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Structural, geochemical and geochronological constraints on the tectonic evolution of the Tabalah and Wadi Tarj areas, central Asir, western Saudi Arabia

Abstract

The Tabalah and Wadi Tarj areas in the central part of the Neoproterozoic Asir Terrane in Saudi Arabia, display typical intra-terrane features. The Tabalah and Wadi Tarj areas contain gabbros and quartz-diorites, which were intruded in an island arc, and tonalites and granodiorites, which were formed during subduction at an active continental margin. These rocks were deformed during two phases of deformation: D1 and D2 as recorded by the Tabalah/ Ta'al Shear Zone. The D1-phase displayed thrusting as illustrated by steep lineations and hanging wall over footwall shear sense indicators. This phase was dated at 779Ma and resulted from E-W compression. The D2-phase displayed dextral strike slip and resulted from NNE-SSW compression. This event was dated at 765 Ma. A granodiorite that displayed characteristics of intrusion at an active continental margin, was dated at 761 Ma.

Early intrusives were intruded in an island-arc environment. The observed deformation phases and late intrusions in the Tabalah and Wadi Tarj area are best explained as intra-terrane deformation and magmatism that resulted from arc-accretion. The change in the directions of compression from D1 to D2 can be best explained by an anti-clockwise change in plate motion of the subducting plate during the arc-accretion.

4.1 Introduction

The formation of the Neoproterozoic Arabian Shield is thought to be a result of arc-accretion of mainly juvenile crust, formed in island-arcs and in oceanic basins (see chapter 2). The terrane concept for the Arabian Shield was based on lithological and geochemical observations (Stoeser and Camp, 1985; Johnson et al., 1987). However few structural studies were performed, which have been important for other areas where arc-accretion was established as in the North American Cordillera. It is only recently that Johnson (1998) and Johnson and Kattan (1999a, 1999b) have demonstrated the importance of such studies in the Arabian Shield, by describing the structural features of thrusts and strike slip zones that were related to arc-accretion. The shear zones, related to the arc-accretion, are represented by NE-SW trending linear belts, and ophiolitic sutures, such as the Bi'r Umq Suture and the N-S trending Nabitah Fault Zone.

The aim of this chapter is to improve the understanding of what happened during island-arc formation and arc-accretion in the Arabian-Nubian Shield. In order to achieve this, a detailed study was undertaken of an area that includes the "traditional" intra-terrane features of a Neoproterozoic terrane.

The Asir Terrane (see Figure 4-1) is the largest and most deformed terrane of the Arabian Shield (Stoeser and Camp, 1985). The Tabalah/Wadi Ta'al "Tectonic Zone" is one of the main intra-terrane structures of the Asir Terrane and is found in the central part of this terrane. Two key-areas on the Tabalah/Wadi Ta'al "Tectonic Zone" were chosen for detailed research, namely the Tabalah and Wadi Tarj areas (see Figure 4-1). These areas display lithologies that are typical of the Neoproterozoic in the Arabian Shield, namely different types of igneous rocks like diorite/gabbro complexes, tonalites and granodiorites (Ernst Anderson, 1977; Greenwood et al., 1986). These rock-types are believed to reflect intrusives related to intra-oceanic and continental subduction (Ernst Anderson, 1977; Greenwood et al., 1986).

The main study area was the Tabalah area, located in the northern central part of the Asir Terrane, some 30-40 km southwest of Bishah (Figure 4-1). The Wadi Tarj area is located 20 km south of the Tabalah area (Figure 4-1). The Tabalah/Wadi Ta'al "Tectonic Zone" is the major structure that runs through the Tabalah and Wadi Tarj areas. In the Tabalah area, the Tabalah/Wadi Ta'al "Tectonic Zone" is represented by a NNW-SSE trending zone of intense ductile deformation. There is a minor bend in the Tabalah/Wadi Ta'al "Tectonic Zone" between the Tabalah and Tarj areas and therefore it trends NW-SE in the Wadi Tarj area. The Tabalah/Wadi Ta'al "Tectonic Zone" is a ca. 5 kilometres wide and over 100 kilometres long in total. Ernst Anderson (1977) and Greenwood et al. (1986) mapped the Tabalah/Wadi Ta'al "Tectonic Zone" in the Tabalah area as two separate "Tectonic Zones", the Tabalah "Tectonic Zone" and the Wadi Ta'al "Tectonic Zone". In the Tabalah area, Greenwood et al., (1986) mapped 5 km of less deformed sequence between the two main tectonic zones. Towards the south, in the Wadi Tarj area, the Tabalah/Wadi Ta'al "Tectonic Zone" grades into one intensely deformed belt and is named "Tabalah Tectonic Zone" (Greenwood et al., 1986).

Most authors believe that these linear belts of intense deformation are relicts of faulting, and therefore refer to them as shear zones (SZ). The Tabalah "Tectonic Zone" was thought to result from "wrench tectonics" (Greenwood et al., 1986). Deformation on the Wadi Ta'al "Tectonic Zone" was attributed to thrusting (Greenwood et al., 1986).

This chapter presents results of field-, microscopical, geochemical and geochronological studies. It will be shown that the Tabalah area contains one broad shear zone instead of the two separate "Tectonic" zones that were described by Greenwood et al. (1986). It is concluded that thrusting at ca. 779 Ma is the oldest deformation phase that occurred in the studied areas. The thrusting took place during subduction at an active continental margin and allowed the accretion of island-arcs onto a continental mass. Intra-terrane strike-slip movement on the Tabalah/Wadi Ta'al SZ followed the thrusting-phase. The strike-slip movement was dated at ca. 765 Ma and took place during continuing subduction at the margin of the terrane. Finally, at ca. 761 Ma a granodiorite has been intruded. This granodiorite is shows characteristics of intrusion at an active continental margin.

The results from study of the Tabalah and Tarj areas will be integrated in Chapter 6 with results from the studies of other areas that were performed in the framework of this thesis, and will be integrated with data from other key areas of the Arabian-Nubian Shield.

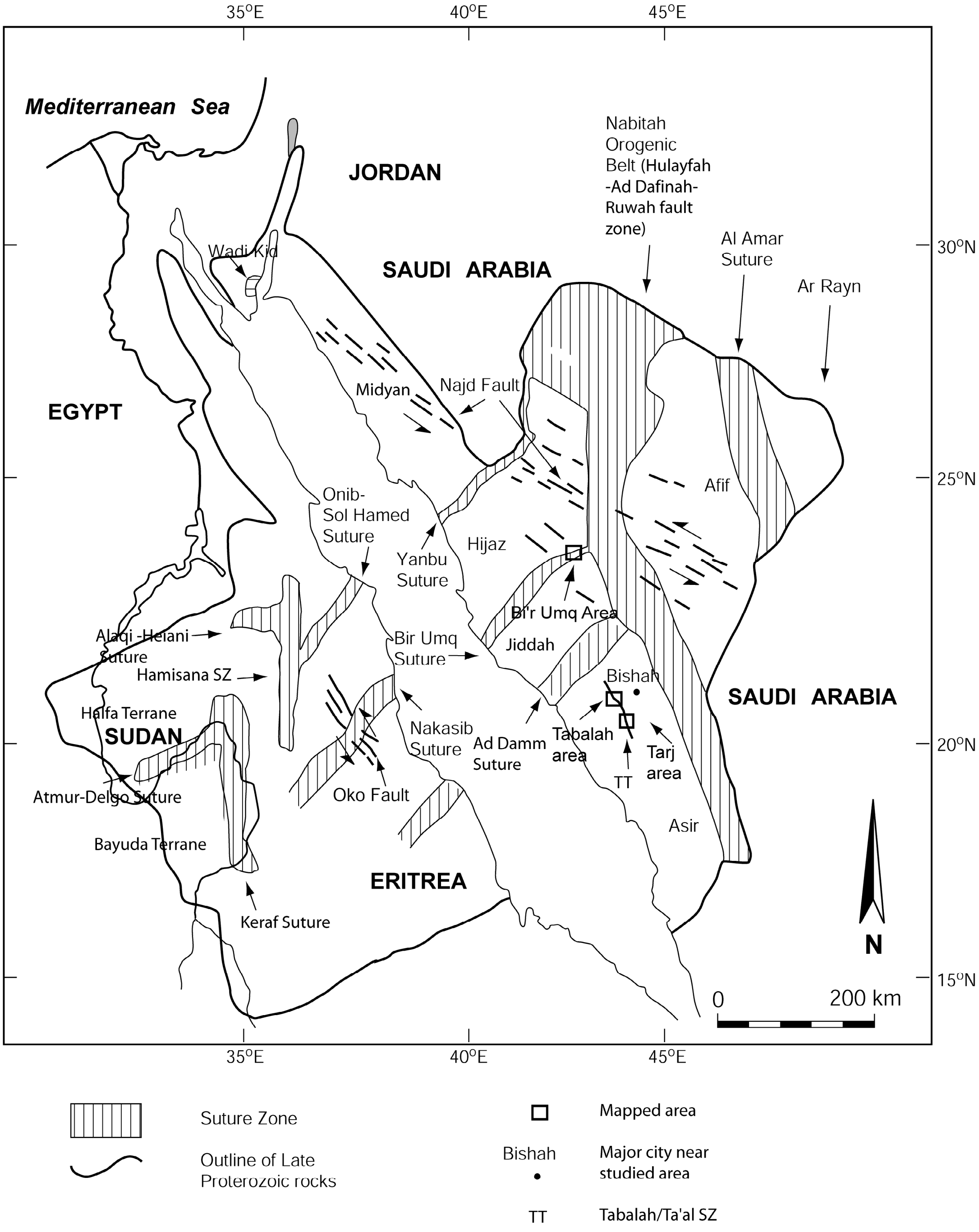

Figure 4-1 Map of the Arabian Nubian Shield that displays the location of the Tabalah and Wadi Tarj areas. TT = Tabalah/Wadi Ta'al Tectonic zone.

4.2 Geological Background

4.2.1 Lithology

The Tabalah and Wadi Tarj areas consist of undeformed and deformed intrusives and schists which are typical for the Asir Terrane as described by Brown et al. (1989). Figure 4-2 shows the main lithologies and structures of the Tabalah area and Figure 4-3 shows the main lithologies and structures of the Wadi Tarj area. The western and eastern parts of the Tabalah area and large parts of the Wadi Tarj area consist of a *mixed gabbro-diorite suite.* The *mixed gabbro-diorite* consists of gabbro rich in pyroxene, with plagioclase and hornblende, and diorite containing plagioclase, hornblende, biotite and quartz. In the Wadi Tarj area, the *mixed gabbro-diorite suite* has a mainly dioritic composition.

The rocks of the *mixed gabbro-diorite suite* are generally undeformed but locally a foliation and a lineation have developed. These ductily deformed NNW-SSE striking bands have thicknesses of 0.5 meter up to 25 meter and are dipping steeply to the ENE. The deformed layers within the *mixed gabbro-diorite suite* are phyllitic. The rocks of the *mixed gabbro-diorite suite* become increasingly foliated towards the schists of the main Tabalah/Wadi Ta'al Shear zones. Here, they grade into hornblende-biotite schists.

The *quartz diorite-tonalite* occupies the central part of the Tabalah area and is found between what was referred to as the Tabalah Shear Zone and Wadi Ta'al Shear zone by Greenwood et al. (1986). This rock is a rather uniformly massive, medium- to coarse-grained linear body that is parallel to the "shear zones". It contains plagioclase, quartz, hornblende and minor amounts of biotite. Occasionally this rocktype contains mafic xenoliths. The *quartz diorite-tonalite* is well foliated and lineated. It is strongly deformed in many places and in these places, it grades into quartzo-feldspathic schist that is similar to the quartzo-feldspathic variety of the *amphibolite* described below.

An undeformed homogeneous *diorite* intrudes deformed gabbro and biotite-schist in the southwestern part of the Tabalah area. This *diorite* is very rich in plagioclase and relatively low in mafic constituents.

A large undeformed homogeneous *granodiorite* body was observed in the southern Wadi Tarj area. It consists of plagioclase, hornblende and minor amounts of quartz. Intrusive and structural relations indicate that the *granodiorite* is the youngest feature in this area.

The *amphibolites* are found in the Tabalah and Wadi Ta'al Shear Zones, in contact with the less- to non-deformed *mixed gabbro-diorite suite* and the strongly deformed *quartz diorite-tonalite*. There are two components to the *amphibolites*: a hornblende-biotite schist and a quartzo-feldspathic schist. The hornblende-biotite schist is rich in hornblende, biotite, plagioclase and minor quartz. These components are observed in all zones of *amphibolites* in the Tabalah and Wadi Tarj areas. Occasionally, clasts of diorite (up to 5 cm in diameter) are found within the biotite-hornblende schists. The quartzo-feldspathic schists are very rich in plagioclase and quartz and contain some minor hornblende and biotite. Locally, schists with an intermediate composition were observed. At the northwestern part of the Tabalah area, a garnet-biotite schist was found in the *amphibolites*. Most of the schists are fine-grained, ± 0.1 mm, but also a coarser variety is observed with grain sizes of approximately 0.5 mm. In places, the

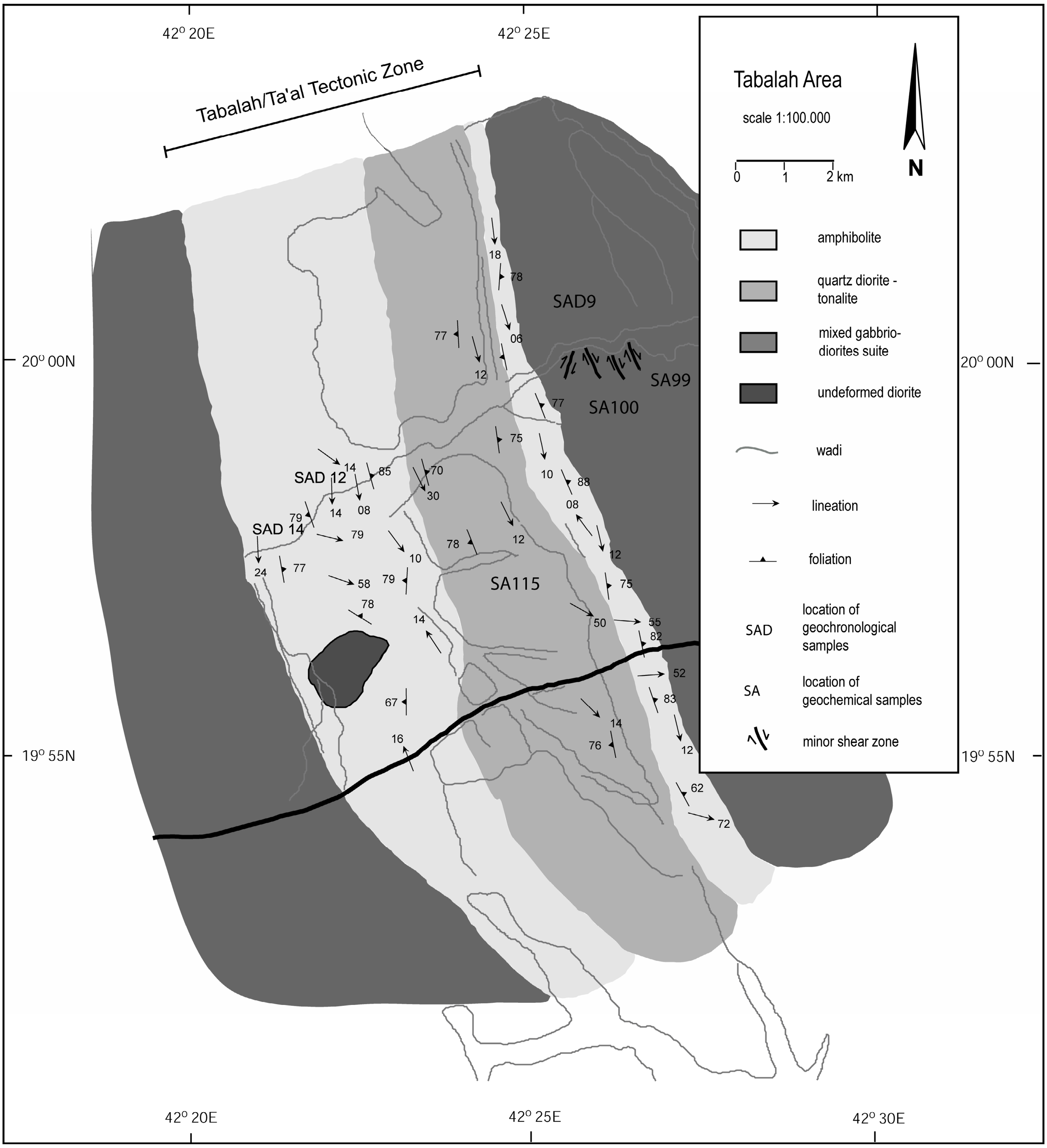

Figure 4-2 Geological map of the Tabalah area (1:100.000).

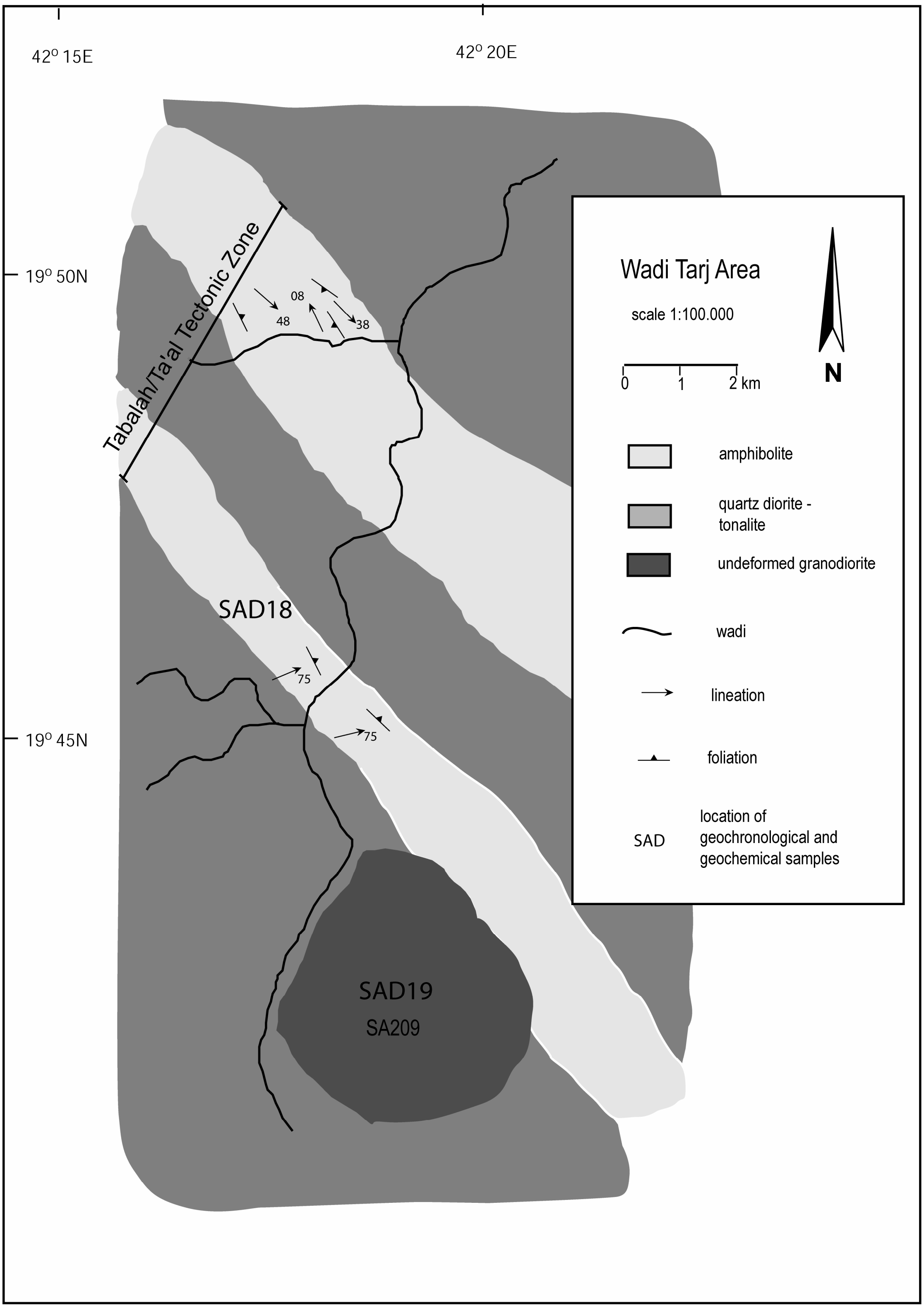

Figure 4-3 Geological map of the Wadi Tarj area (1:100.000).

amphibolites were found interlayered with *quartz diorite-tonalite*, often close to the contact with the main *quartz diorite-tonalite* body. Locally, the *amphibolite* has a gneissic appearance with alternating dark and light coloured bands of approximately 1 to 10 cm thickness. The dark bands consist of fine to coarse hornblende-rich schistose rock. The light coloured bands consist of plagioclase- and quartz rich schistose rocks with minor biotite and hornblende. Occasionally, less deformed parts of *gabbro-diorite suite* and *quartz diorite-tonalite* are found in the schists of *amphibolite*.

A small number of *dykes* was observed. They are slightly to non-foliated and have an andesitic to a basaltic composition with large amounts of plagioclase and minor amounts of hornblende and biotite. They intrude the *mixed gabbro-diorite suite*, *quartz diorite-tonalite* and the *amphibolite*. The dykes strike W-E in the western part of the Tabalah area but have more NW-SE trend in the eastern part (Greenwood et al., 1986).

4.2.2 Metamorphism

The metamorphic conditions were deduced from microscopical studies. The schists of the *amphibolites* and the *quartz diorite-tonalite* display evidence of metamorphism and are thus the only ones for which the metamorphic conditions were assessed. The *mixed gabbro- diorite suite* preserved its primary igneous texture and mineralogy, however locally pyroxene has been replaced by green hornblende. Bluish-green hornblende, as observed in the *amphibolites* and the *quartz diorite-tonalite*, is typical for metamorphic conditions of lower amphibolite facies with relatively low to medium pressure and medium temperature conditions (Miyashiro, 1994). Brown hornblende, which indicates a higher temperature than the bluish-green variety, is only observed in the *amphibolites* at the Wadi Tarj area. Deformation in the *amphibolites* in the latter area occurred thus at intermediate amphibolite-facies conditions. The thin schistose bands in the otherwise undeformed *mixed gabbro-diorite suite* are generally rich in green hornblende and contain minor amounts of biotite. The presence of green hornblende indicates that these rocks were also formed at lower amphibolite grade.

It can be concluded that generally deformation took place at low to intermediate amphibolite grade. Typical temperatures for such grade are 450-530° C and pressures of 4-8 kbar (Miyashiro, 1994). In the Wadi Tarj area, the presence of brown hornblende indicates a slightly higher temperature, at about 550 C (Miyashiro, 1994).

4.3 Structural Geology

4.3.1 Introduction

This section will focus on the ductile structures in the Tabalah area and the Wadi Tarj area. The main structures in the studied areas are the Tabalah and Wadi Ta’al SZ. As stated in the introduction, the Wadi Ta’al SZ was previously interpreted as a thrust (Greenwood et al., 1986). The Tabalah SZ was interpreted as a strike slip fault with sinistral sense of movement that post-dated movement on the Wadi Ta’al SZ (Greenwood et al., 1986).

The belt of *amphibolites* represents the most highly deformed zone in the Tabalah and Wadi Tarj area. The *quartz diorite-tonalite* in the Tabalah area, between the Wadi Ta'al and Tabalah shear zones, is also foliated and lineated and, as will be demonstrated in this chapter, is part of the shear zone-complex. The thickness of the Tabalah SZ is ca. 800-1200 m. The Wadi Ta'al SZ is slightly thicker: 1200 – 2000 m. The total thickness of the foliated sequence, including the *amphibolites* and the *diorite-tonalite*, is about 6-10 km in the Tabalah area (Figure 4-2). Here, the main shear zones trend NNW-SSE (Figure 4-2). The total thickness of the foliated sequence in the Wadi Tarj area is ca. 3-4 km (Figure 4-3). In the Wadi Tarj area, the main structure trends NW-SE (Figure 4-3).

Foliated bands occur within the mainly non-deformed *mixed gabbro-diorite suite*, adjacent to the Tabalah SZ. Their thickness ranges from 0.5 meter, in the eastern part of the area, up to 50 meters close to the main shear zone. The fact that the *mixed gabbro-diorite suite* and the *quartz diorite-tonalite* grade into the deformed units and that relicts of the *mixed gabbro-diorite suite* and the *quartz diorite-tonalite* are found in the deformed units indicates that the *amphibolites* are the deformed equivalent of the *mixed gabbro-diorite suite* and the *quartz diorite-tonalite.*

4.3.2 Foliations

The *amphibolites* and the *quartz diorite-tonalite* form a well-foliated sequence. The foliation is mainly defined by biotites and by flattened recrystallised quartz grains. The foliation in the Tabalah area is steeply dipping to ENE to vertical and strikes NNW-SSE (Figure 4-4). The foliation trend in the *quartz diorite-tonalite* has the same trend as the foliation in the *amphibolites*. The foliations of the thin schistose layers within the *mixed gabbro-diorite suite* also have a similar trend as the main foliation. The contact between the foliated rocks and the undeformed rocks is gradational. In the Wadi Tarj area the foliation shows a NW-SE trend and dips NE (Figure 4-3 and Figure 4-5). The difference in the trend of foliation between the Tabalah area and the Wadi Tarj area is best explained by the fact that the overall trend of the main structure changes slightly from the Tabalah area to the Wadi Tarj area. Throughout the Tabalah and Wadi Tarj areas, no evidence of regional folding was found.

4.3.3 Lineations

Lineations are observed on the foliation-planes of the *amphibolites* and the *quartz diorite-tonalite*. They are mainly defined by growth of minerals and occasionally by the stretching of minerals and stretched xenoliths. The growth of hornblende in a uniform direction represents the mineral lineation. The hornblendes are up to 0.5 cm long. However, in the southern part of the Wadi Tarj area, larger hornblendes were observed. Quartz, plagioclase, hornblende and biotite form the stretching lineation and are parallel to the mineral lineation that is defined by hornblende. Figure 4-6 shows that the lineation in the Tabalah area trends mainly sub-horizontally NNW-SSE. A secondary maximum shows lineations plunging steeply to E to ESE (Figure 4-2 and Figure 4-6). Rarely, randomly orientated hornblendes were also observed near the undeformed diorite of the SW Wadi Tabalah area. This may indicate some form of late thermal overprint due to the intrusion of this diorite. Mineral lineations in the Wadi Tarj area

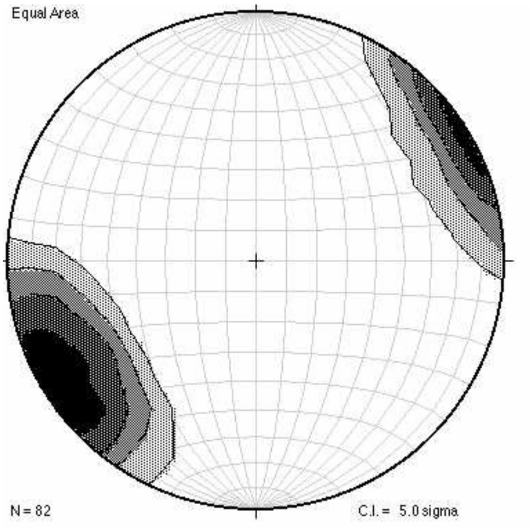

Figure 4-4 Poles to the foliation in Tabalah area.

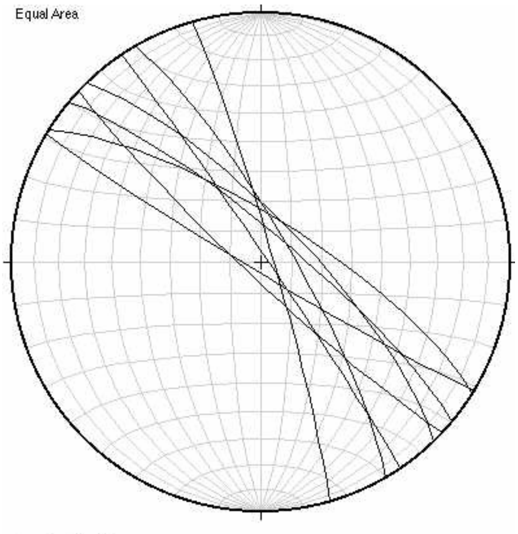

Figure 4-5 Foliation in the Tarj area.

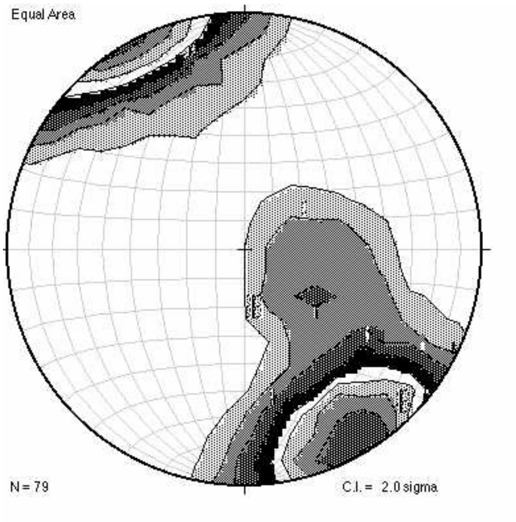

Figure 4-6 Contour of lineations in the Tabalah area.

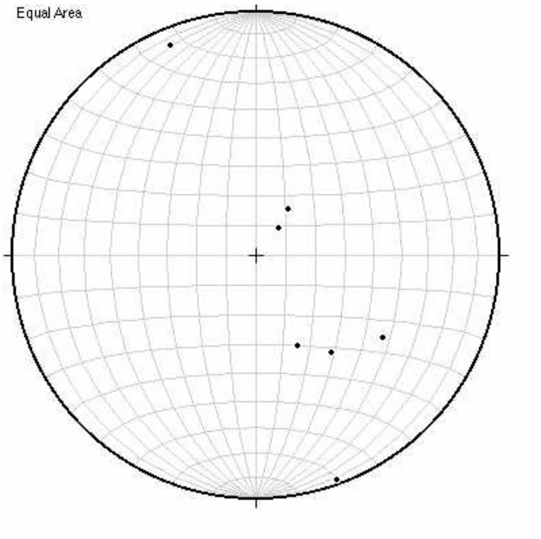

Figure 4-7 Lineations in the Wadi Tarj area.

plunge generally moderately SE and steeply ENE (Figure 4-3 and Figure 4-7). These differences in the trends of lineations is best explained by the fact that the overall trend of the main shear zone and the foliations has a slightly different trend of the main structure in the Wadi Tarj area than in the Tabalah area. The temporal relations between the steep and sub-horizontal lineations could not be assessed from the observed geological features in the field or through the microscopical studies. It will be further assessed in the geochronological section of the chapter.

4.3.4 Evidence for non-coaxial deformation

A number of indicators of non-coaxial deformation were observed in the schistose units of the Tabalah and Wadi Tarj areas. The *amphibolites* and the *quartz diorite-tonalite* contain these indicators. C-C’ fabrics, rotated clasts (Figure 4-8 and Figure 4-10) and mica fish are typical indicators of non-coaxial deformation that are observed in all the schistose units of the Tabalah and Wadi Tarj areas. The C-C’ fabrics and "mica-fish" are generally defined by hornblendes. This indicates that the deformation took place at amphibolite-facies conditions. The rotated σ-clasts consist mainly of plagioclase and rarely of pyroxene relicts. The pressure shadows that are associated with the rotated clasts consist of quartz and hornblende. When formed by hornblendes, these strain shadows are of the displacement-controlled type with deformable fibres as described by Ramsey and Huber (1983). Also massive strain shadows were observed containing quartz. Both types of strain shadows indicate simple shear progressive deformation (Passchier and Trouw, 1996).

The shear sense indicators that are associated with the SSE to SE trending sub-horizontal lineation in the Tabalah and Wadi Tarj areas indicate dextral movement. E to ESE moderately to steeply plunging lineations in the Wadi Tarj and Tabalah areas were associated with shear indicators that displayed top-to-the-W movement, which would indicate thrusting in its current position. The temporal relations between the steep and sub-horizontal lineations and their associated non-coaxial shear indicators could not be assessed from the observed geological

Figure 4-8 A rotated diorite clast indicates a dextral sense of shear.

Figure 4-9 An extensional crenulation cleavage indicates dextral sense of shear in one of the minor shear zones east of the main Tabalah SZ.

features in the field or through the microscopical studies. The fact that indicators of non-coaxial deformation were observed in schistose sequences, shows that these have a mylonitic origin.

Evidence for non-coaxial deformation is also observed in the schists that contain NNW-SSE trending foliations and sub-horizontal lineations within the *mixed gabbro-diorite suite*. Macroscopic diorite clasts and C-C' fabrics (Figure 4-9) display dextral movement. Microscopical extensional crenulation cleavages in the minor mylonites of the *mixed gabbro-diorite suite* also display dextral movement.

4.3.5 Conclusions on structural geology

The *amphibolites* and *quartz diorite-tonalite* contain structures that were formed at amphibolite

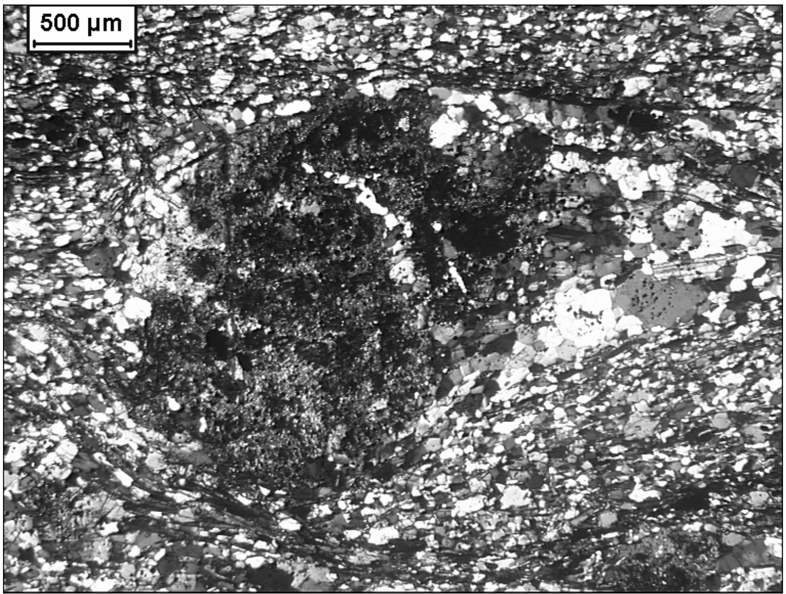

Figure 4-10 Rotated clast with strain shadows indicating dextral movement.

metamorphic grade. A steep NNW-SSE (in the Tabalah area) to NW-SE (in the Wadi Tarj area) striking foliation and a sub-horizontal lineation are the main structural features in these formations. Occasionally, steeply plunging lineations were observed. Top-to-the-W movement was observed along these steeply E-plunging lineations. Dextral strike-slip movement was associated with the sub-horizontal NNW-SSE lineations. Since no temporal relations were observed between the different lineation-trends, it was not possible to assess the temporal relationships between the different phases of shearing. Randomly oriented hornblendes near an undeformed diorite in the SW Tabalah area indicate post-deformational heating at lower amphibolite conditions.

4.4 Geochemistry

4.4.1 Introduction

Much geochemical research has been performed in the Arabian Nubian Shield and it was used as a basis for many of the existing theories regarding the tectonic development of the Arabian-Nubian Shield (e.g. Schmidt et al., 1980; Bentor, 1985; Jackson, 1986; Brown et al., 1989; Harms et al., 1994; Mohammed and Hassanen, 1996). In order to put the structural and geochronological results in a tectonic framework, a limited geochemical study was undertaken, that can then be used as a reference tool with respect to other studies in the Arabian-Nubian Shield. The results of the geochemical analyses were compared to published geochemical data from the Arabian-Nubian Shield and the interpretations of these published studies were integrated over here.

The magmatic rocks have been generally interpreted to belong to one of the three main phases in the Arabian-Nubian Shield: 1) oceanic phase (sub-divided into island-arc and ophiolitic phases) (Bentor, 1985; Brown et al., 1989; Blasband et al., 2000), 2) arc-accretion

(Brown et al., 1989; Blasband et al., 2000), and 3) late orogenic extension (Blasband et al., 2000). Brown et al. (1989) compared some 500 geochemical analyses and concluded that the plutonic rocks in the Arabian part of the Arabian Nubian Shield can be divided into 3 groups:

I) The earliest phase of plutonic activity (900–700 Ma) consists of diorites and gabbros that were intruded in island-arcs and gabbros that were related to ophiolitic sequences;
II) Tonalites and granodiorites intruded during a collisional event around 740-650 Ma;
III) Granodiorites to granites intruded from 650-550 Ma and were related to the late stages of collision and post-tectonic cratonisation.

4.4.2 Samples

Five samples, that are representative for the Tabalah and Tarj areas, were analysed for geochemical studies using XRF and ICP-MS. These samples were selected because they represent the main non- to little deformed and non-metamorphosed lithologies from the Tabalah and Wadi Tarj areas (see also Figure 4-2 and Figure 4-3)

- *An undeformed gabbro* (sample SA99; N 20°01.565’ E42°15.960’) from the *mixed gabbro-diorite suite* in the eastern Tabalah area. It is rich in pyroxene and consists of minor plagioclase, biotite and hornblende. This sample was analyzed because it is one of the main lithologies in the area and pre-dates deformation. Its analysis will give information about the early overall setting of the area.
- *A slightly deformed diorite* (sample SA100; N 20°01.565’ E42°15.960’) from the *mixed gabbro-diorite suite* in the Tabalah area. The sample consists of plagioclase, pyroxene and minor quartz. Like sample SA99, this sample was analyzed because it is one of the main lithologies in the area and pre-dates deformation, and because its analysis may give information about the initial tectonic regime in the areas.
- *A slightly deformed tonalite* (sample SA115; N 19°59.257’ E42°13.539’) taken from the *quartz diorite-tonalite suite* in the central Tabalah area. This sample consists mainly of quartz and plagioclase and some minor biotite. This sample is a major rock-type in the area. It was only observed in a slightly deformed state.
- *An undeformed granodiorite* (sample SA209; N 19°43.244’ E42°21.969’) from the Wadi Tarj area. It consists of hornblende, plagioclase and some quartz and biotite. This granodiorite intrudes the main Wadi Ta’al Shear Zone and should thus give indications on the tectonic setting of the area after the activity on the shear zone ceased.
- *An andesitic basalt* from a dyke (sample SAD9; N 20°01.509’ E42°15.392’) in the central Tabalah area that trends 120° and intrudes the *mixed gabbro-diorite suite*. It consists mainly of plagioclase and hornblende. This undeformed sample was analyzed because it is one of the youngest rocks in the areas and this should give indications on the later tectonic regime in the area.

4.4.3 Techniques

Only non- to slightly deformed rocks were used for geochemical analyses. The samples were ground in a Tungsten-carbide mill. XRF major element analyses were carried out with a Siemens SRS 3440 spectrometer at Utrecht University, the Netherlands. ICP-MS was used for the trace element analyses. 0.1 of sample powder was dissolved in 4 ml HNO3, 3 ml HClO4, and 5 ml HF acid, in Teflon bombs. They were heated to 180° C for 5 hours. The samples were analyzed on an Agilent 7500a ICP-MS instrument at Utrecht, the Netherlands. The analyses were undertaken by the staff of the integrated geochemical laboratory of the Faculty of Geosciences at the Utrecht University.

4.4.4 Major elements

The geochemical analysed samples can be classified on the basis of major elements. This classification is used for the comparison with other geochemical studies on the Arabian Nubian Shield. Table 4-1 shows the results of the major-element analyses of the selected rock samples from the Tabalah and Wadi Tar areas. Diagramic representations of the data obtained are shown in Figure 4-1.

Brown et al. (1989) presented the most extensive geochemical overview study of the Arabian Shield to date. Brown et al. (1989) mainly used Na2O-CaO-K2O diagrams for the classification of their plutonic samples because this type of diagram is suitable for the differentiation between calc-alkaline rocks and others. The analyses of the samples from the Tabalah and Tarj areas were compared to the results of Brown et al. (1989) and followed their interpretations. The *undeformed gabbro* and the *slightly deformed diorite*, both from the *mixed gabbro-diorite* in the Tabalah area, display a similar position in the Na2O-CaO-K2O diagram (Figure 4-11) as the gabbros and quartz-diorites from the "Jiddah Group" and "Baish-Bahah Group" in Brown et al. (1989; figs 19-21). Brown et al. (1989) interpreted these rock-types to have been formed in an island-arc environment. The *slightly deformed tonalite* and *undeformed granodiorite* display a similar position in the Na2O-CaO-K2O (Figure 4-11) diagram as the "Halaban Group" and "Culminant-orogeny rocks" of Brown et al. (1989, figs 19-21). Both, the "Halaban Group" and "Culminant-orogeny rocks" consist mainly of granodiorites (Brown et al., 1986). These granodiorites intruded into a thickened crust (Brown et al., 1986), which typically could have formed during arc-accretion. Jackson (1986) and Stoeser (1986) interpreted tonalites and granodiorites diorites in the Arabian-Nubian Shield to have been formed during subduction at continental Andean-type margins and arc-accretion. The *andesitic basalt*, an undeformed dyke, displays a similar position in the Na2O-CaO-K2O diagram (Figure 4-11) as samples from the "Halaban Group" of Brown et al. (1989) which were related to the arc-accretion.

Table 4-1 Major elements of selected samples from the Tabalah Area measured through XRF (in weight %).

	SAD9	SA99	SA100	SA115	SA209
SiO2	48,1	40,7	45,9	64,6	57,1
Al2O3	13,2	16,0	24,2	15,8	16,1
TiO2	2,50	0,94	0,20	0,40	0,71
CaO	10,0	13,9	13,9	4,71	6,92
MgO	5,65	8,44	4,19	1,98	3,80
Na2O	2,04	0,67	1,59	3,78	3,25
K2O	0,32	0,12	0,20	1,14	1,21
Fe2O3	15,0	12,8	4,44	3,83	7,13
MnO	0,21	0,12	0,075	0,070	0,11
P2O5	0,37	0,093	0,11	0,21	0,24
LOI	0,85	2,37	1,80	1,37	0,59

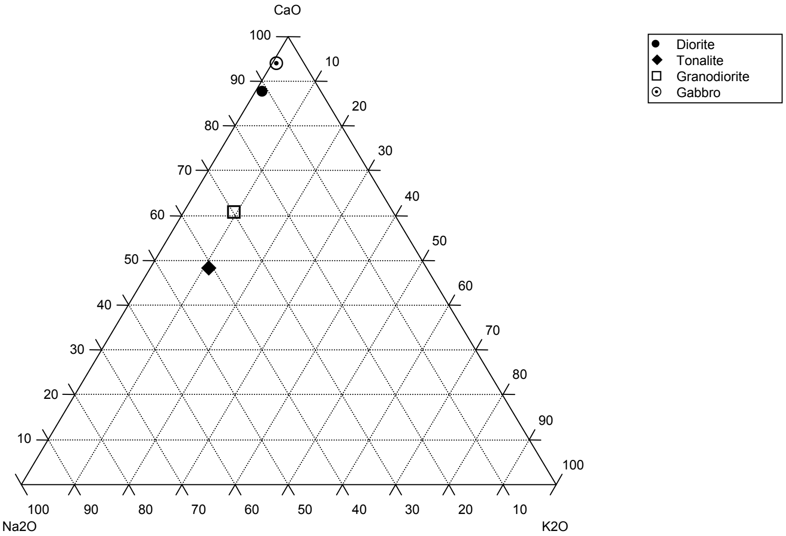

Figure 4-11 Na2O-CaO-K2O diagram for plutonic samples from the Tabalah and Tarj Complex.

4.4.4 Trace elements

4.4.4.1 Introduction

Trace elements are useful in discriminating between magmatic processes and tectonic regimes and have been widely used to assist in tectonic interpretations in the Arabian-Nubian Shield (e.g. Hassanen et al., 1996; Marzouki and Divi, 1989; Mohamed and Hassanen, 1996; Teklay et al., 2002). In this paragraph, the results of the trace element analyses from the Tabalah and Wadi Tarj areas were compared with those of published trace element studies in the Arabian-Nubian Shield. The trace element concentrations for the samples from the Tabalah area are listed in Table 4-2.

The trace elements are presented through N-MORB normalized multi-element diagrams and REE chondrite-normalized diagrams. N-MORB normalized diagrams are especially useful for samples which have originated from of oceanic rocks or underwent an evolution as arc-related rocks from intra-oceanic subduction zones or active continental margins (Rollinson, 1993).

Table 4-2 Trace element analysis through ICP-MS (in PPM).

Sample	SA 99	SA 100	SA 115	SA 209	SAD 9
Rb	1,92	4,16	19,48	28,43	5,21
Sr	215,15	458,98	478,58	346,68	264,32
Y	4,72	4,70	11,42	14,73	63,36
Zr	5,58	6,95	14,08	14,58	144,02
Nb	0,30	0,88	2,92	1,68	8,59
Ba	24,08	68,18	278,88	243,52	97,79
La	0,36	0,79	9,63	9,16	14,78
Ce	1,02	1,90	24,75	22,30	40,95
Pr	0,22	0,32	2,81	3,00	6,39
Nd	1,40	1,60	11,52	13,19	31,96
Sm	0,61	0,56	2,54	3,16	9,33
Eu	0,33	0,50	0,80	0,87	3,07
Gd	0,85	0,74	2,40	3,06	11,07
Tb	0,16	0,14	0,38	0,51	2,00
Dy	1,01	0,93	2,12	2,96	12,18
Ho	0,21	0,20	0,44	0,61	2,67
Er	0,58	0,56	1,28	1,70	7,22
Tm	0,08	0,09	0,20	0,25	1,09
Yb	0,55	0,64	1,39	1,70	6,91
Lu	0,09	0,11	0,24	0,27	1,04
Hf	0,29	0,26	0,76	0,73	4,45
Ta	0,41	1,63	0,43	0,30	1,02
Th	0,03	0,11	2,92	1,72	1,03

The N-MORB normalized diagrams in Figure 4-12 and the REE chondrite-normalized diagrams in Figure 4-13 justify the division into 2 groups of the samples from the Tabalah and Tarj areas:

I) The undeformed gabbro (sample SA99) and the slightly deformed diorite (sample SA100)

II) The slightly deformed tonalite (sample (SA115), undeformed granodiorite (sample SA209) and the andesitic basalt from a dyke (sample SAD9)

The samples of *Group I*, namely the samples SA99 and SA100, have the lowest trace element concentrations and both rock-types have identical trace-element patterns (Figure 4-12 and Figure 4-13). The rock-types of *Group II*, namely the samples SA115, SA209 and SAD9 are more enriched in trace elements than the samples of *Group I.* Their trends are similar to each other but differ from the samples from *Group I* (Figure 4-12 and Figure 4-13).

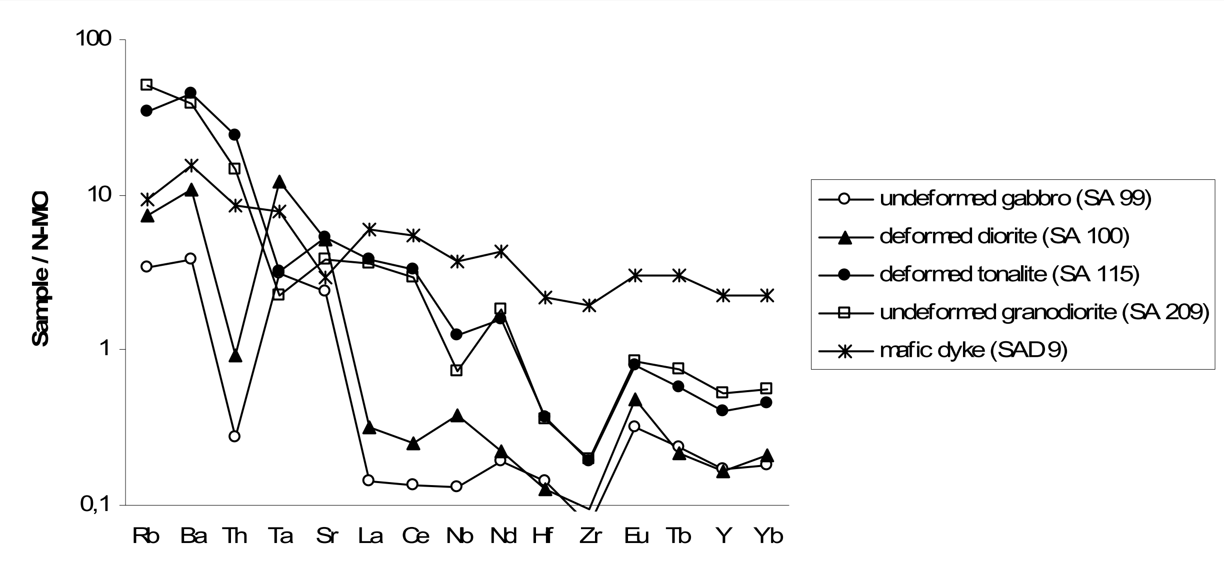

Figure 4-12 N-MORB normalized multi-element diagram for the samples from the Tabalah and Tarj Complexarea. N-MORB values from McDonough and Sun (1995).

4.4.4.2 Group I: The undeformed gabbro (SA99) and the slightly deformed diorite (SA100)

The N-MORB normalized pattern for the undeformed gabbro and the slightly deformed diorite show an overall enrichment of the LFS-elements relative to the HFS-elements with a pronounced Th-trough, a notable La-Ce trough for the gabbro and a minor Nb-peak. The REE-pattern for both rock-types of this group displays a slight depletion for LREE relative to the HREE. Both rock-types have a positive Eu-anomaly.

The LFS-enrichment, as observed in the N-MORB patterns of the *Group I* samples of the Tabalah and Tarj areas, is also observed in a number of other gabbro-diorite suites the Arabian Nubian Shield as the gabbro-diorite suite from the Umm Naggat district in the Eastern Desert of Egypt (Mohamed and Hassanen, 1996) and the gabbro-diorite suite from the Ariab complex in Sudan (Schandelmeier et al., 1994). Mohamed and Hassanen (1996) attribute enrichment of the LFS-element enrichment the fact that these elements are easily mobilized by hydrous fluids that are derived from subducting oceanic crust by dehydration of this subducting slab. The hydrous fluids will then "contaminate" the magma source with LFS-elements. This explanation for LFS-enrichment in island-arc related rocks is similar to the explanation that was put forward by Wilson (1989). Mohamed and Hassanen (1996) further found their samples to plot close to the typical island-arc rock composition in the Nb-Zr-Y tectonic classification diagrams of igneous rocks by Pearce (1982). The gabbro-diorite suite in the Ariab complex was also interpreted to have been formed in an immature island arc (Schandelmeier et al., 1994).

For the samples from *Group I* in the Tabalah and Tarj areas, the diorite has an overall higher trace-element concentrations then the gabbro. This can be best explained by the fact that primitive island arcs will have relatively less enrichment of LFS-elements than the more evolved island arc rocks (Wilson, 1989). Consequently, the undeformed gabbro represents an older immature island arc. Jackson (1986) also indicated that generally island-arc related gabbros in the Arabian Nubian Shield were formed in immature island arcs and the diorites were formed in a more mature island arc

Based on N-MORB normalized diagrams, it can be concluded that the samples of *Group I* are similar to gabbros and diorites from other areas in the Arabian Nubian Shield. They were formed in an island-arc environment. The undeformed gabbro was formed in a younger immature island-arc. The slightly deformed diorite was formed when the island-arc was mature.

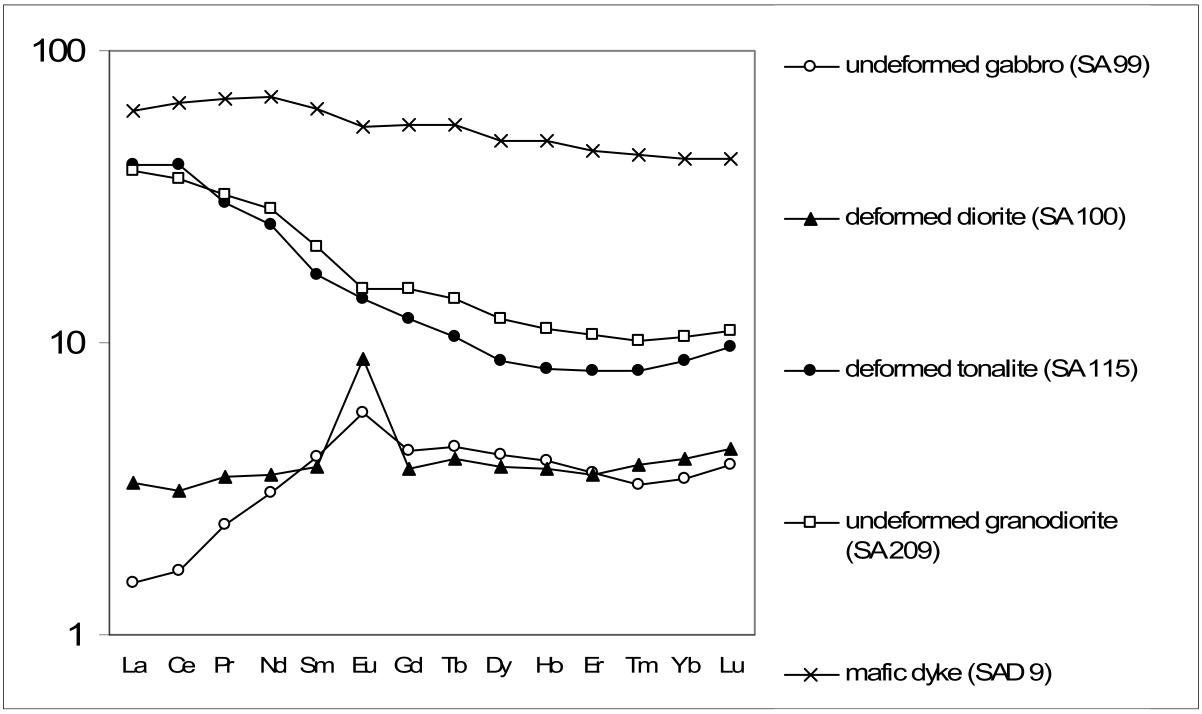

Figure 4-13 Chondrite normalized REE diagram for the samples from the Tabalah and Tarj Complexarea. Chondrite values from McDonough and Sun (1995).

4.4.4.3 Group II: the slightly deformed tonalite (SA115), the undeformed granodiorite and the andesitic basalt from a dyke (SAD9)

The samples of *Group II* have higher concentrations of trace elements than the samples of *Group I*. The N-MORB patterns display a strong LFS enrichment relative to the HFS elements. The rocks of this group display a Ta trough, an Nb trough, and an Nd peak. The slightly deformed tonalite and the granodiorite are enriched in LREE over HREE. Furthermore, the undeformed granodiorite has a slight negative Eu-anomaly and a slight concavity in the DY-YB region (Figure 4-13).

The LFS-enrichment as observed in the samples of the tonalite and the granodiorite, is found in many geochemical studies of tonalites and granodiorites in the Arabian Nubian Shield. For example, geochemical patterns of the granodiorites and tonalites from the Homrit Waggat and El-Yatima areas, eastern Egypt (Moghazi et al., 1996) and the Roded Complex, southern Israel (Bogoch et al., 2002) resemble the geochemical patterns of those of the Tabalah and Tarj areas. The N-MORB patterns for the granodiorites and tonalites from both of these areas display an enrichment of LFS-elements relative to HFS-elements. The Nb-trough is also observed for both areas. These are typical features for plutonic rocks that are formed at an active continental margin where the LFS-enrichment results from dehydration of this subducting slab Wilson (1989). On the basis of the trace element studies, Bogoch et al. (2002) and Moghazi et al. (1999) interpret the granodiorites and tonalites in their respective areas to have been formed by melting of an amphibolitic crust in a subduction setting. This could typically take place during accretion of an island-arc at an active continental margin (Moghazi et al., 1996).

REE-patterns similar to the intrusives of *Group II* in other parts of the Arabian Nubian Shield, are observed for other granodiorites and tonalites in the Arabian Nubian Shield. The granodiorites and tonalites from the Al Amar-Idsas area, Saudi Arabia (Le Bel and Laval, 1986) and the Keraf area, northern Sudan (Bailo et al., 2003), display enrichment of LREE with respect to HREE, the lack of a significant Eu-anomaly and the concavity in the Dy-Yb region. On the basis of their REE-patterns, these rocks were interpreted to have been formed by melting of an amphibolitic or eclogitic crust (Le Bel and Laval, 1986). Le Bel and Laval (1986) found the REE-patterns of the granodiorites from Al Amar-Idsas area to be similar to subduction-related plutonic rocks in western North- and South America. Bailo et al., (2003) interpreted granodiorites in the Keraf area to be indicative of subduction.

The observed Th-, La- and Ce-enrichment for the intrusives of *Group II* in the N-MORB normalized plots is typical for plutonic rocks that are formed at an active continental margin compared to island-arc related rocks (Wilson, 1989; Tormey et al., 1991). This enrichment is explained by the fact that these elements are typically enriched in a sedimentary or amphibolitic continental crust (Wilson, 1989; Tormey et al., 1991).

The enrichment of LREE relative to HREE is generally attributed to garnet fractionation (Rollinson, 1993). Garnet fractionation can indicate melting of an amphibolitic crust (Rollinson, 1993).

Based on N-MORB normalized diagrams and the REE patterns found in this study and their similarity to those published in other studies in the ANS, it can be concluded that the granodiorites and tonalites from the Tabalah and Tarj areas are very similar to tonalites and granodiorites in the ANS that were intruded during subduction at a continental margin.

The *andesitic basalt* is the only non-plutonic rock of the analysed samples. This rock-type has generally the highest concentration of trace elements. The MORB-normalized diagram displays an enrichment of LFS-elements relative to HFS elements with a pronounced Nb trough, and a significant Nd peak, similar to the tonalites and granodiorites. The REE normalized diagram shows LREE enrichment relative to the REE and a small negative Eu-anomaly.

Examples of andesitic basalts from other areas in the Arabian Nubian Shield with similar trace element patterns as for sample SAD9, are found in the Bir Safsaf area, south-west Egypt (Pudlo and Franz, 1994) and in Eritrea (Teklay et al., 2002). Trace element studies from both areas display similar trace element patterns as *andesitic basalt* in the Tabalah area. Their N-MORB normalized diagrams display a pronounced LFS enrichment which is explained by the fact that these rocks were formed in a subduction environment (Pudlo and Franz, 1994; Teklay et al., 2002). The negative Nb-anomaly in the Bir Safsaf samples was interpreted to indicate formation at an active continental margin (Pudlo and Franz, 1994).

Poll and Franz (1994) performed model-calculations on REE data from andesitic basalts in the Bir Safsaf area, Egypt, with a similar pattern to the REE-pattern as the andesitic basalt from the Tabalah area. Their calculations show that the andesitic basalts resulted from melting of garnet-bearing peridotite in the lower crust. According to Poll and Franz (1994), this fact together with the negative Nb-anomaly, indicates that these basalts were formed during subduction at a continental margin.

The *andesitic basalt* displays, like the samples of tonalite and the granodiorite, Th-, La- and Ce-enrichments that indicate proximity of a continental crust. The general enrichment of trace elements in the *andesitic basalt* indicates a higher level of fractionation than for the other studied samples from the Tabalah and Tarj areas.

Based on the trace elements, it can be concluded that the *andesitic basalt* is similar to andesitic basalts in other parts of the Arabian Nubian Shield and that were formed at an active continental margin similar to the one where the tonalites and the granodiorites.

4.5 Geochronology

4.5.1 Introduction

A number of key-samples was dated in order to temporally constrain the tectonic phases that were observed throughout the Tabalah and Wadi Tarj areas. These studies are needed because of the lack of evidence on the relative timing of the observed tectonic events through field relationships. The $^{40}Ar/^{39}Ar$-method was chosen for the dating because this allows dating of amphibolite-grade as well as plutonic rocks through dating of hornblendes. Furthermore, hornblende has good argon retentivity properties with a closure temperature of 525° C for well crystallized hornblende (McDougall & Harrison, 1999). The hornblendes in the samples of the shear zones define the highest metamorphic grades found in these rock-types so their dates are expected to define the age for the peak tectono-metamorphic event.

The samples from the Tabalah and Wadi Tarj areas were crushed, sieved and washed before the actual mineral separation. Sieve fractions of 250-500µm and 125-250 µm were used for hornblende separation with a roll-magnet. The fractions that remained after the separation, were cleaned ultrasonically in demineralised water. Approximately 15 grains of cleaned hornblende were hand-picked microscopically. The samples were irradiated at the ECN/EU high flux nuclear reactor in Petten, The Netherlands. I analysed the samples at the geochronological laboratory of the "Vrije Universiteit", Amsterdam, The Netherlands. The step-heating degassing experiments were carried out with an argon laserprobe as described by Wijbrans et al. (1995). The age- and error-calculations for $^{40}Ar/^{39}Ar$ in hornblende were done as discussed in detail in McDougall and Harisson (1999). A short outline of previous geochronological studies will be given first.

4.5.2 Previous geochronology studies

Previous geochronological data are only available for the intrusives. Diorites in the Wadi Tarj area were dated at 818±95 Ma (Rb-Sr whole rock by Fleck et al., 1980). A quartz-diorite/ granodiorite southeast of Bisha was dated at 723±107 Ma (Rb-Sr whole rock by Fleck *et al.*, 1980). A granodiorite north of Bisha was dated at 623±18 (Rb-Sr whole rock by Fleck *et al.*, 1980). More recently, Johnson et al. (2001) published an age for the undeformed Al Khalij tonalite that intrudes the Tabalah Shear Zone north of the studied area. The tonalite was dated through SHRIMP U-Pb zircon dating at 755 ± 7 Ma. This means that the Tabalah Shear Zone should not have been active after 755 Ma.

4.5.3 Description of samples

Four samples were selected for geochronological studies. These samples represent the rocks of which dating information could present crucial information for the tectonic history of the Tabalah and Wadi Tarj areas. The geographic positions of the samples are shown in Figure 4-2 and Figure 4-3.

- *Sample SAD 12* (N19°59,654' E042°12,318') is hornblende schist from the *amphibolite* in the central Tabalah area. The sample is well foliated and lineated and comes from the main portion of the Wadi Ta'al Shear Zone. It contains plagioclase, metamorphic hornblende, quartz and minor biotite and pyroxene. The hornblendes define a strong uniformly trending lineation, which was subhorizontal in the outcrop from where the sample was taken. Shear indicators at the sample location, displayed dextral shearing.
- *Sample SAD 14* (N20°01,245' E042°14,731') is a hornblende schist from the *amphibolite* in the central Tabalah area. The sample is well foliated and lineated and comes from the main portion of the Wadi Ta'al Shear Zone. It contains plagioclase, metamorphic greenish-brownish hornblende and minor quartz. The hornblendes define a strong uniformly trending lineation, which was subhorizontal

in the outcrop from where the sample was taken. Shear indicators at this location, displayed dextral shearing.

- *Sample SAD 18* (N19°43,261' E042°21,817') is a hornblende schist from the *amphibolite* in the Wadi Tarj area. The sample is foliated and lineated. This sample comes from an outcrop with a steep NE-plunging lineation. It contains plagioclase, metamorphic brown hornblende and minor quartz and pyroxene. The hornblendes define the lineation. The lineations plunge steeply to the ENE and top-to-the-WSW movement was observed along these lineations.
- *Sample SA 209* (N19°41' E042°19') is a sample from the non-deformed *granodiorite* from the Wadi Tarj area and it intrudes the Tabalah/Ta'al Shear Zone over here. It contains hornblende, plagioclase and some quartz and biotite. SAD 209 was also geochemically analysed.

4.5.4 Results

The age spectra for the analyzed samples from the Tabalah and Wadi Tarj areas are shown in Figure 4-14 to Figure 4- 17. The detailed data of the individual step-heating experiments can be found in Table 4-3 to Table 4-6. The identification of plateau ages was done according to the following criteria: a minimum of 3 contiguous of steps of ages within a 2σ error is required; these steps should yield a well-defined isochron; and a significant portion of the ^{39}Ar-release should have taken place during these steps (McDougall and Harrison, 1999). All analyzed samples display clear plateaus with no evidence of a secondary event outside of event that formed the main plateau.

The results of ^{40}Ar/^{39}Ar dating for sample SAD 18, with hornblendes forming a steeply plunging ENE plunging lineation are presented in Figure 4-16. This sample was dated at 779 ± 7 Ma and represents the oldest age found in the Tabalah and Wadi Tarj areas during this study. Kinematics indicated that these hornblendes were associated with WSW directed thrusting. The samples which were taken from the sections of the Tabalah and Tarj Shear Zones where lineated hornblendes were associated with a sub-horizontal NNW-SSE trending lineation, SAD 12 (Figure 4-14) and SAD 14 (Figure 4-15), yield ages of respectively, 765 ± 5 Ma and 764 ± 7 Ma. Kinematics for both samples indicated dextral strike-slip and so it can be concluded that this event took place around 765 Ma. The results of ^{40}Ar/^{39}Ar dating for the undeformed *granodiorite* in the Wadi Tarj area (sample SAD 19) are presented in Figure 4- 17. This sample was dated at 761 ± 6 Ma.

4.5.5 Summary of geochronological studies

From the ^{40}Ar/^{39}Ar-studies, it can be concluded that the thrusting was the oldest event dated during this study with a date of ca. 779 Ma. The dextral strike slip event, as recorded for the main Wadi Ta'al Shear Zone by samples SAD 12 and SAD 14, has an age of approximately 765 Ma. The undeformed granodiorite recorded an age of 761 Ma. The ages of the dextral strike slip event and the cooling of the undeformed granodiorite are very close to each other and fall within each others error. However, field observations show clearly that the granodiorite intruded the shear zone and the granodiorite must have formed later than the dextral strike slip

Table 4-3 Detailed data of the individual step-heating for sample SAD 12.

Incremental Heating			^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age (Ma)	± 2σ	^{40}Ar(r) (%)	^{39}Ar(k) (%)	K/Ca	± 2σ
01M0243A	0,25 W	☐	0,00057	0,18213	0,00268	0,03277	0,76634	613.41	± 37.96	82,09	4,47	0,077	± 0,019
01M0243B	0,40 W	▸	0,00036	5,98142	0,08478	0,44038	13,43907	765.44	± 3.48	99,21	60,04	0,032	± 0,003
01M0243C	0,45 W	▸	0,00001	0,66321	0,00675	0,04181	1,26662	760.94	± 28.16	99,68	5,70	0,027	± 0,004
01M0243D	0,50 W	▸	0,00000	0,68144	0,00772	0,04347	1,31919	761.90	± 4.01	99,99	5,93	0,027	± 0,003
01M0243F	0,55 W	▸	0,00010	1,07567	0,01348	0,07504	2,29595	767.07	± 17.66	98,74	10,23	0,030	± 0,003
01M0243G	0,60 W	▸	0,00009	0,42878	0,00491	0,02919	0,88444	761.09	± 33.56	96,97	3,98	0,029	± 0,004
01M0243H	0,65 W	▸	0,00000	0,27414	0,00267	0,01388	0,42701	770.27	± 10.48	99,99	1,89	0,022	± 0,005
01M0243I	0,70 W	▸	0,00000	0,23043	0,00206	0,01221	0,37886	775.95	± 13.29	99,99	1,66	0,023	± 0,005
01M0243K	0,80 W	☐	0,00002	0,40986	0,00463	0,02734	0,85345	779.66	± 35.54	99,26	3,73	0,029	± 0,004
01M0243L	0,90 W	☐	0,00000	0,09249	0,00022	0,00245	0,07696	783.84	± 50.32	99,99	0,33	0,011	± 0,004
01M0243M	fusion	☐	0,00022	0,29544	0,00266	0,01495	0,47807	795.04	± 64.68	88,11	2,04	0,022	± 0,004
		Σ	0,00137	10,31500	0,13258	0,73349	22,18595						

Information on Analysis	
Sample	VU38-A12
Material	hornblende
Location	Saudi Arabie
Analyst	Brigitte
Project	Bernard2001
Irradiation	VU38
J-value	0,017318
Standard	98,3

Results	40(r)/39(k)	± 2σ	Age (Ma)	± 2σ	MSWD	^{39}Ar(k) (%,n)	K/Ca	± 2σ
Weighted Plateau	30,4807	± 0,1237 ± 0,41%	764.70	± 4.52 ± 0,59%	1,05	89,43 7	0,028	± 0,002
			External Error	± 15.95				
			Analytical Error	± 2.53				
Total Fusion Age	30,2471	± 0,2084 ± 0,69%	759.91	± 5.67 ± 0,75%		11	0,031	± 0,002
			External Error	± 16.22				
			Analytical Error	± 4.27				

Table 4-4 Detailed data of the individual step-heating for sample SAD 14.

Incremental Heating			^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age (Ma)	± 2σ	^{40}Ar (r) (%)	^{39}Ar (k) (%)	K/Ca	± 2σ
01M0244A	0,20 W	☐	0,00054	0,08847	0,00183	0,00427	0,09443	585.52	± 253.16	37,12	0,49	0,021	± 0,011
01M0244C	0,25 W	☐	0,00026	0,03209	0,00064	0,00240	0,02286	275.17	± 550.54	22,74	0,28	0,032	± 0,031
01M0244D	0,30 W	☐	0,00037	0,14238	0,00369	0,01074	0,23183	573.16	± 141.74	67,89	1,24	0,032	± 0,014
01M0244E	0,35 W	▸	0,00003	0,25694	0,00796	0,01695	0,47790	717.35	± 75.51	97,97	1,96	0,028	± 0,006
01M0244F	0,40 W	▸	0,00021	1,14448	0,02738	0,04434	1,28859	735.40	± 30.55	95,37	5,13	0,017	± 0,002
01M0244H	0,45 W	▸	0,00043	5,34062	0,12598	0,17837	5,39849	760.30	± 8.74	97,70	20,65	0,014	± 0,001
01M0244I	0,50 W	▸	0,00053	6,83250	0,17907	0,23707	7,23138	765.15	± 7.43	97,88	27,44	0,015	± 0,002
01M0244J	0,55 W	▸	0,00038	5,24763	0,13762	0,18119	5,49905	762.03	± 10.78	97,97	20,97	0,015	± 0,001
01M0244K	0,60 W	▸	0,00010	1,78620	0,04767	0,06747	1,98719	743.58	± 19.08	98,56	7,81	0,016	± 0,002
01M0244M	0,65 W	▸	0,00000	0,48384	0,01021	0,01626	0,48592	752.58	± 10.03	99,99	1,88	0,014	± 0,002
01M0244N	0,70 W	▸	0,00024	0,84984	0,01738	0,02659	0,74537	713.90	± 72.69	91,41	3,08	0,013	± 0,002
01M0244O	0,80 W	▸	0,00000	0,60548	0,01321	0,02024	0,62988	777.78	± 7.86	99,99	2,34	0,014	± 0,002
01M0244P	0,90 W	▸	0,00009	0,68167	0,01452	0,02268	0,68431	758.44	± 76.95	96,18	2,62	0,014	± 0,002
01M0244R	fusion	▸	0,00004	1,18924	0,02464	0,03540	1,08230	766.66	± 29.87	98,81	4,10	0,013	± 0,001
		Σ	0,00323	24,68137	0,61181	0,86395	25,85949						

Information on Analysis	
Sample	VU38-A13
Material	hornblende
Location	Saudi Arabie
Analyst	Brigitte
Project	Bernard2001
Irradiation	VU38
J-value	0,017318
Standard	98,3

Results	40(r)/39(k)	± 2σ	Age (Ma)	± 2σ	MSWD	^{39}Ar (k) (%,n)	K/Ca	± 2σ
Error Plateau	30,4169	± 0,3168 ± 1,04%	763.39	± 7.48 ± 0,98%	3,00	97,99 11	0,015	± 0,001
			External Error	± 17.00				
			Analytical Error	± 6.48				
Total Fusion Age	29,9317	± 0,2879 ± 0,96%	753.44	± 6.98 ± 0,93%		14	0,015	± 0,001
			External Error	± 16.61				
			Analytical Error	± 5.92				

Table 4-5 Detailed data of the individual step-heating for sample SAD 18.

Incremental Heating			^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age (Ma)	± 2σ	^{40}Ar(r) (%)	^{39}Ar(k) (%)	K/Ca	± 2σ
01M0245A	0,20 W	☐	0,00120	0,11678	0,08205	0,14058	3,50437	647.41	± 10.34	90,78	4,07	0,518	± 0,265
01M0245B	0,25 W	☐	0,00027	0,27318	0,03427	0,06984	1,69482	632.91	± 14.80	95,54	2,02	0,110	± 0,033
01M0245C	0,30 W	☐	0,00029	0,65023	0,10269	0,15263	4,14163	694.93	± 7.04	97,98	4,42	0,101	± 0,015
01M0245E	0,35 W	☐	0,00032	1,19622	0,20596	0,25615	7,36804	729.27	± 3.45	98,71	7,41	0,092	± 0,011
01M0245F	0,40 W	▸	0,00128	5,40952	0,95880	0,95120	29,65339	778.83	± 2.54	98,74	27,53	0,076	± 0,008
01M0245G	0,45 W	▸	0,00131	9,59005	1,59531	1,58630	49,78869	783.13	± 1.95	99,22	45,91	0,071	± 0,007
01M0245I	0,50 W	▸	0,00011	0,65871	0,12019	0,12220	3,79108	775.77	± 10.06	99,12	3,54	0,080	± 0,011
01M0245J	0,55 W	▸	0,00004	0,19493	0,04483	0,04926	1,46599	749.90	± 18.71	99,29	1,43	0,109	± 0,032
01M0245K	0,60 W	▸	0,00000	0,18714	0,01159	0,01461	0,44041	757.79	± 5.88	99,99	0,42	0,034	± 0,010
01M0245L	0,65 W	▸	0,00000	0,10639	0,00784	0,00974	0,29834	767.97	± 7.31	99,99	0,28	0,039	± 0,017
01M0245N	0,70 W	▸	0,00000	0,11352	0,00843	0,00971	0,29465	762.04	± 8.60	99,99	0,28	0,037	± 0,017
01M0245O	0,75 W	☐	0,00000	0,12933	0,01710	0,01746	0,54557	780.41	± 4.56	99,99	0,51	0,058	± 0,022
01M0245P	0,80 W	☐	0,00000	0,11041	0,00782	0,00821	0,26415	798.62	± 9.34	99,99	0,24	0,032	± 0,016
01M0245Q	0,90 W	☐	0,00000	0,21240	0,01560	0,01516	0,48791	799.12	± 8.16	99,99	0,44	0,031	± 0,009
01M0245S	fusion	☐	0,00015	0,55655	0,05103	0,05225	1,59870	767.08	± 14.03	97,23	1,51	0,040	± 0,006
		Σ	0,00498	19,50536	3,26350	3,45530	105,33772						

Information on Analysis	
Sample	VU38-A14
Material	hornblende
Location	Saudi Arabie
Analyst	Bernard
Project	Bernard2001
Irradiation	VU38
J-value	0,017318
Standard	98,3

Results	40(r)/39(k)	± 2σ	Age (Ma)	± 2σ	MSWD	^{39}Ar(k) (%,n)	K/Ca	± 2σ
Error Plateau	31,1704	± 0,2946 ± 0,95%	778.74	± 7.08 ± 0,91%	17,58	79,39 7	0,065	± 0,015
			External Error	± 17.11				
			Analytical Error	± 5.98				
Total Fusion Age	30,4859	± 0,0678 ± 0,22%	764.80	± 3.99 ± 0,52%		15	0,076	± 0,004
			External Error	± 15.81				
			Analytical Error	± 1.39				

Table 4-6 Detailed data of the individual step-heating for sample SAD 19.

Incremental Heating			^{36}Ar(a)	^{37}Ar(ca)	^{38}Ar(cl)	^{39}Ar(k)	^{40}Ar(r)	Age (Ma)	± 2σ	^{40}Ar(r) (%)	^{39}Ar(k) (%)	K/Ca	± 2σ
01M0247A	0,20 W	☐	0,00055	0,03719	0,00252	0,00745	0,42381	1236.90	± 68.67	72,14	0,67	0,086	± 0,118
01M0247B	0,25 W	☐	0,00028	0,03179	0,00068	0,00804	0,21562	687.87	± 119.38	72,15	0,72	0,109	± 0,172
01M0247C	0,30 W	☐	0,00055	0,00000	0,00041	0,01111	0,25948	612.71	± 98.31	61,39	0,99	0,000	± 0,000
01M0247E	0,35 W	☐	0,00076	0,00869	0,00180	0,03318	0,90848	700.22	± 26.02	80,21	2,96	1,642	± 10,195
01M0247F	0,40 W	☐	0,00022	0,02615	0,00183	0,02041	0,53871	679.24	± 57.51	89,39	1,82	0,336	± 0,405
01M0247G	0,45 W	☐	0,00046	0,01811	0,00277	0,01900	0,43179	598.76	± 71.17	75,90	1,70	0,451	± 0,761
01M0247H	0,50 W	☐	0,00037	0,20361	0,01053	0,04211	1,23744	742.11	± 25.31	91,86	3,76	0,089	± 0,019
01M0247J	0,55 W	☐	0,00010	0,89280	0,04456	0,14000	4,36972	779.59	± 7.97	99,32	12,50	0,067	± 0,008
01M0247K	0,60 W	▸	0,00025	1,01290	0,04602	0,14411	4,37608	762.34	± 5.82	98,31	12,86	0,061	± 0,007
01M0247L	0,65 W	▸	0,00035	1,30919	0,05033	0,16392	4,98305	763.02	± 6.50	97,95	14,63	0,054	± 0,006
01M0247M	0,75 W	▸	0,00017	0,85469	0,03348	0,11587	3,55542	768.88	± 9.35	98,56	10,34	0,058	± 0,007
01M0247O	0,80 W	▸	0,00012	0,25450	0,01476	0,05269	1,57454	752.42	± 14.36	97,79	4,70	0,089	± 0,020
01M0247P	0,90 W	▸	0,00030	0,60075	0,02967	0,09841	2,95105	754.57	± 6.56	97,10	8,78	0,070	± 0,009
01M0247Q	fusion	☐	0,00045	2,76779	0,08177	0,26401	8,13496	771.47	± 5.06	98,40	23,57	0,041	± 0,004
		Σ	0,00494	8,01816	0,32114	1,12032	33,96015						

Information on Analysis	
Sample	VU38-A15
Material	hornblende
Location	Saudi Arabie
Analyst	Brigitte
Project	Bernard2001
Irradiation	VU38
J-value	0,017318
Standard	98,3

Results	40(r)/39(k)	± 2σ	Age (Ma)	± 2σ	MSWD	^{39}Ar(k) (%,n)	K/Ca	± 2σ
Weighted Plateau	30,2921	± 0,2364 ± 0,78%	760.84	± 6.11 ± 0,80%	2,18	51,33 5	0,060	± 0,008
			External Error	± 16.40				
			Analytical Error	± 4.85				
Total Fusion Age	30,3128	± 0,1627 ± 0,54%	761.26	± 5.00 ± 0,66%		14	0,060	± 0,003
			External Error	± 16.03				
			Analytical Error	± 3.33				

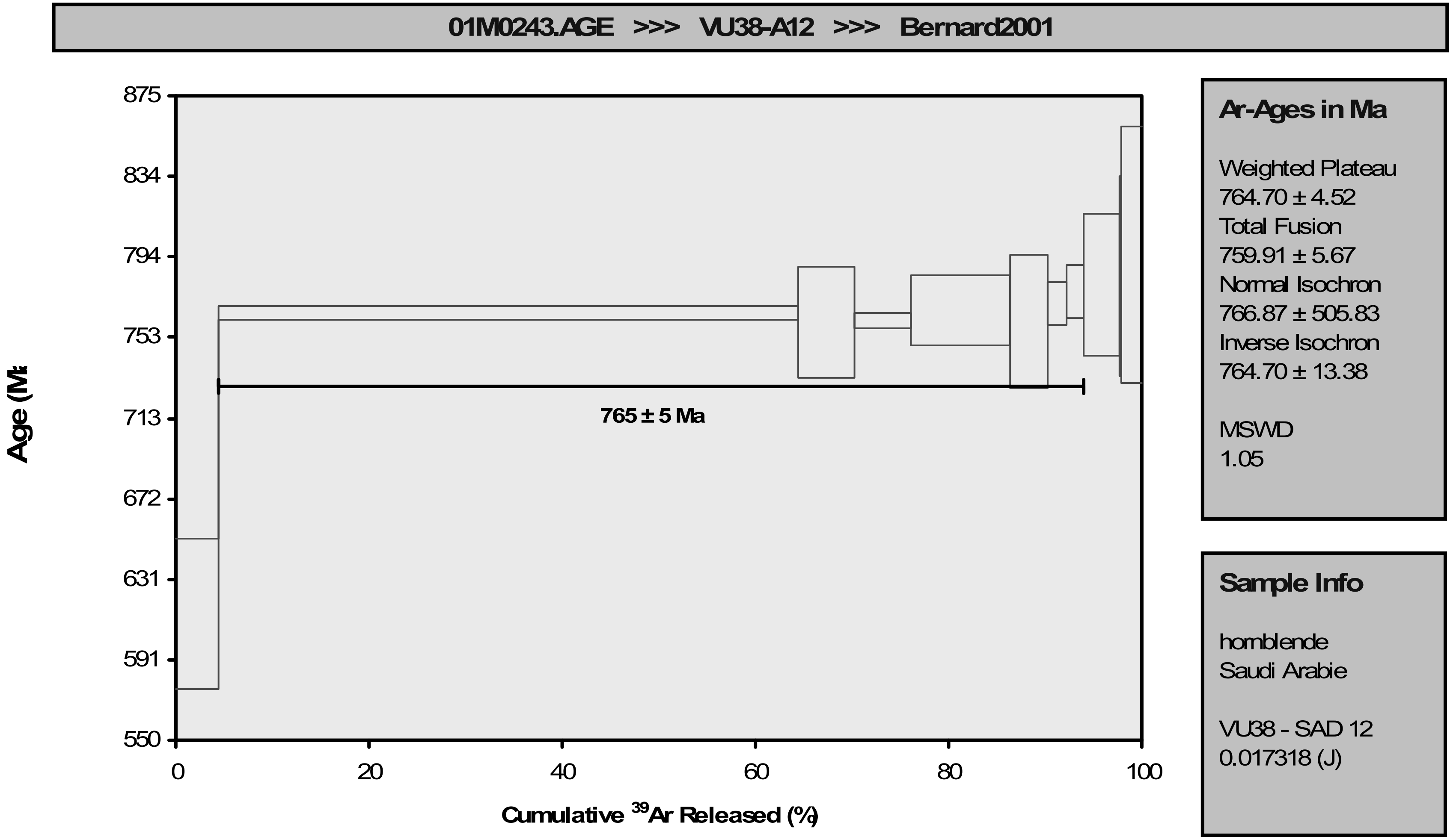

Figure 4-14 Results of ^{40}Ar/^{39}Ar dating for sample SAD 12.

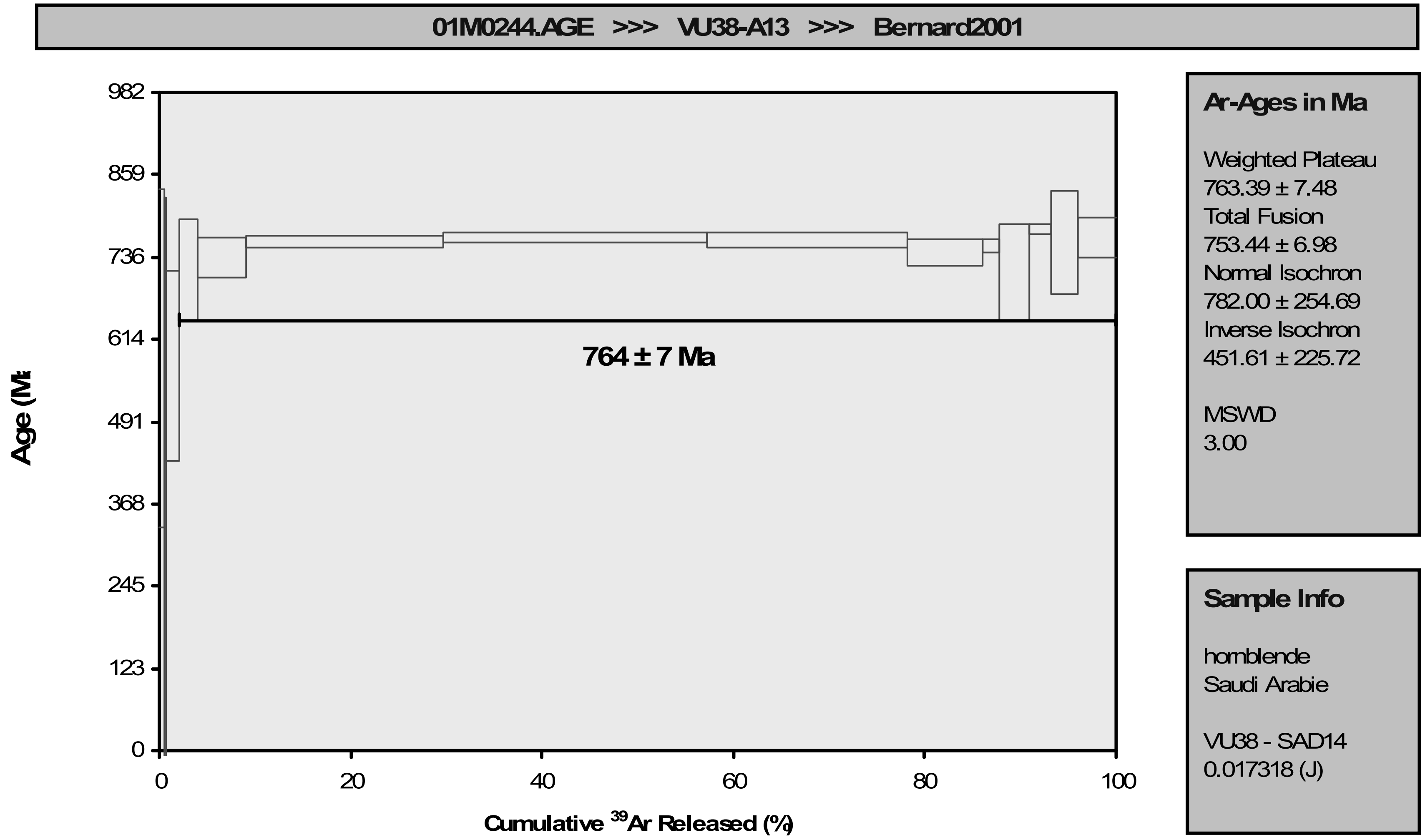

Figure 4-15 Results of ^{40}Ar/^{39}Ar dating for sample SAD 14.

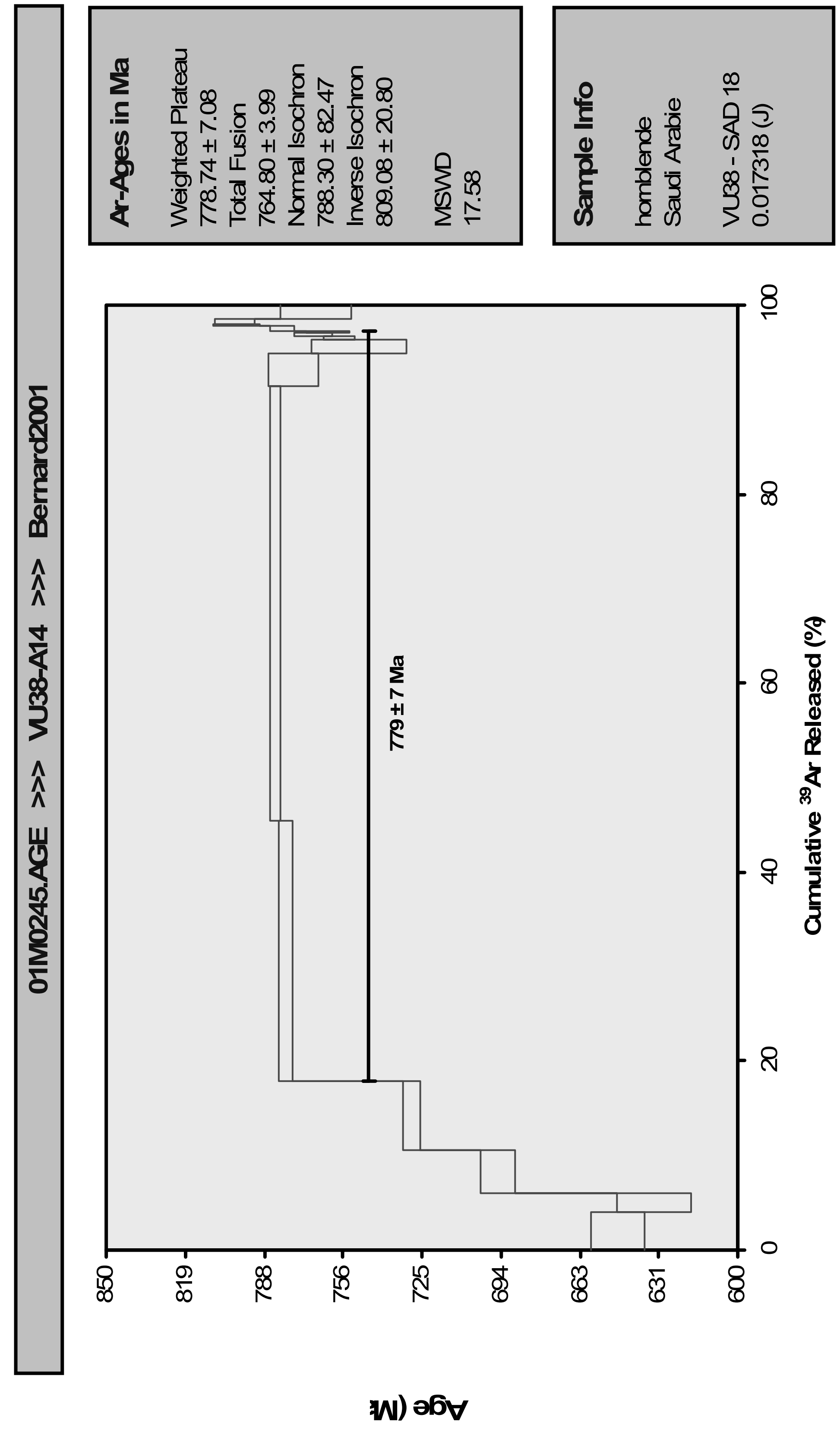

Figure 4-16 Results of ^{40}*Ar/*^{39}*Ar dating for sample SAD 18.*

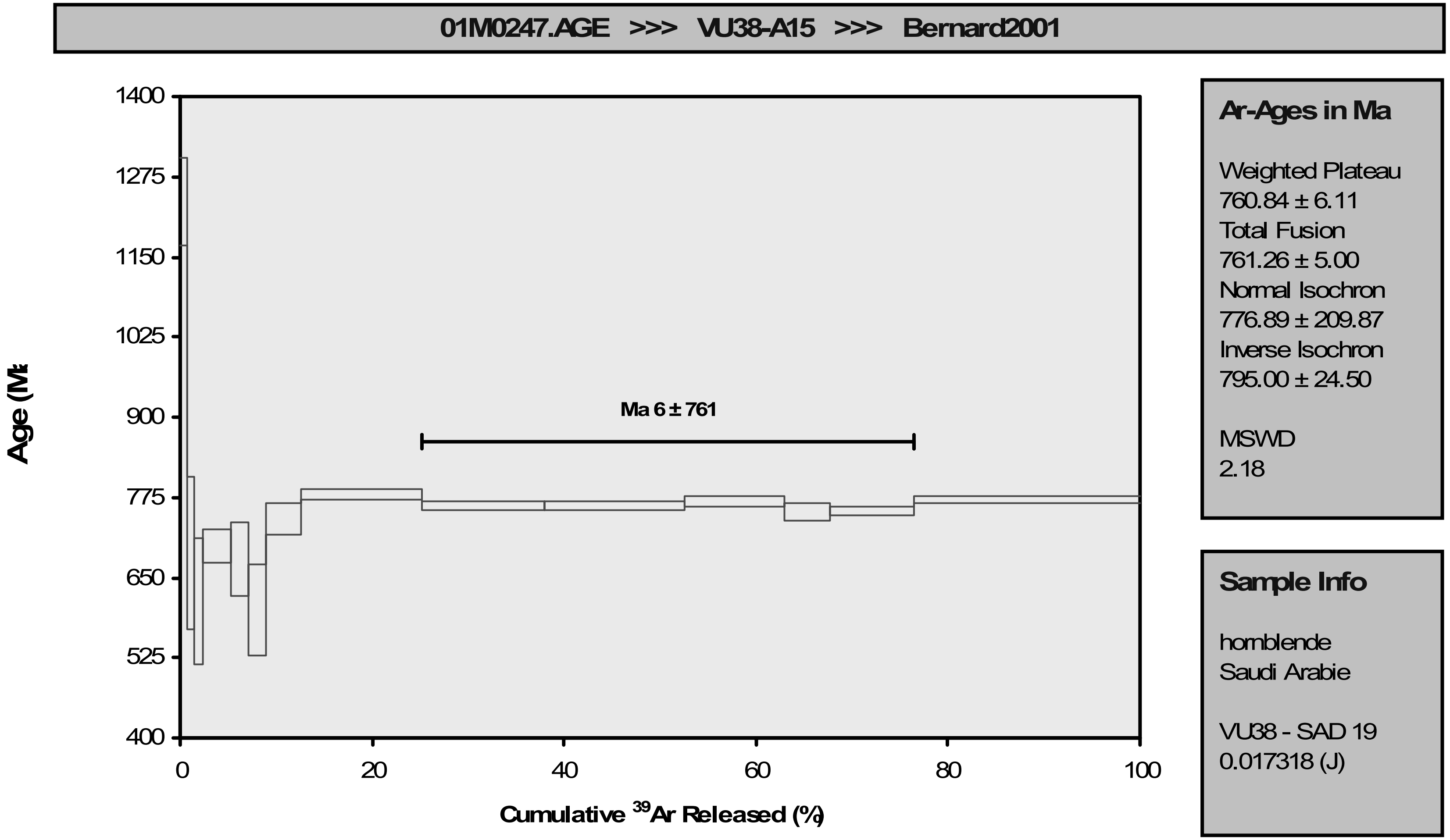

Figure 4-17 Results of ^{40}Ar/^{39}Ar dating for sample SAD 19.

event.

4.6 Discussion and conclusions

4.6.1 Summary of geological evidence

The Tabalah area and Wadi Tarj area contain features that are typical of the Neoproterozoic terranes in the Arabian Nubian Shield as plutons and schistose sequences. The foliated and lineated sequences in the Tabalah and Wadi Tarj areas represent shear zones.

The main lithological units are the *mixed gabbro-diorite suite*, which consists of gabbros and diorites and the *quartz diorite-tonalite*, which consists mainly of tonalite. These intrusives are crosscut by *amphibolites*. Some dikes were observed and they trend W-E. An undeformed *granodiorite* intruded the *amphibolites* in the Wadi Tarj area.

Geochemical studies were conducted on the most important non-metamorphosed and non-deformed rocks to analyse the tectonic environment from which they originate. The results of the analyses were compared to published geochemical studies of similar rocks in other parts of the ANS. The geochemistry of the rocks in the *mixed gabbro-diorite suite* is similar to gabbros/diorites suites in Egypt, Sudan and Saudi Arabia. These gabbros/diorite suites were interpreted to have been formed in island-arc environments. The gabbros were formed in immature island-arcs and the diorites were formed in more mature island-arcs. The geochemical studies indicate that tonalites from the *quartz diorite-tonalite*, the granodiorite in the Wadi Tarj area and the W-E dykes are very similar to tonalites, granodiorites and calc-alkaline volcanics form other parts of the ANS. These were generally interpreted to have been formed in an active continental margin setting. No dates are available for the rocks that were formed in an island-arc setting however the earliest activity on the shear zone that deforms these rocks is dated at approximately 779 ± 7 Ma and so the island-arc phase must have predated 779 ± 7 Ma. The cooling of the granodiorite in the Wadi Tarj area is dated at 761 ± 6 Ma.

The structural studies indicate that the Wadi Ta'al and Tabalah shear zones and the deformed *quartz diorite-tonalite* in between, represent one zone of intense deformation since the main structural features, the foliations, the lineations and the shear indicators, are identical and continuous through these three neighbouring units. The *mixed gabbro-diorite suite* and *quartz diorite-tonalite* grade into the *amphibolites* and are their deformed equivalents. The *amphibolites* are the lithological entities that record the most intense deformation. The small shear zones in the *mixed gabbro-diorite* were also formed during the deformation event that was responsible for the formation of the main Tabalah/Wadi Ta'al SZ. Lineations and shear sense indicators show that there are three phases of deformation:

1) The top-to-WSW movement in the Wadi Ta'al/Tabalah shear zone along steeply NE plunging lineations was dated at ca. 779 Ma. This indicates thrusting in its current position.

2) Dextral strike-slip movement along sub-horizontal NNW-SSE lineations on the Tabalah/Wadi Ta'al shear zone. This event was dated at ca. 765 Ma. It appears to be the main phase of deformation that can be currently observed.

3) Dextral strike-slip movement with a top-to-the-SE component along moderately SE plunging lineations. No dates are available for this phase however the Tabalah/Tarj shear zone system is intruded by the *undeformed granodiorite* that was dated at 761 ± 6 Ma. This should be the lower age limit for the structures t hat are associated with the SE plunging lineations.

From the available data, it can be concluded that the steep ENE plunging hornblende lineations are older than the NNW-SSE subhorizontal hornblende lineations and consequently the thrusting pre-dates the strike-slip event. However no assumptions can be made of the relative age of the SE plunging lineation relative to the other the ages of the other features.

4.6.2 Tectonic model for the Tabalah and Wadi Tarj Complex

The island-arc related rocks, as found in the Tabalah and Tarj Complex, were formed during intra-oceanic subduction, as indicated by their geochemical characteristics. The subduction is thought to initiate at an existing weakness within an oceanic plate, as a strike-slip fault, when plates of a different density are juxtaposed (e.g. Flower, 2003; Stern and Bloomer, 1992; Wakabayashi and Dilek, 2003). The older and denser plate will subside and this will initiate the subduction (e.g. Flower, 2003; Stern and Bloomer, 1992). The colder subducted oceanic lithosphere will dehydrate at depth (Wilson, 1989). The fluids that are derived from the dehydration of the subducting slab will cause partial melting of the mantle wedge and the actual formation of the island-arc with its associated magmatism (Wilson, 1989). This scenario is also applicable for the island-arc related rocks in the Tabalah and Tarj areas which form part of the Asir Terrane which is composed of island-arc related rocks (e.g. Stoeser and Camp, 1985; Johnson et al., 1987; Brown et al., 1989).

Chapter 2 indicates that the earliest evolution of the ANS is explained by formation of ophiolites and island-arc remnants that represent relicts of the oceanic phase which took place at 900-750 Ma. Arc-accretion is the process that caused the amalgamation of island-arcs in the Arabian-Nubian Shield (Stoeser and Camp, 1985). Island-arcs that reach a subduction zone at a margin with characteristics of a continental crust will behave buoyant. They will resist subduction and will accrete upon the continental crust to become part of that same crust. The arc-accretion in the ANS is thought to have been taken place at 810-650 Ma. The sites of obduction are supposed to be represented by ophiolitic suture zones (e.g. Stoeser and Camp, 1985). The ophiolitic sutures in the Arabian Nubian Shield have two trends: 1) SW-NE ophiolitic sutures such as the Bi'r Umq suture and Yanbu suture, with the main period of activity at 800-700 Ma (Johnson, 2001; all of these are found to the N of the Tabalah and Tarj areas); and 2) NNW-SSE to N-S trending sutures such as the Nabitah Suture and Ruwah Suture with the main period of activity around 700-650 Ma (Quick, 1991; Johnson, 2001). From an age perspective, it can thus be assumed that the Tabalah and Tarj areas should contain remnants of the oceanic phase and intra-terrane remnants of the arc-accretion along the NE-SW trending sutures. The timeframes of deformation along the Tabalah/Ta'al SZ, as described in the paragraph on geochronology in this chapter, indicate that the structures in the Tabalah and Wadi Tarj area are likely to be related to tectonic processes that were recorded at the NE-SW trending margins of terranes in the Arabian Shield. They should thus be regarded as intra-terrane responses to arc-accretion at the terrane margins, which are represented by the ophiolitic sutures. This also justifies relating the shear zones in the Tabalah and Wadi Tarj areas to a compressional regime. In such a regime, the E-dipping lineations with the top-to-W-movement indicate thrusting in an E-W compressional regime at ca. 779 Ma. Thrusts do not typically form as steep as the observed current dip of the Tabalah/Ta'al Shear Zone but the steepening of the shear zone after the initial thrusting will discussed later in this chapter.

Dextral strike-slip movement along NNW-SSE trending lineations at the Tabalah/Ta'al Shear Zone took place at ca. 765 Ma. The lineations associated with the strike-slip event were dated at younger ages than the lineations that were associated with thrusting and consequently the strike-slip movement post-dates the thrusting. Dextral strike-slip movement along a NNW-SSE trending shear zone should result from NNE-SSW directed σ_1. As demonstrated above, the deformation in the Tabalah and Tarj areas took place in a period of arc-accretion and compression within the ANS and therefore it can be concluded that the dextral strike-slip along NNW-SSE trending lineation should have resulted from NNE-SSW compression. Since strike-slip faulting takes place along steep shear zones, it is this phase is assumed to have caused the steepening of the initial moderately dipping thrusts.

Strike-slip overprint of thrusting is a commonly observed feature of intra-terrane deformation during arc-accretion in the North American Cordillera (Monger et al., 1982; Van der Heyden, 1992; Chardon et al., 1999; Cole et al., 1999). Over here, the thrusting represents an intra-terrane response to arc-accretion at the terrane boundary (Monger et al., 1982; Van der Heyden, 1992; Chardon et al., 1999; Cole et al., 1999). The intra-terrane shortening features in the North American Cordilleran are mostly parallel to the movement of the subducting plate (Monger et al., 1982; Van der Heyden, 1992; Chardon et al., 1999; Cole et al., 1999). The strike-slip movement obscured much of the earlier thrusting and caused steepening of the shear zones (Chardon et al., 1999; Cole et al., 1999). The intra-terrane strike-slip shear zones in the North American Cordillera were related to oblique convergence that resulted from changes in the direction of plate motion of the subducting plate (Van der Heyden, 1992; Chardon et al., 1999; Cole et al., 1999). The changes in the direction of plate motions can occur within short time-frames of 5-20 Ma as shown for the Middle Cretaceous shear zones of the Coast Plutonic Complex, British Columbia and for the Late Cretaceous McKinley Fault in south Alaska (Cole et al., 1999).

On the basis of the observations in this chapter, a scenario, as described above for intra-terrane arc-accretion related shear zones in the Cordilleran of North America, is also suggested for the Tabalah Complex. In such a model, the Tabalah/Ta'al shear zone is initially formed as an intra-terrane thrust in E-W compression due to accretionary processes at a terrane boundary. This happened at 779 ± 7 Ma. The main structural phase that was recorded on the Tabalah/Ta'al Shear Zone was defined by the dextral strike slip along NNW-SSE trending lineations at ca. 765 Ma. This phase resulted from NNE-SSW compression. Such a change in the direction of compression during arc-accretion can thus be best explained by an anti-clockwise change in plate motion of the subduction plate. On the basis of the above discussion, the different deformation phases can be named as follows:

- D1-phase: A phase of thrusting at 779 ± 7 Ma formed foliations (S1), ENE-plunging lineations (L1) and top-to-W shear sense indicators.
- D2-phase: A phase of dextral strike-slip movement steepened the foliations, and formed NNW-SSE trending lineations (L2) and dextral shear sense indicators. This phase took place at ca. 765 Ma as is indicated by ^{40}Ar/^{39}Ar dating of sub-horizontal NNW-SSE trending hornblendes at 765 ± 5 Ma and 764 ± 7 Ma.

The geochemical data from this study indicate that the Tabalah/Ta'al Shear Zone deformed the *quartz diorite-tonalite* that was emplaced at a lithosphere with characteristics of an active continental margin but predates the *granodiorite*, which intruded at a lithosphere with characteristics of an active continental margin.

4.6.3 Conclusions

The tectonic development of the Tabalah and Tarj areas is illustrated in Figure 4-18 and Table 4-7. The Tabalah and Tarj areas contain many of the features that are typical for an intra-terrane deformation in terranes that participate in arc-accretion events. Examples of these features are the gabbros and diorites that were formed in island-arcs and the granodiorites and the tonalites which contain characteristics of intrusion at continental margins.

Finally, it should be noted that no explanation was found, in the form of folding, for the minor bend in the Tabalah/Wadi Ta'al "Tectonic Zone" between the Tabalah and Tarj areas. It is therefore assumed that later faulting, possibly along the Najd trend, caused the bend in the Tabalah/Wadi Ta'al "Tectonic Zone".

The following tectonic model is suggested for the Tabalah and Wadi Tarj areas:

1) Island-arc related plutons formed probably at ca 820 Ma but surely prior to 779 Ma. The *mixed gabbro-diorite* and the *quartz diorite-tonalite* are the principal relicts of this phase.

2) The thrusting as observed along some parts of the shear zone are intra-terrane remnants of plate movements along a subduction zone at the margin of the terrane of which the Asir was part at the time of deformation. It is dated at about 779 Ma (D1).

3) A major dextral strike-slip event overprinted the thrusting phase. This took place at about 765 Ma (D2). This structure was also related to arc-accretion. Large strike-slips are common features in areas where arc-accretion takes place. In this respect, the Wadi Tabalah area resembles the Coast Plutonic Complex, British Columbia, where large strike slip shear zones were formed within magmatic arcs and overprint earlier thrusting (see Chardon et al., 1999). The change from thrusting towards strike-slip movement is typically due to a change in plate motion of the subducting plate. In the case of the Tabalah/Ta'al Shear Zone, an anti-clockwise change in motion of the subducting plate should have resulted in the change of the style of deformation on the Tabalah/Ta'al Shear Zone.

4) Finally, an arc-accretion related granodiorite was emplaced at about 761 Ma. This indicates that the subduction still continued after the main phase of strike-slip movement in the Tabalah and Wadi Tarj areas.

Table 4-7 Table with the main stages of the tectonic history in the Tabalah and Tarj areas.

Main Geological phases in the Tabalah area

Phase	Lithology	Metamorphism	Structures	Age (Ma)
Island-arc	mixed gabbro-diorite and the quartz diorite-tonalite	N/A	None.	820-779
D1	Amphibolites and deformed the quartz diorite-tonalite	Lower amphibolite	Foliation, steep lineations, shear indicators -> thrusting;	779 Ma
D2	Amphibolites and deformed the quartz diorite-tonalite	Lower amphibolite	Foliation, subhorizontal lineations, shear indicators -> strike slip movement; NNE-SSW	765 Ma
Active continental margin	Granodiorite	N/A	None	761 Ma

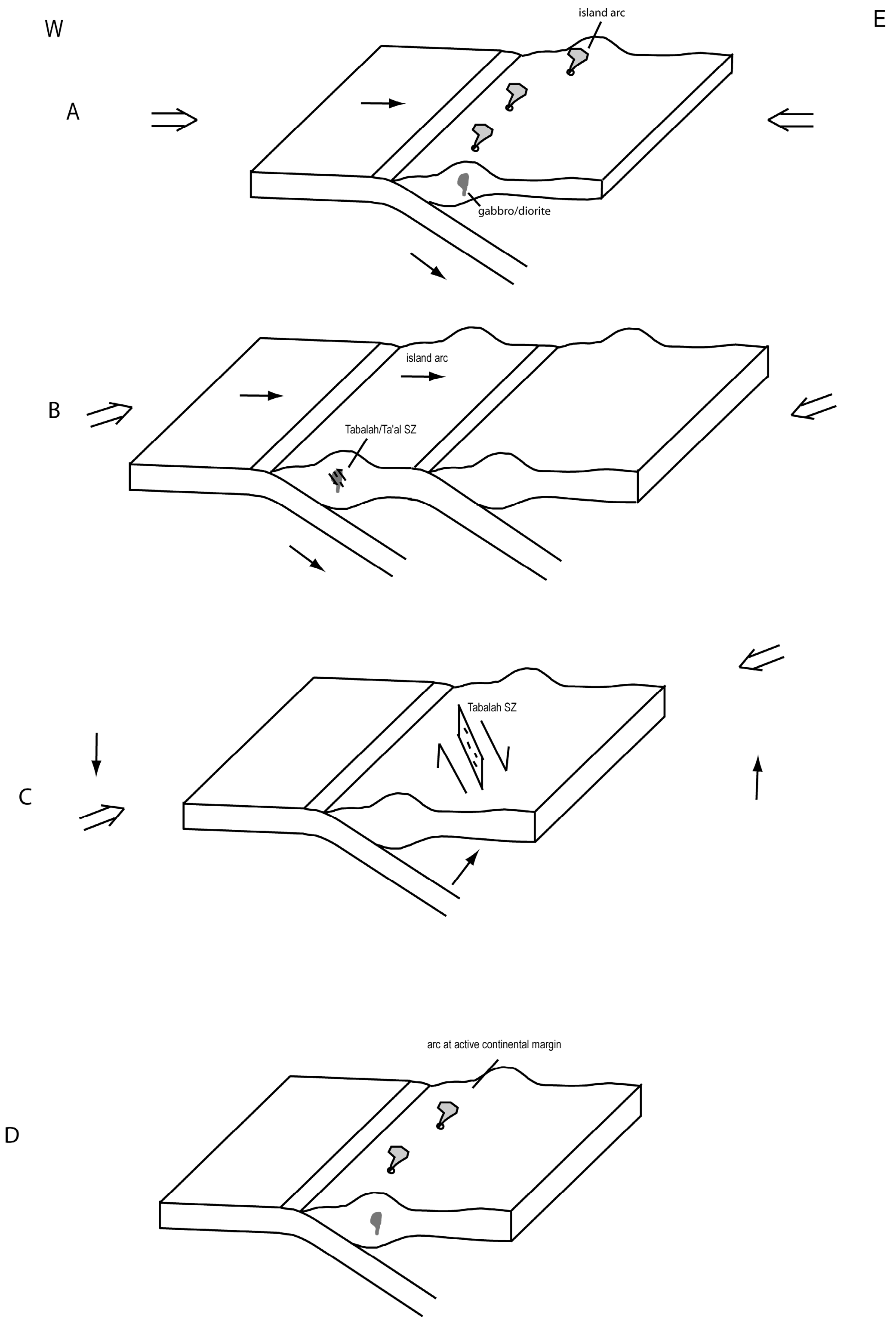

Figure 4-18 Diagrams illustrating the tectonic history of the Tabalah and Tarj areas
a) Formation of island arcs
b) The formation of a intra-terrane thrust (D1) at 779 Ma due to arc-accretion at the terrane margin
c) Continuing arc-accretion leads to dextral strike slip (D2) at 765 Ma. Anti-clockwise change in the direction of plate motion of the subducting plate is responsible for the change in deformation along the Tabalah/Ta'al Shear Zone.
d) Granodiorite intrusion at active margin at 761 Ma