latest stage of compressional deformation along N-S trending Hamisana SZ in Sudan may have taken place when arc-accretion was completed and that this compression resulted from continent-continent collision between East- and West-Gondwanaland. The arc-accretion as described above, for the different island-arcs in the ANS is similar to arc-accretion of terranes that was described in western North America by Coney (1989) and Oldow et al. (1989).

6.4.3 Extensional features in he ANS

The presence of extensional features in the ANS has been subject of discussion over the past decade. In the past it was thought that the main structural features of Neoproterozoic of the ANS were formed in compressional regimes (e.g. Bentor, 1985; Vail, 1985 Ries et al., 1983). Over the last decade, a number of authors have proposed that the Neoproterozoic development of the ANS ended with extension. This was often based on geochemical research of igneous rocks which were thought to have originated from mantle derived magmas that were intruded and extruded in a thinned and extending crust (e.g. Beyth et al., 1994; Hassanen, 1997; Jarrar et al., 2003). Sedimentary basins that were formed at the very late stages of the Neoproterozoic in the ANS were also associated with extension (Jarrar et al., 1991; Jarrar et al., 1992; Greiling et al., 1994).

The Wadi Kid Complex resembles the “gneissic domes” that are found in other parts of the ANS as described in chapter 2. The Meatiq dome and the Hafafit dome are examples of other “gneissic domes” in the ANS. Like the Wadi Kid Complex, these “gneissic domes” contain a lower-crustal unit with a thick mylonitic sequence of amphibolite-grade, overlain by an upper-crustal sequence (see chapter 2 and references within). The mylonitic sequences consist of sub-horizontal foliations, well developed lineations and abundant shear sense indicators (see chapter 2 and references within). A number of authors interpreted the low-angle shear zones of the “gneissic domes” as thrusts (Fowler and Osman, 2001; Habib et al., 1985). This would however require the presence of thrust-duplexes with a vertical repeat of the metamorphic sequence. This is not observed in the domes of the ANS where in fact strong metamorphic breaks were found (see appendix 2). Others interpreted the “gneissic domes” in the ANS as core complexes that are expressions of local extension in the NW-SE strike-slip systems of the Najd SZ (e.g. Bregar et al., 2002; Fritz et al., 2002; Loizenbauer et al., 2001). In such a scenario, the sinistral strike-slip Najd shear zone was thought to have been formed at the later stages of the collision between East and West Gondwanaland (e.g. Bregar et al., 2002; Fritz et al., 2002; Loizenbauer et al., 2001). Core complexes associated with strike slip shear zones generally form with their linear trends parallel to the direction of σ_3 of the strike slip regime or with their linear trends parallel to the strike slip shear zone (Yin, 2004). If the linear trends of the core complexes of the ANS would have formed parallel to σ_3 of a major strike-slip zone as the sinistral NW-SE Najd SZ, the linear features of the core complex would have to trend WNW-ESE. However, they all trend NW-SE, which is in fact parallel to the Najd SZ (e.g. Bregar et al., 2002; Fritz et al., 2002; Loizenbauer et al., 2001). Core complexes that are formed parallel to the strike-slip shear zones should form in a pull-apart regime within the strike slip shear zone. The core complexes of the ANS are however formed outside of the main strike slip shear zones as the Najd SZ. Therefore the formation of the core complexes in the ANS is not related to pull-apart in a strike-slip shear zone.

As demonstrated for the Wadi Kid Complex, the combination of LP-HT sub-horizontal shear zones with NW-SE lineations that are formed at the same time as the NE-SW trending dykes with A-type granites can best explained to have been formed in an extensional regime. Because of their similarity to the core complex of the Wadi Kid Complex, all core complexes in the ANS can be interpreted to have formed in an extensional regime. Consequently, the schistose sequences, overlying the gneissic cores, are interpreted 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 and Harms 1984; Davis and Lister 1989).

Minor strike-slip zones are associated with some of the core complexes in the ANS however this feature is common for core complexes in extensional regimes. The strike-slip zones accommodate part of the extension in the crust (Lister et al., 1986; Faulds and Stewart, 1998).

6.4.4 The transition from compression to extension in the ANS

This study shows that the ANS contains abundant evidence for both a regional compressional regime as well as a regional extensional regime. However in the areas studied during this research, there appears to be no close relation, from a timing perspective, between the compressional regime and the extensional regime. The compressional regimes in the Bi'r Umq Complex and the Tabalah and Tarj Complex ended 160 Ma before the extension that was observed in the Wadi Kid Complex. However, from chapter 2, it can be concluded that compression in the ANS must have continued until 650 Ma on the N-S trending structures throughout the shield. This age is close to the earliest relicts of extension which were dated at 620 Ma (see chapter 2).

In this research, it was shown that the observed geological features in the ANS, as the

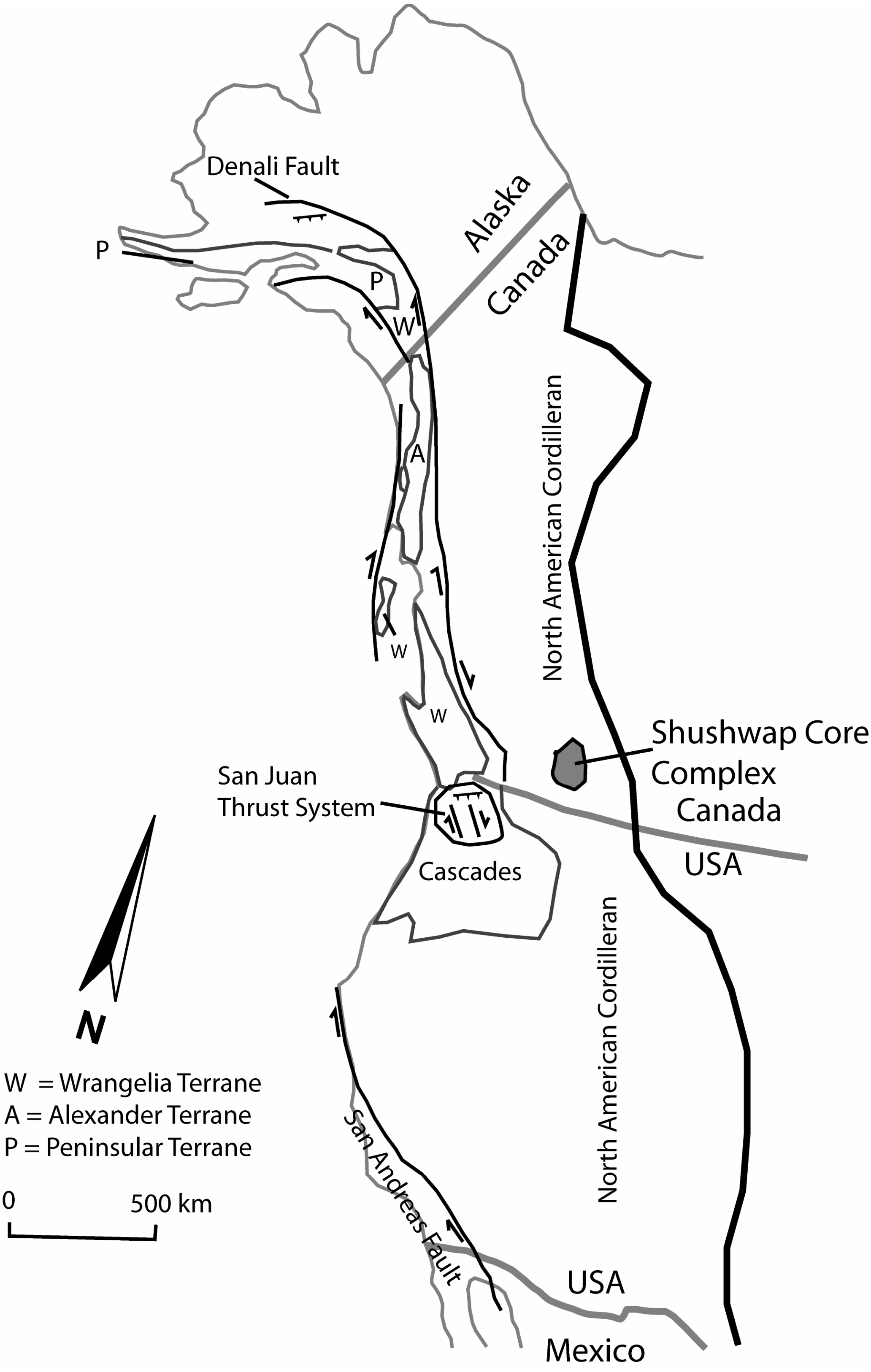


Figure 6-3 Overview of main Cordilleran structures in western North America that are mentioned in this Chapter.

island-arcs, the ophiolitic sutures and the extensional core complexes, justify a comparison with the geological development of western North America during the Mesozoic and Early Cenozoic. The different terranes in the ANS, as the Asir, Jiddah and Hijaz Terranes, consisting of juvenile crust, and bordered by ophiolitic sutures, as the Bi´r Umq Suture, can be compared to the Cordillera of western North America. There, terranes of mainly juvenile composition accreted upon each other to form superterranes before accretion upon the continental margin to form new continental crust (Coney 1989). An example of such a superterrane that underwent "offshore amalgamation", as the Amennakhte Superterrane, is the Wrangellia Superterrane (Coney, 1989; Burchfiel et al., 1992). This superterrane consists of the Wrangellia Terrane, the Alexander Terrane and the Peninsular Terrane (see Figure 6-3 for locations) (Coney, 1989). These terranes consist of island-arc remnants with marine sediments (Coney, 1989). The independent terranes within the Wrangellia Superterrane are bordered by ophiolites (Coney, 1989; Burchfiel et al., 1992). The "offshore amalgamation" of the Wrangellia Superterrane started in the Late Paleozoic but the actual accretion upon the North American continental margin took only place during the Cretaceous (Coney, 1989). The main shear zones that recorded the deformation of the arc-accretion in western North America display extensive strike slip faulting (e.g. Coney, 1989; Burchfiel et al., 1992).

The continuing accretion of superterranes and other allochtonous terranes upon the active continental plate margin of western North America during the Mesozoic, caused fast growth of the continental crust and substantial lithospheric thickening at 155-60 Ma (Liu, 2001 Livacarri, 1991; Platt and England, 1993). A reduction in the rate of convergence during accretion allowed for thermal re-equilibration of the lithosphere and consequent weakening and slow thinning of the thickened lithosphere (Platt and England, 1993; Liu, 2001). At this stage conductive heating of the lithospheric root decreased the strength of the crust (Platt and England, 1993; Liu, 2001). The thickened crust of the Cordilleran became isostatically unstable and consequent delamination of its lithospheric root led to gravitational collapse (Meissner and Mooney, 1998; Liu, 2001; Vanderhaeghe and Teyssier, 2001). This, in turn, led to extension and lithospheric thinning which started at ~55 Ma in the Canadian Cordillera and continued until ~16 Ma in the central Basin and Range (e.g. Dewey, 1988; Platt and England, 1993; Liu, 2001; Livacarri, 1991). Lithospheric thinning, through large low-angle normal shear zones, allowed the intrusion of magmas at higher crustal levels and caused the initiation of core complexes as the Shushwap core complex in the Canadian Cordillera (see Figure 6-3 for location) (Vanderhaeghe and Teyssier, 2001) where the process of transition from compression to extension took place within 20 Ma (Ranalli et al, 1989). The isostatic rebound and the intrusion of these magmas contributed to the doming of the lower crust and the development of metamorphic core complexes (Wernicke and Axen, 1988). Extensive magmatism was associated with the extension throughout the Cordillera (Liu, 2001). Continental sedimentary basins, bordered by normal faults, were formed at upper crustal levels as a response to the extension and allowed the deposition of late orogenic molasse sequences (Beard, 1996; Lucchita and Suneson; 1996).

Many of the geological features observed in the North American Cordillera are also observed in the ANS. Island-arcs, as observed in the Tabalah and Tarj areas and ophiolitic

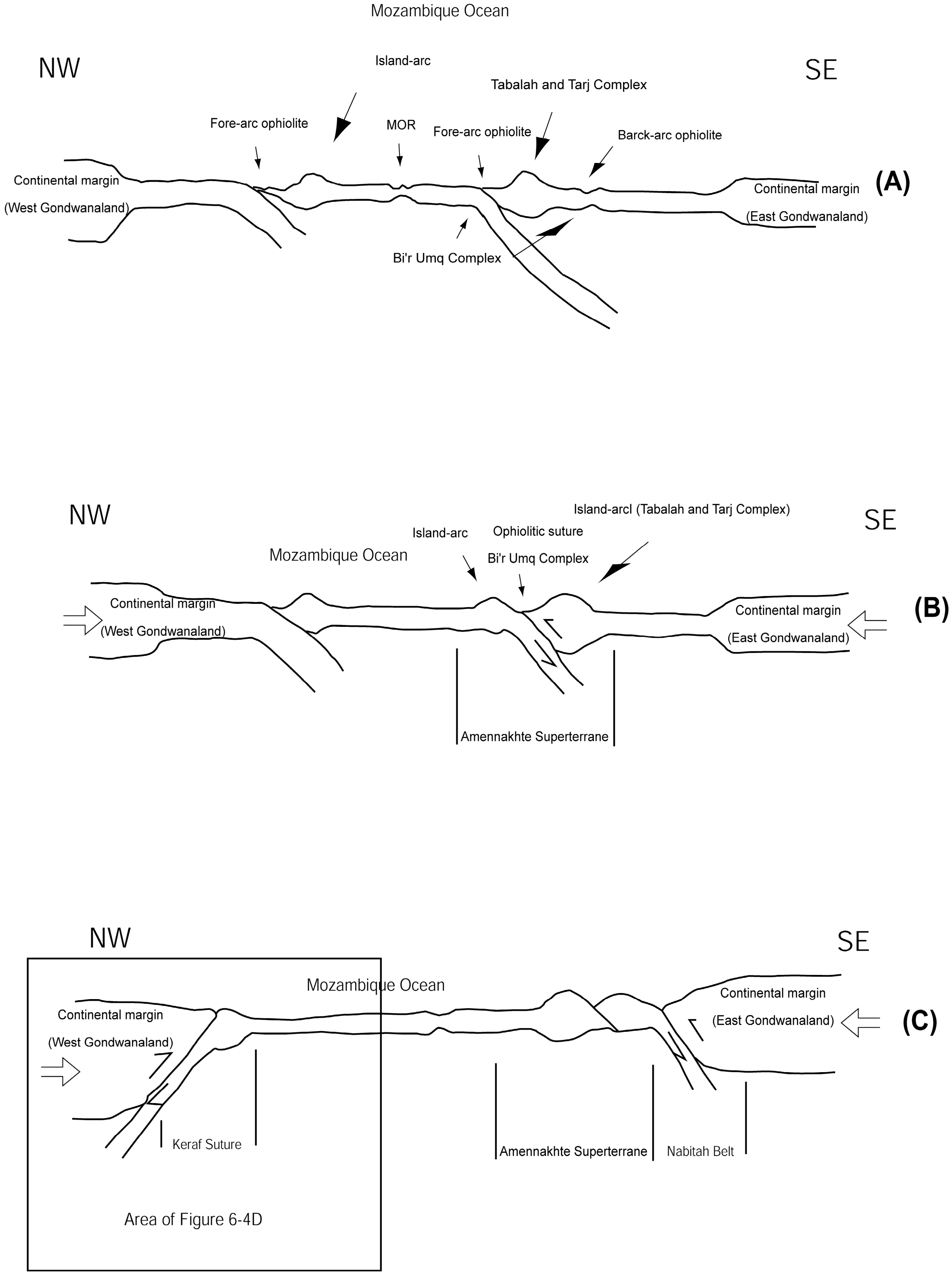
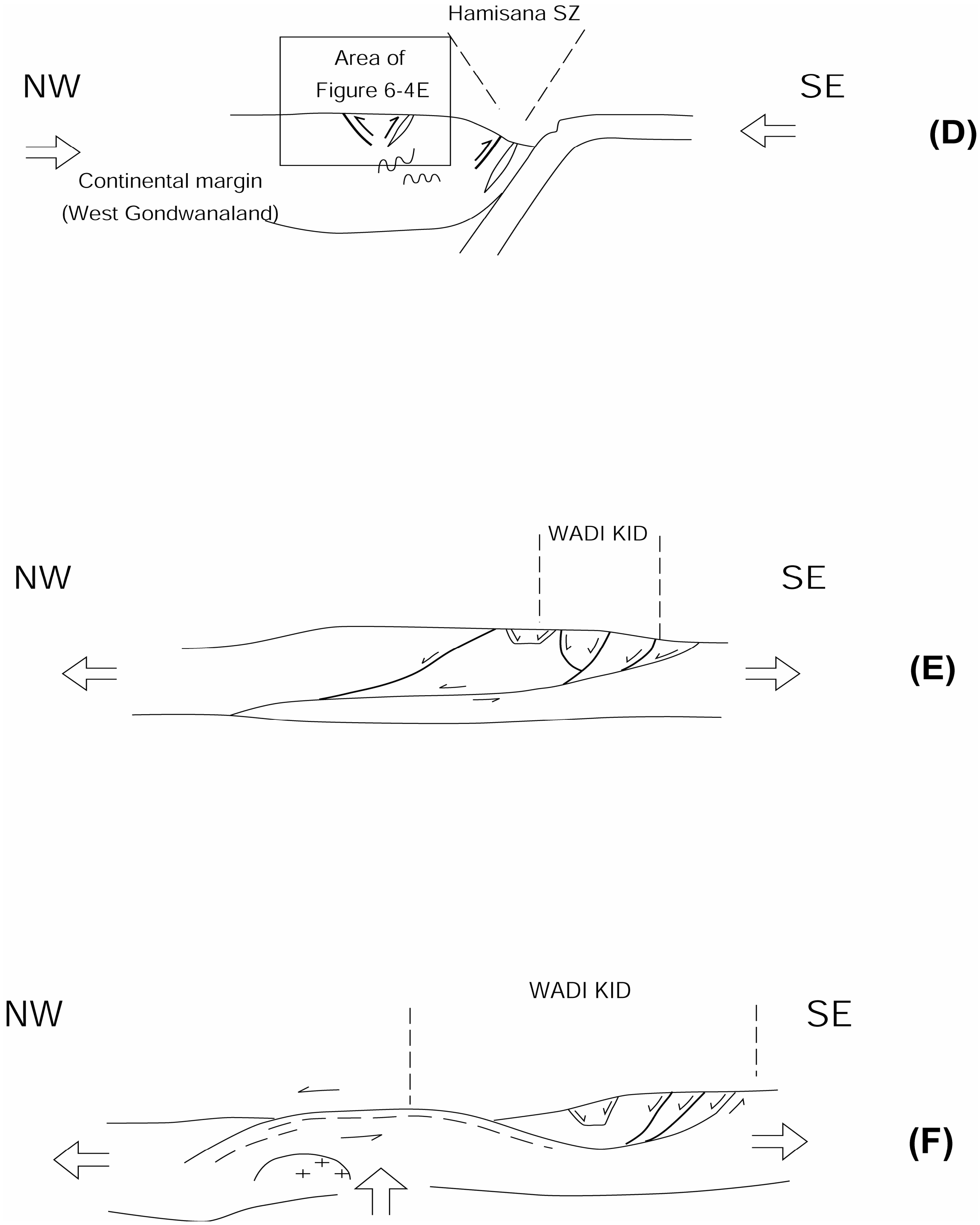


Figure 6-4 A cartoon displaying the different stages of the evolution of the Arabian Nubian Shield The oceanic phase is shown in (A), with island-arcs developing in the Mozambique Ocean. Remnants of the island-arcs were found in the Tabalah and Tarj areas. Oceanic crust was formed at the MOR, in fore-arcs and back-arcs. Remnants of the fore-arcs or back-arcs were found in the ophiolite of the Bi'r Umq Complex. At stage (B), "off-shore amalgamation" or arc-accretion took place. The Bi'r Umq SZ is the location where the Hijaz Terrane accreted upon the Jiddah Terrane to form a superterrane. At (C), subduction at the continental margins took place and accretion of the island-arcs and superterranes started.



Continuation Figure 6-4 At (D), continuing arc-accretion led to lithospheric thickening. multiple arc-accretion led to lithospheric thickening. 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 (E) and (F) refer to the tectonic development of the core complexes as the Wadi Kid area in more detail and a smaller scale with the start of extension in stage (E) and the development of a metamorphic core complex in (F). At stage (E) the lithosphere became gravitationally unstable and collapsed which led to extension and thinning of the crust through crustal-scale shear zones. At (F), tectonic denudation by the main detachment, together with isostatic rebound and the intrusion of A-type granites were resulted in the development of metamorphic core complexes.

Table 6-1 Table that displays the main tectonic phase in the ANS and their relicts as observed in this study and as described by others.

Main tectonic phase	In this study	Others (see Chapter 2 and references within)	Age	Stage in Figure 6-
Oceanic phase	Ophiolites in BUC		~830 Ma	A
	Island-arc related rocks in Tabalah/Ta'al Complex		>780 Ma	A
		Ophiolites throughout ANS	900-740 Ma	A
		Island-arcs throughout ANS	900-780 Ma	A
Arc-accretion phase	Three phases of deformation along suture at BUC		820-760Ma	B
	Two phases of intra-terrane deformation along Tabalah/ Ta'al SZ		780-765 Ma	B
		Arc-accretion along NE-SW trending sutures throughout ANS	820-700 Ma	B
		Arc-accretion along continental margin at N-S trending Nabitah Belt	700-630 Ma	C/D
Gravitational collapse			~620 Ma	D/E
Extensional phase	D2 extensional phase in the Wadi Kid Complex		595 Ma	F
		Core complexes in the Nubian part of the ANS	620-580 Ma	F

sutures, as the Bi'r Umq Suture, are the remnants of arc-accretion in the ANS. The Wadi Kid Complex and other core complexes in the ANS, the A-type granites, acid and basic volcanic sequences and the late orogenic sedimentary sequences as the Hamammat Gp. and Saramuj Gp. represent late orogenic extensional features in the ANS. On the basis of the similarity between the North America Cordillera and the ANS, the transition from compression to extension in the ANS can be best explained by gravitational collapse. A phase of lithospheric thickening needs to pre-date the gravitational collapse. The gap of 160 Ma between the compressional phases of the Bi'r Umq Complex and Tabalah and Tarj Complex, and the extension of the Wadi Kid Complex, is too large. However, compression continued on other structures in the ANS. The shortening along the N-S trending sutures, which included the accretion of the Amennakhte Superterrane at the Nabitah Belt, continued until ~650 Ma. This phase of deformation along N-S trending sutures as the Hamisana SZ and the Nabitah Belt should have caused the lithospheric thickening that led to the gravitational collapse and extension in the ANS.

6.5 Summary of a new tectonic scenario for the Arabian-Nubian Shield

A synthesis of the geological features of the main geological phases in the ANS, justifies the comparison with the Mesozoic and Early Cenozoic development of western North America. The ANS consists, like the Cordillera of western North America, of accreted mostly juvenile terranes which are separated by ophiolitic sutures. These sutures display a complex structural history which includes significant stages of strike slip movement. The younger geological features in the ANS, as core complexes, sedimentary basins and A-type granites, all indicate extension and lithospheric thinning. Consequently, a new tectonic scenario for the ANS is proposed here (see also Figure 6-4 and Table 6-1). It similar to the tectonic scenario that described above for the Mesozoic and Early Cenozoic Cordilleran development of western North America:

The Neoproterozoic era of the ANS started with the formation of the Mozambique Ocean upon the rifting of Rodinia at ca. 900 Ma (e.g. Abdelsalam and Stern, 1996; Rogers et al, 1995; Shackleton, 1996; Unrug, 1996). Island arcs, of which remnants can be found in the Asir Terrane (the Tabalah and Tarj Complex) and other terranes of the ANS, were formed in the Mozambique Ocean (Figure 6-4A). The island-arcs were formed soon after the opening of the Mozambique Ocean and the youngest of these island-arcs were formed as late as 730 Ma. Meanwhile ophiolites, as the Bi'r Umq Suture, were formed at the fore-arcs and back-arcs of the island-arcs (Figure 6-4A).

"Offshore amalgamation" of island-arcs led to the accretion of island-arcs and the formation of a superterrane that consisted of the Asir Terrane, the Jiddah Terrane and the Hijaz Terrane (Figure 6-4B). The accretion took place along the ophiolitic sutures as the Bi'r Umq Suture. This suture recorded the earliest stage of accretion after ~820 Ma. Later stages of deformation that were recorded on the Bi'r Umq Suture and at the intra-terrane shear zones of the Tabalah and Tarj shear zones, indicate strike-slip movement along terrane-boundaries. The changes in sense of shear on the shear zones during arc-accretion are attributed to the change in plate motion during arc-accretion. The activity at the Bi'r Umq Suture and the intra-terrane shear zones of the Asir Terrane ended at ca. 760 Ma. This date indicates the end of the "offshore amalgamation" of the Asir, Jiddah and Hijaz Terranes that formed the Amennakhte Superterrane.

The subduction at the N-S trending continental margins of East Gondwanaland (the Nabitah Belt) and West Gondwanaland (the Keraf Suture and Kabus Suture) started at ca. 730-700 Ma (Figure 6-4C). The arc-accretion at these sutures led to lithospheric thickening (Figure 6-4D). The subduction at the continental margins caused the closure of the Mozambique Ocean at ca. 650 Ma which is the youngest date for deformation on the shear zones which are though to represent the continental margins. No actual collision of the continental masses of East and West Gondwanaland took place, however the continuing accretion of large amounts of juvenile crusts should have caused significant lithospheric thickening. The findings in this thesis confirm the conclusions of Burke and Sengör (1986) and Stern (1994) who state that the Najd SZ formed during the compressional regime. It would then represent a large intra-terrane strike slip shear zone as also observed during arc-accretion in western North America.

A reduction in the rate of convergence at the continental margins of the ANS, initiated thermal re-equilibration of the lithosphere. This caused slow thinning of the thickened lithosphere and initiated the actual gravitational collapse at 650-620 Ma. At this stage conductive heating of the lithospheric root decreased the strength of the crust (Figure 6-4D). The thickened crust became gravitationally unstable. Delamination of the lithospheric root of the ANS caused the actual collapse (Figure 6-4E). This gravitational collapse led to extension in NW-SE direction (Figure 6-4F). Lithospheric thinning, through large low-angle normal shear zones, caused heating and the intrusion of A-type granites, as those that were observed in the

Wadi Kid Complex. The isostatic 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 in a NW-SE extensional regime at 600 Ma (Figure 6-4F). 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 (Figure 6-4F). The extension was accompanied by large igneous activity in the form of the intrusion of A-type granites, the intrusion of NE-SW dykes and volcanics as the undeformed rhyolites in the Wadi Kid Complex.

6.6 Conclusions

The tectonic development of Arabian-Nubian Shield displays many similarities with the Cordilleran Mesozoic and Early Cenozoic development of western North America. The different tectonic stages in the ANS can be summarized as follows:

1. Ophiolitic sequences and island-arcs formed at ca. 900-750 Ma in the Mozambique Ocean. The lithologies of the Tabalah and Tarj Complex and the Bi'r Umq Complex are remnants of this phase.
2. "Offshore amalgamation" led to accretion of island-arcs in the Mozambique Ocean and the formation of the Amennakhte Superterrane. Different compressional and transcurrent deformation phases that were observed in the Bi'r Umq Complex and Tabalah and Tarj areas are remnants of this phase. The intra-oceanic arc-accretion took place at ca. 820 – 760 Ma.
3. Litterature indicates that subduction at N-S active continental margins started at ca. 700 Ma. Arc-accretion at these continental margins led to lithospheric thickening.
4. The start of gravitational collapse of the thickened lithosphere took place at ca. 650 – 620 Ma.
5. Gravitational collapse led to extension. This extension was accommodated by low-angle shear zones of the type that was observed at the Wadi Kid Complex.
6. Isostatic rebound and the rise of mantle derived magmas in the extending crust led to doming of the low-angle shear zones and the actual formation of the core complexes as the Wadi Kid Complex at ca. 600 Ma.

6.7 Recommendations for future research

This research, based on the detailed studies of three key areas, has produced an improved model for the tectonic evolution of the Arabian-Nubian Shield. It provides a pointer for the direction of future reseach. Similar detailed studies in other areas are needed to further improve our understanding of the tectonic evolution of the Arabian-Nubian Shield. There are other subjects of research that deserve attention in the Arabian-Nubian Shield. These include:

1. The real nature (suprasubsubduction or MOR) of the ophiolites remains still subject of discussion. Geochemical investigations may help in getting a better view on their origin. .
2. Generally, little attention has been given to the arc-accretion in the ANS, although it was

this process, which gave the ANS much of its current face. Detailed structural, geochemical and metamorphic research is needed to improve the understanding of this phase so that it can help us to understand the lithospheric thickening, which led to gravitational collapse, in more detail. The relatively low abundance of HP-metamorphism also requires attention.

3. The extend of extension in the ANS is not really clear. NW-SE extension is clearly observed through the core complexes in the Nubian part of the ANS, however it is not clear if, and in which way extension took place in the Arabian part of the ANS.