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Structural evolution of the Neoproterozoic Western Allaqi–Heiani suture, southeastern Egypt

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Abstract

The Neoproterozic Allaqi–Heiani suture in southeastern Egypt is the western extension of the Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture that represents one of arc–arc sutures in the Arabian–Nubian Shield. It extends for more than 250 km from the N-trending Hamisana Shear Zone in the east to Lake Nasser in the west. It separates the 750-Ma-old Southeastern Desert terrane in the north from the 830–720-Ma-old Gabgaba terrane in the south. Structural studies supported by remote sensing investigations including Landsat Thematic Mapper (TM) images show that the western part of Allaqi–Heiani suture zone constitutes three S- to SW-verging nappes in the north overriding an autochthonous block to the southwest. SW-verging, low-angle thrust sheets and folds, forming a 10-km wide imbrication fan, dominate the northern upper nappe (northern allochthon). These folds and thrusts deform shelf metasedimentary rocks including psammitic metasediments, marble and subordinate conglomerate. Volcanic rocks including rhyolites and felsic tuffs dominate the upper part of the northern allochthon. The contacts between the metasedimentary rocks on the one hand and the rhyolites and felsic tuffs on the other hand are extrusive. This allochthon overrides an internally deformed nappe (central allochthon) dominated by arc and ophiolitic assemblages now preserved as felsic and mafic schist, talc schist, serpentinites, and metagabbros. This allochthon is characterized by NW-trending, upright folds, which deform the earlier sub-horizontal structures. The structurally lower nappe (southern allochthon) is dominated by NNE-trending folds which deform amphibolite facies schistose metavolcanic and metavolcanoclastic rocks. The NNE-trending folds deform earlier NW-trending folds to produce crescentic dome interference pattern with well-developed NE-trending axial planar cleavage, consistent with ESE–WNW bulk shortening. The southernmost structural unit is an autochthonous block dominated by arc-related volcanic and volcanoclastic rocks. This block has suffered only minor deformation compared to the nappes to its north. The consistent SW-vergence of the structures indicates tectonic transport from northeast to southwest, followed by ESE–WNW shortening similar to that found in the Hamisana Shear Zone, further east. Collision between the Gabgaba–Gebeit terrane and the Southeastern Desert terrane along the Allaqi–Heiani suture, after the consumption of a marginal basin probably over an N-dipping subduction zone, led to the formation of EW- to NW-trending folds and thrusts. This was followed by ESE–WNW tectonic shortening to form NNE-trending folds, which are found to be overprinting the earlier structures. This latest shortening

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might be due to collision between the Arabian–Nubian Shield and the Saharan Metacraton along an N-trending arc–continent suture represented farther south by the Keraf suture.

Keywords: Allaqi–Heiani; Arabian–Nubian Shield; Egypt; Suture

1. Introduction

The Neoproterozoic rocks of the Eastern Desert of Egypt form a belt of rugged mountains, which widens southward into the Red Sea Hills of the Sudan, and continues into Eritrea, Ethiopia, Somalia, and farther south to Kenya. The Nubian Shield is separated by the Red Sea from its counterpart, the Arabian Shield, exposed in western Saudi Arabia and Yemen. In southern Ethiopa and northern Kenya, the Arabian–Nubian Shield passes into the Mozambique belt of eastern Africa. The two mobile belts are collectively called the East African Orogen that developed during the Neoproterozoic (900–550 Ma) Pan-African orogeny (Stern, 1994).

The Arabian–Nubian Shield is dominated by juvenile crust formed during Neoproterozoic time through accretion of intra-oceanic arcs and/or oceanic plateaux (Kröner et al., 1987; Harris et al., 1993; Stein and Goldstein, 1996). These terranes collided to form the Arabian–Nubian Shield prior to collision between East and West Gondwana (Stern, 1994; Abdelsalam and Stern, 1996). Sutures of the Arabian–Nubian Shield are divided into arc–arc sutures (separating arc terranes) that formed between ∼800 and 700 Ma and arc–continent sutures (separating the Arabian–Nubian Shield from East and West Gondwana) which formed between ∼700 and 650 Ma (Stoeser and Camp, 1985; Pallister et al., 1989; Ayalew et al., 1990; Kröner et al., 1992; Abdelsalam and Stern, 1996). The Arabian–Nubian Shield was subsequently deformed by post-accretionary structures, in the form of N-trending shortening zones such as the Hamisana Shear Zone and NW-trending strike-slip faults such as the Najd fault system. These structures formed in response to the terminal collision between East and West Gondwana, with the Arabian–Nubian Shield being squeezed between them (Burke and Sengor, 1986; Berhe, 1990; Stern, 1994; Abdelsalam, 1994; Abdelsalam and Stern, 1996).

Four arc–arc sutures are identified in the Arabian–Nubian Shield. These are from north to south: the Yanbu–Onib–Sol Hamed–Gerf–Allaqi–Heiani sutures, the Nakasib–Bir Umq suture, the Baraka–Tulu Dimtu suture, and the Adola–Moyale suture (Abdelsalam and Stern, 1996). This work focuses on the western part of the Allaqi–Onib–Sol Hamed–Yanbu suture, herein refered to as the Western Allaqi–Heiani suture. This suture is important to understand Neoproterozoic evolution of the Arabian–Nubian Shield because: (1) It is the northernmost linear ophiolitic belt that defines an arc–arc suture in the Arabian–Nubian Shield (Kröner et al., 1987; Stern, 1994; Abdelsalam and Stern, 1996); (2) It is the only suture in the Arabian–Nubian Shield where a complete ophiolite is preserved at Jebel Gerf (Zimmer et al., 1995; Fig. 1); (3) The suture extends in a general east-west direction and its western end is at a high angle to the proposed N-trending, western margin of the Arabian–Nubian Shield; and (4) Recent tectonic models have resulted in conflicting views about the continuity of the Allaqi–Heiani suture, its structural style, and the overall tectonic transport direction involved. We report new evidence which will contribute to a better understanding of (1) the deformational style along the Allaqi–Heiani suture; and (2) the overall vergence of the structures across the suture. These are used to interpret the tectonic transport direction and infer the dip of the subduction zone that existed prior to the suture formation. The work is based on structural analysis of the Western Allaqi–Heiani suture using Landsat Thematic Mapper (TM) images and field studies. Field studies involved geological traverses along wadis across the suture. Our results show that the Western Allaqi–Heiani suture is defined by distinctive SW-verging nappes forming an E- to ESE-trending fold and thrust belt with an overall tectonic transport from north to south suggesting the existence of an N-dipping subduction zone prior to suturing.

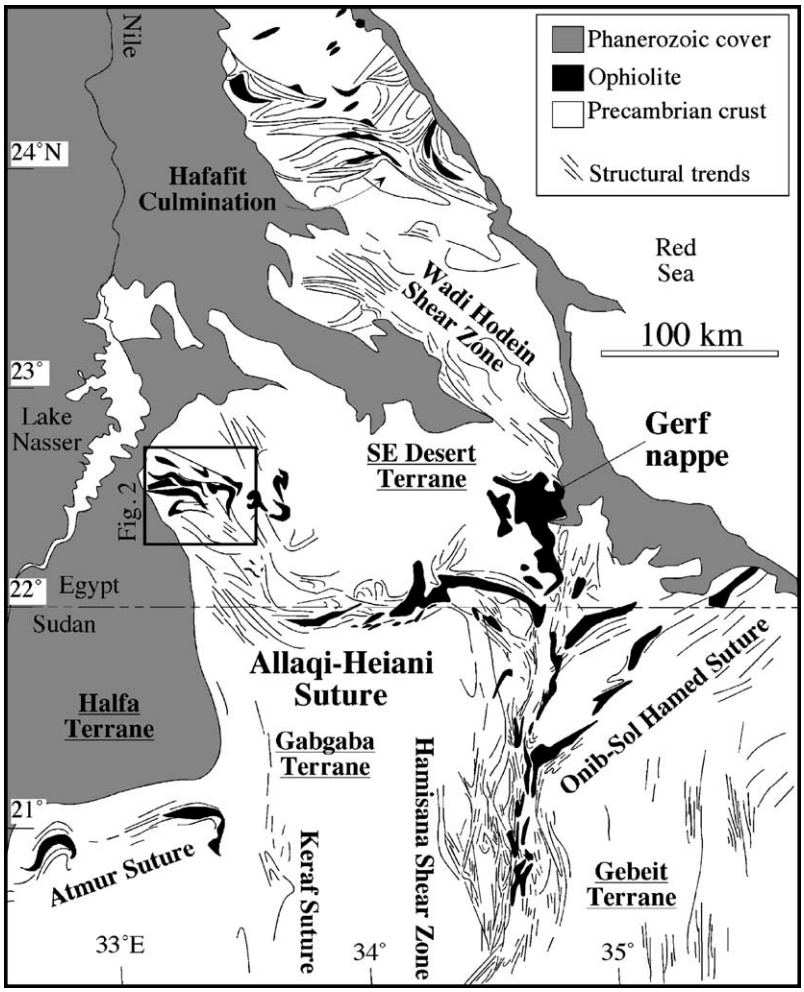

Fig. 1. Tectonic setting of the Allaqi–Heiani suture (modified after Ramadan et al., 2001).

2. The Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture

The E- to NE-trending Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture is defined by an ophiolite-decorated deformation belt that extends from southeastern Egypt, into northeastern Sudan and reappear on the other side of the Red Sea in northwestern Saudi Arabia. It separates the Egyptian Southeastern Desert–Midyan terrane in the north from the Gabgaba–Gebeit–Hijaz terrane in the south (Fig. 1). The Southeastern Desert–Midyan terrane encompasses volcanic and volcanoclastic successions along with ophiolitic rocks and sediments, all metamorphosed to greenschist or amphibolite facies (Bakor et al., 1976; Shanti and Roobol, 1979; Camp, 1984; Stern and Hedge, 1985). To the immediate south of the Allaqi–Heiani suture also lies the Gabgaba terrane which occupies the western part of the Red Sea Hills in Sudan, and is made up of immature arc–volcanic assemblages (Stern et al., 1990). The Gebeit–Hijaz terrane consists of metavolcanic and metasedimentary rocks, which are typically metamorphosed to greenschist facies. These volcanic rocks consist of a bimodal suite of basalt, basaltic andesite, and rhyolite interlayered with subordinate felsic tuff, conglomerate, greywacke, and limestone (Klemenic, 1985; Kröner et al., 1991; Reischmann et al., 1992; Johnson et al., 2002). The

Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture is apparently dextrally displaced by the 640–600 Ma, N-trending Hamisana Shear Zone in the Sudan (Stern et al., 1989, 1990; Miller and Dixon, 1992; de Wall et al., 2001; Fig. 1), and is sinistrally displaced by the 640–560 Ma NW-trending Najd fault system in Saudi Arabia (Stoeser and Camp, 1985). The apparent displacement of the Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture by the Hamisana Shear Zone was due to folding of the former by N-trending antiform which constitutes much of the major structure along the latter (de Wall et al., 2001). In addition, the northern part of the Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture, at around the Jebel Gerf nappe, is deformed by the Wadi Hodein Shear Zone (Fig. 1) which is identified as a sinistral strike-slip fault that might be the continuation of the Najd fault system from Arabia into Egypt (Greiling et al., 1994).

Apart from the Allaqi–Heiani ophiolite (to be discussed latter), ophiolite occurrences along the Allaqi–Heiani–Onib–Sol Hamed–Yanbu suture include those at Gerf (Kröner et al., 1987; Stern et al., 1989, 1990; Zimmer et al., 1995), the Onib–Sol Hamed ophiolites (Fitches et al., 1983; Hussein et al., 1984), ophiolites in northeastern Sudan and southeastern Egypt, the Jebel Ess ophiolites (Shanti and Roobol, 1979) and the Jebel Al Wask ophiolites (Bakor et al., 1976), both in northwestern Saudi Arabia. These ophiolites range in age between ~800 and 730 Ma (Pallister et al., 1989; Kröner et al., 1992).

The Gerf ophiolite occurs in southern Egypt immediately north of the Hamisana Shear Zone (Fig. 1) where it forms a nappe complex that includes a complete ophiolite succession with N-MORB geochemistry (Zimmer et al., 1995). Stern et al. (1989) obtained a single zircon Pb/Pb age of 726 ± 40 Ma and a whole rock Rb/Sr age of 551 ± 28 Ma for a post-nappe granodioritic intrusion from the Jebel Gerf area. Zimmer et al. (1995) obtained Sm/Nd whole rock ages of 720 ± 9 Ma and 758 ± 34 Ma from gabbros and basalts, respectively, associated with the Gerf ophiolite. They also obtained an Sm/Nd internal errorchron age of 771 ± 52 Ma from minerals extracted from gabbro of the Gerf ophiolite. Layered gabbro from the Gerf ophiolite (Fig. 1) gave a single zircon Pb/Pb age of 741 ± 21 Ma (Kröner et al., 1992). Zimmer et al. (1995) suggested that the Gerf ophiolite was emplaced due to collision of island arc complexes between 600 and 700 Ma.

The Sol Hamed ophiolite (Fig. 1) dips steeply to the SE, and faces towards the SE. This led Fitches et al. (1983) to suggest that the ophiolite was obducted over an SE-dipping subduction zone with the subduction-related arc volcanics unconformably overlying the ophiolites. NE-plunging folds subsequently deformed both the ophiolite and the surrounding arc volcanics. Plagiogranite from the Onib ophiolite gave a single zircon Pb/Pb age of 808 ± 14 Ma (Kröner et al., 1992).

The Jebel Ess ophiolite is a fault-bounded complete ophiolitic sequence separating a metasedimentary sequence of shale and polymict conglomerate in the south from structurally and stratigraphically higher sequence of arc volcanics to the north (Shanti and Roobol, 1979). The latter authors concluded that the Jebel Ess ophiolite was a nappe, later folded into an NE-trending synform. To the northeast of the Jebel Ess ophiolite, Bakor et al. (1976) described the Jebel Al Wask ophiolite as an NNE-trending dome with steeply dipping lithological contacts. Camp (1984) suggested that the Jebel Al Wask ophiolite constituted part of an accretionary prism overlying an SE-dipping subduction zone, with the associated arc volcanics of the Hijaz terrane to the southeast. Gabbro from the Jebel Al Wask ophiolite gave a U/Pb zircon age of 776 ± 9 Ma (Pallister et al., 1989).

3. The Western Allaqi–Heiani suture

The Western Allaqi–Heiani suture comprises a few tens kilometers wide zone of highly deformed ophiolitic assemblage, shelf metasediments, arc volcanics and volcaniclastics, and granitoids (Fig. 2).

The ophiolite assemblages mainly occupy the central part of the Wadi Allaqi area (Fig. 2) and exist as imbricate thrust sheets and slices of serpentinites, talc carbonate schist, and metagabbros. These were thrusted from north to south over the island arc felsic and mafic metavolcanic assemblages (Fig. 2). The ophiolites were possibly formed in a back-arc setting (Abd El-Naby et al., 2000). Kröner et al. (1992) obtained single zircon Pb/Pb ages of 729 ± 19 Ma and 736 ± 11.9 Ma from gabbro and diorite, respectively, which intruded the ophiolite (Fig. 2) in the

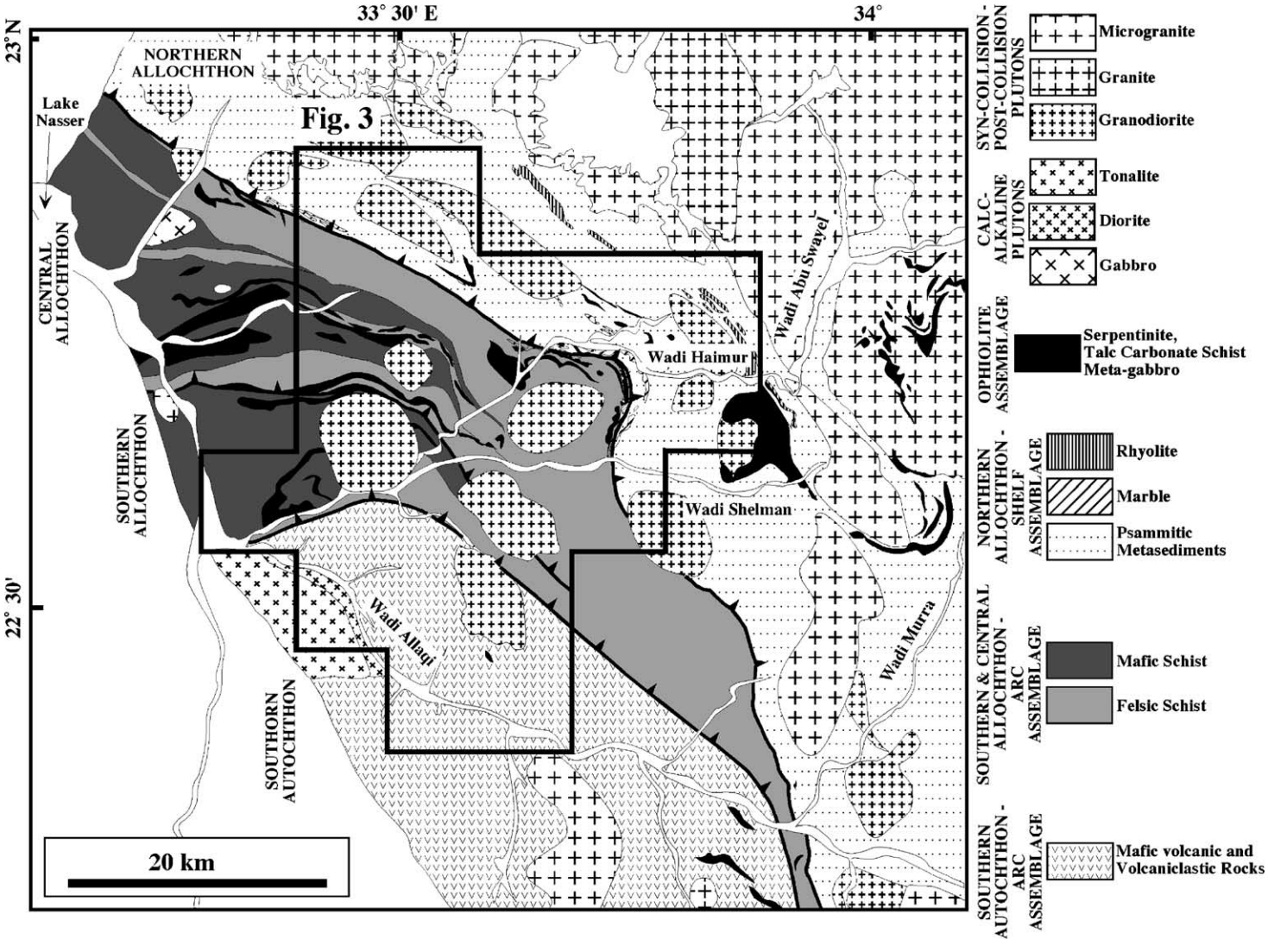

Fig. 2. Geology of the Western Allaqi–Heiani suture.

central part of the Allaqi–Heiani suture. A felsic dyke cross-cutting ophiolitic serpentinite outcropping in the northern side of Wadi Allaqi close to where it drains into Lake Nasser (Fig. 2) gave a single zircon evaporation age of 770 ± 9 Ma (Kröner et al., 1992).

The shelf metasediments dominate the northern part of the suture zone and comprise psammitic metasediments, marbles and subordinate conglomerates, rhyolites, and felsic tuffs. The contacts between the rhyolites and the felsic tuffs in the one hand and the psammitic metasediments on the other hand are extrusive. Stern and Hedge (1985) obtained a whole rock Rb/Sr isochron age of 768 ± 31 Ma from a rhyodacitic outcrop north of Abu Swayel ophiolite (Fig. 2). Zircon ages as old as 3000 Ma were obtained from detrital zircons extracted from different lithologies of the Western Allaqi–Heiani suture indicating the involvement of continental crustal component in the formation of the lithologies of the suture and/or pulses of sedimentary components which came from the Saharan Metacraton in the west (Abdelsalam et al., 2002). Wust (1989) obtained single zircon Pb/Pb ages of 1460 ± 100 Ma, 2400 ± 140 Ma, and 2450 ± 10 Ma for zircons extracted from greywacke of the Wadi Allaqi area. Kröner et al. (1992) obtained single zircon Pb/Pb age of 3017 ± 3 Ma from a detrital zircon extracted from a felsic dyke cross-cutting ophiolitic serpentinite of the Wadi Allaqi area. Farther north, in the Wadi Haimur and Wadi Abu Swayel area, Finger and Helmy (1998) and Abd El-Naby and Frisch (2002) interpreted a belt of gneissic rocks to be of metasedimentary origin, and that the sediments might have been deposited in a back arc basin prior to being metamorphosed at ∼600 Ma. Finger and Helmy (1998) dated the age of metamorphism to be between 620 and 650 Ma using Th–U–Pb systematics. Abd El-Naby and Frisch (2002) obtained ages of 498 ± 17 Ma, 581 ± 17 Ma, 593 ± 18 Ma, and 609 ± 18 Ma using K/Ar age dating on amphiboles and biotites extracted from these gneisses.

The island arc assemblage dominantly occurring south of the ophiolite belt which define the suture is represented by metavolcanics and volcanoclastic layered units and intrusive gabbro to diorite plutons (Fig. 2). El-Kazzaz and Taylor (2001) divided the rocks around the northwestern corner of the intersection of Wadi Shelman and Allaqi (Fig. 2) into three lithological successions bounded by structural contacts. The upper and the lower successions are dominantly volcaniclastic rocks whereas the middle succession consist of shallow water sedimentary rocks. All successions are affected by low-grade metamorphic event. El-Kazzaz and Taylor (2001) further suggested that the geochemical nature of these rocks indicate back-arc tectonic setting. On the other hand, El-Nisr (1997) suggested that the geochemistry of some of these metavolcanic rocks indicates a transitional environment between continental arc and continental margin. Metavolcanic rocks of intermediate to mafic composition dominate the area south of Wadi Shelman (Fig. 2). These rocks were affected by an amphibolite facies metamorphic event at ∼600 Ma. K/Ar ages of 599 ± 18 Ma, 572 ± 17 Ma, 553 ± 17 Ma, 552 ± 24 Ma, and 572 ± 26 Ma were obtained from hornblende grains extracted from amphibolite schists of Wadi Haimur area (Fig. 2) in the central part of the Allaqi–Heiani suture (Abd El-Naby et al., 2000). Whole rock–clinopyroxene, whole rock–hornblende, and whole rock–garnet Sm/Nd ages of 633 ± 61 Ma, 633 ± 42 Ma, and 592 ± 3 Ma were obtained from clinopyroxene amphibolite, metagabbro, and garnet amphibolite of the Wadi Haimur area (Abd El-Naby et al., 2000; Fig. 2).

The syn-tectonic granitoids of the Western Allaqi–Heiani suture are interpreted as collision-related magmatism (Abd El-Naby et al., 2000). These are less abundant than the metavolcanic and volcanoclastic rocks of the island arc assemblages. The intrusions are heterogeneous in composition and include gabbro, diorite, quartz-diorite, and tonalite. The geochemistry of some of these plutons was studied by El-Kazzaz and Taylor (2001), who concluded that they are arc-related, I-type granitoids. Late- to post-tectonic granitic bodies are widespread in the central part of the study area. They occur as deeply eroded, approximately circular features represented by a few isolated low-lying outcrops partially covered by recent sand deposits. Post-tectonic granitic bodies are widely distributed in the northern part of the Western Allaqi–Heiani suture. They are massive, medium grained red granites with high to medium topographic relief. Abd El-Waheb (1998) obtained a whole rock Rb/Sr isochron age of 571 ± 7 Ma from the post-tectonic granite of Jebel Murra (Fig. 2). El-Kazzaz and Taylor (2001) suggested that these are within-plate, A-type granitoids. They intrude the above rock units and are cut by felsic intrusions as well as felsic and mafic dikes.

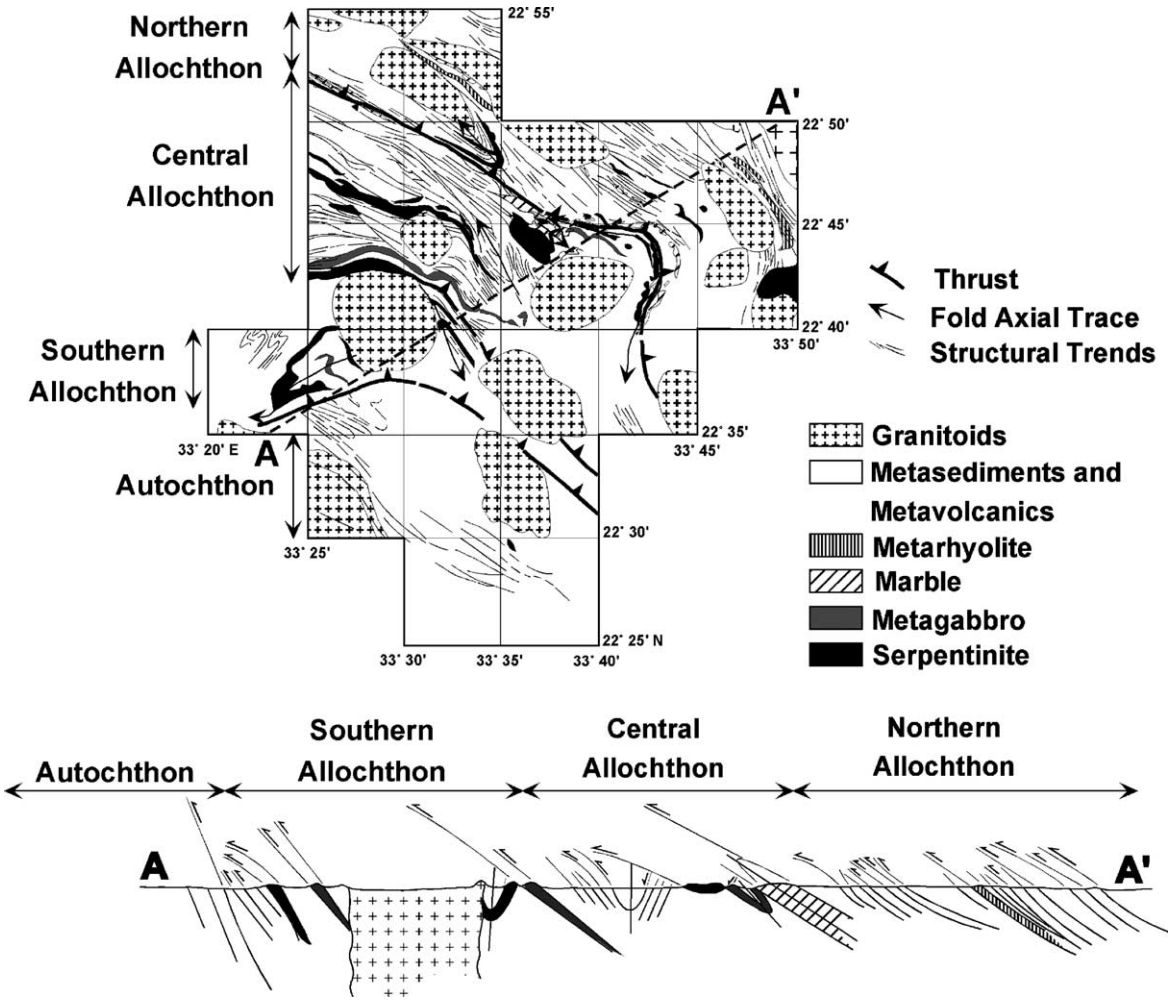

Fig. 3. (A) Structural map and (B) geological cross-section of the Western Allaqi–Heiani suture.

4. Structural analysis

In this study, the Western Allaqi–Heiani suture is divided into four structural complexes (Fig. 3). These are from north to south (i.e. from structurally higher to structurally lower): (1) A northern nappe characterized by an SW-verging imbrication fan. This complex is referred to as the northern allochthon; (2) A central nappe, referred to here as the central allochthon, in which the early SW-verging structures were subsequently deformed by NW-trending, steeply inclined folds; (3) A southern nappe, referred to as the southern allochthon, in which the early S-verging structures are folded about NE-trending, steeply inclined folds and are displaced by sinistral strike-slip faults; and (4) A southern authochthonous block, which is referred to as the southern authochthon. The boundary between the northern and central allochthons in the western part of the study area is defined by an NE-dipping thrust which separate dominantly psammitic metasedimentary rocks from felsic and mafic schists (Figs. 2 and 3) possibly of volcanic origin. NW- to NNW-trending marble layers define this thrust and occupy lowermost part of the northern allochthon. The boundary between the central and the southern allochthons is also defined by an NE-dipping thrust

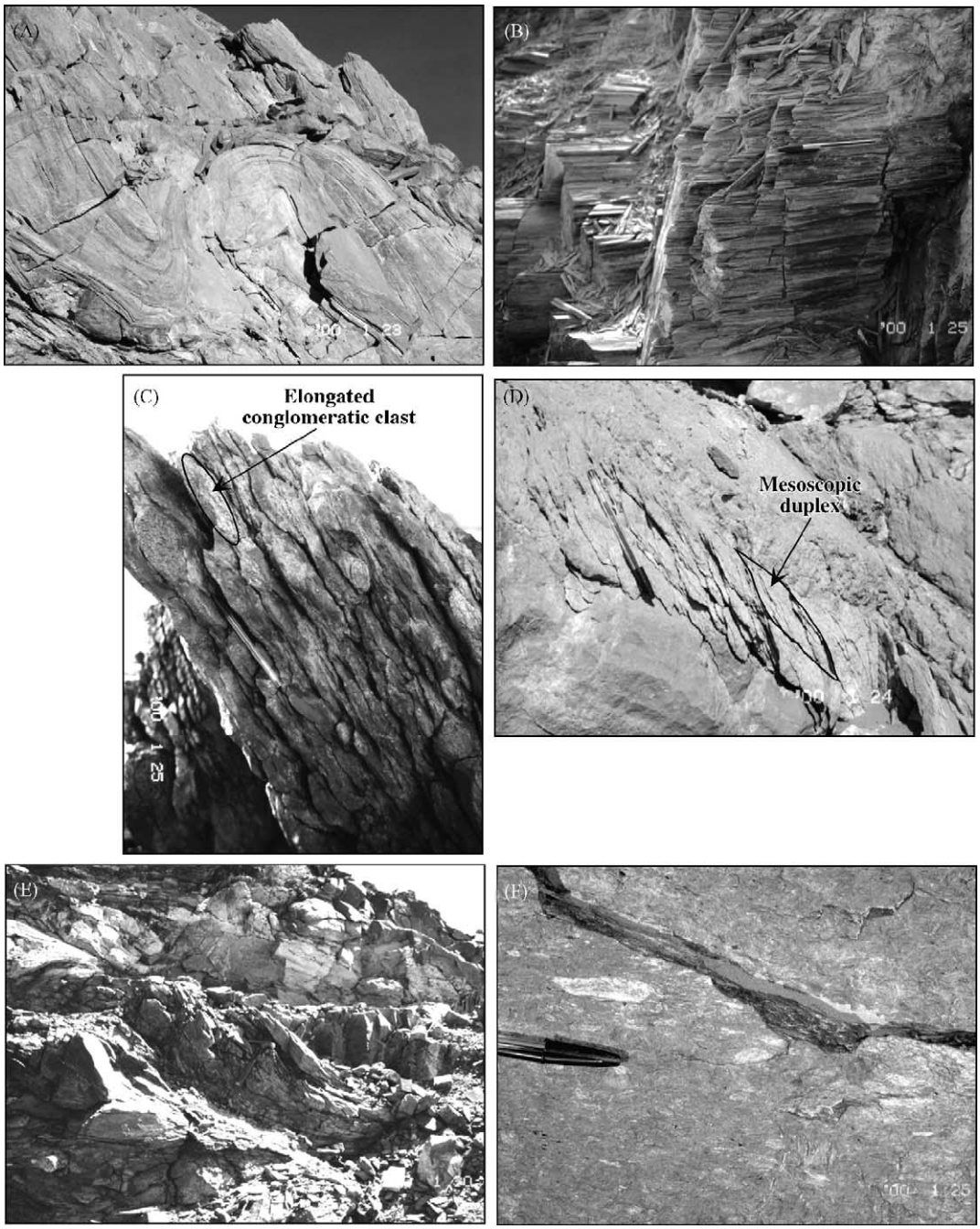

Fig. 4. Mesoscopic structures from the northern allochthon. (A) Primary layering in marble deformed by SW-verging folds. Looking NE. (B) SE-plunging pencil structure in felsic schist developed as a result of intersection between axial planar cleavage associated with early folds and primary layering. Looking NE. (C) Elongated conglomeratic clasts in a dip-parallel section defining the dominant NNW-trending stretching lineation. Looking N. Cleavage is E–W trending and moderately N-dipping. (D and E) Mesoscopic duplexes in psammitic metasediments indicating top-to-the-SSE tectonic transport direction. Looking E. (F) Minor sub-horizontal stretching lineation in E-trending, moderately N-dipping cleavage in quartzofeldspathic schist probably of felsic pyroclastic volcanic origin. Looking S.

occurring between felsic and mafic schists and serpentinite, talc carbonate schist and metagabbro (Figs. 2 and 3). A prominent metagbbro layer occupies the basal part of the central allochthon. The boundary between the southern allochthon and the southern autochthon is defined by an N- to NE-dipping thrust fault that separates dominantly felsic schist from mafic metavolcanics and volcaniclastics (Figs. 2 and 3). The boundary between the northern and central allochthons on the one hand and the southern allochthon and the southern autochon on the other hand become progressively closer to each other towards the southwest and rotate into a more northerly orientation where they constitute what El-Kazzaz and Taylor (2001) referred to as the "Allaqi Shear Zone". Farther southeast, the structures assumes an E–W orientation. Abdel-Meguid et al. (1996) identified three nappe complexes and referred to them as the upper (dominated by serpentinite and metapyroxenites), middle (dominated by sillimanite schist, metavolcanics, and metaproclastics), and southern nappe complexes (dominated by mafic gneisses and quartzofeldspathic mylonites).

4.1. The northern allochthon

This allochthon represents the northern and structurally uppermost nappe in the Western Allaqi–Heiani suture. It contains deformed shelf metasedimentary rocks including marble and subordinate metamorphosed conglomerates, and rhyolite and felsic tuffs (Fig. 3). Metamorphism is dominantly greenschist facies which resulted in the development of minerals such as muscovite and biotite which dominantly define the regional foliation suggesting that metamorphism and deformation were synchornous. The nappe is dominated by S-verging, low-angle thrust sheets. Primary layering mainly preserved in marble and rhyolite is folded around gentle to tight, SW-verging folds with SE-plunging axes (Figs. 4A and 5A). Weak axial planar cleavage in the form of a spaced cleavage is associated with these folds. This cleavage, although generally weak, is sometimes locally pervasive and its intersection with the primary layering results in the development of SE-plunging pencil structure (Fig. 4B). This nappe is also characterized by a well-developed, shallowly N- to NE-dipping shear fabrics and spaced cleavages (Fig. 5B) devel-

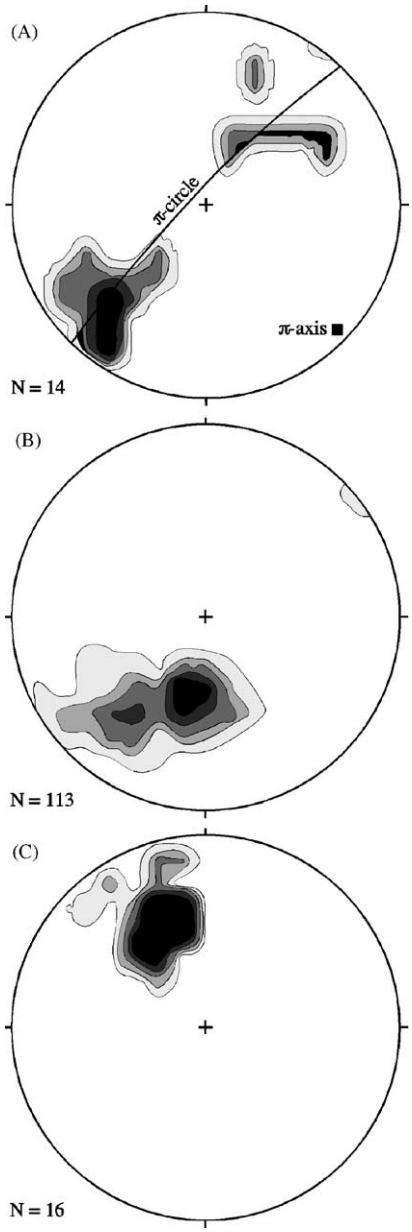

Fig. 5. Stereographic plot of structural data from the northern allochthon. All plots are lower hemisphere, equal-area stereonet projections. Contouring is at interval of 1% per unit area. (A) Poles to primary layering in marble and rhyolite. Layering is folded about an SE-trending, sub-horizontal axis. (B) Poles to shear fabric and spaced cleavage associated with emplacement of thrust sheets from NE quadrant towards SW quadrant. The tight cluster of poles indicate that the E-trending planar fabric dips moderately to the north and is not obviously folded. (C) Stretching lineation with dominant NNW-plunge.

oped along thrust contacts associated emplacement of thrust sheets from N or NE to S or SW. Individual thrust planes are easily identifiable in this allochthon, especially in the northeastern part of Wadi Shelman (Fig. 2) where thrusting resulted in extensive imbrication of thrust sheets constituting psammitic metasediments and marble. In this allochthon, the N-dipping planar fabric has not suffered subsequent deformation. This is shown by the stereonet plot where poles to planar fabric plot in a tight cluster indicating consistent E-trending, moderately dipping to the north planes (Fig. 5B). In addition, no folds that deform the tectonic planar fabric have been found in the northern allochthon. The shear fabrics contain a strong NNW-plunging stretching lineation (Fig. 5C) defined by alignment of flaky minerals such as micas as well as elongated conglomeratic clasts (Fig. 4C). The geometrical relationship between stretching lineation and planar fabrics indicate that the former is not a perfect down-dip lineation. This, together with kinematic indicators such as mesoscopic duplexes (Fig. 4D and E) suggests that emplacement of thrust sheets was from NNW to SSE. This geometry favors the development of oblique faults with dominant thrust component and minor sinistral strike-slip component. Field evidence of such minor sinistral strike-slip component is in the form of local sub-horizontal stretching lineations on sub-vertical, NW-trending planes and is defined by stretched clasts of felsic pyroclastic rocks (Fig. 4F).

4.2. The central allochthon

The central allochthon underlies the northern allochthon and is dominated by folded thrusts in mafic volcanic and felsic schists representing a greenschist to amphibolite facies metavolcanics and volcaniclastics (Fig. 6A and B) and ophiolitic rocks, including gabbros, serpentinite, and talc schist. The regional planar fabric is strongly folded about gently-plunging to NW or SE axes (Fig. 7A) and numerous mesoscopic folds are found in this unit (Fig. 6). The plunge of these mesoscopic folds, and the intersection lineations, and pencil structures coincide with the 1/4-axis for the planar fabric (Fig. 7A, B, and C) in accordance with the mesoscopic folds being geometrically related to some identifiable macroscopic folds in the area. These mesoscopic and

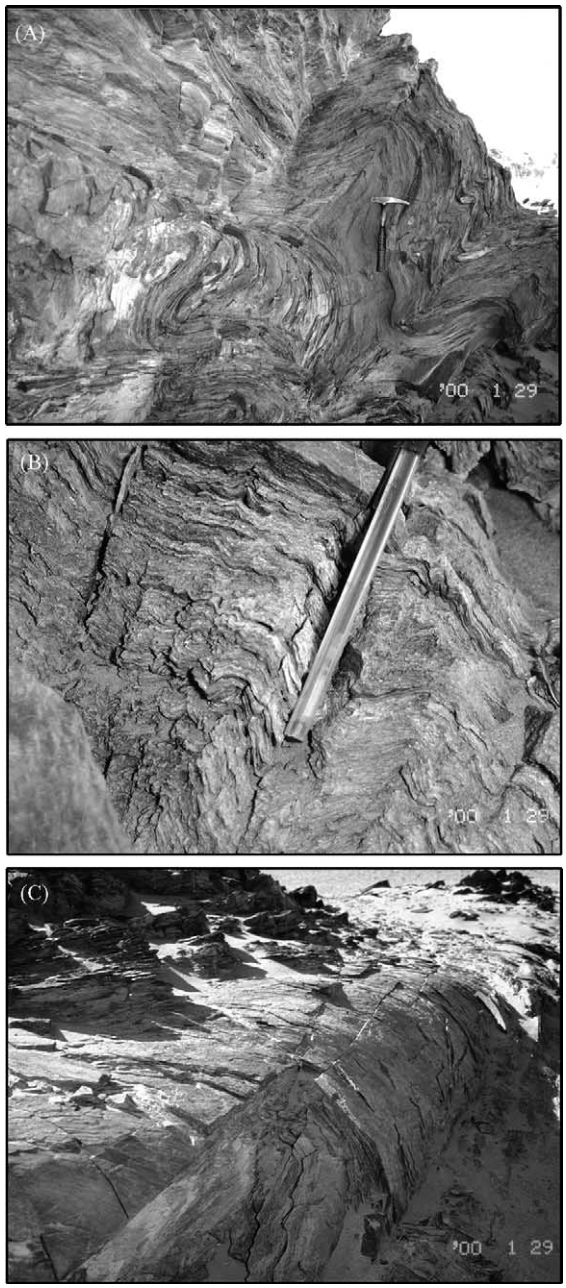

Fig. 6. Mesoscopic structures from the central allochthon. (A) An outcrop of amphibolite schist. The early planar fabric is folded about steep, but SW-verging, gently NW-plunging fold hinges. Looking NE. (B) Steeply NE-dipping, NW-trending axial planar crenulation cleavage developed in amphibolite schist. Looking NE. (C) Early stretching lineation in amphibolite schist with well-developed planar fabric. Both planar fabric and lineation are deformed by late NW-trending, steep fold. Looking NE.

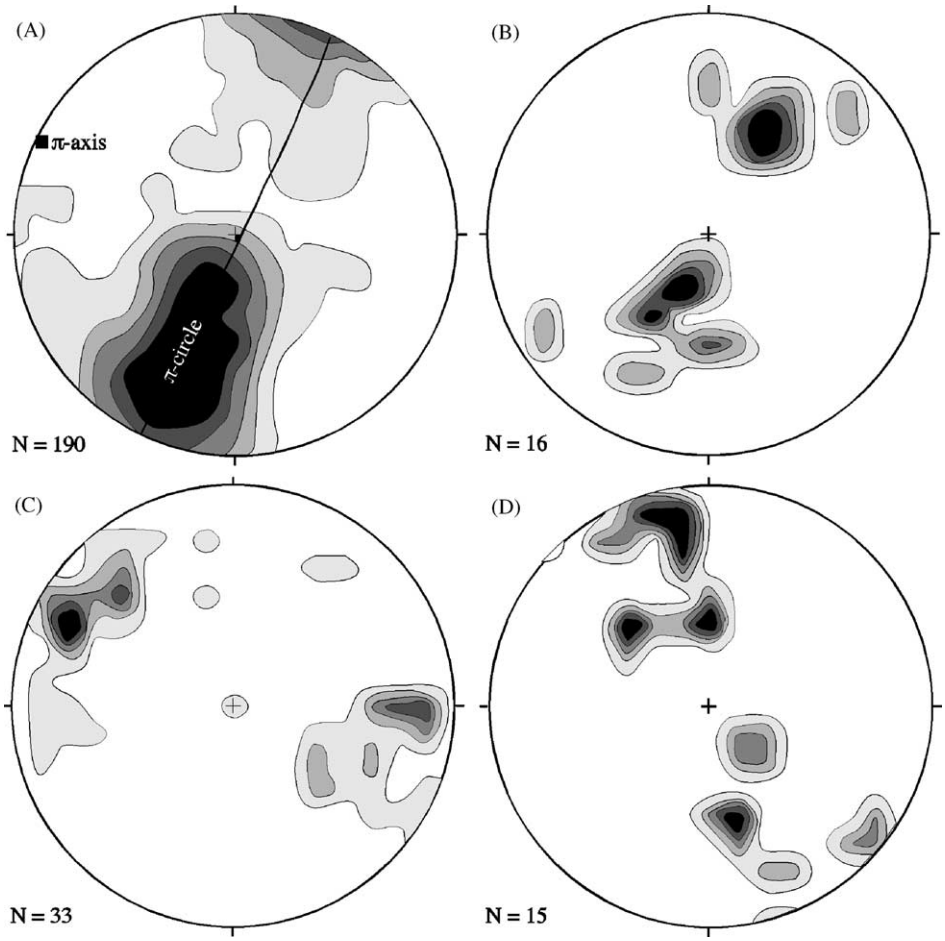

Fig. 7. Stereographic plot of structural data from the central allochthon. All plots are lower hemisphere, equal-area stereonet projections. Contouring is at interval of 1% per unit area. (A) π-diagram showing that early cleavage is folded about NW-trending sub-horizontal fold axis. (B) π-diagram showing that fold axial surfaces associated with early folds are refolded about NW-trending sub-horizontal axis. (C) Lineation related to late folding (dominantly intersection lineation and fold hinges) indicating that fold axes are shallowly plunging to the NW and SE. (D) Early stretching lineation orientation modified by late folds. The plot shows that the trend of lineations remains NNW-SSE but the plunge angle and direction varies from shallowly to the NNE to shallowly to the SSE.

macroscopic folds vary from gentle to open. They have crenulation cleavage as the dominant axial planar structure. The crenulation cleavage strikes NW and dips steeply to the NE or SW (Fig. 6B). Axial surfaces of the SW-verging early generation folds are also folded about gently NE-plunging axes (Fig. 7C). Stretching lineations developed on the regional cleavage are also deformed by late generation folds (Fig. 6C) so that their orientations vary between moderately to gently plunging to the NNW or SSE (Fig. 7D).

4.3. The southern allochthon

This allochthon is dominated by folded thrusts in amphibolite facies schistose metavolcanics and volcaniclastics; and also ophiolitic rocks including gabbros, serpentinite and talc schist (Fig. 8A and B). Unlike the central allochthon, early structures within this nappe are refolded about N-trending axes (Fig. 9A). Superimposition of some of these N-trending folds on early NW-trending folds has formed a crescentic dome that occupies the

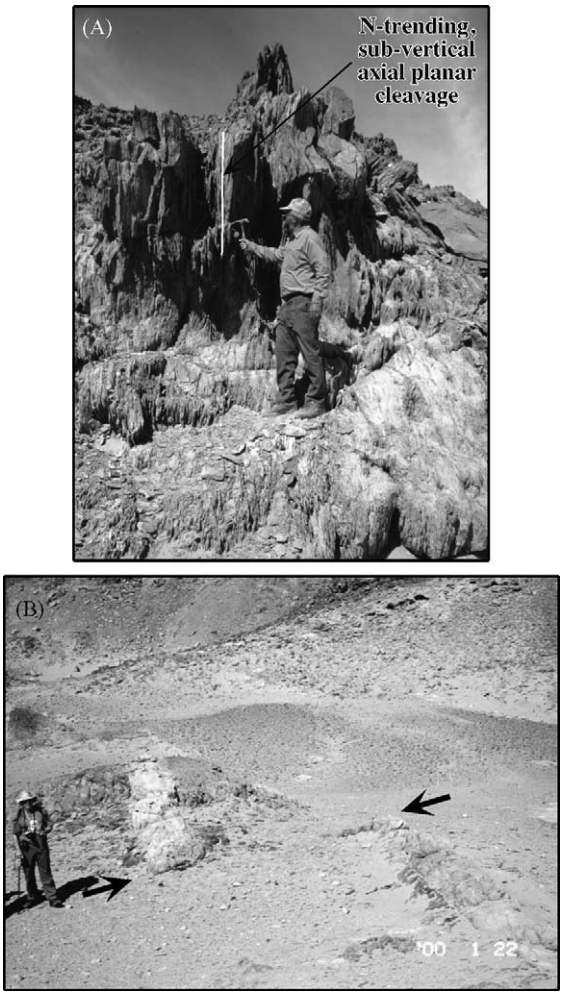

Fig. 8. Mesoscopic structures from the southern allochthon. (A) Amphibolite schist deformed by N-trending sub-vertical axial planar cleavage associated with the macroscopic N-plunging fold. Looking N. (B) NE-trending, sinistral strike-slip fault displacing serpentinite ridge in the northern part of the crescentic dome interference pattern. Arrows indicate the fault orientation. Looking NW.

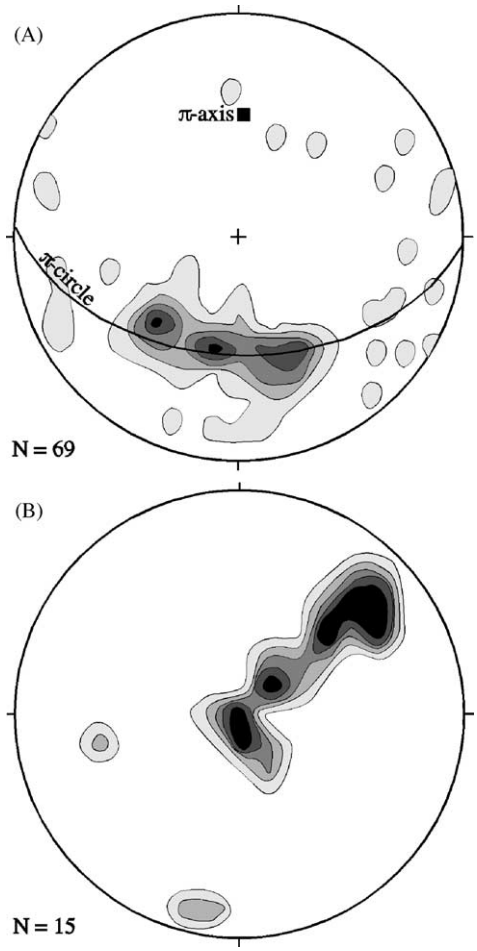

Fig. 9. Stereographic plot of structural data from the northern allochthon. All plots are in lower hemisphere, equal-area stereonets. Contouring is at interval of 1% per unit area. (A) π-diagram showing that early planar fabric is statistically folded about a moderately N-plunging-axis. (B) Lineation related to the late folds (dominantly intersection lineation and fold hinges) indicating that fold axes plunge to the NE with angles varying form sub-horizontal to vertical. The discrepancy between the orientation of the fold axis obtained from (A) and fold-related lineation in (B) is attributed to modification of the orientation of the latter by younger minor deformation event.

southwestern part of the study area (Fig. 3). Mesoscopic linear structure include minor fold axes and intersection lineations which dominantly plunge to the NE with plunge angles varying from steep to gentle (Fig. 9B). The orientation of these lineations (Fig. 9B) is different from that of the π-axis determined from π-diagram of poles to planar fabric (Fig. 9A). In addition, the southern allochthon is deformed by minor NE-trending sinistral strike-slip shearing (Fig. 8B) which displace the N-trending folding. The origin of these linear structures and strike-slip shear zones is not clear and might represent a minor later deformation event.

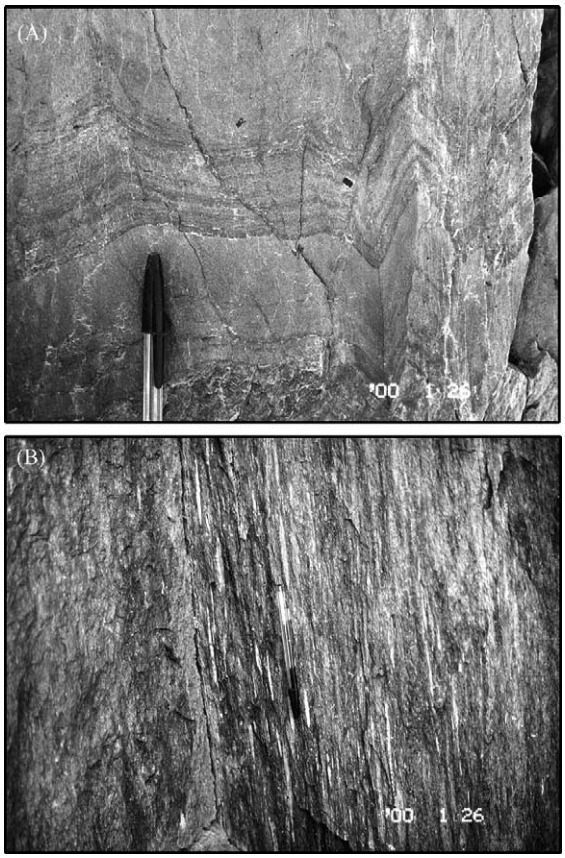

Fig. 10. Mesoscopic structures from the southern allochthon. (A) Steep, NW-trending spaced cleavage deforming mafic volcanoclastic sediments with well developed, shallowly N-dipping layering. Looking E. (B) Flattened pyroclastic clasts reoriented within NW-trending spaced cleavage. Looking SW.

4.4. The southern autochthon

This block (Fig. 3) occupies the southernmost part of the study area. It is dominated by mafic metavolcanic and pyroclastic rocks (Fig. 10A). A weak NW-trending planar fabric dips steeply towards the northeast (Fig. 11) and is associated with NW-trending, upright mesoscopic folds. Flattened volcaniclastic clasts (Fig. 10B) lie within the NW-trending steep planar fabric. The strain is consistent with NE–SW shortening, perhaps in response to collision with the northern, central, and southern allochthons.

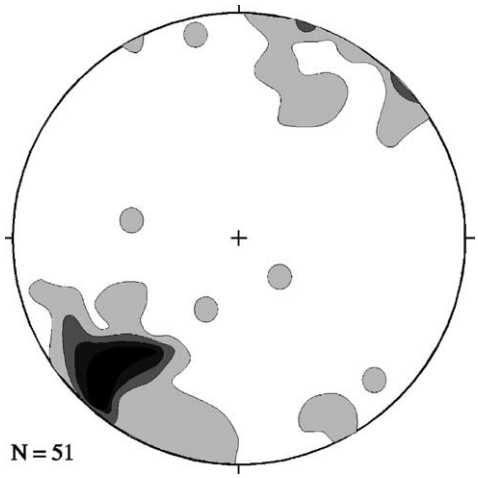

Fig. 11. Stereographic plot to poles to axial planar cleavage from the southern autochthon block in lower hemisphere, equal-area stereonet. Contouring is at interval of 1% per unit area. The plot indicates that the cleavage is NW-trending and sub-vertical.

5. Structural and tectonic evolution

Fig. 12 is a three dimensional illustration that idealizes the macroscopic structures of the Western Allaqi–Heiani suture. This sketch closely follows the line of the cross-section in Fig. 3. Three Neoproterozoic deformational events contributed to the final geometry of the suture. The first two events are interpreted to represent one continuous deformation, with a late stage folding superimposed on the early stage thrusting. The third event was associated with an overall E–W shortening. The deformation sequence is (1) emplacement of nappes from N or NE to S or SW; (2) refolding of the central allochthon about sub-horizontal, NW-trending axes; and (3) refolding of the southern allochthon about N-trending axes.

Nappe emplacement formed strong S- to SW-verging structures that dominate the entire width of the suture. The northern, central, and southern allochthons formed at this time (Fig. 12). Vergence of structures associated with this nappe emplacement is preserved in the northern allochthon, because of its higher structural position. It is likely that this deformation resulted from the early stages of collision between the Gabgaba and Southeastern Desert terranes (Fig. 1). The strong S- to SW-vergence of structures suggest that a roughly N-dipping subduction zone

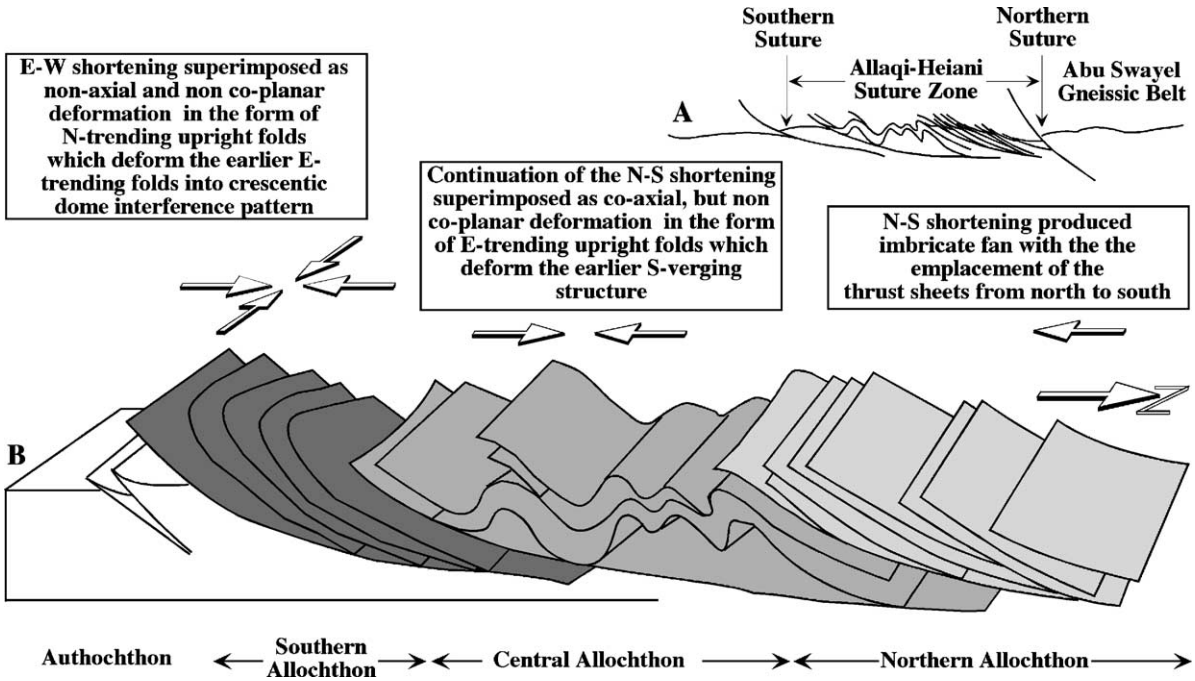

Fig. 12. (A) Extent of deformation in the Western Allaqi–Heiani suture zone. (B) Three dimensional illustration of the structure across the Western Allaqi–Heiani suture. The northern part of the suture is dominated by the northern allochthon which is an SW-verging nappe constituting low-angle thrust faults. The central nappe occupies the central part of the suture and is dominated by NW-trending folds which deform the early SW-verging structures. The southern part of the sutures is marked by the southern allochthon where the SW-verging structures were folded abouut N-trending axes. All allochthons were thrusted from NW to SE over an autochthon which suffered less translation deformation.

existed prior to suturing. The age of this nappe emplacement event can be bracketed by the ages of the ophiolites and rhyolites involved in the deformation and the age of the oldest granitic body that was emplaced after the deformation. The geochronological data outlined in previous sections are consistent with that nappe emplacement occurring between about 770 and 730 Ma, apart from the single zircon Pb/Pb evaporation age of 770 ± 9 Ma obtained from a felsic dyke that cross cuts ophiolitic serpentinite near the entrace of Wadi Allaqi in Lake Nasser (Kröner et al., 1992; Fig. 2).

Continued NE–SW directed shortening resulted in refolding of the nappes by NW-trending, steeply inclined folds (Fig. 12). This deformation was concentrated in the central allochthon. Present geochronological data do not allow the age of this deformation to be distinguished from that of nappe emplacement.

Strain appear to have changed from an overall N-S shortening, related to emplacement of nappes, to a more E–W directed shortening that produced first N-trending folds (Fig. 12), then NE-trending sinistral strike–strike-slip faults. The orientation and style of these last two structures are similar to those of the Hamisana Shear Zone to the east (Fig. 1). The effect of E–W shortening can be observed throughout the suture in the form of open, N-trending upright folds and N-trending steeply dippping foliation, especially in the central part of the Allaqi–Heiani suture where the belt has a more northerly orientation before it resumes its E–W trend at about the Egyptian Sudanese border (Greiling et al., 1994; Fig. 1). In the Western Allaqi–Heiani suture, E–W shortening is restricted to the southern allochthon where it has produced N-trending folds (Fig. 12). Superimposition of N-trending folds on earlier SW-verging folds produced a crescentic dome interference pattern

outlined by prominent ridges of serpentinite and gabbro. The origin of the E–W shortening is not certain, however, models for similar deformation in the Arabian–Nubian Shield, especially of the Hamisana Shear Zone (Stern et al., 1989, 1990; Miller and Dixon, 1992; Fig. 1) suggest that shortening occurred at 640–600 Ma in response to the collision between the Arabian–Nubian Shield and the Saharan Metacraton (Abdelsalam et al., 2002), followed by strike-slip deformation (Abdelsalam, 1994; Abdelsalam and Stern, 1996; de Wall et al., 2001). This deformation might have been accompanied by a localized amphibolite facies metamorphic event dated as between 630 and 550 Ma (Abd El-Naby et al., 2000).

6. Discussion and conclusion

Recent tectonic models present conflicting descriptions of the Allaqi–Heiani suture and its structural style. The E–W trending Allaqi–Heiani ophiolite which strikes at a high angle to the N-trending edge of the Saharan Metacraton (Abdelsalam et al., 2002) led Berhe (1990) to question the interpretation of this belt as a suture. The transposition of the Onib–Sol Hamed ophiolite along the N-trending ophiolite-decorated Hamisana Shear Zone (Fig. 1) led to the proposition that the ophiolites defining the Onib–Sol Hamed suture and the Hamisana Shear Zone (Fig. 1) represent a suture which trends NE in its northeastern part but follows a more northerly trend in the south (Vail, 1985; Berhe, 1990).

Stern et al. (1990) argued that the Allaqi–Heiani suture is the western extension of the Onib–Sol Hamed suture (Fig. 1) and that both are parts of an S-verging, allochthonous, poly-deformed ophiolitic nappe complex. Subsequent deformation localized along the Hamisana Shear Zone was superimposed on the formely coherent Allaqi–Heiani–Onib–Sol Hamed ophiolitic nappe at 660–550 Ma in the form of upright folds which gave rise to the apparent dextral offset of the former (Stern et al., 1989, 1990; Miller and Dixon, 1992; de Wall et al., 2001). Stern et al. (1990), Miller and Dixon (1992), and de Wall et al. (2001) characterized the Hamisana Shear Zone (Fig. 1) as a pure shear strain zone resulting from E–W shortening, with a strong N-S extensional component and minor subsequent dextral strike-slip shearing. Hence, Stern et al. (1990) concluded that the Allaqi–Heiani–Onib–Sol Hamed–Yanbu structure is a suture marked by S-verging nappes rooted not far away to the north in a Neoproterozoic N-dipping subduction zone. This contrasts with the proposed linking of all the Arabian–Nubian Shield sutures with the Mozambique belt, whereby the Onib–Sol Hamed ophiolite (Fig. 1) is connected with the Hamisana ophiolite (Fig. 1) and linking farther south with other N-trending ophiolites until the Mozambique belt (Berhe, 1990).

El-Kazzaz and Taylor (2001) concluded from structural studies of the area around the intersection of Wadi Allaqi and Wadi Murra (Fig. 2) that this part of the Allaqi–Heiani suture is a fold and thrust belt marked by early SW-verging folds and thrusts, affected by late E–W trending folds. They interpreted some NW-trending structures, especially what they termed the “Allaqi Shear Zone” as sinistral and oblique thrusts with an overall tectonic transport from south to north. However, they cautioned that the Allaqi–Heiani structure might not be a suture, despite of the presence of most of the diagnostic features of a suture, including the presence of ophiolite and blue schist facies metamorphism which is localized within “the Jebel Taylor accretionary prism” which occurs at about the intersection of Wadis Allaqi and Shelman (Fig. 2).

The occurrence of the dismembered ophiolitic assemblage overlying the Hafafit culmination (Fig. 1) in the Central Eastern Desert of Egypt led Greiling et al. (1994) to suggest that structural restoration of the Wadi Hodein sinistral shear zone (Fig. 1) may connect the perhaps-once-continuous Allaqi–Heiani and Hafafit sutures to the east of the Hamisana Shear Zone (Fig. 1).

In contrast to all of the above, Shackleton (1994) proposed that the Allaqi–Heiani–Onib–Sol Hamed ophiolites (Fig. 1) mark the northern limb of a folded nappe which underlies the Gabgaba–Gebeit terrane (Fig. 1). Furthermore, the linear nature of the Allaqi–Heiani–Onib–Sol Hamed ophiolite that contrasts the disrupted occurrence of ophiolites further north led Shackleton (1994) to conclude that the Allaqi–Heiani–Onib–Sol Hamed ophiolites are the proximal part of the nappe and the ophiolites further north are distal olistostromal melange deposits. This

implies that the tectonic transport of the Allaqi–Heiani structure was from south to north.

Below is a discussion of the extent of deformation associated with the suture, vergence of the structure, and its structural style.

6.1. Boundaries of the Allaqi–Heiani suture

The Allaqi–Heiani structure meets most of the criteria to be interpreted as a suture. It is a zone of high strain, contains metavolcanic rocks of back-arc setting (El-Nisr, 1997; Abd El-Naby et al., 2000; El-Kazzaz and Taylor, 2001), is defined by ophiolite belts with N-MORB geochemical affinity (Zimmer et al., 1995), and contains blue schist facies metamorphic rocks (El-Kazzaz and Taylor, 2001). However, the northern and southern boundaries of the suture are not well defined which makes it difficult to determine the extent of deformation across the suture zone and to examine to what extent this deformation affected terranes to the north and south. Nevertheless, we tentatively conclude that deformation related to the Western Allaqi–Heiani suture is dominantly confined to the width of the northern, central, and southern allochthons and the "suture line" can be tentatively assigned to the major thrust that separates the southern allochthon from the autochthonous block. This is in agreement with the interpretation of Abd El-Naby and Frisch (2002) who concluded that there is a suture between a "metavolcanic belt" in the south (the equivalent of the autochthonous block) and the "Wadi Allaqi ophiolitic melange" to the north (the equivalent to the southern and the central allochthons; Fig. 12). The northern boundary of the Allaqi–Heiani suture zone can be assigned to a "suture line" suggested by Abd El-Naby and Frisch (2002) to exist between "Wadi Haimar–Abu Swayel metasedimentary belt" in the south (equivalent to the northern allochthon) and the "Abu Swayel gneissic belt" to the north (Fig. 12A). This suture is defined by a metamorphic sole defined by the amphibolites and metagabbros of the Wadi Haimur ophiolite which is interpreted as an obducted sheet overthrusted from north to south across the Abu Swayel gneissic belt (Abd El-Naby et al., 2000). Hence, deformation associated with the development of the Western Allaqi–Heiani suture zone is bracketed between a northern and a southern suture line with the suture zone encompassing the northern, central, and southern allochthons (Fig. 12).

6.2. Deformational style of the Western Allaqi–Heiani suture

This work shows that the Western Allaqi–Heiani suture is an E–W to NW–SE trending fold and thrust belt that constitutes three allochthons and one autochthonous block. No significant strike-slip deformation has accompanied the development of the suture. This work also shows that the structures are SW-verging and the tectonic transport direction was from NE to SW. This conclusion does not agree with El-Kazzaz and Taylor (2001) who concluded on the basis of "facing direction" and folded thrusts pattern that the structure is north verging and the tectonic transport direction was from south to north. We note in this regard that El-Kazzaz and Taylor (2001) maps show that the structures dominantly dip to the north. The study area of El-Kazzaz and Taylor (2001) lies along the eastern extension of the central and southern allochthons and we agree with them that these thrust sheets are folded. However, our field data clearly indicate that the folded thrusts were originally N-dipping as shown by the orientation of the thrust sheets of the northern allochthon. Abdel-Meguid et al. (1996) investigated the region southeast of our study area and identified three N-verging nappes as outlined earlier. These nappes were refolded about E–W axis similar to the central allochthon in this study. Hence, we conclude that the kinematic indicators from the northern allochthon which was not subsequently refolded are the ones which provide unequivocal evidence for the tectonic transport direction of nappes in the Western Allaqi–Heiani suture.

Deformational style in the Western Allaqi–Heiani suture changes sharply in the central part of the Allaqi–Heiani suture, immediately east of the present study area, where the trend of the suture follows a more N- to NW orientation. In this part of the suture, deformation is in the form of N-trending shortening zones dominated by N-trending folds and N- to NW-trending strike-slip faults (Greiling et al., 1994; Abdeen et al., 2002).

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