3

The Bi'r Umq Complex and Shear Zone: an ophiolitic suture in the Arabian-Nubian Shield

Abstract

The Bi'r Umq Complex (BUC) is a Neoproterozoic ophiolite complex (ca. 830 Ma) at the northern margin of the Mahd Group in the central part of the Arabian part of the ANS. Locally, it defines the contact between the Jiddah and Hijaz Terranes. It has been folded and extensively sheared during three phases of deformation. The D1-deformation phase resulted in folding, development of foliation, the formation of steeply plunging mineral lineations, and shear indicators. D1 took place under ductile conditions during a phase of greenschist-facies metamorphism. D1 involved SE-vergent thrusting on the Bi'r Umq Shear Zone (BUSZ) at the southern margin of the BUC, and on the minor shear zones within the BUC. The D1-deformation phase was a result of NW-SE compression and was responsible for the emplacement of the Bi'r Umq ophiolite in the overriding plate. The second deformation phase, D2, was marked by dextral strike-slip with a minor transpressive component in the central zone of the WSW-ENE-trending BUSZ and resulted in the formation of sub-horizontally WSW-plunging stretching lineations that are marked by elongated clasts. D2 took place during WNW-ESE compression. The third phase, D3, involved shear reversal and resulted in sinistral strike-slip with a minor transtensional component on the BUSZ. This phase took place during NNE-SSW directed compression. The D1-D3 deformation phases in the Bi'r Umq Complex (BUC) occurred during obduction of the Bi'r Umq ophiolite and ended at ca. 760 Ma. The structures and structural history in the region are of the type expected to be associated with the closure of an oceanic basin by subduction and are consistent with the history of arc-accretion in the Arabian shield established elsewhere. The changes of the sense of movement on the main structures in the BUC can be attributed to a change in plate motion of the subduction plate, as observed during Mesozoic arc-accretion in western North America.

3.1 Introduction

The formation of the Neoproterozoic rocks of the Arabian part of the ANS is thought to be a result of arc-accretion of juvenile crust that was formed in island-arcs and oceanic basins (see Chapter 2). The oldest juvenile rocks of the Shield were formed at about 900 Ma and accretion- and subduction-processes continued to approximately 650 Ma (Blasband et al, 2000). The concept of terrane-accretion for the Arabian Shield was based on lithological and geochemical observations (Johnson et al, 1987). However, few structural/kinematic studies, which have been so important for the understanding of the geotectonic evolution of other areas where arc-accretion was established, were performed in the Arabian Shield. It is only in recent years, that

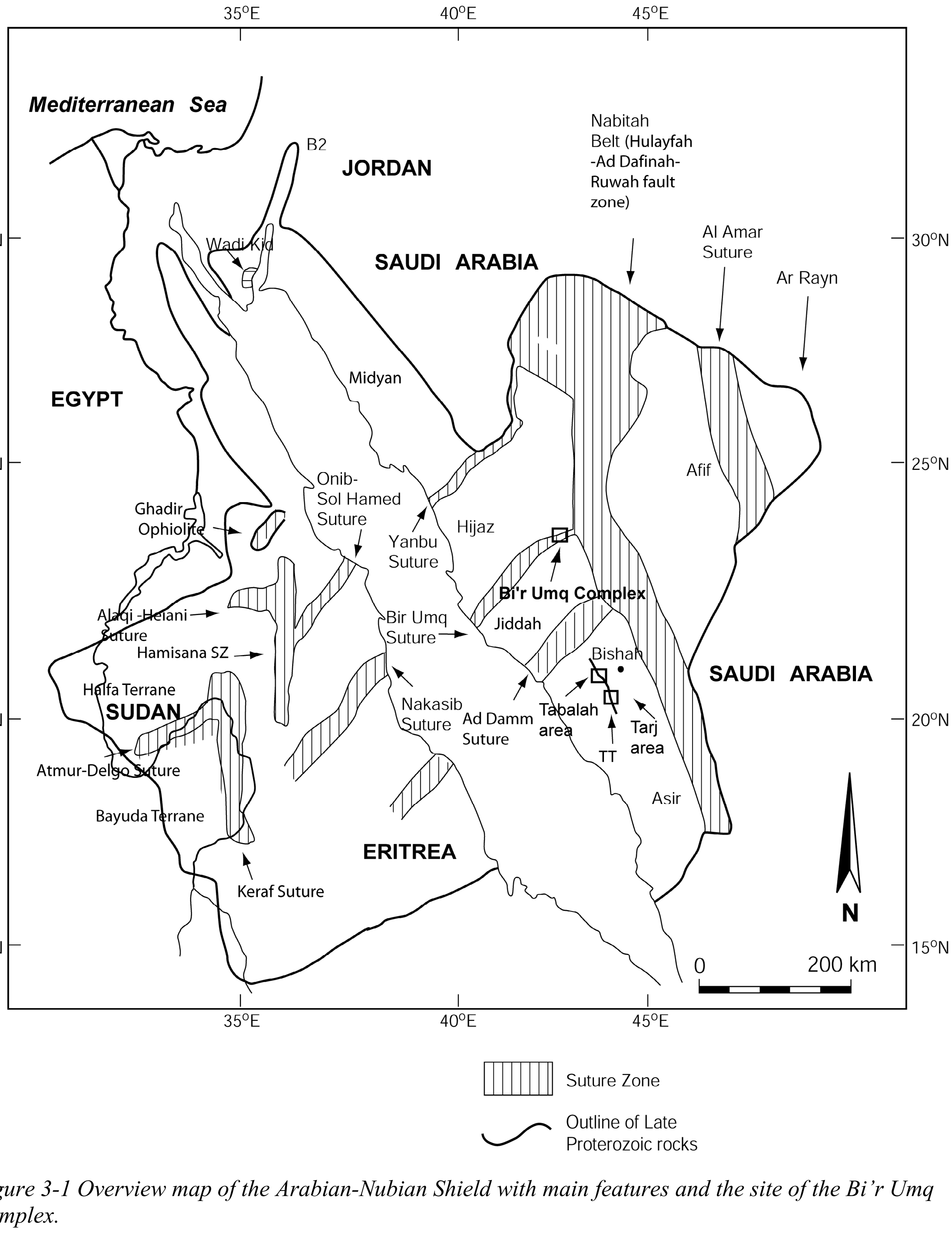


Figure 3-1 Overview map of the Arabian-Nubian Shield with main features and the site of the Bi'r Umq Complex.

Johnson (1998, 1999a, 1999b) has demonstrated the importance of these studies in the Arabian Shield. Shear zones, related to the arc-accretion, are represented by NE-SW trending linear belts such as the Bi'r Umq-Nakasib Suture and the Yanbu Suture, the NNW-SSE trending Hulayfah-Ad Dafinah-Ruwah shear zone and the N-S trending Nabitah Belt (see also Chapter 2 and references within for more details on these structures). These shear zones are interpreted as ophiolite-bearing sutures (Stoeser and Camp, 1985; Johnson et al., 2001). The results of a detailed structural study of the Bi'r Umq Complex (BUC) and its surrounding areas are presented in this chapter. The BUC itself is thought to be a typical example of a part of an ophiolitic suture (e.g. Pallister et al. 1988; Johnson et al., 2002).

Detailed structural and kinematic studies are crucial for the understanding of the complicated accretion processes, which are assumed to be responsible for the formation of the Arabian-Nubian Shield (Stoeser and Camp, 1985; Johnson et al, 1987; Blasband et al., 2000). The aim of this chapter is to more fully understand these tectonic processes through integrated structural and kinematic studies. These studies will in turn provide a basis for a more comprehensive interpretation of the tectonic evolution of the ANS. Through this structural and kinematic study, it will be shown that the observed structural features are indeed typical of an area that has experienced arc-accretion.

The Bi'r Umq Complex (BUC), the subject of this study, forms the NE portion of the Saudi part of the generally NE-SW trending Bi'r Umq/Nakasib suture (Figure 3-1). The total length of the suture is some 600 km (Johnson et al., 2002). The Saudi part of the suture, referred to as the Bi'r Umq suture, defines the border between the Jiddah and Hijaz terranes (Johnson et al., 2002). The BUC trends WSW-ENE and is some 25 km long and 10-15 km wide. It consists of a sequence of rocks that are thought to form a dismembered/disrupted ophiolite (Stoeser and Camp 1985; Pallister and others 1988). This assumption is based on the presence of ultramafic rocks, basalts, and chert in the BUC. The rocks in the BUC are locally deformed. The Bi'r Umq Complex derives its name from the village of Bi'r Umq, which lies in the middle of the area. The main tectonic feature in the complex is the Bi'r Umq Shear Zone (BUSZ) in the southern part of the complex. This shear zone defines the contact between the Jiddah Terrane and the less deformed part of the BUC. Minor shear zones are found within the BUC, and south of the BUSZ, within the Jiddah Terrane. The border between the Bi'r Umq Complex and the Hijaz Terrane in the north is not visible due to the lack of outcrop.

This chapter concentrates on the structural features of the Bi'r Umq Complex and its surrounding areas, and consequently special attention was given to the structurally complicated areas as the BUSZ. The results from study of the Bi'r Umq Complex 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.

3.2 Geological Background

3.2.1 Lithology

The lithological sequence of the Bi'r Umq area will be described from south to north starting with the *Mahd Group*. Figure 3-2 shows a simplified geological map of the Bi'r Umq Complex. The *Mahd Group* forms the northernmost part of the Jiddah terrane and southernmost of the studied area. The BUC itself is regarded as one lithological entity. The northern border of the BUC is not visible because it is covered by Quaternary sediments.

The rocks that are found to the south of the BUC belong to the *Mahd Group*. The rocks of this unit were studied in order to define the southern contact of the Bi'r Umq Complex. The *Mahd Group* consists of (meta)basalts, (meta)andesites, and different varieties of (meta) sedimentary rocks. The metasediments are slates, very fine-grained (meta)sandstones and chlorite-schists. The chlorite-schists contain quartz, plagioclase, chlorite and minor white mica. Locally the schists are carbonated. Rhyolites, andesites and basalts are found close to the contact with the Bi'r Umq Complex. The basalts are found in massive and vesicular varieties. Locally the volcanics are foliated and form bands of schist with a thickness of up to approximately 5 meters. Towards the contact with BUC the rocks become increasingly deformed as indicated by increasing foliation intensity. Outside of the studied area, the *Mahd Group* is intruded by many (grano)dioritic plutons (Johnson et al., 2002).

The BUC, which forms the main subject of this chapter, starts north of the Mahd group. The rocks at the contact with the *Mahd Group* consist of an orange-pale red carbonate-rich rock. Most workers in the area interpreted these rocks as peridotites that were carbonated (Hopwood 1979, Bowden and others 1981, Al-Rahaili 1982). The *carbonated ultramafics* are between 100 and 500 m thick. Occasionally the carbonated ultramafic rocks disappear laterally and instead serpentinite is found at the contact of the BUC with the *Mahd Group*. The carbonated rocks are generally undeformed but locally foliated carbonated ultramafics were found and close to the contact with the *Mahd Group*, the carbonated ultramafics are always foliated. The *carbonated ultramafics* consist of carbonates and minor chlorite and serpentine. Towards the contact between BUC and the Mahd Group, an increasing number of elongated basaltic clasts from the latter formation are found.

A dark gray to dark brownish gray *serpentinite* layer is found north of the carbonated ultramafic rocks and continues along the contact with the *Mahd Group* where carbonated ultramafics are lacking. This layer is also 100 to 500 meters in thickness and strikes ENE-WSW. The *serpentinite* contains up to 90% serpentine with olivine pseudomorphs and minor Fe-oxide, carbonates and chlorite. Occasionally pyroxene pseudomorphs are observed in the *serpentinite*. The *serpentinite* is found in a foliated and in a massive variety. The massive serpentinite grades into layers of serpentinite schist that are 10 to 100 of meters thick. Serpentinite schists contain clasts of undeformed massive serpentinite, ranging in size from a few millimeters to 10s of centimeters. The schistose parts form mostly low ground in the wadis and good outcrop of the *serpentinite* schist only occurs where schist is adjacent to massive outstanding ridges of dyke rock or basalt.

The *serpentinite* is thought to be meta-harzburgite (Hopwood, 1979). The serpentinite schist contains biotite in places, but only when close to a contact with the *Mahd Group* and the Basalts north of the *serpentinite*. All visible contacts with other lithologies are foliated.

Figure 3-2 A simplified geological map of the Bi'r Umq Complex and its surrounding areas. A-A'-B-B' represents cross-section of Figure 3-12.

However, poor outcrop masks most contacts and in many cases the nature of the serpentinites at the contacts could not be studied. Close to the contact with the *Mahd Group*, the *serpentinite* schist contains many clasts of undeformed basalts, ranging in size from a few centimeters to 10s of meters. These clasts are locally foliated and oriented (sub)parallel to the main foliation of the serpentinite schist.

A large ENE-WSW trending basalt and chert layer is found north of the main serpentinite. The basalt, which locally grades to andesite, is mostly massive and stands out in ridges. It is locally foliated, mainly near its contacts with the ultramafic rocks where it forms chlorite-or biotite-schist. The undeformed basalts are often silicified and contain fine-grained chlorite. Locally pillow structures are found in the basalts. Occasionally bands of serpentinite-schist were found within the basalts. These layers are as much as several 10s of meters thick. In the northern part of the BUC, a carbonated peridotite layer is associated with such serpentinite schist. Chert, which also forms prominent ridges, is mainly found in the northern part of the complex as interbeds in the basalt. Some of the chert-basalt contacts are strongly schistose.

A large ENE-WSW layer of *carbonated ultramafics* cross-cuts the basalt- and chert sequence in the central part of the BUC. In the northern part of the BUC a carbonated ultramafic lens of some 100 m thick and 1 km wide is observed within the basalt- and chert sequence.

The northern most outcrop of the BUC consists of (meta)andesites, (meta)dacites and chlorite-schists. The chlorite-schists contain up to 20% quartz and large amounts of chlorite and appear to have a volcanic or sedimentary origin. The northern edge of the BUC is not exposed and the location of the northern contact of the BUC is therefore uncertain.

Basaltic to andesitic dikes occur in the area and are generally undeformed. Late dykes cross-cut all other lithologies. The undeformed ENE-trending basaltic dykes contain mainly plagioclase and hornblende and are in part chloritized. N-S trending dykes have an andesitic composition, containing plagioclase and minor amounts of hornblende and quartz. They are not chloritized and this indicates that the ENE-trending dykes have undergone some form of metamorphism. The N-S trending dykes postdate the phase of greenschist metamorphism and should thus be youngest.

An undeformed microdiorite body is found in the southeastern part of the BUC. It is intrusive to the surrounding serpentinites and basalts. An undeformed plagiogranite intrudes the serpentinite schist in the southwestern part of the BUC.

Although no complete ophiolitic sequence was observed in BUC, the presence of a variety of ultramafics next to basalts and cherts justifies the interpretation of the BUC as a dismembered ophiolite. This interpretation is in accordance with those of others who worked in the area (e.g. El-Rahaili 1982; Pallister et al., 1988; Johnson et al., 2002).

3.2.2 Metamorphism

The inferred metamorphic conditions are based on microscopic observations together with earlier reports (e.g. Hopwood, 1979; El-Rehaili, 1980; Bowden and others, 1981). The rocks of the *Mahd Group* are typically non- to slightly metamorphosed. The meta-sediments of the *Mahd Group* contain chlorite and occasionally actinolite. This indicates lower-middle greenschist facies. Within the BUC, serpentine, minor amounts of talc, chlorite and biotite are found. These rocks, like the rocks in *Mahd Group*, display low- to medium-greenschist grade metamorphism.

3.2.3 Origin of igneous rocks

Most of the rocks in the BUC and the Mahd group are of magmatic origin. Geochemical studies of these rocks may present useful information on their tectonic environment. The igneous rocks in the Mahd Group consist of rhyolites, andesites and basalts. Johnson and others (2002) concluded, on the basis of geochemistry and on the basis of the geology of adjacent areas, that they were formed in a supra-subduction setting. The rocks of the BUC consist of ultramafic rocks as harzburgite and dunite and combined with (pillow) basalts and cherts, they resemble ophiolites (e.g. Al-Rahaili, 1980; Stoeser and Camp, 1985). Le Metour and others (1982) suggested that the serpentinites were formed from peridotites which have Cr-spinel compositions that are comparable to Tethyan ophiolites. Johnson and others (2001) compared the geochemical data of Le Metour and others (1982) with the standardized chromian spinel diagrams of Dick and Bullen (1984). On the basis of these diagrams, Johnson et al. (2002) concluded that the Bi'r Umq serpentinized peridotite was formed at a juvenile mid-oceanic ridge close to an island-arc or at a fore-arc. The (grano)diorites that are found south of the BUC are thought to be intruded in to a volcanic arc (Pallister et al., 1988; Johnson et al., 2002)

3.2.4 Geochronology

Pallister et al. (1988) performed a geochronologic study (U-Pb zircons) in several ophiolitic sequences of Saudi Arabia. They dated a number of rocks from the Bi'r Umq area. A diorite in the northeastern part of the BUC was dated at 838 $\pm$ 10 Ma. This date was related to the formation of the ophiolite in the BUC. An undeformed plagiogranite in the southwestern part of the complex (named "keratophyre" by Pallister et al., 1988) that intrudes the serpentinite schist was dated at 764 $\pm$ 3 Ma. This date should give an upper limit of the age of the deformation phase that was responsible for formation of the serpentinite schist. Dunlop et al. (1986) dated a nearby trondhjemite and a pyroxene separate from a gabbro, thought to be related to the formation of the ophiolite, at 828 $\pm$ 47 Ma. Diorites in the Jiddah Terrane, intruded in to a volcanic arc south of the BUC, were dated at approximately 810 Ma (Calvez and Kemp, 1982; Stoeser and Stacey, 1988; Pallister et al, 1988). A rhyolite of the Mahd group was dated at 772 $\pm$ 28 Ma (Calvez and Kemp, 1982). Other intrusives related to arc magmatism south of the BUC, intruded at 780-760 Ma (Johnson et al., 2002).

From these geochronologic data, it can be concluded that the ophiolite was formed before 820 Ma. The tectonic phase that caused the deformation in the serpentine schists, ended by 760 Ma. The beginning of the deformation phase is temporally unconstrained, however it should post-date the age of the youngest ophiolite-related rocks that were dated at ca. 820 Ma (Dunlop et al., 1986; Pallister et al., 1989).

3.3 Structural Geology

3.3.1 Introduction

The structural features in the Bi'r Umq area, will be described according to their inferred mode of formation, namely those which have been classified as part of a shear process (shear zone related structures) or those which have been classified to have formed independently from the shear process (structures outside the shear zones). As implied by the terminology, shear-zone related structures occur in foliated and sheared rocks that displays indications of non-coaxial shear; non-shear-zone related structures are outside such shear zone. The main structural trend of the Bi'r Umq Complex is WSW-ENE.

For the structural study, reference will be made to the 3 principal structural domains: a) the Mahd group area in the south, b) the main Bi'r Umq Shear Zone (BUSZ), and c) the BUC, excluding the BUSZ. The BUSZ itself marks the contact between *Mahd Group* (Jiddah Terrane) and the BUC (Al-Rehaili, 1980; Johnson et al., 2002). Strictly speaking, on the basis of lithology, the BUSZ is part of the BUC but since it is much larger in comparison with other structures in the BUC and records a significantly more complicated structural history than any other structure in the area, it is described as a separate structural entity.

3.3.2 Previous studies

Most authors, who worked in the area, have concentrated on the BUSZ, and many have interpreted it as a thrust-complex related to a southward dipping subduction zone (Al-Rahaili, 1982; Stoeser and Camp, 1985; Pallister et al., 1988; Johnson et al., 2002). A post-thrust dextral strike-slip phase has been postulated for the entire Bi'r Umq/Nakasib Suture (Johnson et al, 2002).

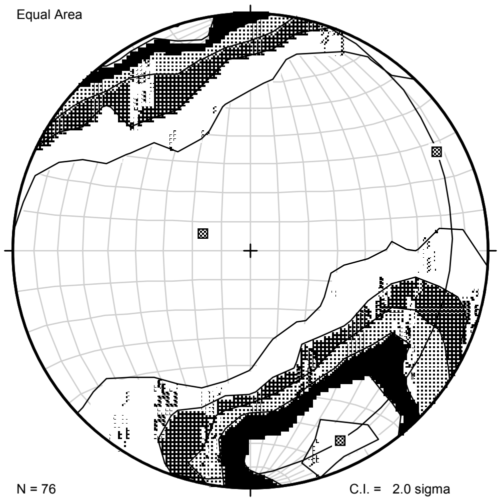
3.3.3 Shear Zone related structures

3.3.3.1 Introduction

This section describes lineations, foliations, and structures associated with non-coaxial deformation, which are observed in the shear zones that are present in the study area. These include minor shear zones in the Mahd group with widths up to 50 m; the Bi'r Umq Shear Zone (BUSZ) which is 200-1000 m wide and is the main shear structure in the area; and minor shear zones in the BUC, north of the BUSZ, with widths up to 50 m. The southern margin of the BUSZ is drawn at the southernmost outcrop of ultramafic rocks, either the orange colored carbonated ultramafics or, where these are absent, serpentinite schist. The northern margin is drawn at the southernmost outcrop of massive basalt of the BUC.

3.3.3.2 Foliations

Foliations are pervasive structures in the shear zones, and are particularly well developed in serpentinite schists and carbonated ultramafic rocks along the contact between the Mahd Group and the Bi'r Umq Complex. This contact-zone is referred to in the literature as the Bi'r Umq



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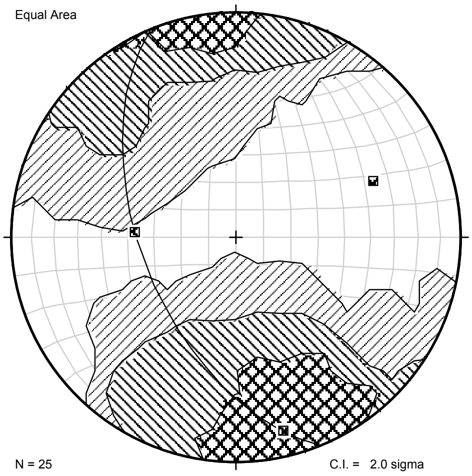

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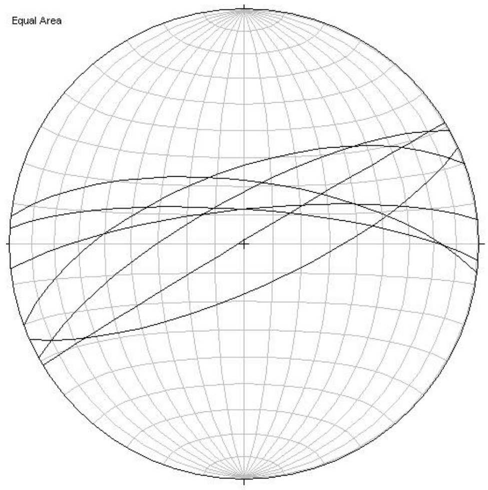

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Figure 3-3 Stereoplots of planar structures in the shear zones; (a) contour-plot of the poles to the foliation in the BUSZ; (b) contour-plot of the poles to the foliation in the minor shear zones of the BUC; (c) Stereoplot of the foliations in the minor shear zones in the Mahd Group.

Shear Zone (e.g. El Rahaili, 1980; Johnson et al., 2002) and this term will also be used in this chapter. The foliated rocks in the BUSZ are formed by serpentine schist, foliated carbonated ultramafics, biotite schists and chlorite schists. The foliation in the BUSZ is mainly defined by serpentine, whereas foliations in the minor shear zones in the BUC and the Mahd group are defined by serpentine, biotite and chlorite. The foliation in all shear zones is sub-vertical and strikes WSW-ENE to SW-NE (Figure 3-3a and Figure 3-3b). Outcrops of the Mahd Group next to the BUSZ are also well foliated.

3.3.3.3. Lineations

Lineations, defined by elongate minerals or mineral aggregates, and elongated clasts, are well developed in the BUSZ and in the minor shear zones of the BUC and Mahd group. Mineral lineations mostly consist of fibrous serpentine (Figure 3-4) but in places they also consist of elongate quartz pods, actinolite needles and elongate pods of biotite. Fibrous serpentine is formed on the foliation planes and individual fibers reach lengths of 2 cm. Other mineral lineations are not longer then 2-3 mm and are also formed on the foliation planes. The mineral lineations throughout the BUSZ plunge generally steep-moderate to the NW (Figure 3-6a) and are found on NNW dipping planes. Sub-horizontal mineral lineations were rarely observed in the BUSZ (see Figure 3-6a). Mineral lineations in minor shear zones in the *Mahd Group* and BUC were observed on SSE-dipping foliations and mostly plunge moderately to the SE (Figure 3-7a) but some lineations in minor shear zones in the *Mahd Group* and BUC plunge steeply to the NW in shear zones with NW-dipping foliations (Figure 3-7a).

Throughout the BUSZ, the clast lineations are the most commonly observed type of lineation (Figure 3-5). These clast-lineations consist of elongated clasts of basalt, carbonated ultramafics and massive undeformed serpentinite-clasts within the serpentinite schist and carbonated ultramafic rocks. These clasts are several centimeters to several decimeters long; several centimeters to a decimeter wide; and several centimeters to a decimeter thick. Their shortest axes are perpendicular to the foliation and their longest axes trend in generally uniform directions as indicated by clearly defined maxima in Figure 3-6b. In the BUSZ, the clast-lineations plunge mostly sub-horizontally to the WSW but also have a secondary maximum plunging steeply to the NW (Figure 3-6b). It is only close to the contacts of the BUSZ with the Mahd Group and the contacts of the BUSZ with the non-sheared parts of the BUC that the clast lineations are plunging steeply instead of sub-horizontally (Figure 3-5). Close to the contact with the Mahd Group, the clasts are basaltic and away from this contact more massive serpentinite clasts were found. In the minor shear zones of the BUC itself and the *Mahd Group*, clast-lineations plunge mainly toward the NW (Figure 3-7 b).

On the outcrop scale, no overprinting relations were observed between the steeply NW-plunging lineations, the moderately SE plunging lineations and the sub-horizontally WSW-plunging lineations. However, the conditions at which the different lineations trends were formed, may give an indication of their relative age relations. The presence of fibrous serpentine lineations and actinolite lineations indicates that their formation took place under greenschist-facies conditions. These mineral lineations were only observed as the steeply NW-

Figure 3-4 Fibrous serpentine lineation in the BUSZ.

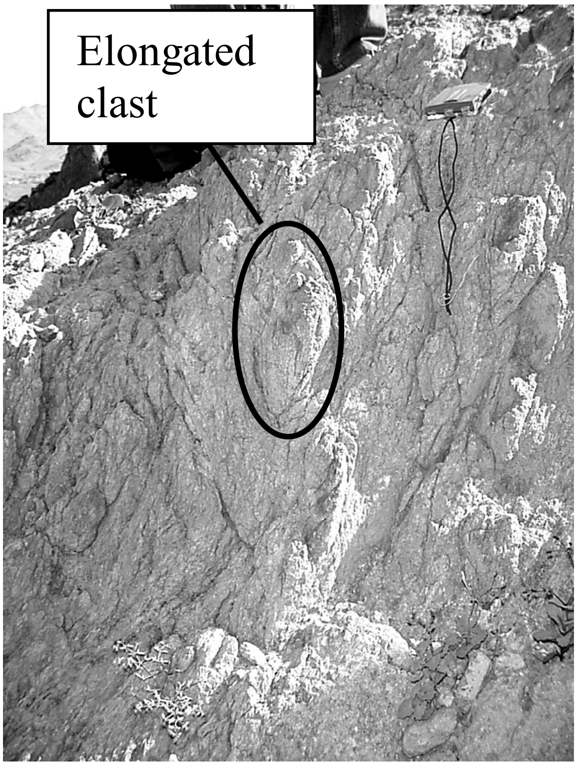
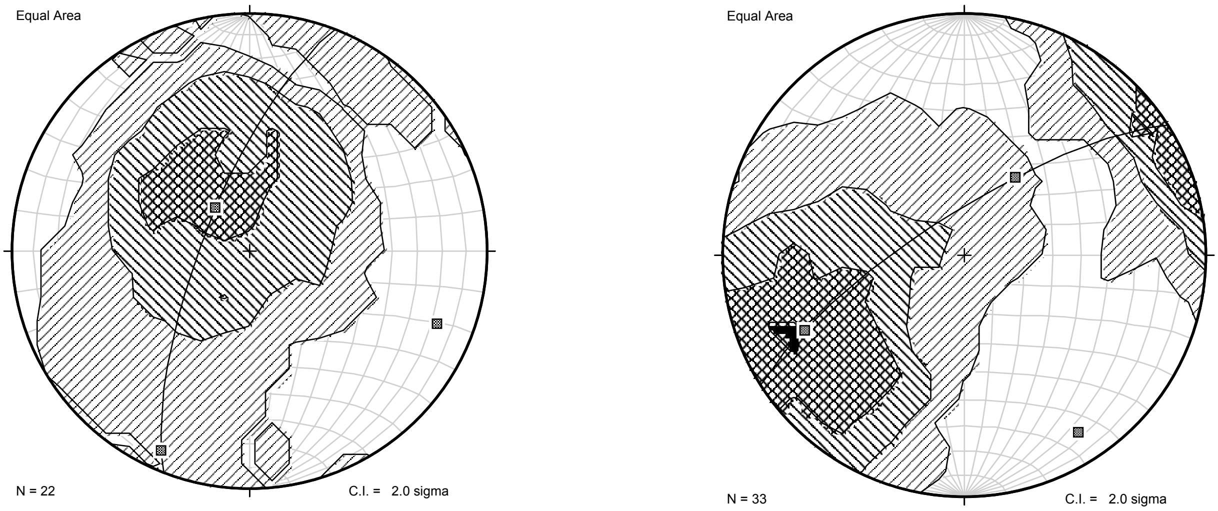


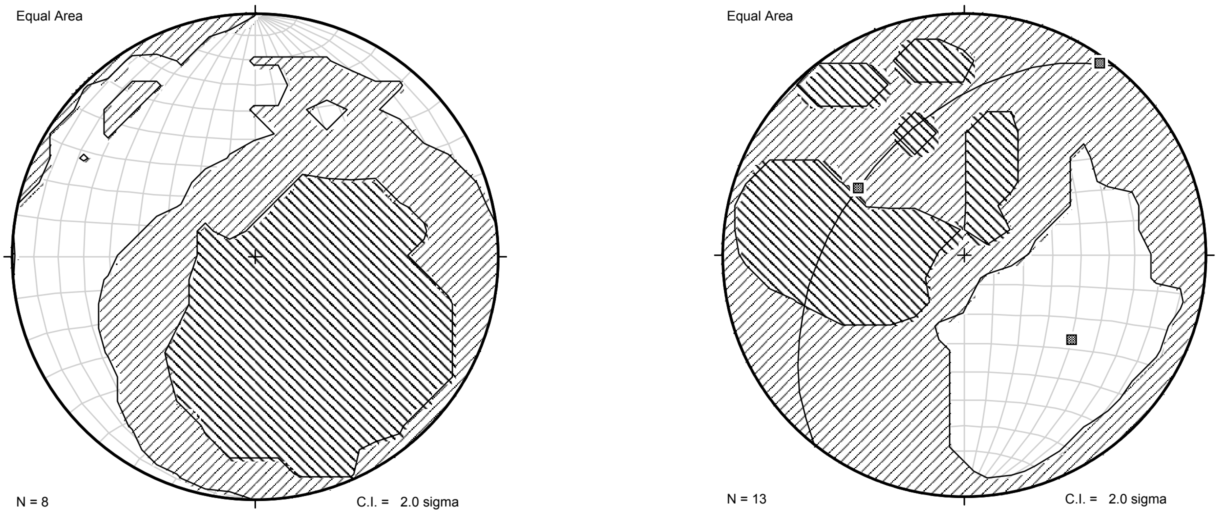
Figure 3-5 Steep clast lineation (dark elongate structures in carbonated ultramafic).

plunging lineations in the BUSZ and moderately SE-plunging lineations in the minor shear zones of the BUC. Clast-lineations can form at the very lowest metamorphic grades when rocks were deformed by very low-grade deformation processes as pressure solution. No indications of thermal overprinting were observed with respect to the mineral lineations in the BUSZ, and therefore it is inferred that the steeply NW-plunging mineral lineations reflect the earliest phase of formation of lineations in the BUSZ because they developed at a higher temperature than the



a b

Figure 3-6 Contour-plots of linear features in the BUSZ; (a) mineral lineations in the BUSZ; (b) clast lineations in the BUSZ.



a b

Figure 3-7 Contour-plots of linear features in the minor shear zones outside of the BUSZ; (a) mineral lineations in the shear zones outside of the BUSZ; (b) clast lineations in the shear zones outside of the BUSZ.

sub-horizontally plunging WSW clast-lineations. By association it is interpreted that all steeply plunging linear structures, other than the mineral lineations in the BUSZ (see also Figure 3-2 and Figure 3-6), are a part of the early, relative high temperature phase of deformation.

The mineral lineations in the BUC and in the *Mahd Group* have a different trend but were formed at the same metamorphic grade as the mineral lineations in the BUSZ; namely under greenschist conditions. Also in the *Mahd Group*, no thermal overprinting was observed on outcrop scale with respect to the mineral lineations. Therefore, like in the BUSZ, the mineral lineations in the BUC and the *Mahd Group* are interpreted to be the oldest linear features observed.

In summary, it can be concluded that the lineation in the BUSZ trends can be divided into two groups: a) steep-moderate plunge to NW-N; b) shallow plunge to WSW; and into two groups in the BUC and *Mahd Group*: moderate plunge to SE; b) steep-moderate plunge to NW. Steeper plunging clast- and mineral-lineations pre-date the sub-horizontal clast-lineations. Furthermore the mineral lineations were formed at a higher grade than the clast lineations. Any clast lineations that formed parallel to mineral lineations should have formed in the same deformation phase. For the complete interpretation of the tectonic significance of lineations and foliations, other structural information is required such as shear sense indicators and fold geometries. These features will be described in the section below.

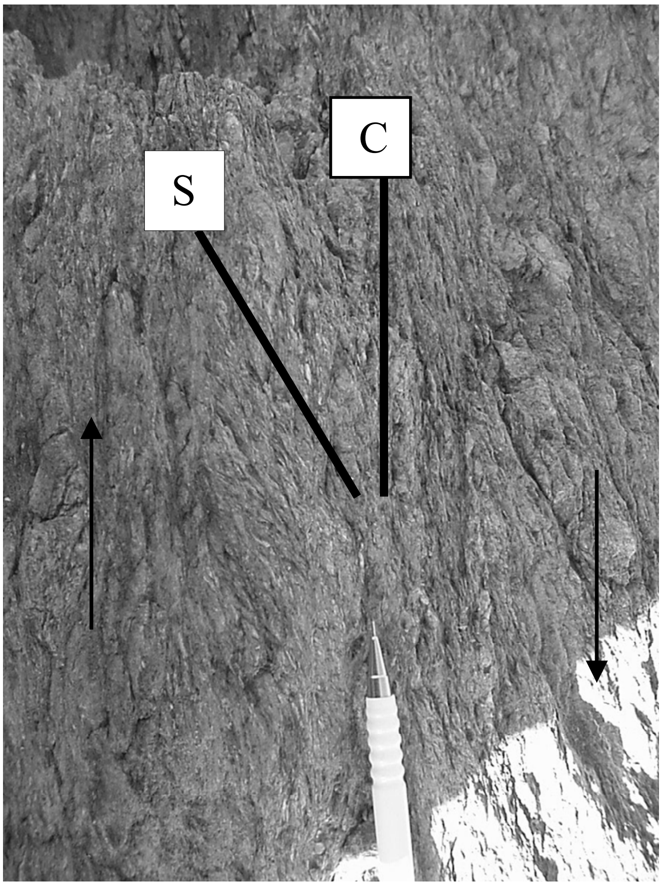
3.3.3.4 Evidence for non-coaxial deformation

In order to understand the tectonic significance of the foliations and lineations, other structural features such as shear-sense indicators and fold geometries were studied. Lineations formed during non-coaxial deformation will be associated with asymmetric shear indicators when viewed parallel to the lineation and perpendicular to the foliation. Lineations that are related to regional folding will often form parallel to the fold-hinges (Price and Cosgrove, 1990; Twiss and Moores, 1992). In the BUSZ and in the distinct schistose zones in the Mahd Group and BUC, referred to as shear zones, no structures were observed that are indicative for regional folding as axial planar cleavages, intersection lineation and "fold-hinge lineations", however indicators of non-coaxial deformation were widespread.

Prior to the use of shear sense indicators to ascertain non-coaxial deformation, it is important that the lineation-trends are analyzed carefully. From Figure 3-6 and Figure 3-7 it was concluded that the lineation trends in the BUSZ can be divided into two groups: a) steep-moderate to NW; b) shallow to WSW; and into two groups in minor shear zones of the BUC and *Mahd Group*: a) moderate to SE; b) steep-moderate to NW. Each of these sets is associated with indicators of non-coaxial movement.

The shear sense indicators associated with the lineations that plunge steeply to the NW in the steeply dipping ENE-WSW striking BUSZ, include asymmetric clasts, SC-fabrics (Figure 3-8a), and asymmetric folds (Figure 3-8b). These indicators all display top-to-SE movement along NNW dipping shear zones. The shear sense indicators in the schists of the Mahd Group near the contact with the BUSZ also display top-to-SE movement through their steep lineation and asymmetric basalt clasts.

The clast-lineations that plunge shallowly to the WSW are the most commonly observed linear structures in the ENE-trending BUSZ. Rotated clasts, asymmetric pressure shadows, C-C'-fabrics, S-C fabrics, microscopic tension gashes and asymmetric folds are the typical indicators of movement that are related to the shallowly dipping clast lineation in the BUSZ. Both, a dextral sense of shear (Figure 3-9) and a sinistral sense of shear were observed perpendicular to the shallowly WSW plunging lineations. The shear indicators with the dextral sense of shear are the most abundantly observed ones in the BUSZ and are ductile in nature. Brittle to brittle-ductile C-C'-fabrics display a sinistral sense (Figure 3-10) and overprint the



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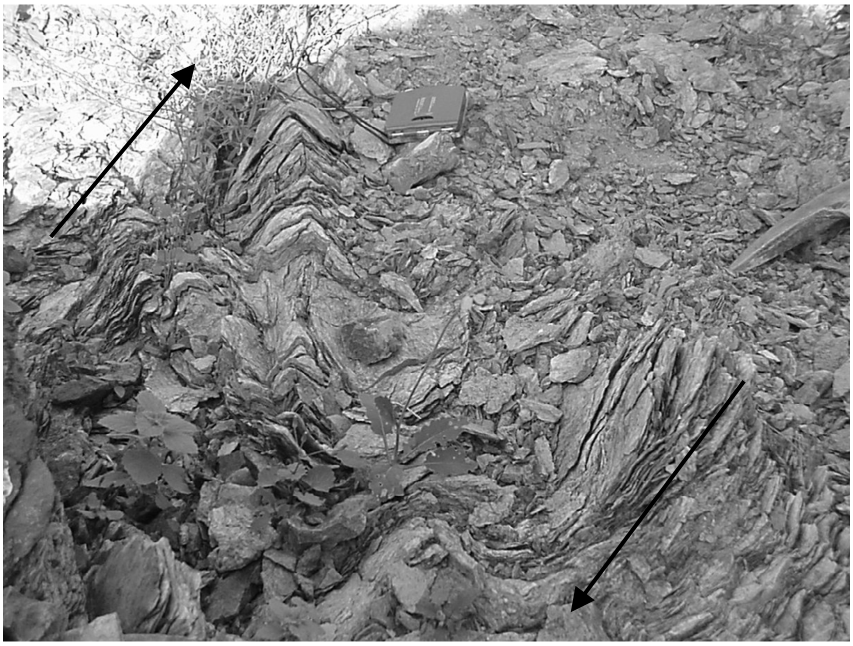

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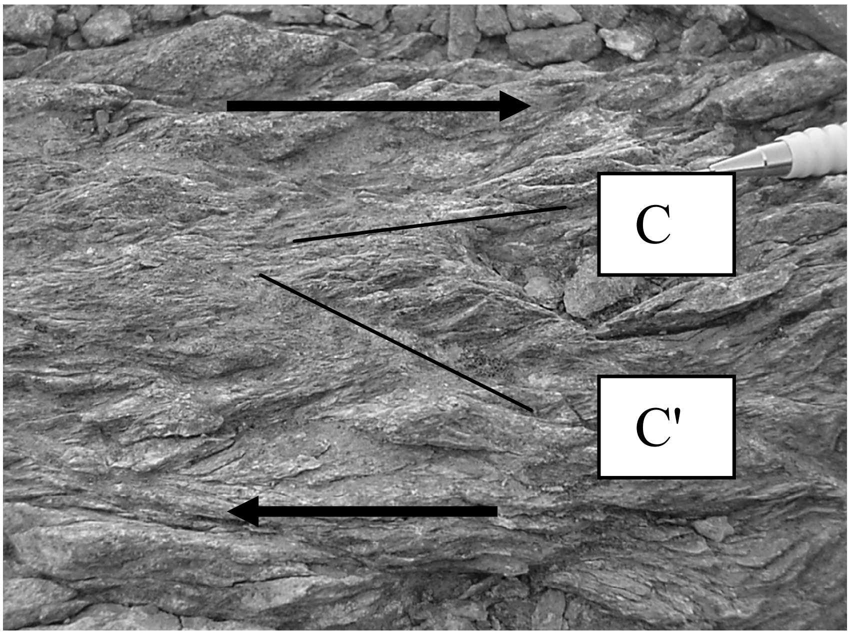
Figure 3-8 (a) SC fabric indicating top to the SE on NNW- dipping plane in the BUSZ (b) Asymmetric fold indicating top to SE-movement on NNW-dipping plane (fold axis is perpendicular to lineation) in the BUSZ.

ductile dextral structures. On the microscopical scale, sinistral brittle C-C'-fabrics overprint dextral asymmetric folds.

a



b

Figure 3-9 (a) Rotated clast of a non-deformed ultramafic clast with pressure shadows of serpentine schist (b) Ductile extensional crenulation cleavage in the BUSZ indicating dextral movement.

Since no other linear features were observed in these outcrops than the shallowly WSW plunging clast lineation, it is interpreted that the brittle sinistral C-C'-fabrics also to be associated to the elongated clasts with a shallowly plunging WSW trend. Since the sinistral brittle C-C'-fabrics overprint the ductile structures on outcrop scale, it is interpreted that they to postdate the formation of the ductile structures that are related to the steeply plunging lineations and the ductile dextral structures related to the WSW plunging lineation. The brittle shear indicators that display a sinistral overprint on the sub-horizontal lineations represent thus a

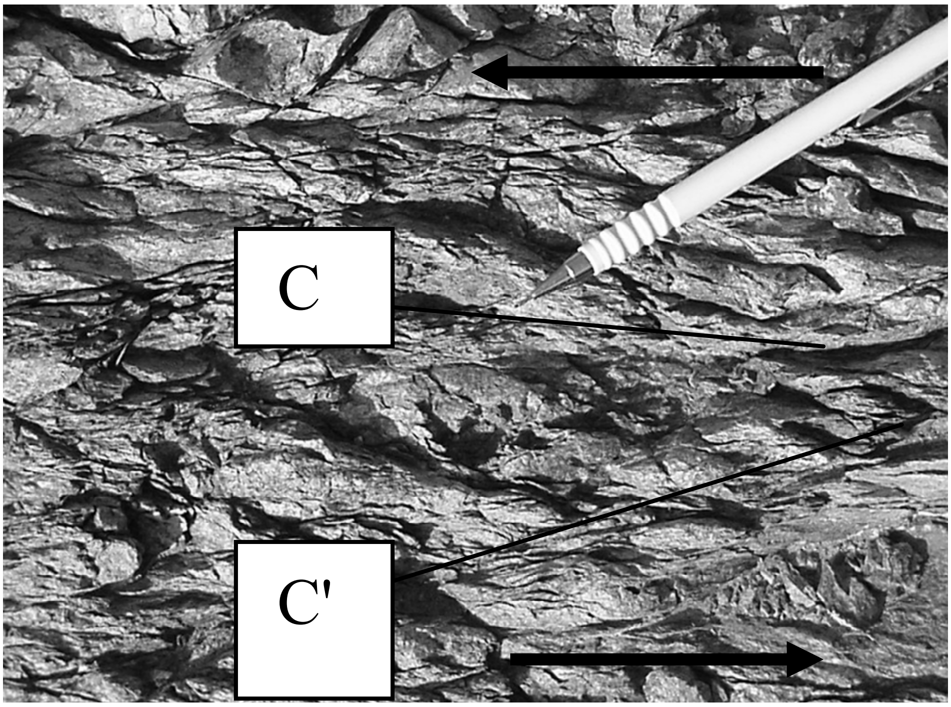


Figure 3-10 Late brittle-ductile extensional crenulation cleavage in the BUSZ indicating sinistral sense of shear.

phase of shear-sense reversal. The relationships between the plunge of lineations and their associated shear sense in the BUSZ is shown in Figure 3-11.

Shear sense indicators were associated with moderately SE plunging lineations in the ENE-WSW striking minor greenschist grade shear zones in the northern part of the BUC (Figure 3-2 and Figure 3-7). The shear indicators include asymmetric folds, asymmetric pressure shadows and C-C'-fabrics. They all record top-to-the NW movement, and so these shear zones record NW-vergent thrusting. In the ENE-WSW striking minor shear zones of the central BUC, the lineations plunge moderately to the NW (Figure 3-2 and Figure 3-7). The shear sense indicators associated with lineations in the minor shear zones of the central BUC all indicate top-to-the-SE movement and thus display thrusting. Rarely, SSW shallowly dipping elongated clasts were observed in the northern part of the BUC (Figure 3-2). Shear indicators associated with this lineation, namely rotated clasts and extensional crenulation cleavages, display sinistral movement.

3.3.3.5 Formation of shear-related structures

The co-occurrence of foliations and lineations together with indicators of non-coaxial shear in the ENE-trending BUSZ and in parts of the ENE-trending schistose units of the BUC and the *Mahd Group* (see Figure 3-11 and Figure 3-12) indicate that all these structures developed during non-coaxial deformation.

The lineation trends were divided into two groups in the BUSZ: a) steep-moderate to NW; b) sub-horizontal to WSW; and into two groups in the minor shear zones of BUC and Mahd Group: moderate to SE; b) steep-moderate to NW (see Figure 3-11). Indicators of non-coaxial deformation trends were associated with all of the lineation-trends. The steeply NW-plunging lineations in the BUSZ and the moderately SE plunging lineations in the northern BUC were developed at the highest grade of metamorphism in the region and no thermal overprint was observed (see section 3.3.2). For this reason, they were interpreted to have been formed at the same time. Shear indicators that were associated with the steeply NW-plunging lineations in the BUSZ, indicate top-to-SE movement which would imply thrusting with a minor dextral component in its current geographic position. This would indicate a NW-SE compressional regime, however thrusts rarely form as steep as observed at the BUSZ. In the minor SE -dipping shear zones of the BUC, SE-plunging lineations are associated with top-to-the-NW shear indicators, suggesting NW-vergent thrusting in a NW-SE compressional regime (Figure 3-2, Figure 3-11 and Figure 3- 12). The minor NW-dipping shear zones with NW-plunging lineations in the BUC and in the Mahd Group also display thrusting to the SE and, consequently, were also formed in a NW-SW compressional stress regime.

Since the NW- and SE-plunging mineral lineations were formed in the same stress regime and at the same metamorphic condition, they were interpreted to have been formed simultaneously during the same phase of deformation. The NW-plunging clast-lineations throughout the entire Bi´r Umq area were also associated with the shear indicators that indicate thrusting to the SE and were thus also formed in the same NW-SW compressional stress regime, as the mineral lineations. Therefore, these NW-plunging clast-lineations and their associated top-to-SE shear indicators also belong to the earliest deformation event in the Bi'r Umq area.

Since the steep lineations in the BUSZ, and the other NW- and the SE-plunging lineations, represent the oldest observed phase of deformation in the Bi'r Umq area, they were named L1-lineations which were formed during a D1-deformation phase. Only one foliation was formed in the shear zones and this must have formed simultaneously with the L1-lineation because these lineations were formed on the foliations. This foliation, formed during D1, is thus named S1.

To conclude, the D1-deformation was responsible for the formation of shear zones in the in the Bi'r Umq area with a sub-vertical WSW-ENE striking foliation (S1), the steeply plunging NW- and SE-plunging mineral lineations and the steeply NW-plunging clast-lineations (L1), and the shear indicators that indicate thrusting with a minor dextral component along all L1-lineations. These D1-features were formed in a NW-SE compressional regime. Thrusting on steep shear zones as the BUSZ is rare, however this issue can only be discussed when all the structural features of the area have been assessed and therefore this will be discussed at a later stage in this chapter.

Sub-horizontally WSW-plunging lineations on the ENE-trending BUSZ exclusively consist of elongated clasts that formed at a lower grade than the mineral lineations and other steep linear features. These sub-horizontally plunging clast-lineations were interpreted to be the younger set of lineations observed in the Bi'r Umq area because no thermal overprint was observed with respect to the steeply plunging mineral lineations. Consequently, the sub-horizontally WSW plunging lineations are referred to as L2-lineations. The L2-lineations in the core of the WSW-ENE trending BUSZ are associated with ductile shear indicators displaying dextral movement and brittle shear indicators displaying sinistral movement. The brittle

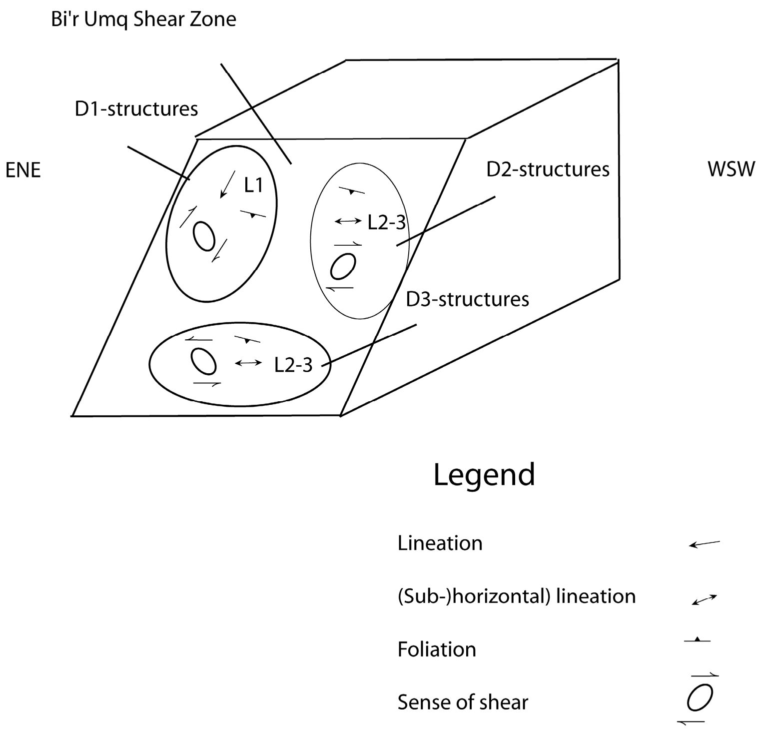


Figure 3-11 Block diagram of main structural features (foliations, lineations, and shear sense indicators) in the BUSZ .

sinistral shear indicators overprinted the ductile dextral shear indicators. Therefore the dextral ductile shear indicators are interpreted to be older than the sinistral brittle shear indicators and thus belong to the deformation phase that is referred to as D2. The brittle shear indicators that display a sinistral overprint on the sub-horizontal lineations represent thus a phase of subsequent shear-reversal which is referred to as the D3-deformation phase. The D2- movement along the sub-horizontally WSW-plunging lineations of the BUSZ displayed dextral strike-slip with a minor transpressive component and resulted thus from WNW-ESE directed σ_1. The D3-sinistral movement along these same lineations displayed sinistral strike-slip with a minor transtensional component and resulted consequently from NNE-SSW directed σ_1.

Since no other foliation was found then S1, it is assumed that both, the D2- and D3-deformation events used the S1-foliations to accommodate their planar deformation. The L2-lineation accommodated the linear deformation during D3. It should be noted that the strike-slip deformation did not affect the contacts of the BUSZ since L2 and horizontal shear indicators are absent over here.

It is assumed that no strike-slip movement took place on the minor shear zones because they only contain steeply plunging lineations and infer, consequently, that the minor shear zones were only active during D1, with the exception of the northernmost shear zone where sub-horizontal lineations are locally observed together with brittle sinistral shear sense indicators (Figure 3-2). Therefore it is assumed that the later deformation mainly concentrated on the BUSZ.

In summary, the history of shearing in the Bi'r Umq area is:

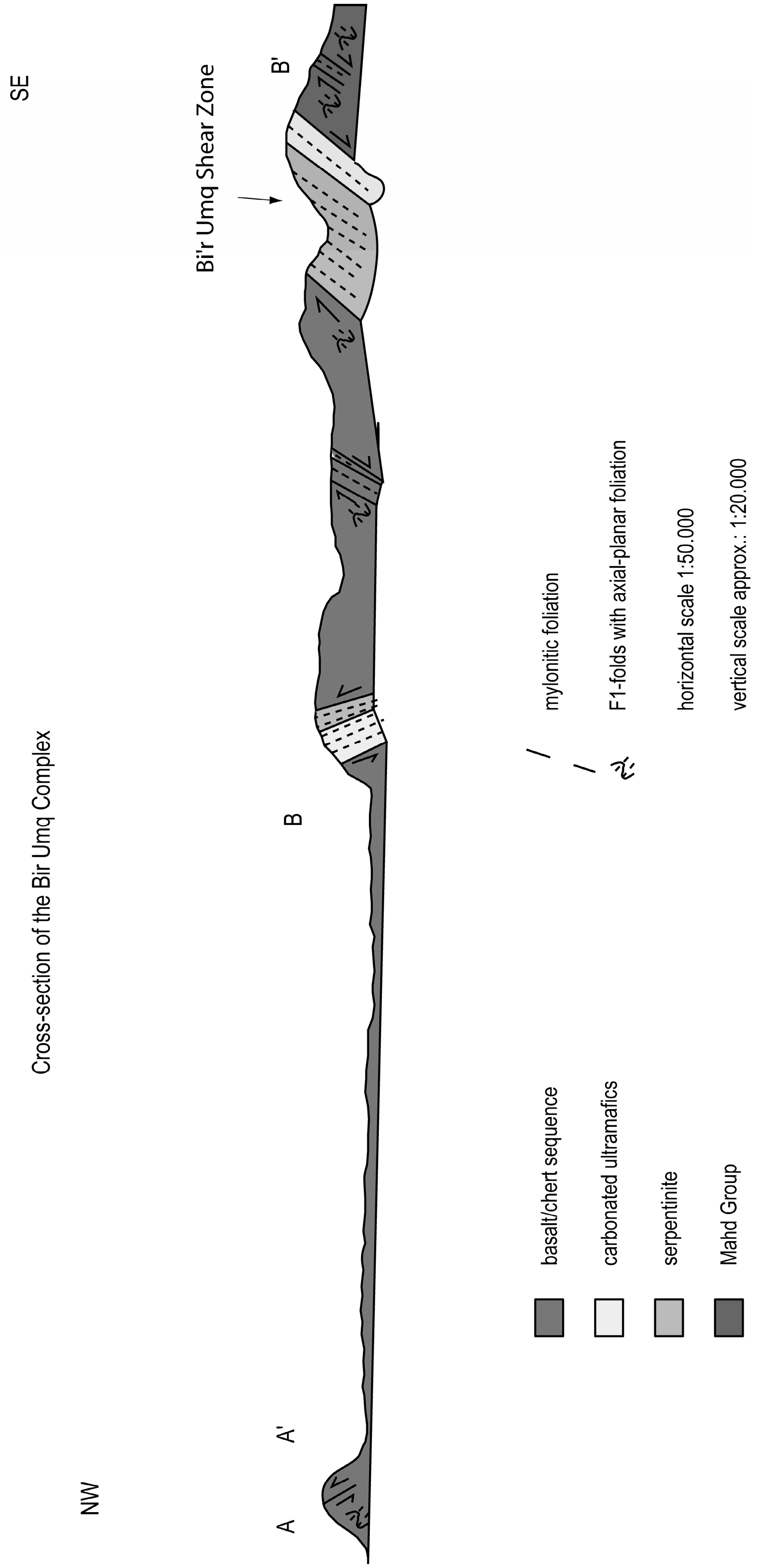


Figure 3- 12 NW-SE cross-section of the Bi’r Umq Area.

1. Thrusting with a minor dextral component along NW-plunging lineations on the WSW-ENE trending BUSZ and the minor shear zones in the BUC at greenschist grade (D1, NW-SE shortening)
2. Dextral strike-slip with a minor transpressive component at very low greenschist grade on the WSW-ENE trending BUSZ (D2, WNW-ESE directed σ_1).
3. Sinistral strike-slip with a minor transtensional component – a phase of shear reversal - on the BUSZ (at brittle conditions) and locally at the northern most shear zone in the BUC (D3, NNE-SSW directed σ_1).

No reliable ages are available for the start of the deformation at the Bi'r Umq Complex, however the youngest available date of formation for any ophiolite related rocks in this area is ca. 825 Ma (Pallister et al., 1989). The end of deformation in the Bi'r Umq Complex is constrained by the undeformed microdiorite in the Bi'r Umq Complex that was dated at ca. 760 Ma (Dunlop et al., 1986; Pallister et al., 1989). Consequently it may be concluded that D1-deformation should have started after 820 Ma and that D3-deformation should have ceased by 760 Ma.

3.3.4 Structures outside the shear zones

3.3.4.1 Introduction

Some of the foliated rocks in the BUC and the Mahd group contain no indicators of non-coaxial deformation. They are treated as not being directly related to the shear zones, and they are described below.

3.3.4.2 Folding

Meso-scale folds were observed to fold S0 bedding (Figure 3-13) and they define F1-folds. Folding of the S0 bedding defines a NE to ENE trending fold-axis (Figure 3-14a). The meso-scale fold axes are sub-horizontal and trend NE to ENE (Figure 3-14d), indicating NW-SE to NNW-SSE compression. In places, a WSW-ENE striking axial planar foliation (Figure 3-14e) was observed in the meso-scale folds. The trend of these planes is parallel to the main foliation outside of the shear zones and therefore, this foliation is interpreted to be the result of the folding about WSW-ENE fold axes.

3.3.4.3 Foliation

Slates and schists in the Mahd group constitute foliated sequences of a centimeter to a few meters wide within otherwise undeformed volcanic and sedimentary rocks that occur outside of the shear zones in the Bi'r Umq area (Figure 3-13). The schists belong mainly to greenschist-facies as indicated by the presence of quartz, albite chlorite and white mica. Bedding (S0) was occasionally observed and in places where bedding and foliation were observed together, the foliation appears bedding-parallel. This relationship is commonly observed as the initial bedding foliation relationship in regionally folded rocks (Ramsey and Huber, 1983). Foliated sections in the BUC consist mainly of biotite schist (Figure 3-13b). Bedding (S0) in these rocks strikes WNW-ESE and dips steeply to vertical (Figure 3-14a). The main trend of foliation in the Mahd group and the BUC is WSW-ENE (Figure 3-14b and Figure 3-14c).

3.3.4.4 Formation of structures outside the shear zones

The structures observed outside the shear zones as outlined above, comprise folds and foliations. The main trend of the regional foliation strikes NE-SW to WSW-ENE (Figure 3-14b and Figure 3-14c) similar to fold axial planar foliation (Figure 3-14e). Associated fold axes trend WSW-ENE (Figure 3-14d), and all the structures are consistent with a NW-SE to NNW-SSE directed shortening. Folding of S0 indicates a similar trend (Figure 3-14a). This indicates that this phase of deformation was related to NW-SE to NNW-SSE shortening and that the regional foliation is related to F1-folding. Although no evidence of non-coaxial strain was observed in the areas where S0-bedding and F1-folding, the relative proximity to the BUSZ justifies a relationship between the structures observed in the BUSZ and those outside which provide evidence for non-coaxial deformation. NW-SE to NNW-SSE shortening can be related to NW-SE to NNW-SSW compression during coaxial strain, it can be related to dextral strike-slip movement on an E-W trending N-dipping shear zone, or it can be related to sinistral strike-slip movement on an N-S trending W-dipping strike-slip shear zone. The orientation of shortening indicated by the folds and foliation is (sub-)parallel to the D1-shortening that was deduced from the shear zone-related structures. Therefore it is assumed that the F1-folds and the foliation that developed outside the shear zones were formed during that same D1-deformation event.

3.4 Discussion and conclusions

3.4.1 Review of new data for the Bi'r Umq Complex

Table 3-1 and Figure 3-15 summarize the Neoproterozoic history of the Bi'r Umq area. The Bi'r Umq Complex and its surrounding areas are interpreted as ophiolitic sequences, which were formed before 820 Ma. The presence of ultramafics, pillow basalts and cherts in the BUC support this. Layered gabbros and sheeted dykes are missing and therefore, together with the sequence of ultramafics, pillow basalts and cherts in the BUC, they form a dismembered ophiolite. The ophiolite is characterized by mixed MORB/island-arc geochemistry (Johnson et al., 2002).

The rocks of the Bi'r Umq area display a variety of structures that can be related to one of the three of deformational events described in this chapter. Structures within the shear zones, namely S1-foliations, L1-lineations and shear indicators, as well as structures outside the shear zones, namely F1-folds and an associated foliation, are remnants of the oldest (D1) ductile deformation phase. This phase involved thrusting with a minor dextral component on the BUSZ and on the minor shear zones in the BUC, and represents a regional NW-SE to NNW-SSE compression event at greenschist conditions.

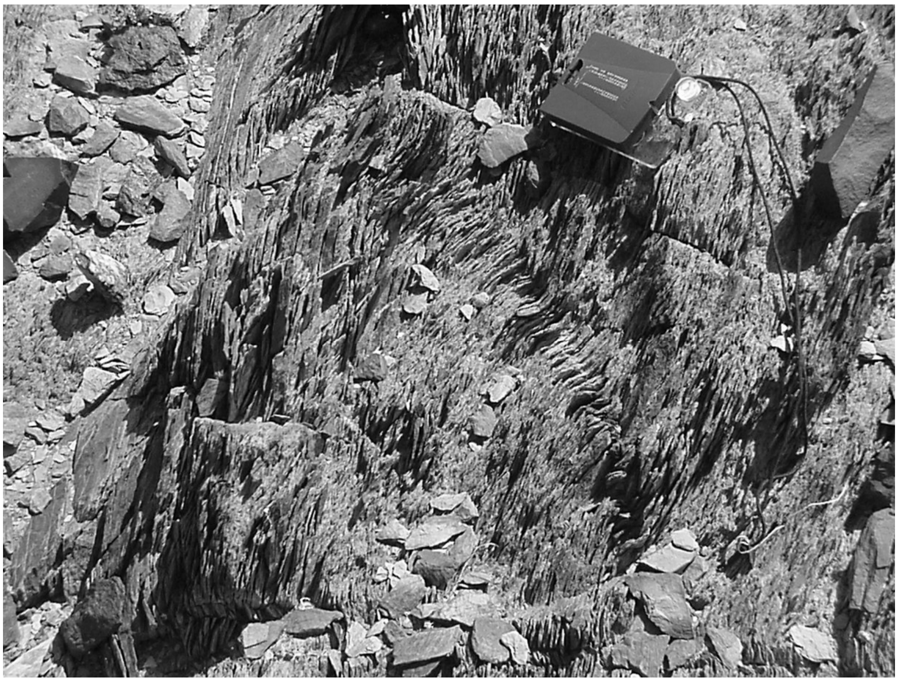


Figure 3-13 Example of non-shear zone related structures away from the shear zones: Foliated basalt in Mahd group, close to contact with BUSZ. A mesoscale late kinkfold is shown in this photograph.

D1 was followed by D2, which is characterized by dextral strike-slip with a minor transpressive component along the WSW-ENE trending BUSZ. It occurred during lower greenschist grade. The deformation is recorded by sub-horizontally WSW plunging elongated clasts and an abundance of dextral shear indicators. These structures resulted from WNW-ESE directed σ_1.

D2 was followed by sinistral-strike slip with a minor transtensional component along the same WSW-ENE trending shear zone at brittle conditions. This phase is referred to as the D3-deformation phase and formed during NNE-SSW directed σ_1. The D1- to D3-deformation events postdated formation of the ophiolite at ~820 Ma and predated the emplacement of ca. 760 Ma undeformed intrusives that cross-cut the BUSZ (Pallister et al, 1988).

As mentioned previously, thrusts do not form initially as steeply as the BUSZ, and so other indications of thrusting are required, such as metamorphic breaks between rocks at both sides of a shear zone. The Mahd Group, S of the BUSZ, consists of upper-crustal volcanics, and the rocks in the BUC (including those in the BUSZ), just N of the contact with the Mahd Group, consists of lower parts of an oceanic crust. Consequently it can be assumed that SE-vergent thrusting along the steep NW plunging lineation at the BUSZ juxtaposed the Mahd Group and BUC. This justifies the conclusion that the top-to-the SE movement along the steeply NW plunging lineations took place during SE-vergent thrusting. The BUSZ is a steeply dipping shear zone and this is very rare for thrusts. However, strike-slip shearing took place along steep shear zones and since the strike-slip movement in the BUSZ took place along the same shear zone as the thrusting, the strike-slip events is assumed to have caused the steepening of the foliation during D2 and D3. The fact that the metamorphic conditions of deformation on the moderately dipping minor shear zones of the BUC, formed during NW-SE compression, were the same as the highest metamorphic conditions on the steeply plunging lineations of the

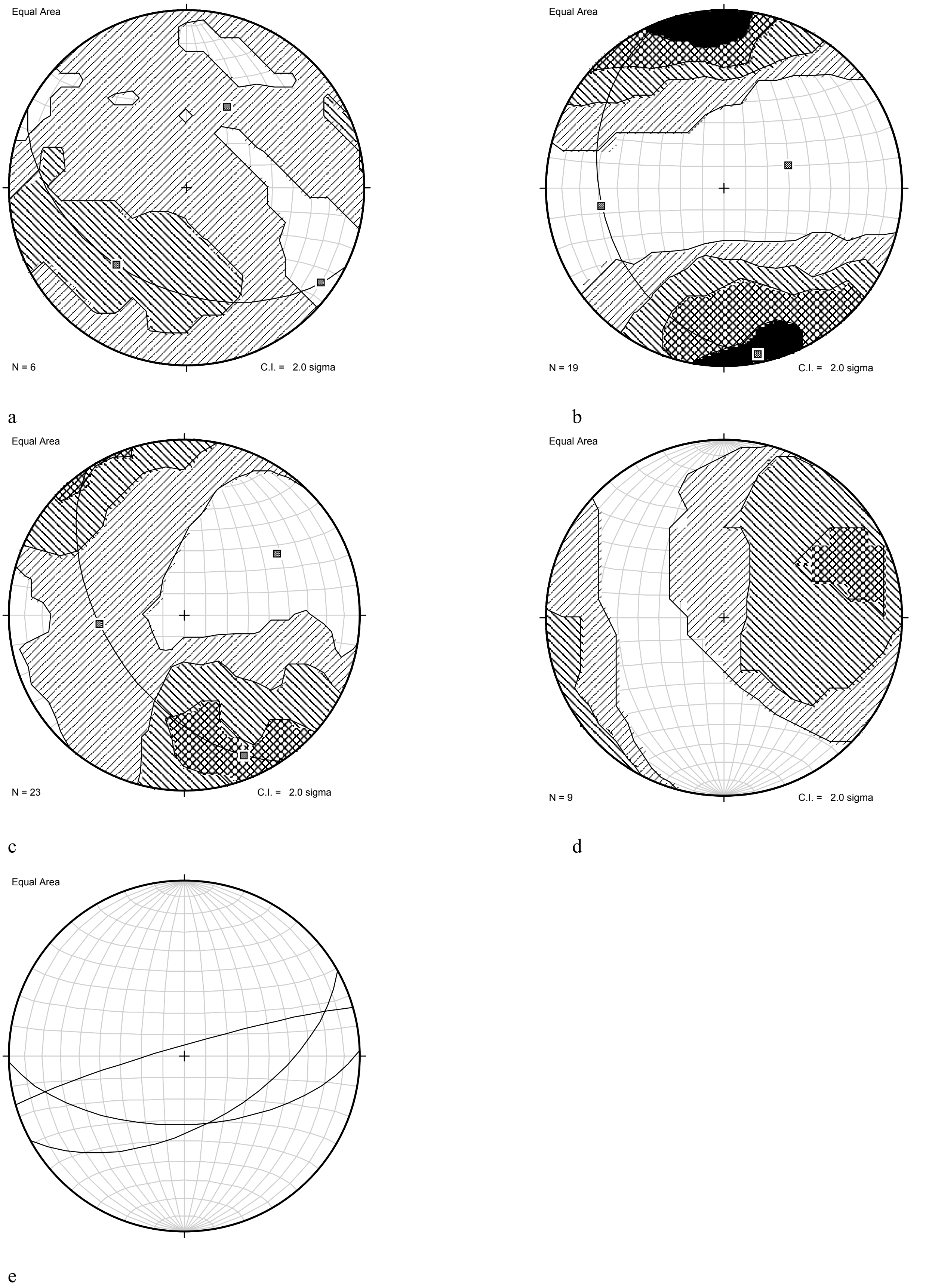


Figure 3-14 Stereo plots of structural features outside shear zones in the BUC and Mahd Group. (a) Contour plot of the poles to the S0 bedding in the Mahd Group (no data from shear zones included); (b) Stereo plot of poles

to the foliation in the Mahd group (no data from shear zones included). (c) Stereo plot of poles to the foliation in the BUC (no data from the shear zones included). (d) Stereo plot of fold axes in the Mahd group and the BUC (no data from the shear zones included). (e) Stereo plot of axial planes of folds in the Mahd group and the BUC (no data from the shear zones included).

BUSZ indicates that the steepening on the BUSZ didn't lead to a rotation of the lineations. Therefore the steeper L1-lineations of the BUSZ were also formed at a NW-SE compressional regime, however initially at a moderate plunge.

3.4.2 A tectonic model for the Bi'r Umq Complex

In the past, ophiolites were thought to be relicts of oceanic crusts that were formed at mid oceanic ridges (Dilek, 2003). However, over the past two decades, evidence was found for the formation of ophiolites in suprasubduction zones (e.g. Dilek, 2003; Hawkins, 2003; Pearce, 2003). In these cases, the formation of ophiolites is related to "local" extension above a subduction zone (e.g. Flower, 2003; Stern and Bloomer, 1992). The extension, that forms these suprasubduction ophiolites, takes place in the back-arcs and in fore-arcs of island arcs (e.g. Flower, 2003; Stern and Bloomer, 1992). Ophiolites from fore-arcs form at the initial stages of subduction when extension occurs and is related to early slab roll-back that forms the actual subduction zone (Flower, 2003; Stern and Bloomer, 1992). In such a scenario, astenospheric material flows into area between the future overriding plate and the subsiding plate (Fowler, 2003; Stern and Bloomer, 1992). Back-arc ophiolites form due to extension that is related to continuing slab roll-back after the initial stages of the intra-oceanic subduction (Hawkins, 2003). The geochemical characteristics of back-arc ophiolites are close to those of ophiolites that are supposed to be derived from mid oceanic ridges but may also contain characteristics of nearby island-arcs. Fore-arc ophiolites have geochemical characteristics that are intermediate between mid oceanic ridges and island-arcs (Pearce, 2003). The geochemistry of the Bi'r Umq Complex is intermediate between typical mid oceanic ridges and island arcs (Johnson et al., 2002). Detailed geochemical data are required to differentiate between the two modes of ophiolite-formation presented here, however this is not available for the Bi'r Umq Complex. The fact that the ophiolites of the Bi'r Umq Complex have a mixed MORB/OIB geochemistry, together with the fact that the Bi'r Umq Complex is actually close to the island-arc relicts of the Jiddah Terrane and Hijaz Terrane, suggest that the Bi'r Umq Complex as a suprasubduction ophiolite that was formed in a fore-arc or a back-arc in accordance with the interpretation of Johnson et al. (2002) and Dilek and Ahmed (2003). In recent studies other ophiolites in the ANS, as the Halaban ophiolite, the Garf ophiolites and the Fawakhir ophiolite, have also been interpreted to have been formed in fore- or back-arcs (Al-Salah and Boyle, 2001; El-Sayed and El-Nisr, 1999; Zimmer et al., 1995).

Two important environments of emplacement of ophiolites are recognized (e.g. Ernst, 2003; Wakabayashi and Dilek, 2003): 1) emplacement at Alpine (or Thetyan) orogenic belts; 2) emplacement at Pacific (or Cordilleran) orogenic belts. Emplacement of ophiolites at Alpine orogenic belts is characterized by presence of a granitic gneiss basement, UHP metamorphism, a large age differences between the different units and little to no calc-alkaline magmatism

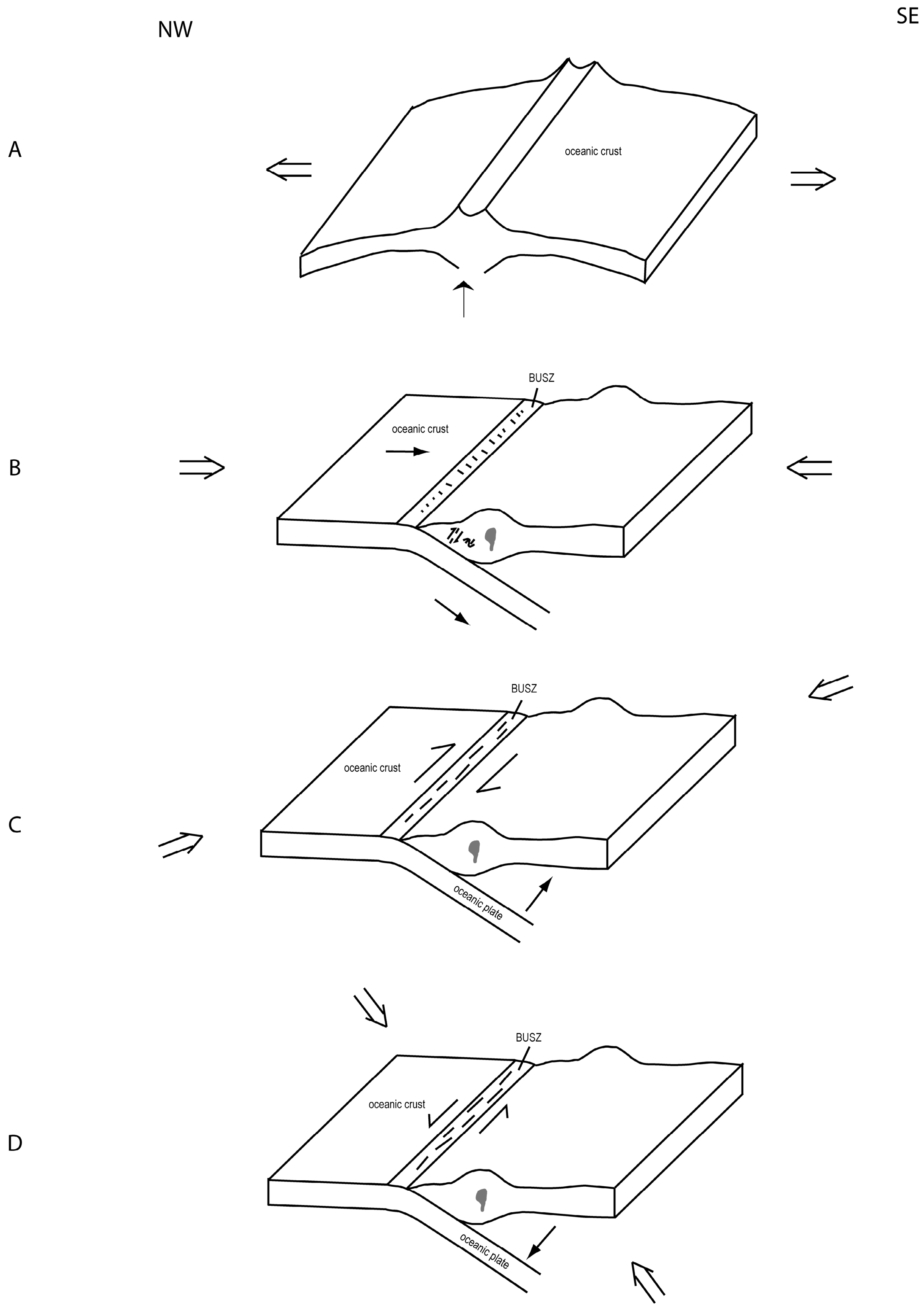


Figure 3-15 The tectonic evolution of the Bi'r Umq Complex: (a) Formation of an ophioliteas recorded by the presence of ultramafics; (b) Subduction and arc-accretion led to thrusting during NW-SE compression in the BUC; (c) A change in plate-motion results in WNW-ESE compression as recorded by dextral transpressional strike-slip movement along the BUSZ during continuing arc-accretion; (d) Another change in plate-motion results in shear reversal along the BUSZ results in NNE-SSW compression.

(Ernst, 2003). The emplacement of ophiolites at a Pacific orogenic belt is characterized by presence of large amounts of island-arc remnants (in the form of island-arcs and suspect terranes), HP metamorphism, a small range of ages, calc-alkaline magma associated with emplacement and the presence of paired metamorphic belts (Ernst, 2003). The differences are related to the fact that at Alpine orogenic belts parts of continental crusts are subducted together with the oceanic lithosphere (Ernst, 2003). This typically happens in smaller oceanic basins that are close to continental margins (Ernst, 2003; Wakabayashi and Dilek, 2003). During Pacific-type orogenies, enormous amounts of oceanic crust with island-arcs are subducted and this leads to the extensive calc-alkaline magmatism (Ernst, 2003). This type of ophiolite emplacement is often associated with arc-accretion (Wakabayashi and Dilek, 2003). The Bi'r Umq Complex and its surrounding areas display mainly geological features that can be associated with emplacement during a Pacific-type orogen, as the island-arc remnants of the Hijaz Terrane and the Jiddah Terrane, a small range of ages, a lack of UHP metamorphism and abundant calc-alkaline intrusives. The ophiolites would be thrusted into the accretionary prism during subduction of the oceanic crust below the overriding plate. The subduction that caused the emplacement the ophiolites took place at 820-760 Ma. In this period no subduction at was recorded an active continental margin in the ANS (see chapter 2). The emplacement of the ophiolite of the Bi'r Umq Complex should thus have taken place at an island-arc.

It is generally accepted that the ANS went through a period of subduction and arc-accretion from ca. 800-620 Ma (see Chapter 2 and references within). The structures of D1, D2 and D3 in the Bi'r Umq Complex were thus formed in a period when the Shield was mainly experiencing compression through subduction processes and arc-accretion. The D1-phase of NW-SE compression fits well into the arc-accretion along the NW-SE trending ophiolitic sutures that took place at ca. 800-700 Ma in the Arabian Nubian Shield (see Chapter 2). This phase should thus also have been responsible for the initial emplacement of the ophiolitic rocks of the Bi'r Umq Complex. The timing of the deformation of D2 and D3 indicates that these deformation phases also took place during the arc-accretion along the NE-SW trending sutures in the ANS. Consequently, the WNW-ESE directed σ_1 of D2, that caused the dextral strike-slip with a minor transpressional component along the BUSZ, resulted from WNW-ESE compression. The NNE-SSW directed σ_1 of D3, which caused sinistral movement with a minor transtensional component on the same ENE trending BUSZ, resulted from NNE-SSW compression.

The changes in the style of deformation, from thrusting to strike-slip deformation (with oblique components), during arc-accretion, is commonly observed in "traditional arc-accretion" systems such as those that were form during the Mesozoic and Cenozoic in western North America (e.g. Oldow et al., 1989; Cole et al., 1999; Wolf and Saleeby, 1992). As an example, the accretion of the Wrangelia Terrane to Southern Alaska, from 85 to 55 Ma, went through an era of pure shortening, and was followed by strike-slip movement at the later stages of arc-accretion (Cole et al., 1999). The shift in the compression-field during the Wrangelia accretion onto Alaska was related to a change in plate motion of the subducting plate (Cole et al., 1999).

Table 3-1 Table with the main Neoproterozoic geological events in the Bi'r Umq Complex.

Main geological and deformation phases in the Bi'r Umq Complex

Phase	Lithology	Metamorphism	Structures produced	Age constraints (in Ma)
Ophiolitic phase	Chert, basalt, peridotites (now as carbonated ultramafic), harzburgite (now as serpentinite) .	N/A	None.	> 820
D1	Serpentenite, greenschist, diorites in Jiddah Terrane	greenschist	F1 folds, S1, L1, reverse shear indicators (thrusting) -> NW-SE compression	820-760
D2	N/A	Very low greenschist	L2, dextral shear indicators -> WNW-ESE compression	820-760
D3	N/A	Brittle	Sinistral shear indicators -> NNE-SSW σ_1	820-760

Strike-slip movement with oblique components is commonly associated with oblique subduction during Pacific-style arc-accretion (Oldow et al., 1989). As an example, the Kings River Ophiolite in Western U.S.A. recorded a component of transpressional strike-slip movement during subduction and arc-accretion in the early Mesozoic during the Cordilleran Orogeny (Saleeby, 1982). Transtension along strike-slip faults was also observed during arc-accretion and during subduction at Pacific-style orogenies. Examples for this type of deformation have been described for the Cenozoic in the Pacific Northwest and Alaska in North America (Oldow et al., 1989), the Nevadan Orogeny (Saleeby, 1982; Shervais et al., 2005) and faulting that was related to the subduction of the Cocos Ridge beneath Costa Rica (Fisher et al., 1994). The shift from compression to transtension during the Nevadan Orogeny in the North American Sierra Nevada was also attributed to the changes in plate-motion, in this case by a change in plate motion of the subducting Proto-Pacific plate (Wolf and Saleeby, 1992).

As demonstrated above, the combination of an ophiolitic sequence with a deformation history of thrusting followed by strike-slip movement (with an oblique component) is typical for "ophiolitic sutures" related to obduction of oceanic crust followed by the closure of an oceanic basin along a subduction zone during arc accretion. The obduction of a fragment of oceanic crust and emplacement within the overriding plate took place through thrusting during D1 in the BUC in a NW-SE to NNW-SSE compression regime. The abundance of arc-related igneous rocks to the south of the Bi'r Umq Complex, would imply a SE dipping subduction zone during D1. Continuing subduction with changes in the direction of plate motion led to dextral strike-slip movement with a transpressional component (D2). Sinistral strike-slip shear reversal occurred at brittle-ductile conditions (D3), reflecting another change in the trend of plate motion and consequently a change in the trend of collision of an oceanic plate upon the new continental plate, following incorporation of the Bi'r Umq ophiolitic complex.

It should be noted that the Bi'r Umq Suture in the Saudi Arabian part of the Arabian-Nubian Shield, of which the ENE-trending BUSZ is the main structural remnant in the BUC, and the Nakasib Suture, which is the Sudanese continuation of the Bi'r Umq Suture, trend NE-SW (see Figure 3-1). No description exists in generally available literature for shear related lineations in other parts of the Bi'r Umq Suture and the Nakasib Suture. It is however generally assumed that the initial movement on the Nakasib and Bi'r Umq Sutures (named D1 in most studies) was related to NW- or SE-vergent thrusting (e.g. Abdelsalam and Stern, 1993; Abdelsalam and Stern, 1996; Wipfler, 1996; Johnson et al., 2002). These NW- and SE-vergent thrusts were formed during NW-SE compression, parallel to the D1-phase in the Bi'r Umq area. Because the earliest phase of deformation in the Bi´r Umq area and in the other parts of the Bi´r Umq and Nakasib Sutures are parallel, it can be concluded that during D1, the BUSZ was already trending WSW-ENE, at a small angle with the general NE-SW trend of the Bi'r Umq and Nakasib Sutures. Most studies of the Nakasib and Bi'r Umq Sutures also indicate that early 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.

Summarizing, it can be concluded, from the geological observations that were presented in this chapter, that the main geological features observed in the Bi'r Umq Complex, an ophiolite that recorded thrusting and significant phases of (oblique) strike-slip movement, justify the interpretation as an ophiolitic suture that was obducted during arc-accretion in the Neoproterozoic. The time-spans and the shifts in compression-fields are similar to those observed in "traditional arc-accretion" systems. The Bi'r Umq Suture, of which the Bi'r Umq Complex is part, represents the contact between the Jiddah Terrane and the Hijaz Terrane. Both terranes consist of remnants of island-arc complexes (Johnson et al., 1987; Stoeser and Camp, 1985). The deformation that was recorded in the Bi'r Umq Complex should thus reflect the kinematics that was responsible for the emplacement of the ophiolites of the Bi'r Umq Complex and the juxtaposition of the Jiddah Terrane and the Hijaz Terrane. Since ophiolite-emplacement and the juxtaposition of terranes should have been taken place in a relatively short time-interval of less than 50 Ma, they should be related to each other.

The following tectonic model is suggested for the Bi'r Umq Complex:

1) An oceanic sequence was formed at a fore-arc or back-arc before 820 Ma. Ultramafics, basalts and cherts are remnants of this phase.

2) After ca. 820 Ma, obduction of a fragment of oceanic crust started in a NW-SE trending compressional field due to SW-directed subduction and caused emplacement of the ophiolite in the overriding plate. The D1-phase of deformation resulted in the formation of a shear zones at the border of *Mahd Group* and the Bi'r Umq Complex and within the Bi'r Umq Complex. The NW-SE to NNW-SSE compression resulted in the formation of folds with an axial planar cleavage outside the shear zones. The emplacement of the ophiolite took place at an island-arc. The NW-SE compression was also described in literature for other parts of the Bi'r Umq Suture, and its Sudanese continuation, the Nakasib Suture.

3) Dextral strike-slip deformation with a minor transpressive component (D2) overprinted the thrusting phase (D1). During this phase, the BUSZ was steepened. Strike-slip movement is a common feature at the later stages of arc-accretion. This is for example observed in the ophiolites of Western North America. D2 took place during WNW-ESE compression. A change in plate motion causes the observed structural changes in the shear zones of the Bi'r Umq Complex.

4) A second change in plate-motion resulted in shear reversal along the Bi'r Umq Shear Zone. Brittle structures that were formed during sinistral strike-slip with a minor transtensional component overprinted D2-structures. This phase of deformation was referred to as D3. This phase took place during NNE-SSW compression.