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El Sibai gneissic complex, Central Eastern Desert, Egypt: Folded nappes and syn-kinematic gneissic granitoid sheets – not a core complex

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Abstract

The El Sibai area of the Central Eastern Desert (CED) of Egypt consists of an ophiolitic association of arc metavolcanics, ophiolitic rocks, mélange, metasediments and minor mafic intrusions; and a gneissic association of amphibolite, gneissic diorite, tonalite, granodiorite and granite. Previous studies of the El Sibai area have identified the gneissic association as a lower crustal infrastructure in sheared contact with upper crustal ophiolitic association suprastructure, and have presented it as an example of a metamorphic or magmatic core complex. Detailed structural remapping of the El Sibai area reveals that the gneissic association rocks are not infrastructural but form a unit within the ophiolitic association nappes. Furthermore, the El Sibai structure is not domal in shape, and is not antiformal. The main gneissic association rocks are tabular intrusions roughly concordant with the shears dividing the ophiolitic association into nappes, and are syn-kinematic with the nappe stacking event (~700–650 Ma). The gneissic granite tabular intrusions and their ophiolitic host were later folded about upright NW–SE trending mainly open folds during a NE–SW directed shortening event (~625–590 Ma). Subsequently, NW–SE regional extension effects became evident including low angle normal ductile shear zones and mylonites. The latest gneissic red granites are syn-kinematic with respect to these shear zones. Probably continuing from the low-angle shearing event were steep normal faults, and sinistral WNW and N–S trending transcurrent faults (~590–570 Ma). The normal faults mark the southeastern and maybe also the northwestern limits of the El Sibai gneissic association rocks. The El Sibai complex is not a core complex, but exemplifies the overlap of NW–SE folding and NW–SE extensional which is a significant theme of CED regional structure.

Keywords: Syn-kinematic granitoid intrusions; Gneissic complex; Regional extension parallel to fold hinges

1. Introduction

Egyptian Eastern Desert Neoproterozoic gneissic complexes (Fig. 1) are intriguing structures that form a key characteristic of the Central Eastern Desert (CED). Equivalent structures are absent from the North Eastern Desert (NED) (though have been reported in the Sinai), and they exist in the South Eastern Desert (SED) but have more irregular geometry. These structures consist of mainly granitoid and mafic orthogneisses, amphibolites and paragneisses divided into subunits by mylonite zones, and separated from overlying mainly lower greenschist facies metavolcanics, metasediments and ophiolitic mélanges by a mylonitic or sheared schistose carapace. The database for these structures has steadily increased since the 1980s, particularly with the wealth of data that has appeared on the Meatiq gneissic complex (Ries et al., 1983; Sturchio et al., 1983a,b; Habib et al., 1985; El Gaby et al., 1988; Wallbrecher et al., 1993; Fritz et al., 1996; Neumayr et al., 1998; Loizenbauer et al., 2001), the El Sibai gneissic complex (El Gaby et al., 1984, 1988; Khudeir et al., 1992, 1995; Kamal El Din, 1993; Hamimi, 1996; Ibrahim and Cosgrove, 2001; Fritz et al., 2002; Bregar et al., 2002) and the Hafafit gneissic complex (El-Ramly et al., 1984;

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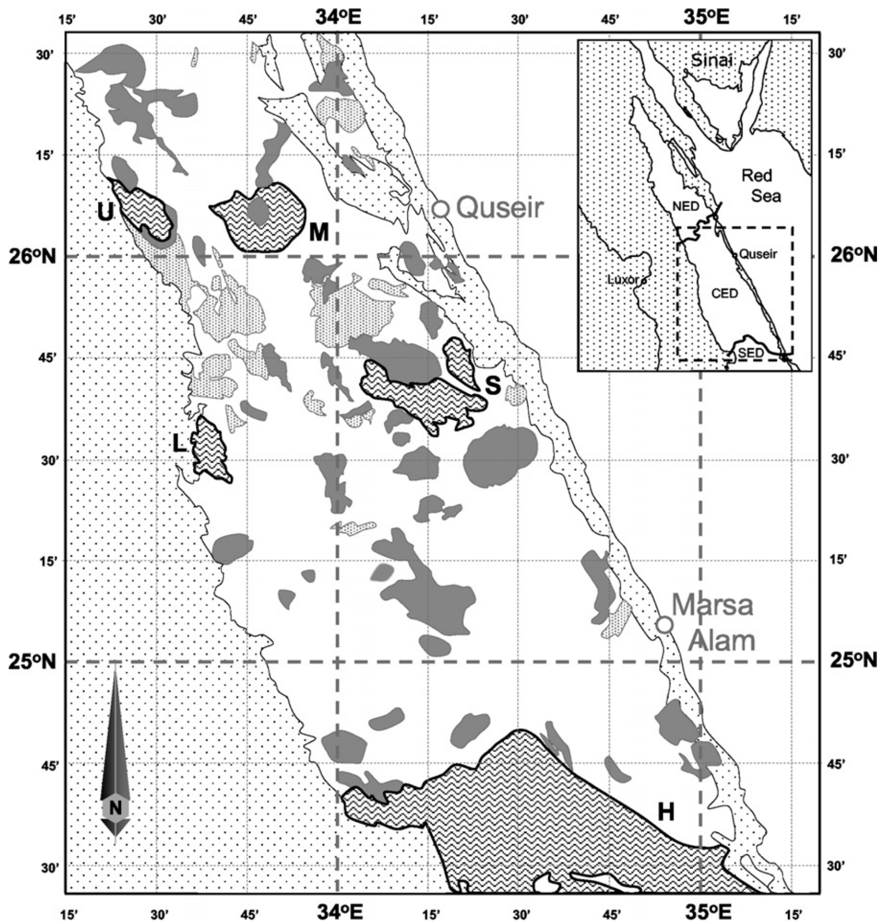

Fig. 1. Map of the Egyptian Eastern Desert showing the location of the gneissic complexes: Meatiq (M), Um Had (U), El Shalul (L), El Sibai (S) and Hafafit (H) complexes. Also shown are Hammamat Group (fine stipple) and post-kinematic granitoids (grey colour). Light stipple represents Phanerozoic sedimentary cover. Interestingly, the majority of the Hammamat Group outcrops lie within the quadrangle limited by the Meatiq, Um Had, El Shalul and El Sibai complexes. Inset shows the location of the regional map in the framework of the Egyptian part of the Arabian–Nubian Shield (NED = North Eastern Desert; CED = Central Eastern Desert; SED = South Eastern Desert).

Greiling et al., 1984, 1988; Rashwan, 1991; El-Ramly et al., 1993; Kröner et al., 1994; Fowler and El Kalioubi, 2002). The CED gneissic complexes are relatively small structures with simple outlines and well-preserved boundary relations with the surrounding low-grade rocks. In the CED these complexes are found at Gabal Meatiq, Wadi Um Had, Gabal El Shalul and Gabal El Sibai (Fig. 1). The Hafafit complex at the northern end of the SED is commonly included in this group (Fig. 1).

The most contentious aspects of these complexes have been the origin of the gneisses and spatially related high-temperature metamorphic rocks, their structural history and tectonic significance. The gneissic complex discussed in this contribution is the El Sibai complex (Fig. 1). It provides a good example of how ideas on these complexes have alternated between two categories of models. In the first category are models proposing that the low- and high-grade metamorphic rocks are contemporary, share a common protolith, formed in the same tectonic environment and have experienced similar structural events. In the second category are two-tier models, involving an older gneissic infrastructural basement and a younger allochthonous low-grade suprastructural cover.

1.1. Aims of the study

Opinions on the origin and significance of the El Sibai complex are not yet settled on either category of structural or tectonic models. It is the purpose of this paper to present the results of comprehensive structural remapping of the El Sibai complex completed during four seasons between 2001 and 2005. The results provide the basis for a substantially different non-basement-cover model.

2. Previous work

Early comprehensive mapping of the El Sibai complex by Hume (1934) and Schürmann (1966) recognized these orthogneisses as distinct from the old crystalline basement elsewhere in Egypt. Both wondered if the El Sibai gneisses had the same or younger age than the enclosing rocks. Sabet (1961) found no reason to separate the geology into basement and cover and regarded the low- to medium-grade metamorphic rocks including the amphibolites as having been derived from the same sediments and volcanics. He reported the existence of garnet–biotite and hornblende schists well outside the commonly drawn limits of the gneissic complex. El-Ramly (1972) also accepted a metasedimentary origin for the hornblende schists in the El Sibai area. Thus at this early stage neither the amphibolites nor the granite gneisses at El Sibai were considered to constitute an infrastructure.

The idea that the El Sibai gneisses were pre-Neoproterozoic crust remobilized in the Neoproterozoic – Early Paleozoic (900–520 Ma) during overthrusting of ensimatic cover nappes was championed by El Gaby (1983), and El Gaby et al. (1984, 1988) who proposed that El Sibai and Meatiq were mantled gneiss domes along a single NW-trending regional antiform.

Doubts about the existence of pre-Neoproterozoic lithosphere underlying the Eastern Desert were raised by Ries et al. (1983) and Sturchio et al. (1983a,b) at Meatiq, but momentum for this challenge came from work on the Hafafit gneissic complex, which favoured island arc geochemistry, Pan-African geochronology and oceanic tectonic setting for the Hafafit gneisses (Greiling et al., 1988; El-Ramly et al., 1984; Kröner et al., 1988; Greiling et al., 1994; Kröner et al., 1994). However, the infrastructure–suprastructure model remained popular for the El Sibai complex with the work of Kamal El Din et al. (1992), Kamal El Din (1993) and Khudeir et al. (1992, 1995). These authors identified and named individual gneissic granitoid units of the infrastructure and determined their relative ages. The oldest unit was described as an "amphibolite–migmatite" complex by Kamal El Din et al. (1992). Geochemical studies of the amphibolites showed them to have an island arc tholeiitic basalt parent in contrast to the metasedimentary origin earlier proposed for these rocks. Kamal El Din (1993) showed that the gneissic granitoids were subduction zone-related.

The structural history of the El Sibai complex was divided into eight deformation phases by Khudeir et al. (1992) and Kamal El Din (1993). Kamal El Din et al. (1992) described the El Sibai gneissic rocks as forming the core of an elongate doubly plunging NW–SE trending antiform. El Gaby et al. (1994) reported a zone of high-temperature metamorphic almandine–hornblende schists and migmatites in the core of the Deleihimi antiform to the east of the Sibai gneisses – an area usually included within the suprastructure. Hamimi (1996) preferred a fold origin for the El Sibai complex.

Greiling et al. (1993) described the folded shear zone separating gneissic rocks from low-grade cover in the CED as being a normal-sense shear zone, produced by NW–SE extension that accommodated a gravitative uplift of the El Sibai complex as a metamorphic core complex. Bregar et al. (1996) confirmed that the SE margin of the gneissic complex was a low-angle normal fault. They showed the normal fault as a link between sinistral NW–SE strike-slip faults which frame the complex in a similar manner to those described from the Meatiq gneissic complex by Fritz et al. (1996). The Meatiq model for metamorphic core complex rise by extension in a strike-slip corridor was applied to the El Sibai complex by Fritz and Messner (1999). Fritz et al. (2002) and Bregar et al. (2002) referred to the close relationship between magmatism and buoyant rise of the El Sibai complex.

Ibrahim and Cosgrove's (2001) structural model for the El Sibai complex returned to the idea that the boundary shear surrounding the El Sibai gneissic rocks is a folded thrust, and they questioned whether buoyancy processes may have been overstated in the origin of this structure. Recent resurveying of the eastern half of the CED by Akaad and Abu El Ela (2002) did not recognize the existence of basement versus cover rocks of the El Sibai complex and surroundings. Abdeen and Greiling (2005) have also questioned the relevance of buoyancy in the rise of the Meatiq and Sibai complexes and have concluded that interference folding may equally be responsible.

3. General geology

The El Sibai gneissic complex can be considered as consisting of two major lithological associations. One of these includes arc metavolcanics, metavolcaniclastics, ophiolitic masses and mélange (*ophiolitic association*). Although the rocks of this association are typically metamorphosed to greenschist facies there are examples reaching amphibolite facies and showing local migmatization. The second association occupies a more limited area surrounded by the first (*gneissic association*). It consists of typically gneissic textured granitoids (diorites, tonalites, granodiorites, granites), amphibolites and schists.

3.1. Ophiolitic association

Surrounding the gneissic granitoids of the Sibai complex are extensive greenschist facies metamorphosed ophiolitic rocks (ultramafites, gabbros, dolerites, pillow basalts and mélange), island arc-related volcanics and volcaniclastics, and metasedimentary rocks (Fig. 2a). These lithologies comprise a series of low-dipping nappes identified as the Abu Ziran Group by El Gaby (1983). The ophiolitic units are thought to have formed in a back-arc basin setting (Khudeir and Asran, 1992), while the metavolcanics are calc-alkaline arc volcanic (Kamal El Din, 1993). The mainly greenschist facies metamorphism of these rocks occurred during thrusting (Khudeir and Asran, 1992).

3.1.1. Ultramafic and related rocks

Large slices of meta-ultramafic rocks are found mainly along the western contact of the Delihimmi granite and in Wadi Sitra and Wadi Wizr (Fig. 2a). These serpentinous rocks are also found as slivers in shear zones within the metavolcanics. Ophiolitic metagabbros, diabase and

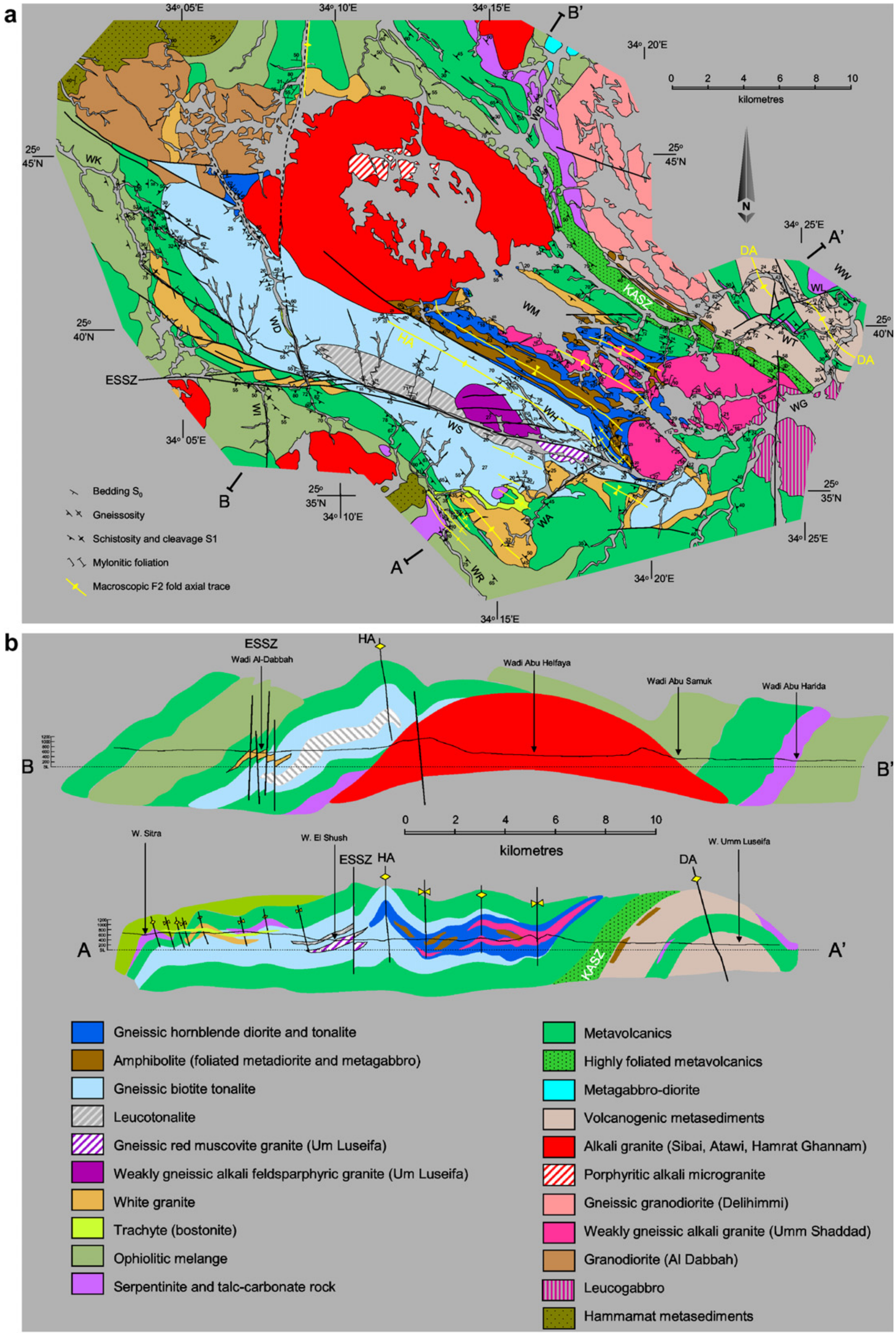

Fig. 2. (a) Geological map of the El Sibai study area showing the main gneissic and ophiolitic association units. Planar structural data and macroscopic fold axial traces are also shown. DA = Delihimmi Antiform; HA = Higlig Antiform; KASZ = Kab Ahmed shear zone; ESSZ = El Shush shear zone. Faults are strike-slip. A–A′ and B–B′ are cross-sections presented in (b). Wadis: WA = Wadi Al Hamra; WG = Wadi Um Gheig; WL = Wadi Um Luseifa; WT = Wadi Talat Salah; WM = Wadi Abu Markhat; WH = Wadi Higlig; WD = Wadi El Dabbah; WS = Wadi El Shush; WR = Wadi Sitra; WW = Wadi Wizr; WB = Wadi Sharm El Bahari; WI = Wadi Abu Garadi; WK = Wadi Kareim. (b) Cross-sections A–A′ and B–B′ referenced to (a). The legend explaining the colour coding for rock units is relevant to both (a) and (b). The dotted line in both sections represents sea level.

metabasalts in close association with the serpentinites are described by Khudeir and Asran (1992) from Wadi Wizr.

3.1.2. Ophiolitic mélange

Enclosed within the metavolcanics is a significantly thick sheet of mélange consisting of blocks of ophiolitic rock and metasediments in a metamudstone matrix. This unit surrounds the El Sibai complex except on its eastern and southern sides (Fig. 2a). The mélange matrix is locally bedded and is likely to be silicic volcanic origin.

3.1.3. Metamorphosed volcanics and volcaniclastics

These rocks are metamorphosed andesitic volcanics, lesser basalts, silicic volcanics, volcanic breccias, volcaniclastics and conglomerates. The metavolcanics NE of the El Sibai complex are andesitic and basaltic lavas, while SW of the complex the main metavolcanics are silicic and volcaniclastic. Mafic metavolcanics show greenschist facies assemblages but there are higher grade facies assemblages with stable hornblende. Many rocks show both actinolite and hornblende, and both may define the tectonic foliation in these rocks. Silicic metavolcanics typically include biotite, but may have phengite and/or chlorite.

3.1.4. Metasediments

Fine-grained to pebbly metasediments rich in micas and amphiboles form two NW–SE trending belts on the NE side of the El Sibai complex (Fig. 2a). One belt (forming the core of the Delihimmi anticline) is represented by garnet mica schists with large slender hornblende porphyroblasts showing parallel to random grain orientations. Another belt extends SE from the southern end of the Delihimmi granite, and has locally migmatitic metasediments and schists (Fig. 3b) associated with foliated metagabbro lenses and thick concordant tabular gneissic granitoid intrusions.

3.1.5. Intrusive rocks in the ophiolite association

Numerous tabular intrusions are found within the ophiolitic association. These lie generally parallel to the layering or along sheared contacts between units. They include metamorphosed gabbros, dolerites and microdiorites that are typically a few metres to tens of metres thick. These tabular intrusions show tectonic folding and commonly have a tectonic foliation. As with the mafic metavolcanics the metamafic intrusives commonly contain hornblende and/or actinolite (Fig. 4c).

3.2. Gneissic association

The gneissic rocks occupy the central part of the El Sibai area (Fig. 2a). The El Sibai granite and El Dabbah granodiorite intrusions limit the gneissic rocks on the NW. Previous studies have determined the relative ages of the granitoid units, while some absolute ages have been provided by Bregar et al. (2002).

3.2.1. Amphibolite

The amphibolites of the gneissic association are recognized as xenolithic masses or roof pendants within the Abu Markhat granodiorite (Fig. 2a). Migmatitic amphibolites have been mentioned by Khudeir et al. (1992). An igneous origin for the amphibolites, with MORB or tholeiitic arc basalt or intermediate geochemistry, was suggested by Khudeir et al. (1992) and Kamal El Din (1993). Along Wadi Abu Markhat (Fig. 2a) the amphibolites typically show low strain allowing recognition of primary igneous textures. These rocks are metamorphosed gabbro, dolerite, diorite and porphyritic microdiorite. Hornfelsic fabrics are also present. The amphibolites form tabular masses (typically 10–100s m in long dimension). A weak gneissic foliation locally appears (Fig. 3c) as a result of shear strain and may locally become mylonitic. Along the SW side of Wadi Abu Markhat the amphibolites are gneissic and banded by injection of tonalitic magma along foliations and ductile shears (Fig. 3d). A massive diorite incorporating xenolithic blocks of sheared greenschist metavolcanics is found in Wadi El Dabbah (Fig. 2a). These diorites lie along strike from the amphibolites and granodiorites forming the SW flank of Wadi Abu Markhat (Fig. 2a) and we consider them to be northerly equivalents of the amphibolites. They show spaced narrow ductile shear zones but are not otherwise foliated.

3.2.2. El Shush gneissic tonalite

The El Shush gneissic tonalite is a NW–SE trending elongate intrusion with an outcrop width of about 6 km. The El Shush is a folded tabular body with estimated actual thickness of about 2 km (Fig. 2b). The lowest parts of the intrusion are found near its NE margin. The upper contact of the intrusion is represented by its SW margin. This contact is tectonic and is partly obscured by red granite intrusions.

The El Shush is a composite intrusion consisting of biotite tonalite in its upper half, and mainly diorite in the lower half. A mingling zone of diorite enclaves in tonalite lies between the upper and lower halves of the intrusion. A separate syn-magmatic intrusion of biotite-muscovite granodiorite is also located roughly at the halfway level in the intrusion (Fig. 2a). The El Shush intrusives commonly show a distinct gneissosity or a linear fabric. The gneissosity typically does not involve high bulk strains and may appear as a weak schistosity in less strained rocks. In the lower more heterogeneous parts of the El Shush there are schlieren, flow banding and flow oriented phenocryst fabrics. The gneissosity lies at a small angle to these primary fabrics.

3.2.3. Abu Markhat gneissic granodiorite

This unit intrudes the amphibolites (Fig. 2a) and incorporates them as tabular xenoliths. The unit grades into tonalitic compositions. It is a white typically flow banded or gneissic looking rock with gneissic bands parallel to its contacts with amphibolites. Linear fabric is

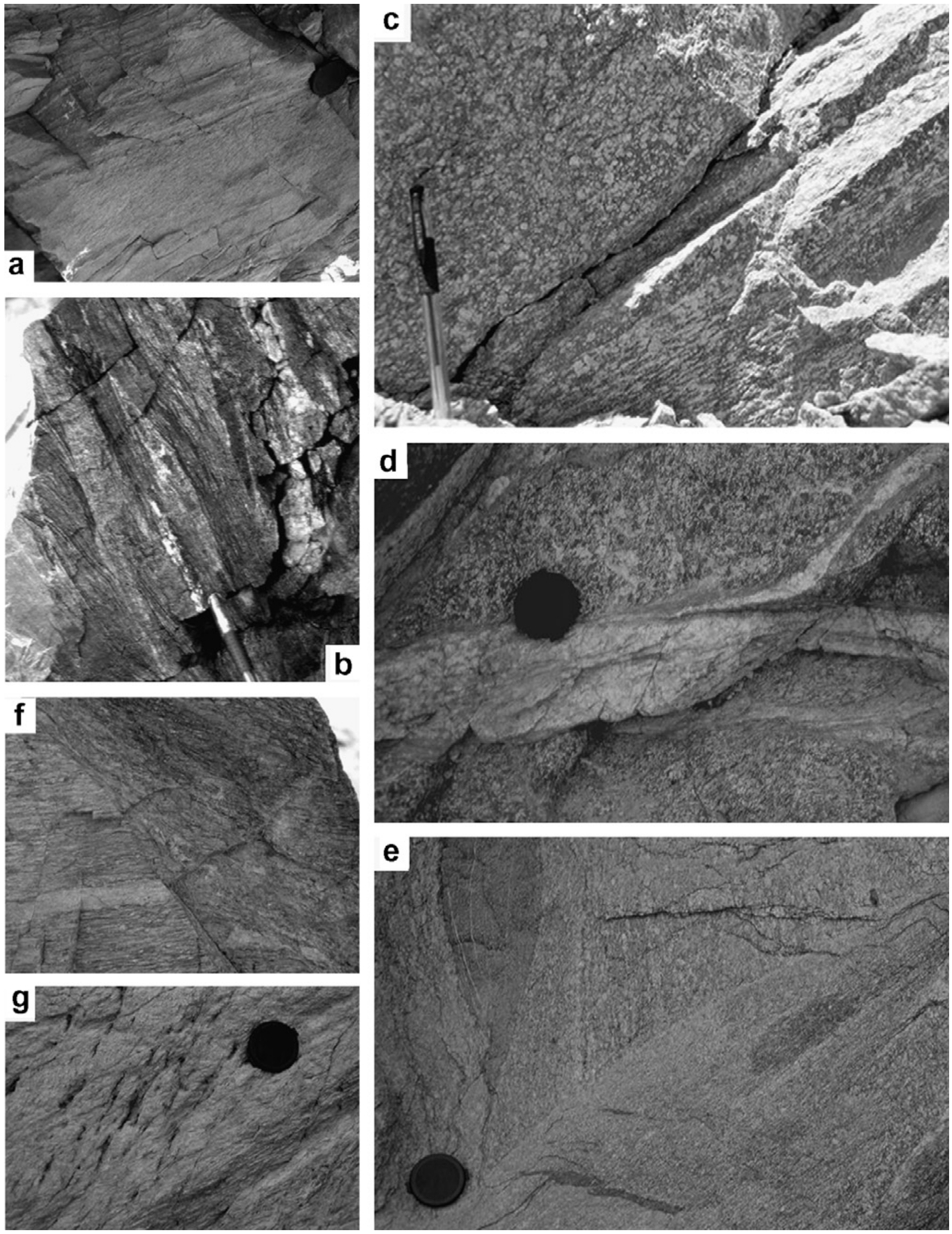

Fig. 3. Field photographs (a, b) are of features found in the ophiolitic association outcrops. (c–g) lie within the gneissic association. (a) Bedding (dipping gently to the left) is overprinted by S_1 cleavage (more steeply dipping to the left) in metasediments from the eastern end of Wadi Um Luseifa (vertical section, looking south. Width of photograph is about 70 cm). (b) Migmatized metasediment near the Delihimmi granite, Wadi Um Luseifa (see pen scale at bottom). (c) Porphyritic diorite, massive above and gneissic below with small ductile shear between them (Wadi Higlig, near Wadi El Shush). (d) Gneissic granite veinlet syn-kinematically intruded along ductile shear in metagabbroic amphibolite. Shear sense on the ductile shear is top to the NW (Wadi Abu Markhat). (e) Cross-cutting intrusive bodies of tonalite. Each shows a magmatic foliation (lower part of El Shush gneissic tonalite, Wadi Higlig). (f) South-dipping brittle normal fault cutting through mylonitized red granite and showing cataclastic disruption in the hangingwall (entrance to Wadi Abu Markhat). (g) Extensional crenulations cutting across shear foliation related to normal-sense shear zone (Wadi El Dabbah).

also developed in these rocks. It forms veins, dykes and sheeted complexes with the amphibolite. Strain effects are more common in the Abu Markhat than in the amphibolites and, apart from foliations, are demonstrated by boudinage of veins and dykes. Like the amphibolites the Abu Markhat also shows local mylonitization.

3.2.4. Delihimmi gneissic granodiorite

The Delihimmi pluton (Fig. 2a) is a gneissic biotite granite to granodiorite that lies a few kilometres east of the El Sibai complex. Similar gneissic textures are also found amongst the granitoid sills within metasediments lying SE of the Delihimmi intrusion. Hamimi (1996) recognized the Delihimmi granite as a gneissic body and considered it to be an extension of the gneissic association exposed in the core of an anticlinal structure. Akaad and Abu El Ela (2002) regarded the Delihimmi intrusion as a Younger Granite.

3.2.5. Um Luseifa gneissic granite

This unit forms an elliptical body of biotite-rich megacrystic pink gneissic granite intruded into the El Shush gneissic tonalite, and truncated by the El Shush shear zone (Fig. 2a). The Um Luseifa intrusion is cut by three E–W trending sinistral shear zones. The gneissosity of this intrusion is interrupted by cm-spaced sinistral shear bands with similar orientation to the El Shush shear zone. The Um Luseifa has been represented as a stock by Kamal El Din et al. (1992), however its 3D form is more likely to be a gently buckled tabular structure. The contacts of the intrusion are parallel to its consistently gently south-dipping gneissosity. This gentle dip (25–35°) is different to the dip of the gneissosity of the enclosing El Shush tonalite (50–65°).

3.2.6. Um Shaddad gneissic granite and other gneissic red granites

This red granite mass has an approximately elliptical outline with an E–W long axis. It can be traced across Wadi Abu Markhat to another large mass of identical granite at the junction of Wadi Abu Markhat and Wadi El-Shush (Fig. 2a). These granites outcrops are one continuous intrusive unit as shown petrologically and structurally by El-Sayed et al. (1999) and Bregar et al. (2002). Identical red granites farther to the NW along Wadi Abu Markhat form low-dipping tabular masses and veins within the amphibolites. The SE margin of the Um Shaddad granite is a normal fault (Fritz and Messner, 1999). Bregar et al. (1996) showed that the Um Shaddad has a gently SE dipping tabular geometry constrained by low-angle normal faults that controlled its intrusion. The Um Shaddad and related red granites are syenogranites with high K calc-alkaline chemistry (El-Sayed et al., 1999).

The red granites sometimes show schlieren and flow aligned large microcline phenocrysts. Gneissosity where developed is usually weak. However, mylonite zones are common in this unit. Sheets of similar K-feldspar porphyritic red granite showing extreme sericitic alteration and locally strong shearing are intruded at or near the contact between the El Shush gneissic tonalite and low-grade metavolcanics of the ophiolitic association at the western side of the El Sibai complex (Akaad and Abu El Ela, 2002) and SW of Wadi El Dabbah. The sheets roughly parallel the contact but are irregular in detail and contain numerous xenoliths of metavolcanics.

3.2.7. Leucogranites

A white to grey coarse-grained leucogranite referred to as the El-Mirifiya garnetiferous gneissose granite by Kamal El Din et al. (1992) forms a thin tabular intrusion cropping out on both sides of Wadi Abu Markhat near the El Sibai Granite (Fig. 2a). It intrudes along the foliation of red granites and includes blocks of them as xenoliths. It also contains mylonite zones. It has been identified as a highly differentiated late orogenic granite by El-Sayed et al. (2002).

3.2.8. El Sibai granite and El Dabbah granodiorite

The El Sibai granite forms a ring-shaped intrusion at the NW end of the gneissic complex (Fig. 2a). It has been recognized as an A-type granite by Abdel-Rahman and El-Kibbi (2001) and El-Sayed et al. (2002). Its contact is outward dipping, steplike in detail and there are low-dipping apophyses extending out into the wallrocks. There are pegmatitic patches and xenolith swarms near its contact. A fine- to medium-grained porphyritic phase of the El Sibai granite is present in the core of the intrusion. The El Dabbah intrusion (Fig. 2a) is a locally porphyritic biotite syenogranite or monzogranite. It shows no foliation in outcrop but has some minor deformation microstructures.

4. Structure

4.1. Mesoscopic structures in the ophiolitic association

4.1.1. S_0 bedding and other primary structures

Bedding and other primary structures are preserved in the ophiolites (banding in gabbros), mélange matrix (pebbly bands), arc metavolcanics (flow banding, pillow structures and bedding, ripples and loadcasts in the metatuffs) and metasediments (bedding, laminations, graded bedding and pebbly bands) (Fig. 3a). In Fig. 5a bedding poles describe a full girdle with gently NW-plunging π-axis.

4.1.2. S_1 cleavage and schistosity and F_1 folds

Metavolcaniclastics, metasediments and mélange matrix commonly show a well-developed tectonic cleavage or schistosity (S_1). It varies from parallel to bedding to inclined at 30° to the beds (Fig. 3a) and is defined by parallel preferred orientation of metamorphic minerals (chlorite, biotite, sericite, actinolite and hornblende). S_1 is axial plane to asymmetric (F_1) folds in beds and sills. F_1 fold vergence directions are usually towards the WNW, and bedding – S_1 cleavage angular relations are in agreement with this. However, some F_1 folds along the north-eastern reaches of Wadi Um Gheig show clear SE vergence. On the stereogram in Fig. 5b poles to S_1 foliation define a girdle with gently NW-plunging π-axis. F_1 folds are plotted in Fig. 5c where N to NE and S to SW trends and variable plunges are evident.

4.1.3. L_1 stretching lineations and pencil structures

A stretching lineation (L_1) is developed on S_1 surfaces in most lithologies. It is defined by parallelism of long axes of stretched sedimentary particles and elongate metamorphic grains (particularly amphiboles). The metamorphic grains commonly show brittle extension with fragments of the grains displaced in the stretching direction. There are

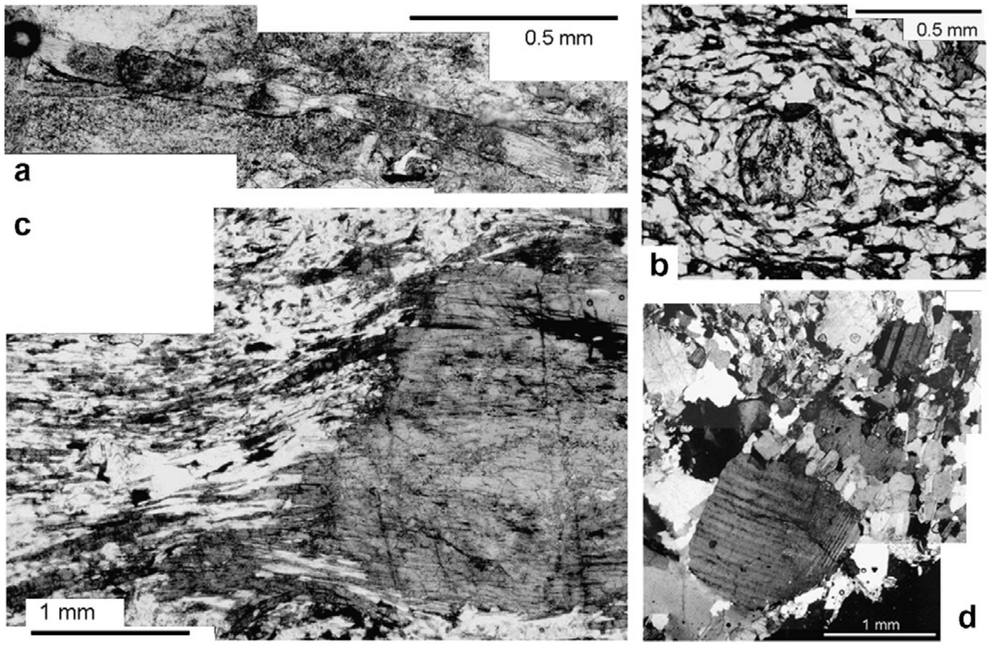

Fig. 4. Photomicrographs from rocks of the ophiolitic association (a–c) and from the gneissic association (d). (a) Amphibole porphyroblasts pulled apart by extension associated with development of L_1. The amphibole is hornblende with actinolite forming fringes and connecting the displaced parts of the porphyroblast (metasediments of Wadi Um Luseifa). (b) Garnet porphyroblast in metasediment showing biotite S_1 foliation deflecting around it (Wadi Um Luseifa). (c) Strongly schistose metavolcanic showing S_1 foliation defined by hornblende, with hornblende fringes on relict mafic phenocrysts (between Wadis Um Luseifa and Abu Markhat). (d) Porphyritic El Shush tonalitic gneiss. Plagioclase phenocryst is pulled apart by extension during gneissosity development, and the space between the displaced parts is filled by magmatic textured quartz, plagioclase, K feldspar and biotite, indicating syn-magmatic deformation. Altogether the strain is low (Wadi Higlig).

metamorphic minerals occupying the spaces between the fragments indicating syn-metamorphic stretching (Fig. 4a). L_1 data are shown on Fig. 5d to have gentle plunges mainly to the ESE and NW. Pencil structure is common in the El Sibai area as it is in most of the CED. Pencil structures are developed in the hinge zones of F_2 folds (see description below) and are parallel to F_2 axes (Figs. 5e, 6a).

4.2. Mesoscopic structures in the gneissic association

4.2.1. Primary magmatic banding and flow lineations

The El Shush, Um Luseifa, Um Shaddad and related red granite intrusions show minor flow banding, schlieren, cross-cutting flow-banded dykes (Fig. 3e), flow elongate enclaves and phenocryst flow lineations. Flow foliation data are shown in Fig. 7b where the poles are seen to define a full girdle with gentle NW-plunging π-axis. Flow lineation data have NW-plunges (Fig. 7e).

4.2.2. Gneissosity, schistosity and related lineations

Gneissosity is the dominant tectonic structure in the gneissic association rocks and is defined by biotite folia deflecting around the edges of feldspar grains. As gneissic banding weakens it passes into a spaced schistosity defined by flattened biotite clots. Gneissosity and magmatic foliation are distinct surfaces. However, submagmatic textures contribute to the gneissosity, for example, tectonically dismembered plagioclase phenocrysts commonly have magmatic textured quartz and feldspar between the displaced parts of the phenocrysts (Fig. 4d). This indicates that gneissosity began to form before complete crystallization of the magma. The formation of the gneissosity does not generally involve high strains. Orientation data for gneissosity and schistosity are shown in Fig. 7a and c where they are seen to have similar patterns of poles defining a girdle with gentle SE-plunging π-axis. While the amphibolites are mainly isotropic they have a weak schistosity which increases in intensity towards the SW areas. Poles to amphibolite schistosity define a girdle with gentle SE-plunging π-axis (Fig. 7d). Stretching lineations are defined by parallel grain long axes on gneissosity and schistosity surfaces (Fig. 7e–g). All show gentle to moderate plunges on trends in the NW and SE quadrants.

4.3. Mesoscopic structures common to both associations

4.3.1. F_2 folds and S_2 crenulation cleavage

A later generation of folds, referred to as F_2, fold bedding and S_1 cleavages in the ophiolitic association, and also magmatic foliations, gneissosity and schistosity of the gneissic association. These folds are widespread. They have approximately upright axial planes (Fig. 6b) and gentle to moderately NW and SE plunging hinges (Fig. 6a). F_2 folds vary from tight to open, though interlimb angles $\geqslant 130°$ are most common. F_2 folds in the schistose metasediments tend to be tighter and show a spaced crenulation axial plane

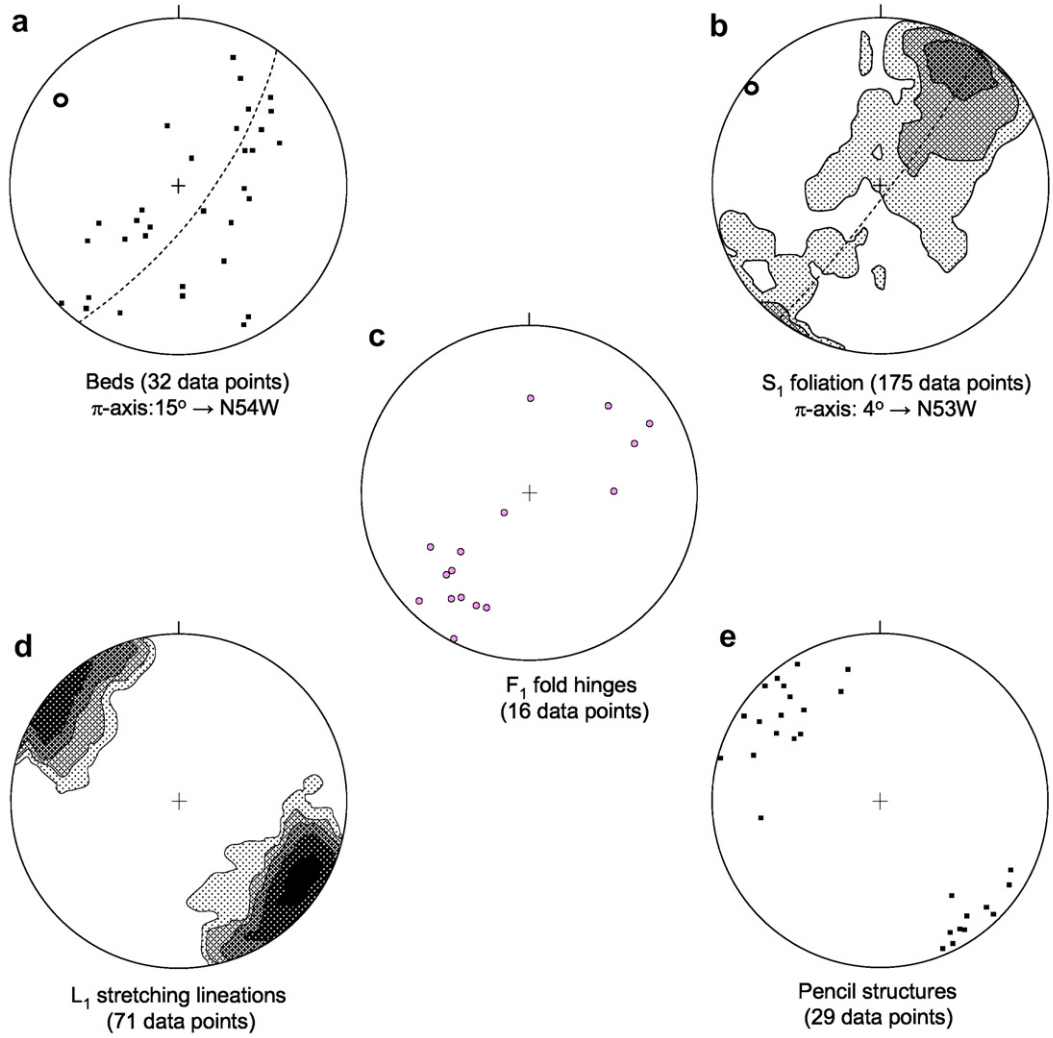

Fig. 5. Stereographic projection (Schmidt net, lower hemisphere) of planar and linear structural data from the ophiolitic association exposures. Girdle axes for planar data are shown. (a) Poles to bedding (S_0). (b) Density contoured poles to S_1 cleavages (contours are at 8%, 4%, 2% of data). (c) F_1 fold hinges. (d) Density contoured L_1 stretching lineations (contours are at 32%, 16%, 8%, 4%, 2% of data). (e) Pencil structures.

structure (referred to as S_2) near the hinge zones. S_2 crenulations deform L_1 mineral lineations. S_2 is defined by low-grade metamorphic minerals chlorite and sericite.

4.3.2. Mylonites, mylonitic lineations and syn-mylonite folds

Thin mylonite zones are commonly found in the Umm Shaddad and equivalent red granites, the amphibolite and leucogranites of the gneissic association, and are present in the ophiolitic gabbroic intrusions. Poles to mylonitic foliation are found to concentrate in one small area of the stereogram (Fig. 6c) corresponding to gentle SE dips. This feature and the field observation that the mylonites are either unaffected by F_2 folding or only open folded about upright SE plunging F_2 folds indicate that the mylonites were weakly affected by the F_2 folding and also partially post-date it. Almost all microscopic shear sense indicators (systematic inclination of quartz ribbon long axes to foliation; extensional crenulations) show top to the SE shear sense parallel to the mylonitic lineation (Fig. 6d). There are rare asymmetric small folds confined to the mylonite zones but are also cut by them so these are clearly syn-mylonite folds. Their hinges are usually parallel to the mylonitic lineation (Fig. 6e). Kamal El Din (1993) suggested that these fold hinges were rotated towards parallelism with the mylonitic lineation.

4.4. Macrostructure

4.4.1. Macrofold geometry of the El Sibai area

Two vertical NW–SE cross-sections are presented in Fig. 2a. Cross-section A–A′ cuts across the Delihimmi antiform, a well-known fold structure located by El Gaby et al. (1994). Metasediments form the core of the anticline. They are overlain by metavolcanics then serpentinites in sheared contact with another metasedimentary sequence, which is intensively intruded by gneissic metagabbros, tonalite and granodiorite sheets. These rocks are bounded above by the low-grade schists of the Kab Ahmed shear zone (Fig. 2b). This shear zone dips concordantly with the foliations of the rocks above and below it, and separates the metasediments from another mafic metavolcanic unit.

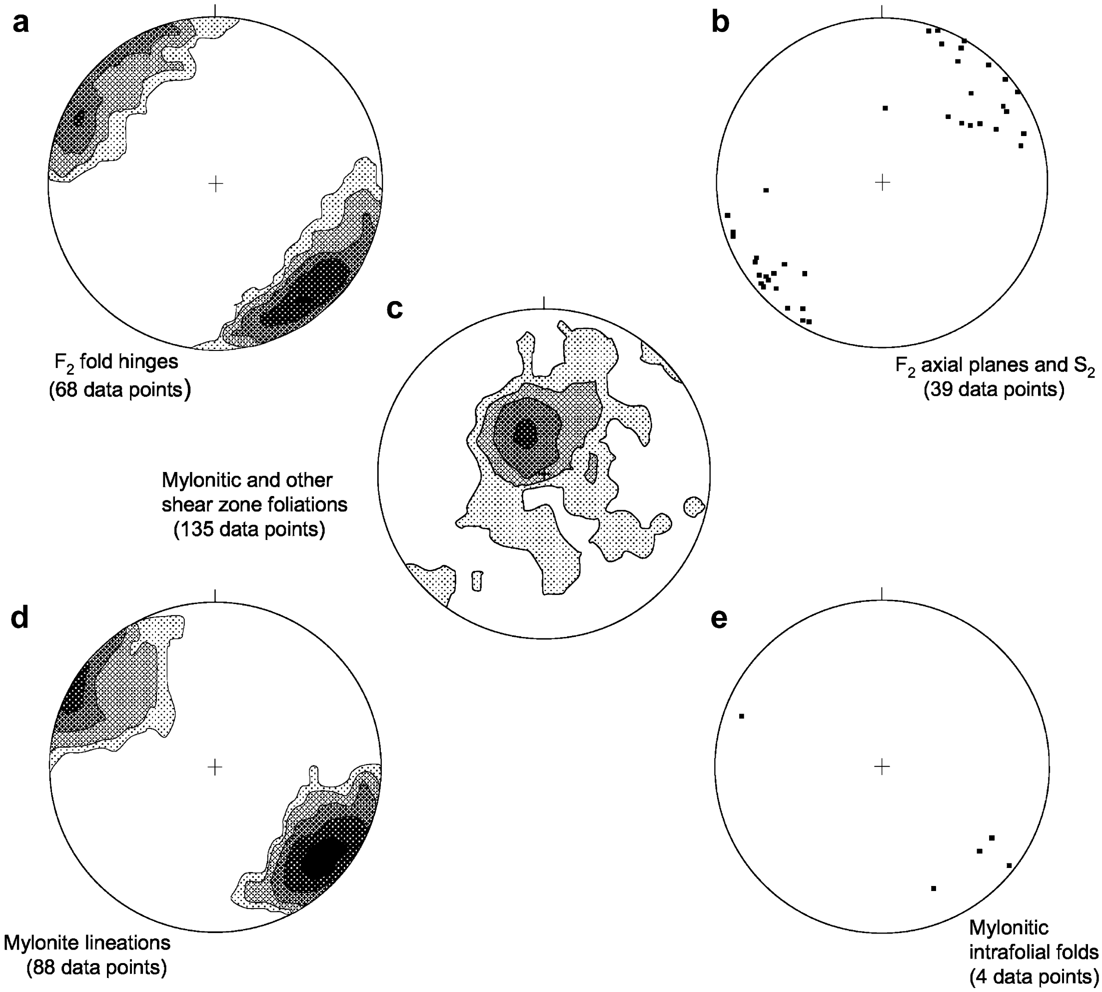

Fig. 6. Stereographic projection (Schmidt net, lower hemisphere) of planar and linear structural elements common to both ophiolitic and gneissic association exposures. (a) Density contoured F_2 fold hinges (contours are at 32%, 16%, 8%, 4%, 2% of data). (b) Poles to F_2 fold axial planes and S_2 cleavages. (c) Density contoured poles to mylonitic and other shear foliations (contours are at 16%, 8%, 4%, 2% of data). (d) Contoured mylonitic lineations (contours are at 32%, 16%, 8%, 4%, 2% of data). (e) mylonitic intrafolial folds.

The continuous SW dip of beds, foliations and magmatic foliations is clear all the way from the SW limb of the Delihimmi antiform to the NE edge of the El Sibai complex (Fig. 2a). Cross-section B–B′ also shows that the ophiolitic association rocks in the NE have steep mainly SW dips.

Two extremely important points must be made about these cross-sections. The first is that the macroscopic fold structure of the El Sibai area is not simply antiformal as has been claimed in previous studies (Fig. 2a). The two dominant antiforms (Delihimmi and Higlig) have no special relationship to the gneissic association rocks and are separated by a series of lower amplitude antiforms and synforms. A somewhat similar combination of large and small amplitude folds characterizes the cross-sections provided by Ibrahim and Cosgrove (2001) and Abdeen (2003). The second point is that the main gneissic granitoids of the complex occupy an intermediate position, sandwiched between ophiolitic association units. From this it is clear that the gneissic granitoids are not infrastructural in relation to the ophiolitic association rocks. The gneissic granitoids encountered below the Kab Ahmed shear zone in Wadi Um Luseifa are not fold repeated equivalents of the main area of gneissic rocks of the complex. They occupy separate structural levels and are quite distinct in their characteristics.

The regional folds shown in the two cross-sections are NW–SE trending F_2 folds. Stereograms in Figs. 5a and b and 7a–d show folding of S_0, S_1 and magmatic foliations about gently NW plunging F_2 axes, while gneissosity and schistosity in the granitoids and amphibolites are folded about SE plunging F_2 axes. We explain this in a schematic NW–SE section along the trend of the F_2 folds (Fig. 8). In Fig. 8 S_0 and magmatic foliation have a gentle NW dip component explaining the gently NW plunging π-axes for these data. Gneissosity and schistosity lie 10–15° to magmatic foliation providing a gentle SE dip component consistent with gently SE plunging π-axes for these data. S_1 lies at a smaller angle to S_0 giving a very low dip towards the NW consistent with the gently NW-plunging S_1 π-axis.

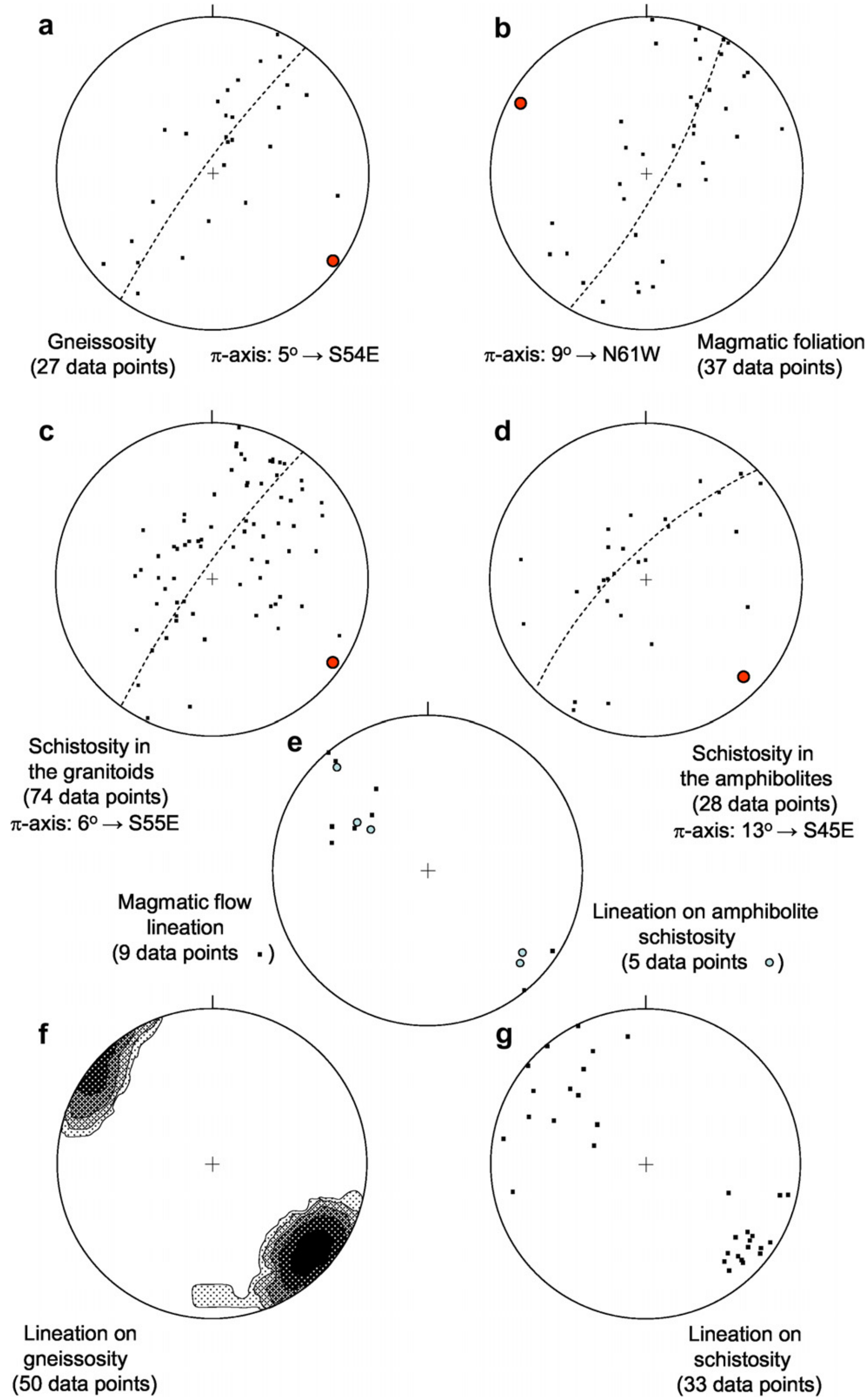

Fig. 7. Stereographic projection (Schmidt net, lower hemisphere) of planar and linear structural data from the gneissic association exposures. Girdle axes for planar data are shown. (a) Poles to gneissosity. (b) Poles to magmatic foliation. (c) Poles to schistosity. (d) Poles to schistosity in the amphibolites. (e) Magmatic flow lineations and amphibolite stretching lineations. (f) Density contoured stretching lineations on gneissosity (contours are at 48%, 24%, 12%, 6%, 3% of data). (g) Stretching lineations on schistosity.

Finally we assess the claim that the El Sibai gneissic association rocks describe a doubly plunging structure. The map of F_2 fold hinge orientations and other lineation data in Fig. 9 do not support the single plunge reversal model, though there is evidence for small homogeneous orientation domains that may be

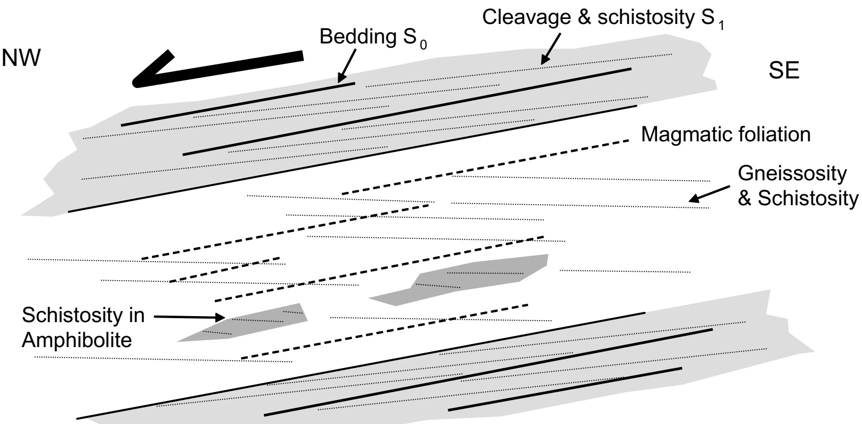

Fig. 8. An idealized simple sketch representing a NW–SE vertical cross-section of the study area. The figure shows the angular relations between the planar structures (S_0, S_1, magmatic foliation, gneissosity, schistosity) at the close of the top-to-NW nappe stacking event. The apparent NW dips of S_0, S_1 and magmatic foliation explain NW-plunging π-axes on their stereographic pole diagrams as a result of later F_2 folding (which has NW–SE upright axial planes). The apparent SE dips of gneissosity and schistosity explain their SE-plunging π-axes on stereographic pole diagrams.

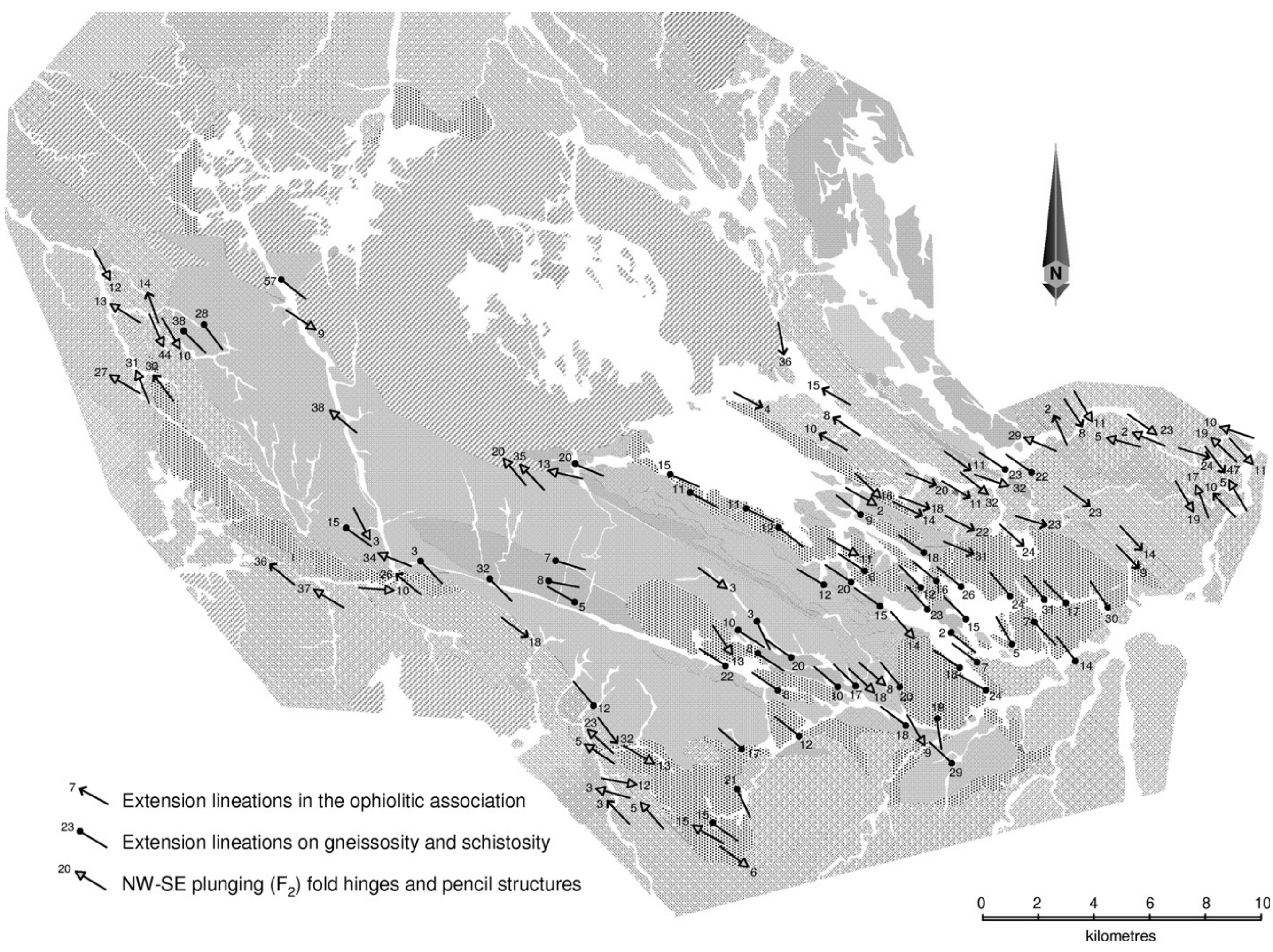

Fig. 9. Map of the El Sibai study area (with geological units in subdued grey tones to make the structural elements clearer) showing the more important linear structures F_2, pencil structures and stretching lineations. There are small domains of homogeneous orientation for each class of lineations, for example the gneissic association rocks in the SE part of Wadi Abu Markhat. The significance of these is discussed in the text.

consistent with several small plunge reversals, perhaps due to open NE–SW trending folds as suggested by Hamimi (1996).

4.4.2. Macroscopic shear systems of the El Sibai area

4.4.2.1. Early top-to-the NW shears leading to nappe stacking. The earliest evidence for regional scale shearing in the El Sibai area involves the stacking of the ophiolitic association units as shear bounded subhorizontal sheets or nappes of metasediment, metavolcanic and mélange (El Gaby et al., 1994). This event has been described as a NW-directed thrusting event with simultaneous low-grade regional metamorphism. The systematic inclination of S_1 foliation to S_0, and gneissosity and schistosity to magmatic foliation, shown in Fig. 8, and the main vergence direction of F_1 folds are in agreement with the top-to-NW displacement for these nappes. The El Shush gneissic tonalite and Um Luseifa gneissic granodiorite tabular intrusions are concordant to the nappes and were probably syn-kinematically intruded along active shears at the nappe contacts.

What has been illustrated as the NE upper boundary of the El Sibai area gneissic granitoids is in fact the *lower* boundary of this main tabular zone of gneissic granitoids (cross-section A–A′, Fig. 2b). The mafic metavolcanics below this contact show numerous ductile shear zones with the same top-to-NW sense of shearing. Deeper again is the Kab Ahmed shear zone. Most recent tectonic models of this area have interpreted this shear zone as a sinistral strike-slip shear related to the Najd system (Fritz and Messner, 1999; Bregar et al., 2002; Fritz et al., 2002). However, the pitch of stretching lineations on the shear foliation is consistently SE and averages about 20°, and shear sense indicators we found indicated dextral rather than sinistral, apparent shear, which unfolds to top-to-NNW shear sense. The shear zone shows strong curvature – inconsistent with strike-slip shear sense.

4.4.2.2. Top-to-SE (and top-to-NW) extensional ductile shears and mylonite zones. Kamal El Din et al. (1992) and Greiling et al. (1993) reported top to the SE displacement on the SE dipping low-angle shear zone exposed near the SE end of the area of gneissic rocks. Top to the SE shear sense has been confirmed by Kamal El Din (1993) and Bregar et al. (1996, 2002) for mylonitized Um Shaddad red granites intruded along these shears. This implies tectonic extension in the NW–SE direction at the time of formation of the mylonites (Greiling et al., 1993) and intrusion of the red granites (Bregar et al., 1996). It is clear that the mylonitic shearing event is later than the top-to-the-NW shearing described above. Mylonite foliations cut through the gneissic foliations and are gently folded about SE plunging folds even in places where the host gneisses have been folded to steep orientations about F_2 hinges. Poles to mylonitic foliation show no significant spread along a girdle (Bregar et al., 1996, 2002, and Fig. 6). From this we conclude that the mylonites have formed near the end of F_2 folding but have been weakly affected by them. This clearly shows that NE–SW compression was accompanied by NW–SE extension. The Um Shaddad intrusion is a gently SE dipping sheet that has also been folded as have the other red granite sheets along Wadi Abu Markhat. The tight asymmetric folds in the mylonitic foliation are likely to be related to F_2 folding during the mylonitic shearing event.

A similar set of shear foliated rocks are the metavolcanics lying above the El Shush gneissic tonalite in the SW part of the El Sibai area (Fig. 2b). These shears are gently F_2 folded and are characterized by schistose metavolcanics by schists with sericitic and calcitic hydrothermal alterations. At about the same time, the metavolcanics were also intruded by thin sheets of hydrothermally altered mylonitized red granite showing top to the S or SE shear displacement. Along Wadi El Dabbah there are numerous examples of foliated ductile normal shears with E–W to NE–SW strike and moderate N or NW dips (Fig. 3g).

4.4.2.3. Brittle steep normal faults and development of cataclastic structure. The low-dipping mylonitic shears at the SE end of the El Sibai complex are succeeded by brittle tensional effects. These are represented by locally pervasive cataclastic disruption of the mylonites, and the development of normal faults with steeper SE dips. The cataclastic deformation is associated with the same hydrothermal phases as the ductile sheared rocks described above and the brittle effects were probably a continuation of the same stress regime. These cataclastic effects have been reported by most workers in the area, especially Sabet (1961). Steep SE dipping normal faults cut through the low-dipping mylonites at the SE boundary of the gneissic rocks along Wadi Um Gheig (Fig. 3f). These faults postdate the low-angle normal faults (LANFs) described by Bregar et al. (1996).

4.4.2.4. Strike-slip fault systems. The El Sibai area contains an impressive system of strike-slip faults, with the best known example being the Wadi El Shush fault. The Wadi El Shush fault has WNW trend and a 6 km sinistral displacement determined by restoring the SW margin of the El Shush gneissic tonalite (Fig. 2a). Sinistral NW-trending faults splay from the Wadi El Shush fault at its western end. E–W (to ENE–WSW) trending sinistral faults affect the Um Luseifa gneissic granite and the Delihimmi antiform. N–S sinistral strike-slip faults cut through the red granites. These faults are younger than the NW, WNW, E–W and ENE trending faults (Abdeen, 2003).

The strike-slip faults have ductile aspects related to hydrothermal alteration softening. So the hydrothermal alteration regime noted above for the extensional shears and normal faults probably persisted (or recurred) during the strike-slip faulting.

4.5. Structural history

In this section we organize and summarize the structural events of the El Sibai area consistent with our results. An attempt to place these events into a time frame is presented in Fig. 10.

4.5.1. NW-translated nappe stacking event

During this event vertical stacking of metavolcanic, metasedimentary and ophiolitic mélange nappes was accomplished via low-angle shears involving top-to-NW displacement. A generally low-grade regional metamorphism accompanied this event, and S_1 cleavage in the

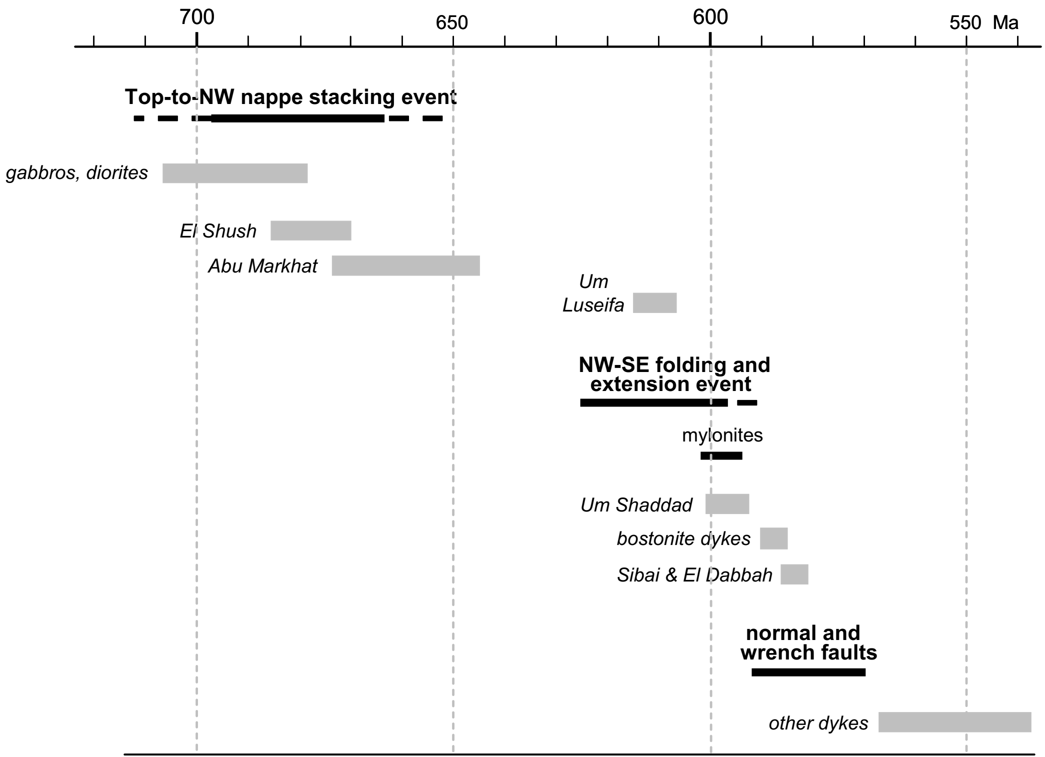

Fig. 10. An attempt to place the deformation events D1, D2 and D3 in a time frame along with the main intrusive events (written in italics) of the El Sibai area. The diagram is compiled from some available radiometric dates (Bregar et al., 2002 – for the El Shush and Abu Markhat intrusions) and from field relations between intrusions, shear zones, folds and sedimentation events in the El Sibai area, supplemented with observations from other parts of the CED. The structural elements generated at each event are shown, and tectonic events responsible are hypothesized. NB some of the ages of the intrusives shown (e.g. Um Shaddad, El Sibai and El Dabbah intrusions) are essentially deductions based on their field relations to the structural events.

nappes was formed. L_1 stretching lineation was developed indicating NW–SE extension. F_1 folds verging to the NW were also formed. Thin gabbro, dolerite and diorite sheets followed by thick El Shush tonalite, Abu Markhat granodiorite and probably Delihimmi granodiorite intrusions were emplaced syn-kinematically into the shear zones. These intrusions show magmatic foliation and in their latest stages of crystallization were solid-state deformed by continued shearing to produce gneissosity and schistosity also with NW–SE trending stretching lineations. The intrusions provided local heating of the sheared wall rocks to produce medium-grades of metamorphism represented by the phases hornblende, biotite and garnet.

4.5.2. *NW–SE regional folding and extension event*

All of the above planar and linear structures were deformed by mainly open but locally tight NW–SE trending upright F_2 folds during this event. The folding is evidently a result of NE–SW tectonic shortening. The structures produced include mesoscopic and macroscopic F_2 folds, local S_2 crenulation foliation along F_2 fold axial planes, and in lower strain areas, pencil structure.

A group of structures indicating NW–SE tectonic stretching began to form in the late stages of this event. The main structures formed are mylonitic foliations, stretching lineations and intrafolial folds. The shear sense is consistently top-to-SE in the SE part of the complex, and in the low-dipping sericitic schistose shear zones forming the upper boundary of the gneissic granitoids at the SW margin of the complex. Top-to-NW normal ductile shears also formed in the N half of the complex. Numerous low-dipping sheets of porphyritic red granite intruded along active extensional mylonite and schistose shear zones. These include the Um Shaddad and Um Luseifa granites. The sericitic schists, normal ductile shears, mylonitic foliations and red granite sheets are only modestly affected by F_2 folding.

4.5.3. *Normal faulting and strike-slip faulting event*

The latest structures in the El Sibai area are steep normal faults (associated with common cataclastic effects), and sinistral strike-slip structures with NW–SE, E–W, ENE–WSW and N–S trends. The most important of these is the Wadi El Shush fault. It is possible that the more WNW structural trends found in the El Sibai area compared to areas to its north may be due to anticlockwise rotational effects associated with these sinistral faults.

5. Discussion

There are two further topics relating to the El Sibai complex that merit discussion. These are the origin and significance of the higher temperature metamorphism locally found in the ophiolitic association, and the status of the El Sibai as a core complex.

5.1. Origin of local medium-grade metamorphism in the ophiolitic association

The ophiolitic association rocks are generally reported to be low-grade (greenschist facies). Occasional mention is made of higher metamorphic grades reaching amphibolite facies, though there is rarely any explanation or discussion of this aspect. In the El Sibai area the only work on this topic, to our knowledge, is by El Gaby et al. (1994). These authors noted that higher temperature facies assemblages with hornblende and garnet are found in the nappes along Wadi Um Luseifa. They suggested that there were two separate metamorphisms: the first being the regional low-grade metamorphism accompanying the formation of (S_1) cleavage, and the second a later static thermal metamorphism unrelated to any exposed intrusion, producing an almandine/hornblende zone. We note several features indicating that the medium and higher grade metamorphic assemblages are related to the syn-kinematic gneissic granitoid intrusions:

(1) Both low-grade and higher grade assemblages define S_1 foliations and L_1 lineations.
(2) In thin section the hornblende porphyroblasts show dynamic recrystallization in foliated rocks, and signs of deformation, e.g. brittle extension of the hornblende parallel to L_1, and deflection of S_1 around some hornblende and garnet porphyroblasts indicating syn-S_1 high-temperature porphyroblast growth (Fig. 4b).
(3) High-temperature metamorphic effects are found in belts associated with the gneissic granitoid sheets in the ophiolitic nappes, e.g. migmatized metasediments and high-temperature schists against gneissic tonalite and granodiorite sheets south of the Delihimmi granite.
(4) In some rocks hornblende defines S_1 foliations overprinting lower temperature phases. Elsewhere, high-temperature hornblende-bearing hornfelsic rocks or foliated rocks are deformed by S_1 low-temperature foliations. A good example of this is the Kab Ahmed shear zone, where slivers of amphibolite and hornblende grains are enclosed in low-grade foliations.

The simplest explanation for these features is that the nappe stacking shear zones were active in different parts of the nappes at different times. Hot magma sheets (gabbros, tonalites, granodiorites) were injected also at different times and places delivering enough heat to locally raise the rocks to higher temperatures.

5.2. El Sibai is not a basement dome and not a core complex

The El Sibai area is popularly described as consisting of gneissic infrastructure lying beneath a domed major shear zone that separates it from overlying low-grade cover nappes. On the basis of this it has long been referred to as a basement dome. Our re-investigation of the area concludes however that:

(1) the regional structure cannot be described as antiformal,
(2) the gneissic association rocks do not represent the structurally deepest units in the area, i.e. they are not infrastructure. They form a suite of syn-kinematic foliated tabular intrusions interposed between nappes of the ophiolitic association rocks,
(3) stereographic diagrams and structural maps do not support a model of a doubly plunging structure,
(4) the main area of gneissic rocks is not bounded by a single shear surface. The boundary is a normal fault at the SE boundary; a SE vergent low-angle ductile shear zone (representing the upper boundary of the El Shush gneissic tonalite) folded to SW dip at the SW boundary; a weakly sheared contact (representing the lower boundary of the gneissic rocks) rotated to a steep SW dip at the NE boundary; and probably a NW dipping steep normal shear at the NW boundary (though this area is obscured by later intrusions). These boundaries have different ages and different significances. These observations are not consistent with the gneissic association rocks being basement infrastructure. Neither are they consistent with the El Sibai macrostructure being domal. This in itself invalidates the models for the El Sibai as a basement dome, and therefore as a core complex.

5.3. Transpression-related exhumation models

In the following text we briefly examine the evidence presented by Bregar et al. (2002) for their model of El Sibai magmatic core complex rise, including an evaluation of regional strain partitioning during oblique convergence, and the relationship of the El Sibai complex to the evolution of the Kareim basin to its north (Fritz and Messner, 1999).

According to Bregar et al. (2002) the events at El Sibai began with (1) *nappe stacking* and syn-kinematic intrusion of deep crustal granitoids (El Shush gneissic tonalite) at 670–690 Ma. This was followed by (2) *early transpression* expressed as orogen-parallel (NW–SE) extension accompanying activity on internal sinistral shears which were syn-kinematically intruded by mid-crustal granitoids (Abu Markhat gneissic granodiorite) at ~650 Ma; (3) *later transpression* expressed as NW–SE extension accommodated by NW and SE dipping normal faults, and simultaneous activity on external sinistral strike-slip faults. This system controlled the intrusion of upper crustal granitoids (Um Shaddad and El Sibai red granites) also at about 650 Ma; (4) intrusion of felsic granitoids (El Dabbah granodiorite, Um Luseifa gneissic granite and gneissic leucogranites). In terms of the core complex model, stage (2) amounted to mild uplift and exhumation, while stage (3) triggered rapid exhumation of the complex. These two stages of mild and rapid core complex uplift were correlated by Fritz and Messner (1999) with two stages of development of the Kareim basin, involving first slow subsidence and low sediment supply and later rapid subsidence and massive sediment supply. The two stages were referred to as low-velocity exhumation by magmatism and rapid tectonic exhumation by Fritz et al. (2002).

Some conclusions of the present study are in strong disagreement with the history outlined above, particularly in the role of the strike-slip shears of the El Sibai area. The internal shears at stage (2) do not exist. The Abu Markhat granodiorite is not vertically foliated, though it has steeply dipping foliations defining a tight macroscopic synform parallel to and just NE of the Higlig antiform (Fig. 2a). Elsewhere along Wadi Abu Markhat the same unit has gently dipping foliations describing lower amplitude, more open F_2 folds. Poles to mid-crustal granitoid foliations plotted by Bregar et al. (2002) show a girdle pattern more consistent with folding about a gently SE plunging fold axis, similar to our Fig. 7a for magmatic foliations. The external sinistral strike-slip shears of stage (3) shown on maps by Khudeir et al. (1995), Bregar et al. (1996, 2002), Fritz and Messner (1999), Fritz et al. (1996, 2002), Shalaby et al. (2005, 2006) also do not exist. The NE and SW boundaries of the El Sibai complex are not strike-slip faults, as has been discussed above. The strike-slip faults of this region, e.g. El Shush shear zone have mainly WNW–ESE to E–W strike (with later N–S strikes) and formed after the mylonitic low-angle normal shears. We emphasize that the onset of NW–SE regional extension in the form of low-angle normal shears pre-dates any activity on the strike-slip faults. These results are incompatible with the model of strain partitioning into orogen-parallel extension and strike-slip motion.

A second major divergence of our model from the El Sibai core complex models is in the role of regional NW–SE folding. The importance of these folds are overlooked in the core complex models despite the well documented folds in the cover rocks surrounding the complex (e.g. Khudeir and Asran, 1992; El Gaby et al., 1994), and within the complex itself (Khudeir et al., 1992; Kamal El Din, 1993; Kamal El Din et al., 1992; Ibrahim and Cosgrove, 2001). In our opinion, the NW–SE folding is paramount in the macrostructure of this area. This was also the conclusion of Fowler and Osman (2001) for the gneissic dome of the Um Had area, and a similar view for the whole CED has been expressed recently by Abdeen and Greiling (2005). The NW–SE regional extension event overlaps in time with the NE–SW shortening event that produced the regional F_2 folds. Fowler and El-Kalioubi (2004) reported an overlap between low-angle extensional shears and folding west of Meatiq, but there the NW–SE folding outlasted extension. The precise nature of the relationship between NW–SE folding and approximately coeval regional extension parallel to the fold hinges in the CED is not known at present. One possibility is that hinges have formed parallel to a direction of convergent flow of orogenic material (Twiss and Moores, 1992, p. 334) such as may be expected in a constricted tectonic environment.

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