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Journal of African Earth Sciences 46 (2006) 201–220
Journal of African Earth Sciences
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The significance of gneissic rocks and synmagmatic extensional ductile shear zones of the Barud area for the tectonics of the North Eastern Desert, Egypt

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Received 16 July 2005; received in revised form 21 December 2005; accepted 28 April 2006
Available online 12 July 2006

Abstract

The mainly tonalitic gneissic rocks, amphibolites, schists and rarer migmatites of the Barud area, at the southern margin of the Egyptian North Eastern Desert (NED) have previously been viewed as products of ultrametamorphism or granitization of pre-PanAfrican basement. The Qena–Safaga Line of approximately NW-striking steeply dipping faults was also regarded as marking the boundary between these NED rocks and the low grade metavolcanics and ophiolitic melange of the Central Eastern Desert (CED). Detailed investigation of the Barud area indicates that the amphibolites, schists and migmatites formed by shearing and medium grade metamorphism of similar arc metavolcanics to those of the CED in normal shear sense extensional ductile shear zones heated by numerous synkinematic dolerite, gabbro, diorite, granodiorite, tonalite and granite dykes. They are thus hot sheared equivalents of the CED metavolcanics and basic arc plutonites, accompanied by sheared mafic and felsic intrusive rocks, and are not deep-seated crystalline basement rocks. The shear zones are interpreted as having formed by arc-rifting, not necessarily reaching the stage of marginal basin formation. Arc-accretion structures and those produced by later orogen squeezing are also described. The somewhat gneissic Barud Tonalitic is found to be entirely magmatic. Following intrusion of the Barud Tonalite, and before or during Hammamat and Dokhan deposition, the NED experienced a rapid uplift relative to the CED (∼620–600 Ma) that was not achieved by thrusting along the Qena–Safaga Line.

Keywords: Neoproterozoic; North Eastern Desert; Extensional hot ductile shear zones; Amphibolites; Arc tectonics; Qena–Safaga Line

1. Introduction

A fundamental aspect for tectonic models of the Arabian–Nubian Shield in Egypt is in understanding of the origin of orthogneisses, migmatites and other high temperature metamorphic rocks exposed there. These rocks have been generally surveyed by Hume (1934), El Ramly and Akaad (1960), Schürmann (1966), Hunting (1967), Dixon (1979), El-Gaby et al. (1984, 1988), Bennett and Mosley (1987), El-Gaby et al. (1990), Hassan and Hashad (1990), Hegazy (1991) and El-Gaby (1994). El-Gaby et al. (1988) interpreted the gneissic rocks as remobilized early Proterozoic or older continental crust overthrusted by Neoproterozoic ensimatic rocks towards the west. However, most geochemical and geochronological investigations have emphasized the similarities between these rocks and the low-grade ensimatic structural cover, leading to models viewing the gneisses as high temperature metamorphic equivalents of the Neoproterozoic rocks (Kröner et al., 1994).

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doi:10.1016/j.jafrearsci.2006.04.011

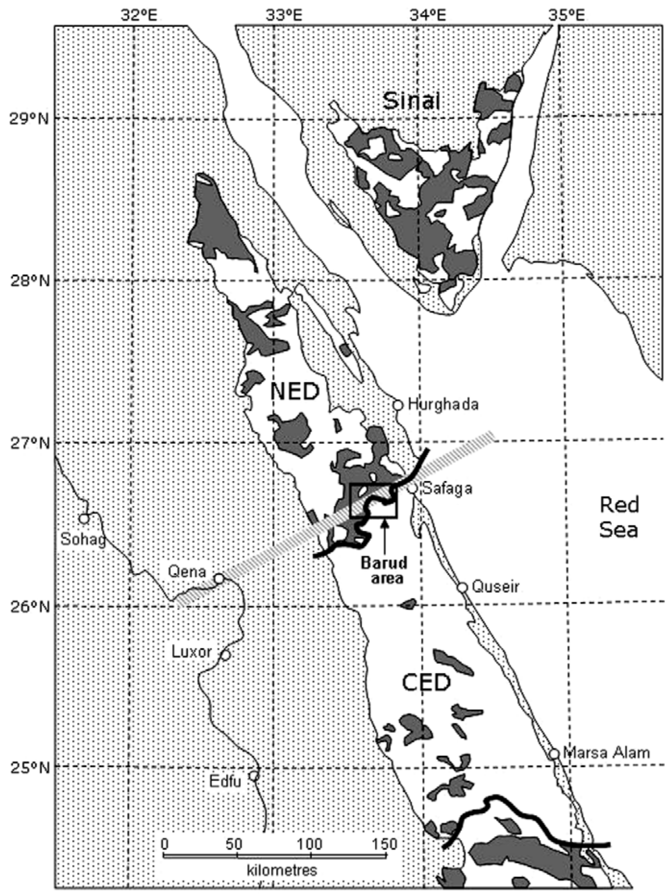


Fig. 1. Regional map of the Egyptian Eastern Desert and Sinai basement rocks showing the North Eastern Desert (NED), Central Eastern Desert (CED) and South Eastern Desert (SED, southeast corner of the map). The basement rocks are represented as grey areas ("Older" Granites or granodiorite–diorite–tonalite (GDT) association of Abdel-Rahman, 1990) with the remaining white areas undifferentiated basement. The approximate boundaries between the NED and CED, and between the CED and SED according to Greiling et al. (1994) are shown as thick dark lines. The Qena–Safaga Line of El-Gaby et al. (1988) and El-Gaby (1994) is shown as a straight thick grey hatched line trending WSW from Safaga. The Barud area is indicated. The chosen area incorporates both Greiling's et al. and El-Gaby's et al. proposed NED–CED boundary.

The Barud area is part of a huge complex of gneissic calc-alkaline (Older) granitoids in the southern part of the North Eastern Desert (NED) of Egypt (Fig. 1). The field relations of the gneisses, amphibolites and migmatites in this area have been used as an example for remobilization of pre-Pan-African continental crust during the later Pan-African orogenic phase (El-Gaby et al., 1988).

This contribution first describes the regional geological setting of the Barud area. Following this, the petrographic and structural characteristics of the amphibolites and other high T metamorphic and magmatic rocks are described in detail, and their relations to ductile shear zones are demonstrated. A structural tectonic model is derived to explain the history of the Barud area, and aspects of this model are discussed in the context of the tectonics of the North Eastern Desert.

2. Geology of the Barud area

2.1. Location and previous investigations

The study area (here referred to as the Barud area) measures approximately 550 km^2, and lies roughly between the Safaga–Qena road (26°43′N) and mountainous terrain south of Wadi Safaga (26°33′N) (Figs. 1 and 2a). The study area is bordered to the east by the Tertiary clastics and Cretaceous phosphatic deposits of Wadi Mohammad Rabah at longitude 33°49′E, and to the west by longitude 33°31′E.

The Barud area was originally investigated by Hume (1934), El-Akkad and Dardir (1965) and Habib (1970, 1972) and forms a part of the region covered by the Safajah Quadrangle 1:100,000 geological map (Dardir et al., 1987), and the Al Qusayr Quadrangle 1:250,000 geological map (Masoud et al., 1992). Fundamental ideas on the relations between gneissic granitoids and supposed older pre-Pan-African continental crust were partly based on a study of this area by Akaad et al. (1973). Detailed regional studies have also been completed by El-Gaby and Habib (1980, 1982) and Habib (1987a,b). Mainly geochemical studies of the granitoids in the Barud area have been reported by Ghobrial and Girgis (1982), Dardier and Al-Wakeel (1998), El-Shazley and El-Sayed (2000) and Kamal El-Din (2003). Abd El-Wahed and Abdeldayem (2002) reported on the structural history of the Barud area.

We follow closely the stratigraphic nomenclature for the map units in the Barud area suggested by El-Gaby and Habib (1980, 1982), modified by Habib (1987a,b). However, we do not subscribe to the relative ages given to these units by El-Gaby and Habib (1980, 1982) since the boundaries between them are mainly faults and shear zones (Fig. 2a). In the following description of the rock units of the area we begin with the structurally lowest unit, the El-Zarga metasediments, then describe the progressively higher units. The sheared contacts between units dip to the north, so progressively higher units are found further to the north. The structurally assembled units include low grade and medium grade rocks of magmatic, volcanic and sedimentary origin. There has been no radiometric dating of these units, however estimated ages for these units, based on the geological history of the area and data from surrounding areas, is found in Table 1.

2.2. El-Zarga metasediments

The El-Zarga metasediments crop out as a thin belt in the SE part of the mapped area (Fig. 2a). They are described as fore-arc basin metasediments by Habib (1987a) and referred to the Abu Ziran Group by El-Gaby and Habib (1982). The contact with the overlying Abu Marawat metavolcanics is a reverse fault intruded by a thick weakly sheared dolerite intrusion (Fig. 2a and b). These metasediments consist mainly of planar bedded and laminated greyish to blackish metasiltstone, phyllite

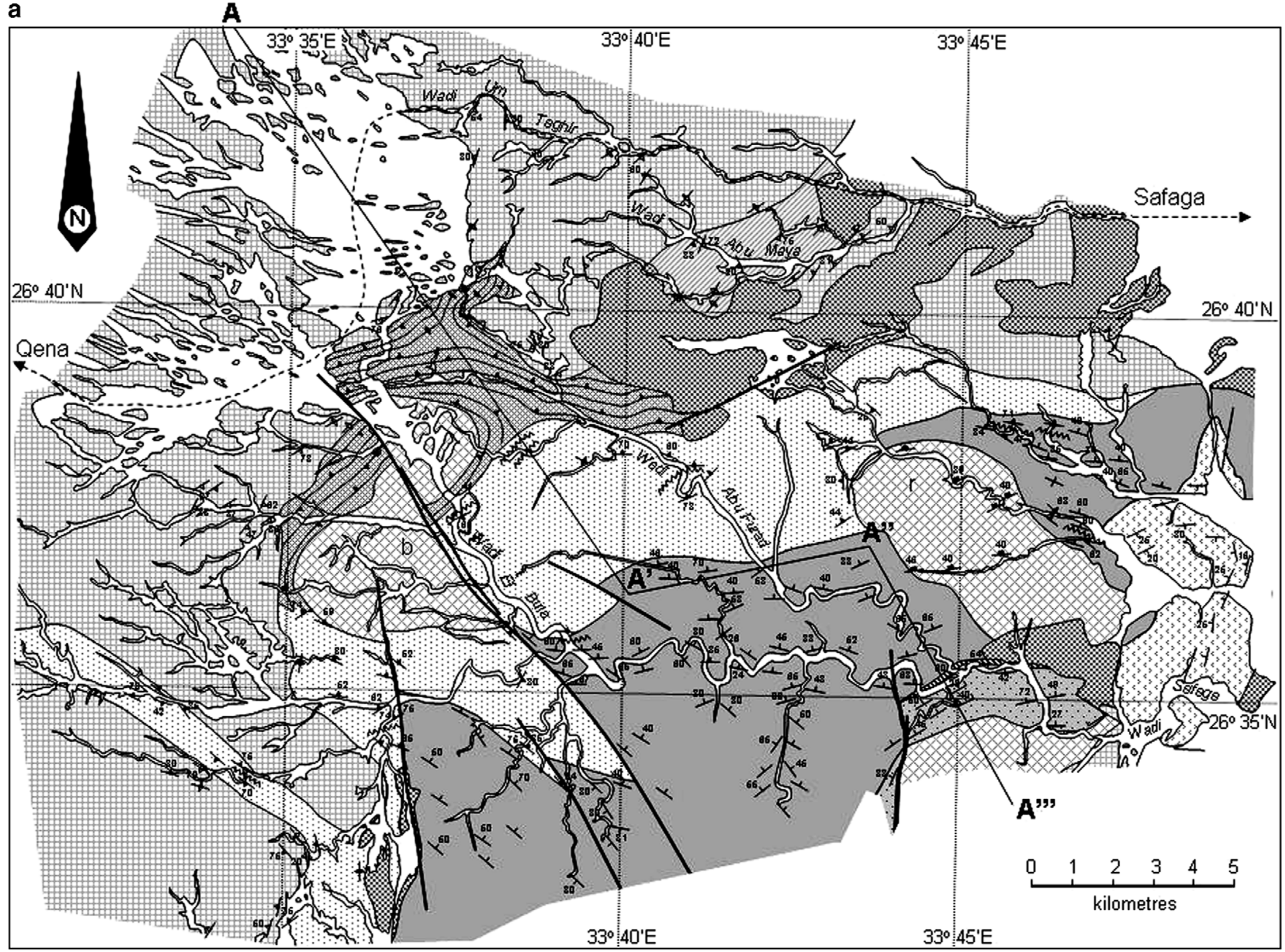


Fig. 2. (a) Geological map of the Barud study area. Map legend is presented in (b). The dashed line labeled "Qena" and "Safaga" represents the sealed main road connecting Qena with Safaga. Bold lines represent faults. (b) Cross-section A–A′A″–A‴ has no vertical exaggeration. On the cross-section, trend lines are also shown representing bedding dips variations in the metavolcanics and metasediments, and S_1 foliations in the amphibolites (continuous lines) and in the metagabbro–diorites (crossed short lines). Heavy lines are faults. The dominant NW-striking sinistral faults are probably Najd faults.

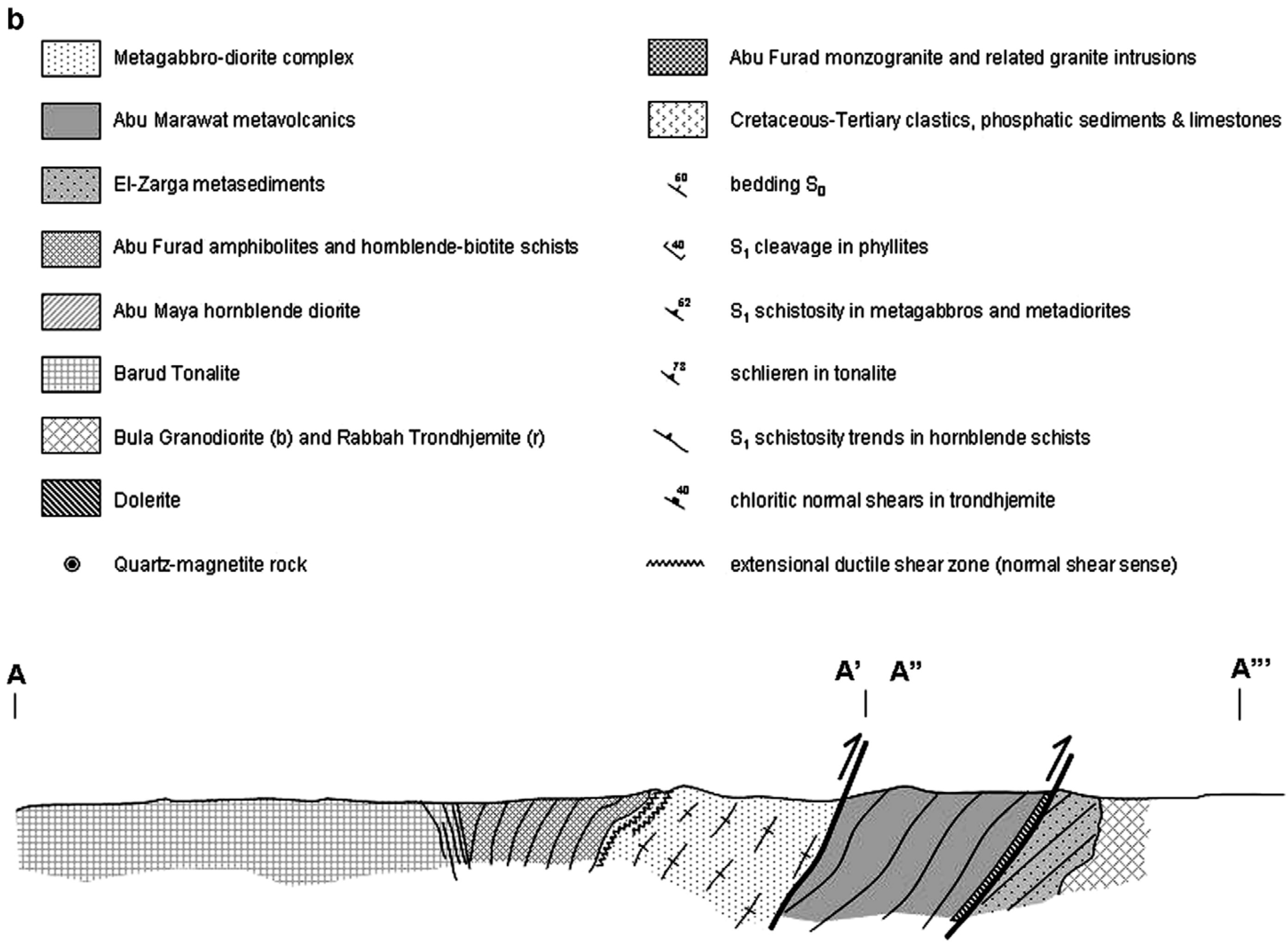


Fig. 2 (*continued*)

and greywacke with minor greenish conglomerate. There are numerous white carbonate concretions in the finer grained metasediments. Graded bedding in the sandier metasediments indicates consistent upward younging for the sequence. The characteristic "cross-bedding" reported by El-Gaby and Habib (1980) is probably of tectonic origin representing cleavage oblique to bedding (Fig. 3a).

The phyllite and metasiltstone are composed of fine angular quartz particles and untwinned sodic plagioclase. Parallel-aligned flakes and wisps of sericite, greenish to colourless chlorite and brown biotite define the slaty cleavage. The greywacke includes plagioclase, recrystallized quartz and particles of silicic volcanic groundmass clearly indicating a silicic volcanic provenance for the sediments.

Individual weakly deformed to undeformed thick dolerite sills are common in the El-Zarga metasediments. In one location the cleavage in the metasediments is distorted and truncated by the dolerite intrusion, suggesting that at least some of these intrusions post-date the formation of cleavage in the rocks.

2.3. Abu Marawat metavolcanics

These metavolcanics form a wide belt of moderately to steeply dipping lavas structurally overlying the El-Zarga metasediments in the southeastern part of the Barud area (Fig. 2a). They consist typically of 2–4 m thick flows of dark green to grey amygdaloidal meta-andesite and to a lesser extent of metabasalt, with regular alternations of pale green to pink commonly flow-banded metadacite, metarhyolite and reddish brown columnar jointed felsite lavas. They generally do not contain sedimentary interlayers. The lavas are subaerial on the evidence of ignimbritic textures, pumice inclusions in the silicic lavas (Fig. 3b) and the absence of pillow structures in the mafic lavas. Habib (1987a) described these volcanics as bimodal, with an estimated thickness of 5600 m (Habib, 1987b). Dardier and Al-Wakeel (1998) reported a tholeiitic affinity for the metavolcanics. El-Shazley and El-Sayed (2000) confirmed the tholeiitic chemistry and concluded that the trace element abundances are consistent with a back-arc environment.

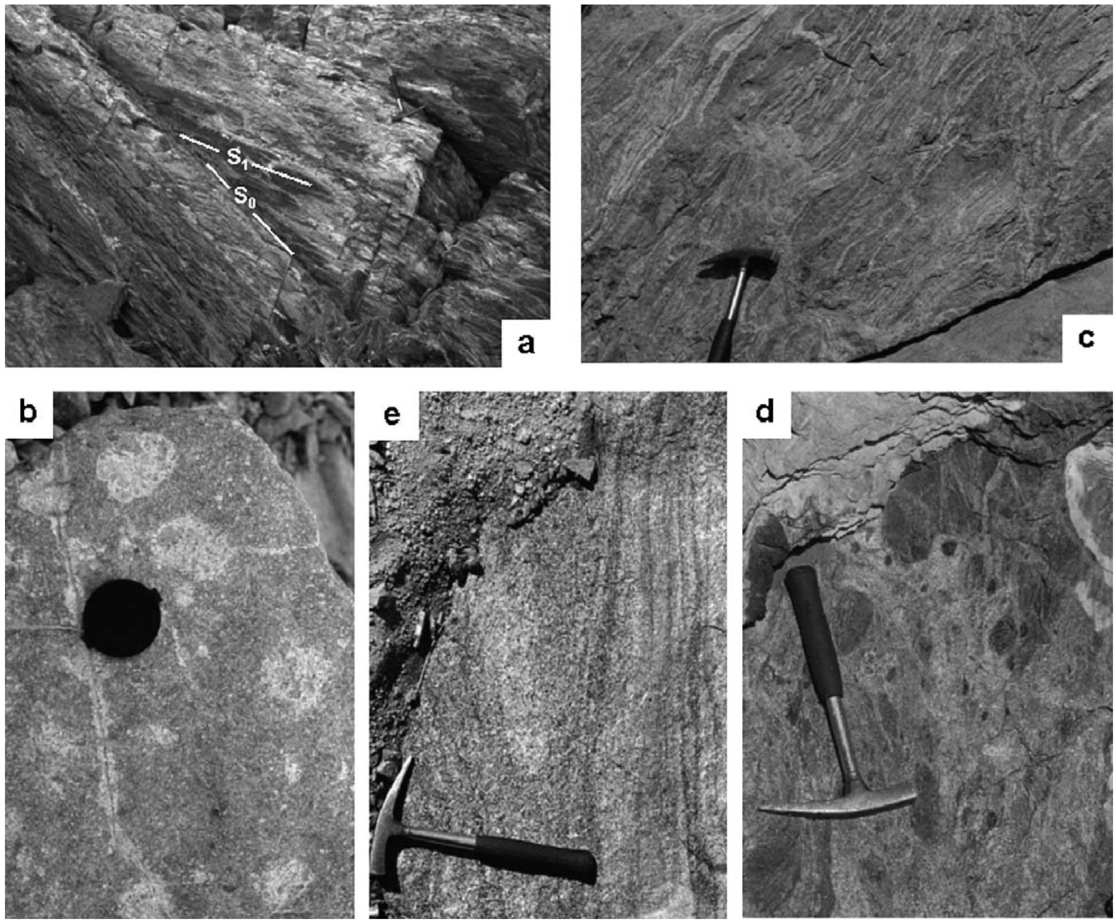


Fig. 3. (a) Bedding (labelled as S_0) and S_1 cleavage in the El-Zarga metasediments (here graded lithic wacke). (b) Pumice fragments in silicic unit of the Abu Marawat metavolcanics (lens cap scale 5 cm diameter). (c) Migmatite in the marginal parts of the Barud Tonalite consisting of foliated metadiorite (dark areas) interlaced with veinlets of lighter coloured tonalite (see Fig. 9h). (d) Magma contamination zone with partly digested xenoliths of metadiorite in Barud Tonalite (see Fig. 9g). (e) Hornblende-rich schlieren in the marginal parts of the Barud Tonalite.

The igneous textures of these rocks are well preserved, and most examples show only alterations or pseudomorphing by greenschist facies minerals. All of the metavolcanics have plagioclase phenocrysts, often zoned and usually sericitized or replaced by clinozoisite. Resorbed quartz phenocrysts are found in the metarhyolites. Mafic phenocrysts consist of hornblende replaced by actinolite, and biotite replaced by chlorite. Groundmass textures are usually preserved and consist of flow-oriented plagioclase laths with interstitial quartz, chlorite, actinolite, clinozoisite, Ti oxides and opaques. Micrographic textures are found in the felsites.

Up to 30 m thick dolerite and gabbro sills are present throughout the sequence. These are identical to those found in the El-Zarga metasediments. There are also thick sills of diorite and granodiorite. These sills are later intrusions into the Abu Marawat.

2.4. Metagabbro–diorite complex

An approximately 4 km wide strip of greenschist facies metamorphosed weakly deformed gabbro and diorite suite lies structurally upon the Abu Marawat metavolcanics in a central position in the study area (Fig. 2a and b). These mafic intrusive rocks are generally referred to as ‘‘metagabbro–diorite complex’’ or ‘‘epidiorite’’ (El Ramly and Akaad, 1960; Ghanem, 1972; Dardir and Abu Zeid, 1972; Francis, 1972; Sabet et al., 1972) though they have also been described as gabbro–diorite–tonalite (GDT) by Abdel-Rahman (1990, 1995). They are a calc-alkaline series believed to have formed in an intraoceanic subduction zone environment (Abdel-Rahman, 1990), island arc marginal basin (Ghoneim et al., 1992) or active continental margin setting (El-Gharbawi and Hassen, 2001).

Massive to weakly deformed gabbro and dolerite form xenoliths within later diorite. Small intrusions and dykelet networks of tonalite, granodiorite, granite, aplite within the mafic rocks are also characteristic. Melt reactions with xenoliths or dyke wallrocks are common, leading to magma contamination, and hydrothermal alteration is also present. Deformation of these rocks is typically weak with faint foliations and faulting being the main secondary structures.

The metamorphic grade of the metagabbro–diorite is generally greenschist facies chlorite zone. Metagabbros are composed of sericitized plagioclase (Fig. 4a) and pallid clinopyroxene partially altered to chlorite and epidote, and

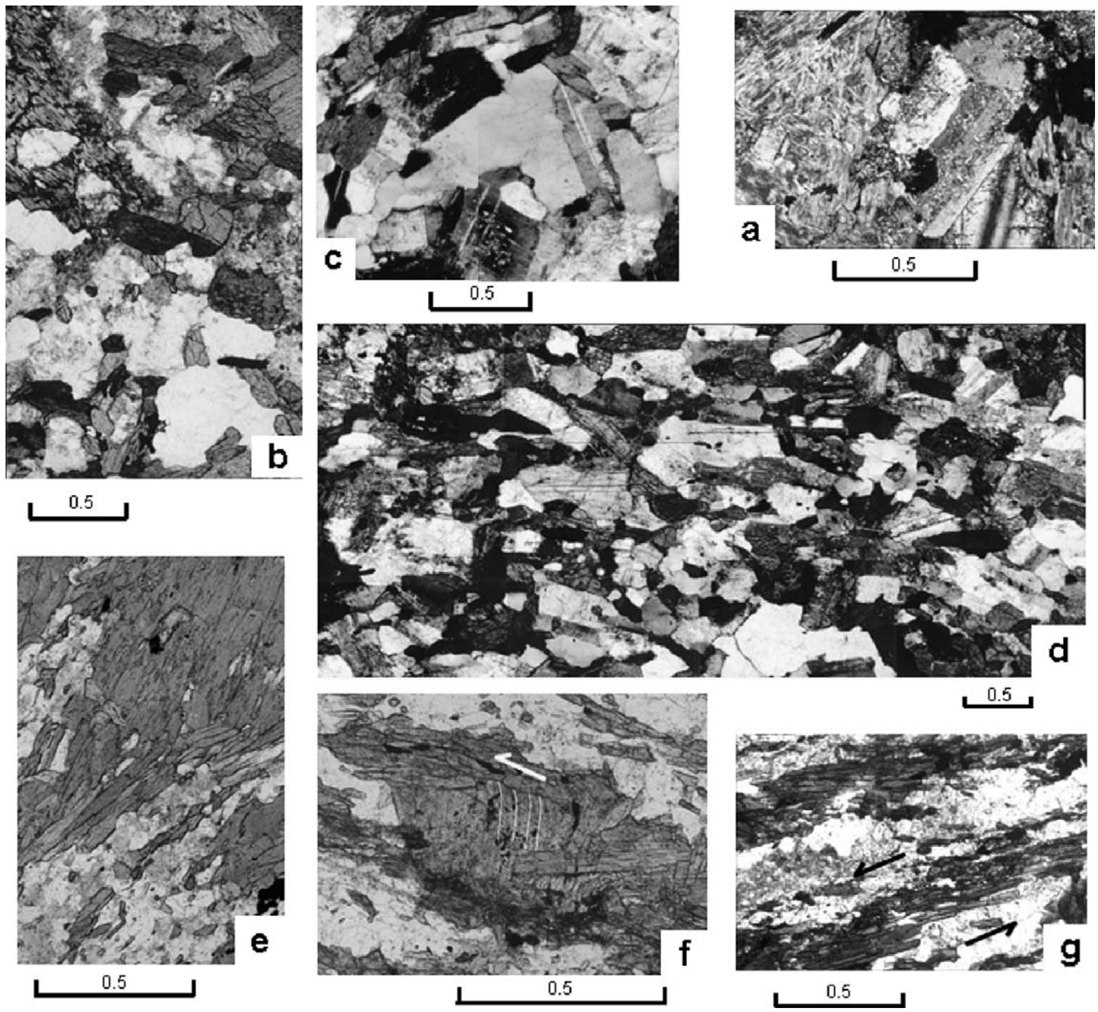


Fig. 4. Photomicrographs from the Barud study area. pp = plane polars, xp = crossed polars. (a) Diorite of the metagabbro–diorite complex (xp) consisting of subhedral plagioclase and secondary amphibole replacing hornblende (left half). (b) Barud Tonalite (pp): quartz (white), plagioclase (cloudy grey), chlorite after biotite (flecked with opaque granules), hornblende (upper right quarter). (c) Example of consistent elongation of interstitial (primary magmatic) quartz grains (xp). Long axes are sub-parallel to other magmatic textures e.g. (d) Preferred orientation of subhedral plagioclase long axes and Albite twins in Barud Tonalite (xp). Note the parallelism of interstitial quartz grain long axis (white grain right of midpoint of bottom edge of photograph). (e) Recrystallization of hornblende at the edge of a mafic porphyroclast (pp). The recrystallized hornblende defines the foliation in the rock. (f) and (g) Shear sense indicators from the Abu Furad amphibolite (pp). (f) Shear-related bending of hornblende cleavages and (g) systematic inclination of hornblende crystal axes to the folia. Both sections were cut normal to the S_1 foliation and parallel to the L_1 lineation, giving a subvertical section trending NW–SE. Observation direction in both (f) and (g) is towards the NE.

fringed by actinolite. Diorites show phenocrysts of plagioclase, clinopyroxene, hornblende and biotite with similar groundmass phases supplemented by interstitial quartz. Tonalite and granodiorite have progressively more quartz and biotite and less hornblende, and have low colour index. The boundary between the metagabbro–diorite complex and the metavolcanics is difficult to locate. Previous mapping of the area has placed a reverse fault boundary at quite radically different locations. This is due to the fact that the boundary is intensively intruded and obscured by dolerites.

2.5. Abu Furad amphibolites and schists

This fascinating unit has been interpreted as eugeosynclinal metasediments and metavolcanics belonging to the lowest sections of the Abu Ziran Group (Sabet et al., 1972; Akaad et al., 1973; Dardir et al., 1987; Asran, 1992; Masoud et al., 1992; Dardier and Al-Wakeel, 1998) as defined by El Ramly and Akaad (1960). Alternatively, these amphibolites and schists have been labeled as the Abu Furad Gneiss, grouped together with granitoid gneissic rocks, and considered as part of the pre-Pan-African continental crust (Barud infrastructure) by El-Gaby and Habib (1980, 1982); Habib (1987a,b); El-Gaby et al. (1988); El-Gaby (1994) and El-Shazley and El-Sayed (2000). A part of these amphibolites was identified as Meatiq Group by Masoud et al. (1992).

The relatively small area of Abu Furad amphibolites and schists lies between the metagabbro–diorite and the Barud batholith (Fig. 2a and b). This unit consists of metre-scale alternations of typically intensely foliated and stretched fine-grained blackish hornblende schists or amphibolites and lighter coloured foliated felsic rocks derived from diorites, tonalites and granodiorites (Fig. 5a and b). There are sheared metadolerite and metagabbro lenses preserved locally within the anastomosing foliation (Fig. 5c), as well as sill like masses of these mafic rocks as found in the previously described units. The contacts between the amphibolites and felsic schists are sharp and usually parallel to the foliation (Fig. 5d) and these contacts are paralleled by magmatic features, such as schlieren, flow bands and flow oriented phenocrysts. A few concordant bodies of banded quartz–magnetite rock and felsic metatuff are also found within this unit (Fig. 2a). Bishara and Habib (1973) have reported similar silicified iron rich bands in the silicic metavolcanics at Gabal Semna (10 km south of the Barud area at 26°26′N 33°34′E), and iron-rich horizons are associated with foliated metavolcanics and metadolerites at Umm Anab (20 km north of the Barud area at

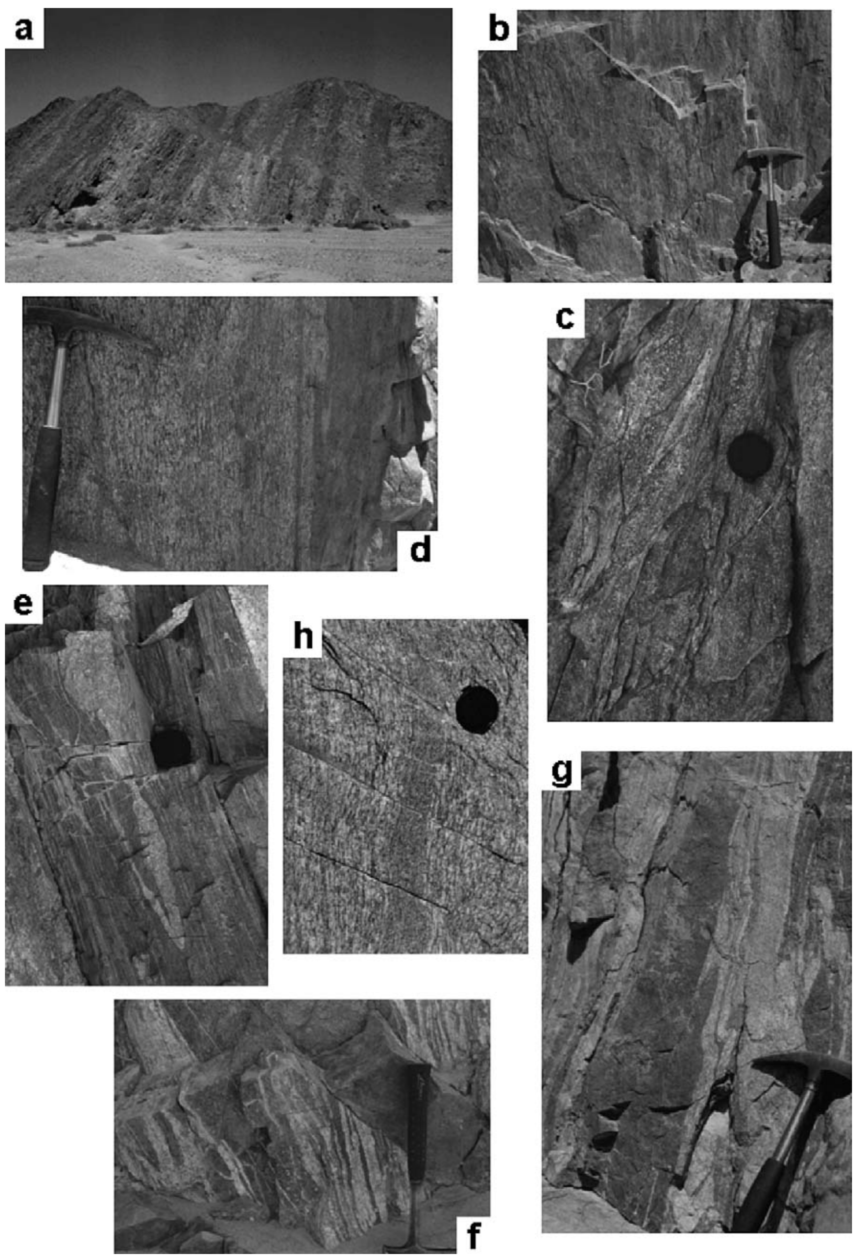


Fig. 5. (a) Abu Furad amphibolites showing pervasive sheetlike intrusion along foliation by light coloured tonalites and diorites. (b) Well-developed linear structure (L_1) on S_1 foliations in the Abu Furad amphibolite. (c) Discrete ductile shear strands cut through metagabbro. (d) Foliated boundary of tonalite against sheared diorite in the Abu Furad amphibolite. (e) Abu Furad gneissic amphibolite with boudinaged and folded granite veinlet. (f) Striped outcrop of mainly flow structured intrusive rocks in a ductile shear zone within the Abu Marawat metavolcanics. Dark stripes are porphyritic microdiorite. Light stripes are tonalite. Flow streaking of the two magma phases was evidently followed by some parallel solid state deformation producing local foliations and boudinage of the stripes (see Fig. 9o). (g) Same locality as (f) above. Microdiorite with tonalitic flow-banded veinlets showing asymmetric tectonic F_1 fold (see Fig. 9m). (h) Gneissosity in tonalite, parallel to magmatic flow structure (darker central band).

26°52′N 33°33′E) (Sabet et al., 1972). Folded and boudinaged pink granite dykes and pegmatites inject along and across the foliation (Fig. 5e) and incorporate the amphibolites as xenoliths.

In thin section the foliation and lineation in the amphibolites and hornblende schists are defined by slender blue–green metamorphic hornblende grains with a high degree of shape preferred orientation and a parallel fabric of chloritized biotite platelets (Fig. 6a). Sericitized untwinned plagioclase and rarer quartz form a polygonal granoblastic mosaic with grain long axes parallel to the foliation. Opaques are accompanied by sphene or rutile. The metamorphism of these hornblende rich rocks is medium grade on the basis that the hornblendes show clear evidence for dynamic recrystallization. The metamorphic aspects of these rocks are further discussed in Section 3.2. The felsic schists have a foliation defined by retrograde chloritized biotite platelets. Other phases such as plagioclase, quartz and metamorphic hornblende are anhedral though have grain long axes systematically disposed subparallel to the foliation. In addition to foliated fabrics, the same mineral assemblages as found in the amphibolites and felsic schists are rarely found to have hornfelsic textures. The boundary between the Abu Furad amphibolites and the metagabbro–diorite complex will be detailed in Section 3.2 and discussed in Section 4.3.

2.6. Abu Maya hornblende diorite

This unit was identified by Akaad et al. (1973) as a coarse homogenized hornblende gneiss, and was later named the Abu Maya diorite gneiss by El-Gaby and Habib (1980, 1982). It forms a northeast-trending mass within the Barud Tonalite (Fig. 2a). It is a typically coarse- to medium-grained hornblende biotite quartz diorite (Fig. 7) lacking any foliations. The coarse homogeneous diorite incorporates huge blocks of amphibolite, foliated microdiorite and gneissic tonalite which appear to be xenolithic remnants of an along strike extension of the Abu Furad amphibolites. The xenoliths preserve evidence of complex relations between felsic magmas and sheared mafic wall-rocks (Fig. 3c and d) which will be detailed later in Section 3.2. The voluminous Barud Tonalite has later intrusive relations against the Abu Maya diorite.

2.7. Barud Tonalite

The Barud Tonalite (Barud Gneiss of Hume 1934) forms a huge batholithic mass extending across the entire width of the NED, west of Safaga (Figs. 1 and 2a). The batholith margins are clearly discordant to the foliation trends of the Abu Furad amphibolite (Fig. 2a and b) and cut across the contacts between these amphibolites, the metagabbro–

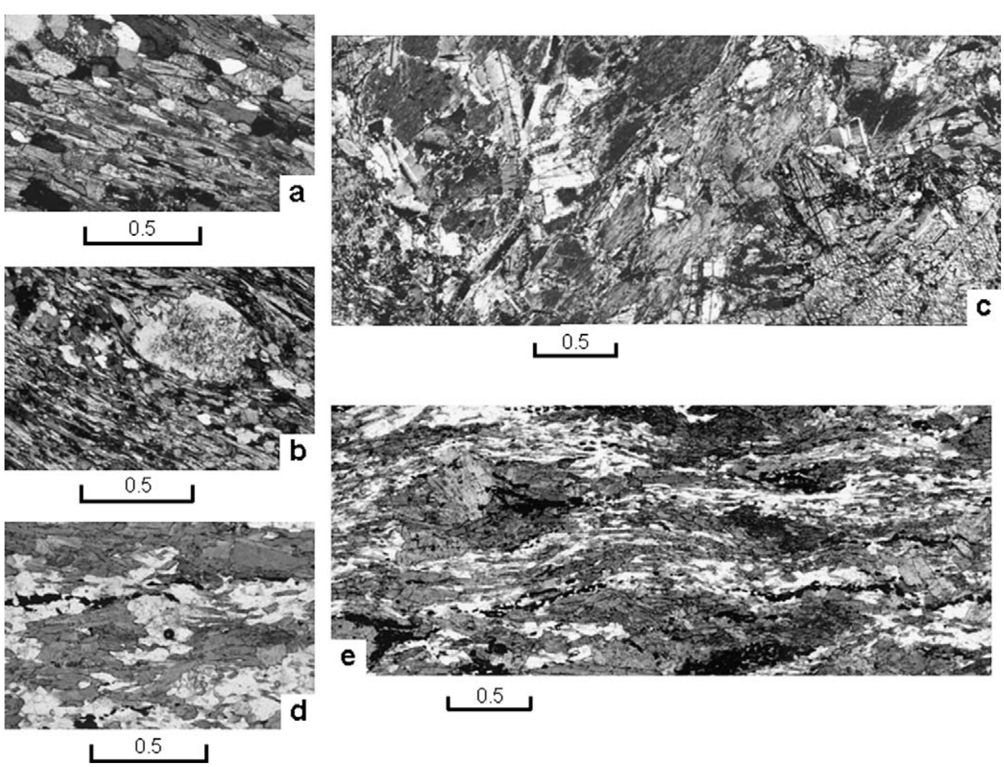


Fig. 6. Photomicrographs of medium grade metamorphic rocks from the Barud study area. (pp) pp = Plane polars, xp = crossed polars. (a) Example of typical hornblende-rich schist from the Abu Furad amphibolites (xp). (b) S_1 foliation defined by slender hornblende crystals in sheared meta-andesite from the Abu Marawat metavolcanics (xp). Plagioclase phenocryst is preserved in the upper right part of the figure. (c) Low strain deformation of metadolerite intrusion collected from the Abu Marawat metavolcanics. Note the preservation of sub-ophitic texture on the left side of the photograph (xp). (d) Well developed S_1 foliation in a metadiorite still preserves traces of the original mafic phases as mafic clots (pp). (e) High strain deformation of metadiorite yielding fine grained (S_1) foliated hornblende–plagioclase–quartz groundmass with recrystallized mafic augen of hornblende.

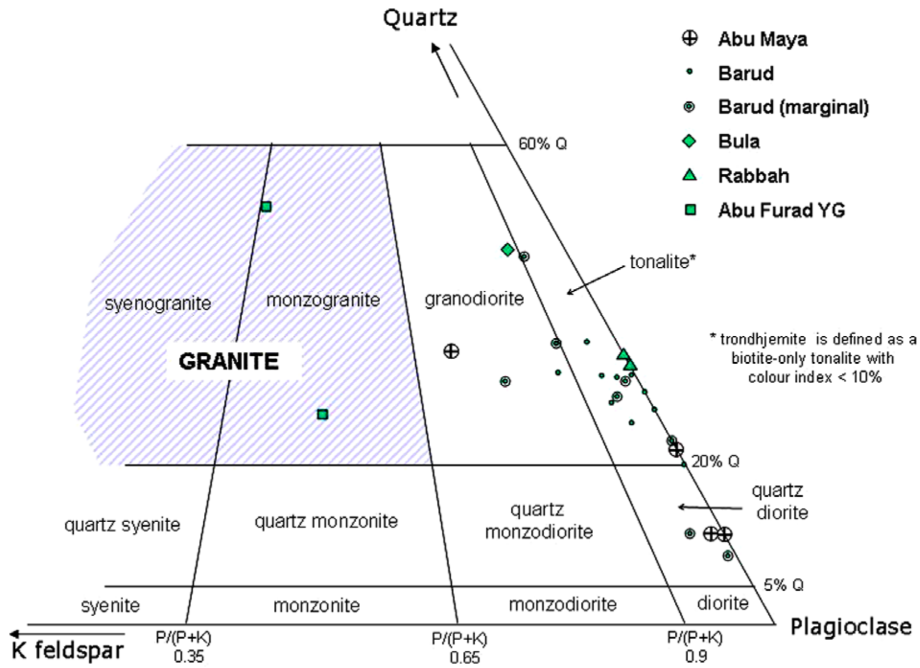


Fig. 7. Part of the Streckeisen (1976) classification diagram for coarse-grained igneous rocks showing the modal compositional variations for the Abu Maya hornblende diorite, the Barud Tonalite (with marginal zone compositions plotted separately), Bula granodiorite, Rabbah trondhjemite and Abu Furad pink granite. Q = quartz, P = plagioclase, K = alkali feldspar.

diorite complex, and the Abu Marawat metavolcanics. The intrusive margin is invaded by apophyses of several kilometres extent penetrating the wallrocks. The features of this batholith are consistent with it being an entirely intrusive igneous body, and not an autochthonous granitoid detached from a remobilized granitized pre-Pan-African basement, as proposed by Akaad et al. (1973), El-Gaby and Habib (1980, 1982), Habib (1987a,b), El-Gaby et al. (1988), El-Gaby (1994), El-Shazley and El-Sayed (2000). It is identified as part of the syn- to late-tectonic Older or "grey" granite group (Akaad et al., 1973; Dardir et al., 1987; Masoud et al., 1992; Dardier and Al-Wakeel, 1998; Kamal El-Din, 2003). El-Shazley and El-Sayed (2000) referred to it as El-Markh tonalitic gneiss. It is grouped with the granodiorite–adamellite–leucogranites by Abdel-Rahman (1995), and is described as tonalite–granodiorite by Helmy et al. (2004). Recent petrochemical studies of NED tonalite–granodiorite batholiths confirm them to be subduction-related volcanic arc melts of probable mantle origin (Hussein et al., 1982; Abdel-Rahman and Martin, 1987; Abdel-Rahman and Doig, 1987; Abdel-Rahman, 1990, 1995; Moghazi, 1999; El-Shazley and El-Sayed, 2000; El-Sayed et al., 2003).

The majority of this pluton (the part that covers the study area) is a monotonous medium to coarse-grained biotite hornblende tonalite (Fig. 7) showing weak to distinct mafic phenocryst flow lineations and schlieren (Fig. 3e). The tonalite has plagioclase phenocrysts. Quartz is usually present as interstitial grains accompanied by minor microcline. The mafic phases are interstitial green hornblende and brown biotite (Fig. 4b). The colour index is rarely more than 10. Some Barud granodioritic phases are richer in microcline and quartz, have biotite as the main mafic mineral, and have accessory piemontite. There is usually very minor deformation e.g. kinking and bending of plagioclase twins, undulose extinction in quartz, and complex kinking of the chlorite grains.

A broader range of rock compositions is found in the marginal zone of the batholith. These include tonalite, quartz diorite and granodiorite. These marginal zones show better developed schlieren, numerous plagiophyric microdiorite enclave swarms (zones 10's metres wide) in various stages of interaction with the tonalite magma (Figs. 3e, 8 and 9). Some enclaves are ovoid, while others are highly flattened and extended. Some xenoliths are identified as blocks of the Abu Furad amphibolite. The magmatic character of the schlieren is demonstrated by the igneous-textured hornblende and biotite that define them, and the parallelism of the schlieren to other magmatic textures including: euhedral plagioclase crystal long axes, Albite Law growth twins (Fig. 4d), elongate single crystals of interstitial quartz showing magmatic resorption relations with euhedral plagioclase (Fig. 4c and d), and flow aligned magmatic apatite needles.

2.8. Other plutons in the Barud area

The Bula Granodiorite is an elliptical pluton divided by a sinistral transcurrent fault into two halves. Before faulting it measured 3.5 km along a shorter NW–SE axis and

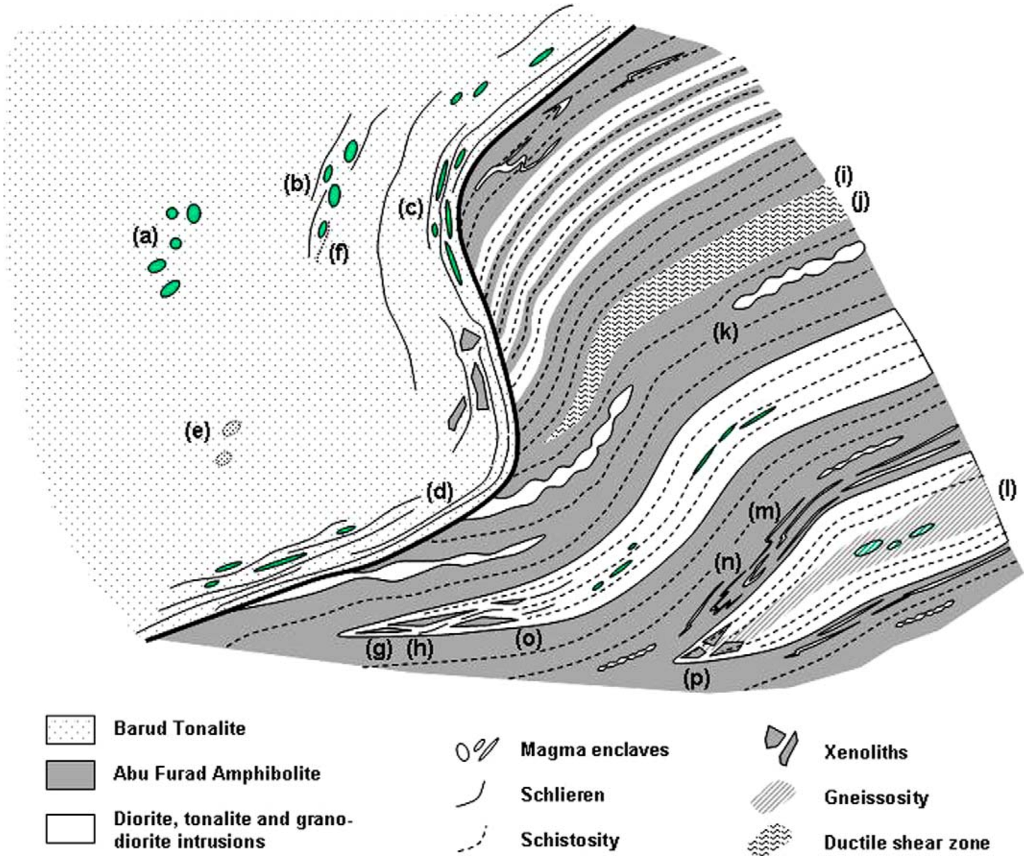


Fig. 8. Idealized sketch of the Barud Tonalite and its contact with the Abu Furad amphibolites. The contact is intrusive and locally peneconcordant. Within the Barud the contact is paralleled by belts of schlieren, drawn out enclaves and xenolith zones with varying degrees of magma contamination. The structure of the Abu Furad amphibolites is more complex with both magmatic features: dykes, veinlets and sheeted intrusions, with solid state deformation overprinting them: boudinage, folding, ductile shearing and foliations. See text for full discussion. Alphabetic letters refer to features shown in Fig. 9.

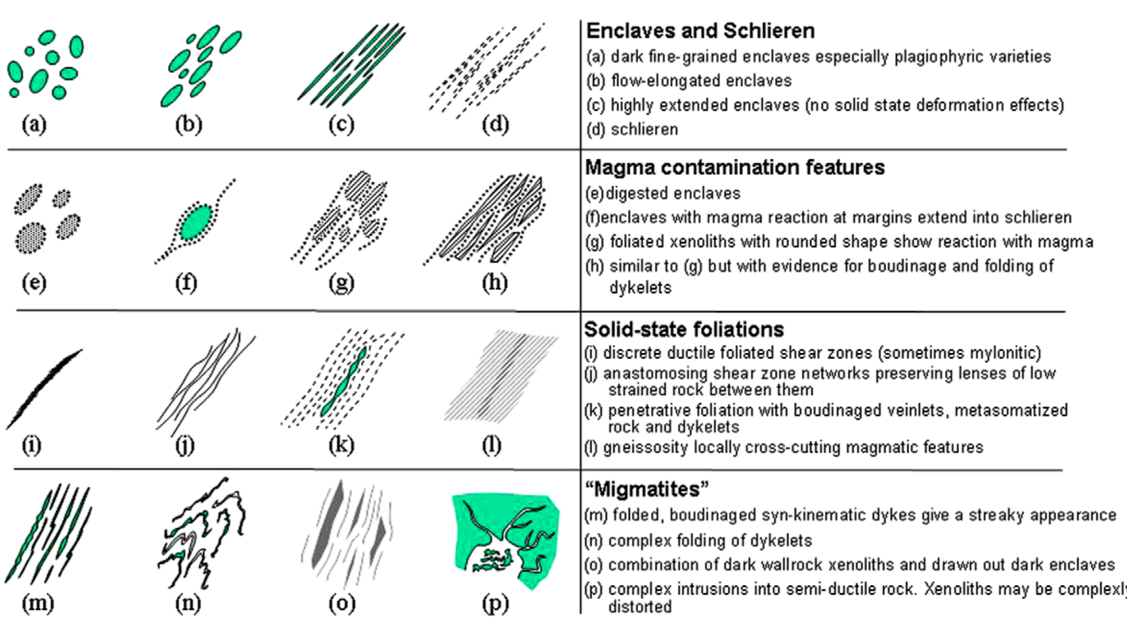


Fig. 9. Informal grouping of magmatic and solid-state structures seen in foliated outcrops of the Barud Tonalite and surrounding rocks. The spatial relations between these structural elements are shown in a model of the Barud Tonalite and its contacts in Fig. 8.

4 km along a longer NE–SW axis (Fig. 2a). It is a white, very coarse-grained massive biotite granodiorite (Fig. 7) without foliation (El-Gaby and Habib, 1980, 1982), and is probably related to the Barud Tonalite as a satellite pluton. The foliation trends of the Abu Furad amphibolite are distorted along pluton margins (Fig. 2a). This pluton was

identified as an intrusive "grey granite" by Akaad et al. (1973), and was petrogenetically investigated by El-Shazley and El-Sayed (2000). The Rabbah Trondhjemite is a small elliptical pluton lying in the eastern part of the study area (Fig. 2a). It is also referred to as the Rabbah intrusive tonalite by El-Gaby and Habib (1982). It is essentially a trondhjemite (plotting in the tonalite field in Fig. 7, with colour index < 10 and biotite as the almost exclusive mafic phase). It shows intense hydrothermal alterations, particularly chloritization, especially along and near the many NW-dipping normal faults cutting through it. Both the Rabbah and the Bula pluton are identified as syn-tectonic by Masoud et al. (1992), El-Gaby and Habib (1980, 1982) and Habib (1987a,b).

The Abu Furad Granite is a coarse-grained monzogranite composed dominantly of reddish microcline and milky quartz. Its southern margin dips moderately towards the north and the overall shape is suggestive of a north-dipping tabular pluton, as proposed by Habib (1987a, Fig. 3, his cross-section B–B′). Another similar Younger Granite pluton is found near the point where Wadi Safaga rapidly narrows in the southeastern part of the area (Fig. 2a).

3. Structure and metamorphism of the Barud area

3.1. Structure of the low grade metamorphic rocks

The El-Zarga metasediments show numerous faults and ductile shears along the bedding planes, producing intensely foliated bedding-parallel tabular zones of phyllite within the metasiltstone (Fig. 10a). The cleavage (S_1) strikes similarly to the local bedding (S_0) but has ⩽25° lower angle of dip than the bedding (Fig. 10b). Some S_1 cleavage surfaces appear to have been activated as slip surfaces, so that the bedding laminations in the hangingwall of the slip plane have been drag folded to produce tight to nearly isoclinal NE–SW trending angular folds (F_1) clearly indicating a top-to-the-NW (i.e. normal) sense of slip on the shears (Figs. 10b, c and 11a). These features are independent of bedding dips which range from 30° to 75° towards the NW quadrant (Fig. 2a). Our interpretation of these facts is that the S_1 cleavage has formed during a top-to-NW bedding-parallel shearing event that occurred under low-temperature metamorphic conditions and before the beds obtained their moderate to steep dips.

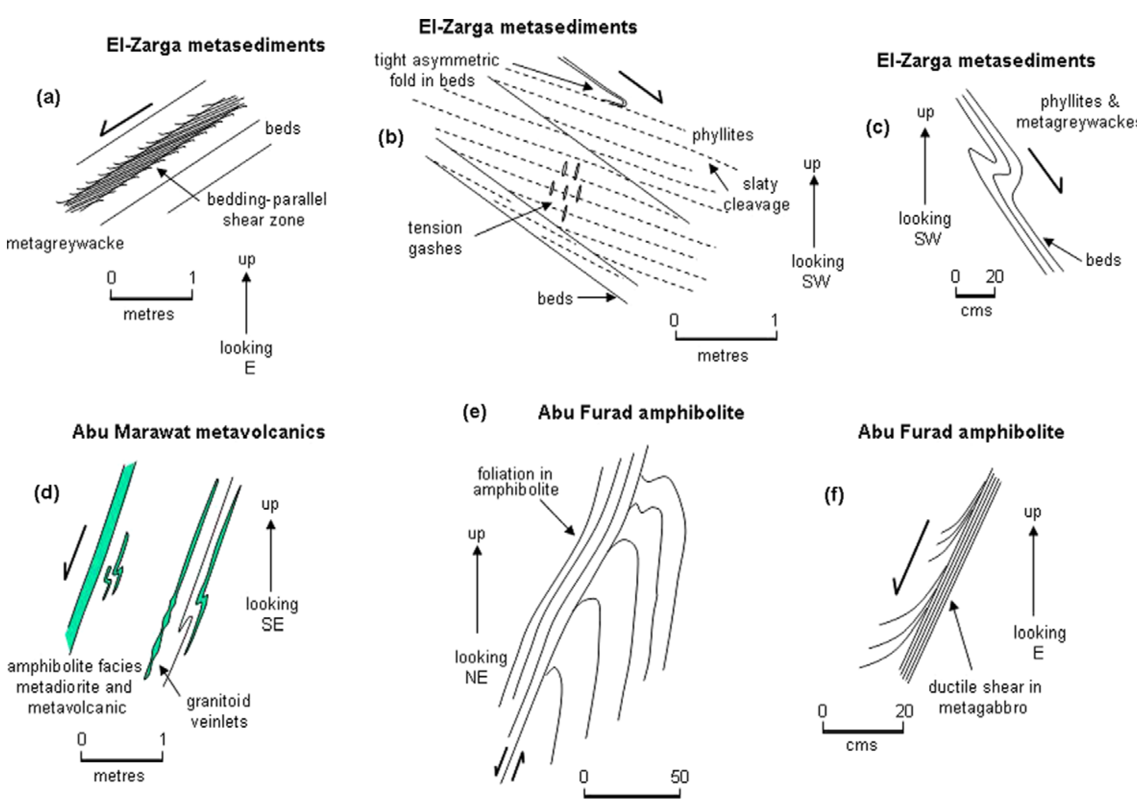


Fig. 10. Outcrop-scale sense-of-shear criteria from the Barud study area. (a) Consistent inclination of shear foliation to bedding parallel shear in the El-Zarga metasediments. (b) Consistent angle of S_1 cleavage (dashed lines) to bedding (bold lines), and tight asymmetric F_1 fold in El-Zarga metasediments (see Fig. 3a). (c) Tight asymmetric F_1 fold with axial plane almost parallel to bedding in the El-Zarga metasediments. (d) Asymmetric folded veinlets parallel to foliation in shear zone in the Abu Marawat metavolcanics (see Fig. 5g). (e) Apparent drag of foliation against ductile shear zone in the Abu Furad amphibolites. (f) Curvature of S_1 foliation trajectories in the wall of a ductile shear zone in the Abu Furad amphibolites.

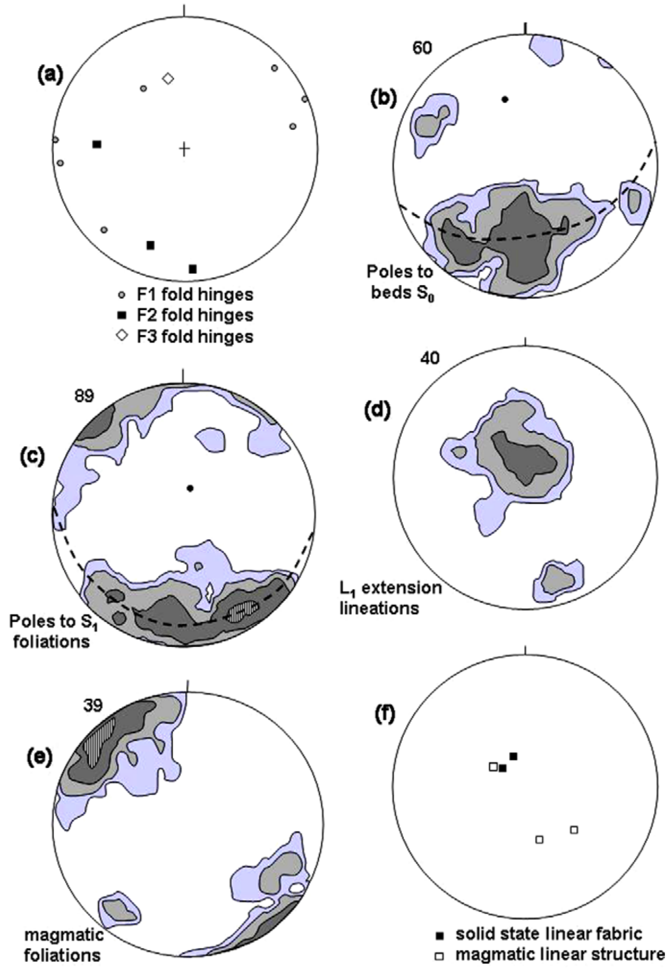


Fig. 11. Stereograms of mesoscopic structural data for the Barud study area. All stereograms are Schmidt net equal-area lower hemisphere projections. (a) Mesoscopic F_1, F_2 and F_3 fold hinges. The one F3 data point has orientation 44/345, i.e. very close to the π-axis for (b). (b) Density contoured poles to bedding (60 data points) mainly from the Abu Marawat metavolcanics (contours at 2%, 4%, 8%). These poles define a girdle with π-axis 46/344. (c) Density contoured poles to S_1 foliation (89 data points) mainly from the Abu Furad amphibolites (contours at 2%, 4%, 8%, 16%). These define a girdle with π-axis 71/005. (d) Density contoured L_1 extension lineations (40 data points) mainly from the Abu Furad amphibolite (contours at 3%, 6%, 12%). Average orientation is 81/011. (e) Density contoured poles to magmatic foliations (39 data points) from the Barud Tonalite (contours at 3%, 6%, 12%, 24%). These define an average orientation with approximately 050 strike and 80 dip to the SE. (f) Orientation of solid state linear fabric and magmatic linear fabric from the Abu Furad amphibolites and Barud Tonalite.

The structurally overlying Abu Marawat metavolcanics show bedding planes defined by successive lava flows, and a weakly developed low-grade cleavage (S_1) with the same strike as the bedding. Dip of cleavage is generally shallower than bedding. The beds and S_1 cleavages in the metavolcanics are affected by very minor rounded mesoscopic folds with near horizontal axial planes, but no axial plane cleavages are developed (F_2 – Fig. 11a). F_2 folds are younger than and distinguished from F_1 folds by the fact that they fold S_1 cleavages and do not have S_1 parallel to their axial planes as F_1 folds do. Insufficient data exists to determine the significance of F_2.

The mapped pattern of bedding orientations and stereographic analysis of S_0 and S_1 data reveal macroscopic folds with more-or-less upright north–south trending axial planes and moderate to steep northerly plunging hinges (Figs. 2a and 11a–c). Examples of these folds are the small symmetrical macroscopic folds in the metavolcanics south of Wadi El Bula, with wavelengths of about 2 km (Fig. 2a). Mesoscopic folds of this generation are extremely rare (Fig. 11a). The folds deform S_1, so are post-F_1. We believe they are also younger than F_2 folds (i.e. they are F_3 folds) because F_2 axial planes are always normal to beds and thus appear to have been folded along with the beds by the F_3 macroscopic folds. The intensity of F_3 folding declines northwards.

Apart from the hot ductile shears described in the next section, the metagabbro–diorite complex contains little other usable structural data. However, there are faint solid-state foliations and widely spaced shear zones. The shears have the same top-to-the-NW movement sense as those found in the metavolcanics and metasediments, and may be equivalents of them.

3.2. Hot ductile shear zones – their structure, metamorphism and intrusions

Within the low-grade Abu Marawat metavolcanics there are discrete tabular zones characterized by (a) better development of S_1 foliations; (b) appearance of steeply pitching stretching lineations (L_1) on S_1 planes (Fig. 11d); (c) higher ductile strains associated with L_1 and S_1; (d) evidence for shear strain parallel to the zones with consistent shear sense; (e) a higher temperature than greenschist facies assemblage of metamorphic minerals defining S_1; and (f) presence of sheared sills of mafic to felsic intrusive rocks concordant with S_1. These tabular zones have NE-, E–W or NW-strikes and dip steeply to the NW, N or NE, respectively. Similar tabular zones are found in the metagabbro–diorite complex, especially near its contact with the Abu Furad amphibolites (Fig. 2a). The text below describes and identifies these tabular zones as complex ductile shear zones heated by syn-shearing intrusions and compares them to the Abu Furad amphibolites.

3.2.1. Hot shears in the Abu Marawat metavolcanics

These zones are found in the northern exposures of the metavolcanics, close to their contact with the metagabbro–diorites, e.g. east of the Rabbah Trondhjemite and along Wadi El Bula (Fig. 2a). The simplest examples are about 10 m thick, and have excellent S_1 foliation and L_1 lineation, and S_1 almost parallel to S_0, consistent with higher strains in these zones. In contrast to the Chlorite Zone greenschist facies metamorphic grade of the metavolcanics bordering the zones, the rocks within the zones have higher grade and include hornblende schists and biotite sericite schists. Relict textures of quartz, plagioclase and mafic phenocrysts are the same as those in the nearby greenschist facies metavolcanics (Fig. 6b), indicating that the hornblende schists are higher temperature metabasalts and the biotite sericite schists are higher temperature silicic metavolcanics. S_1 in the hornblende schists is defined by parallel-aligned blue–green hornblende prisms and granoblastic plagioclase, quartz, clinozoisite, sphene and opaques. Extensional strain parallel to L_1 is evidenced by the pulling apart of plagioclase phenocrysts with phases hornblende, chlorite, quartz and plagioclase filling the voids between fragments. The foliated silicic metavolcanics have a foliation defined by parallel biotite flakes. The recrystallization and growth of neoblasts of metamorphic hornblende indicates stability of this phase and therefore medium grade metamorphic conditions. The source of heat for the higher metamorphic grade in these zones are the numerous dolerite intrusions which form sills within the shear zone and are also ductile sheared. The increased strain in these shear zones is also probably due to thermal softening. Sub-ophitic textures of the metadolerites (Fig. 6c) are partially preserved in olive-green hornblende pseudomorphs of original pyroxene (Fig. 6d and e). The pseudomorphs are reduced at higher strains to porphyroclasts with recrystallized margins merging into S_1 folia (Fig. 4e and f). Microstructural shear sense indicators from the sheared metadolerites include σ-type porphyroclasts and shear-deflected hornblende cleavages (Fig. 4g). These indicate a top-to-the-NW, i.e. an apparently normal shear sense on these shears.

Thicker, more complex shear zones (>100 m thick) in the metavolcanics are found NE of the Rabbah Trondhjemite and along Wadi El Bula (Fig. 2a). In these examples the shear zones are also intruded by peneconcordant bodies of microdiorite, microtonalite and microgranodiorite. These intrusions show numerous magmatic flow structures parallel to the boundaries of the shear zone e.g. schlieren, and smeared-out enclaves (Fig. 5f), also flow-aligned plagioclase and hornblende phenocrysts parallel to schlieren bands, and phenocryst concentrations related systematically to the schlieren. Some intrusions contain xenoliths which have reached temperatures of partial fusion to produce migmatites. Shear sense indicators in these zones include asymmetric drag folds in deformed granite veinlets indicating top-to-the-NW (normal) shear sense on these zones (Fig. 5g and 10d). Solid-state deformation effects (e.g. folding of veinlets, ductile shearing, boudinage) overprint the magmatic structures.

3.2.2. Hot shears in the metagabbro–diorite complex

Particularly near the contact of the metagabbro–diorite complex with the Abu Furad amphibolites (Fig. 2a and b), there are up to 100 m thick complex shear zones similar in structure and lithologies to the shear zones noted above in the Abu Marawat metavolcanics. An example of these zones is found in the metagabbro–diorite complex along Wadi El Bula just south of the Bula pluton (Fig. 12). Here the mafic and felsic metavolcanic and intrusive rocks show strongly inhomogeneous strain indicated by differences in the intensity of S_1 foliation in the rocks. Some appear to be protomylonites. It is clear on the basis of xenoliths that the felsic melts (mainly tonalite and granodiorite) are younger than the dioritic and gabbroic melts. The felsic melts were injected along the foliation in the mafic rocks, and show folding, deformation and shear foliations. These facts suggest a syn-kinematic (i.e. syn-shearing) timing of intrusion of the felsic magmas. The zone of shearing, higher temperature metamorphic effects and intensive intrusion is at least 90 m thick and passes directly into greenschist facies massive

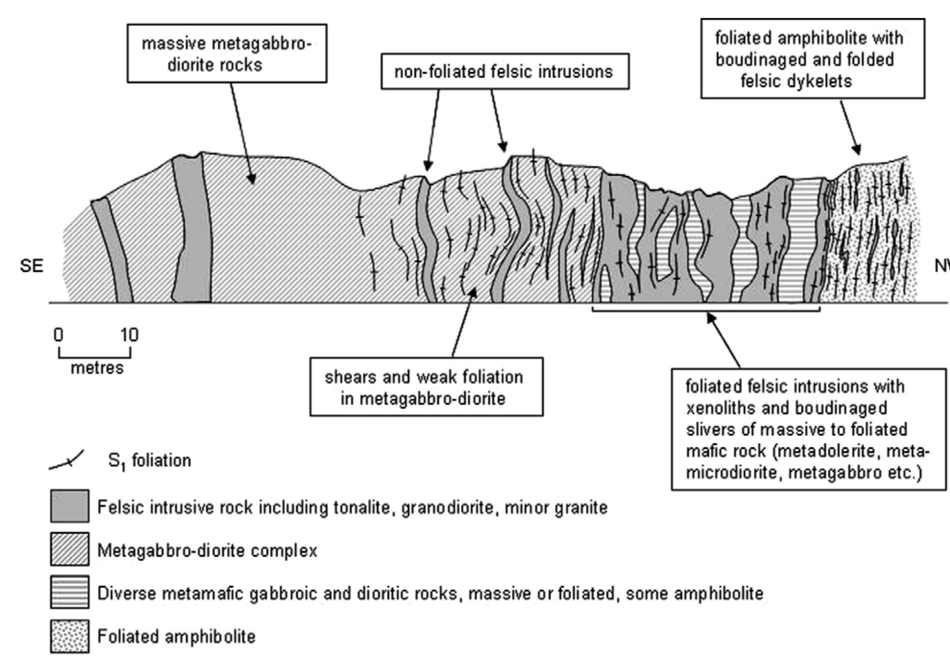


Fig. 12. Section showing the characteristics of a multiply-intruded ductile shear zone in the metagabbro–diorite complex just south of the Bula granodiorite along Wadi El Bula.

metagabbro–diorite rocks. Medium grade metamorphic temperatures during shearing are demonstrated by decussate aggregates of recrystallized metamorphic blue–green hornblende and recrystallized granoblastic plagioclase in the metagabbros. Hornblende and lesser biotite are also the phases defining the S_1 foliations in these shear zones. Some metadiorites lacking visible strain show hornfelsic textures, though most show a ductile foliation. Weakly foliated metagabbros lying away from the zones of intensive felsic intrusion show the effects of shearing under greenschist facies conditions. In these cases, the metagabbros appear to develop ductile foliations mainly as a result of alteration softening by sericitization and chloritization.

3.2.3. Shear foliated Abu Furad amphibolites and schists

The lithologies, microstructures and outcrop structures of the Abu Furad amphibolites are strikingly similar to those described above in the shear zones of the Abu Marawat metavolcanics and the metagabbro–diorite complex. Shear sense indicators in thin section (Fig. 4f and g) and in outcrop (Fig. 10e and f) in the Abu Furad amphibolites all indicate a normal sense of shear, with top-to-the-NW (or N, or NE) shear sense on the foliations according to their present orientation. Lithologically the Abu Furad rocks are more similar to the hot shear zone rocks of the Abu Marawat metavolcanics in that both are dominantly fine-grained lineated hornblende-plagioclase schists with minor biotite. One difference is that the Abu Marawat commonly includes sheared silicic metavolcanics interlayered with the hornblende schists. These are not common in the Abu Furad, their place being taken by numerous sheared silicic intrusions – mainly tonalites.

The term "amphibolite" has been applied by most workers dealing with the Abu Furad to refer to some of the metagabbros and metadiorites that have the medium grade metamorphic assemblage plagioclase plus hornblende, and a distinctly foliated or linear fabric. The connotation of regional metamorphism associated with this term has unfortunately given the impression that the Abu Furad amphibolites are deep seated basement rocks. On the contrary, these are syn-shearing intrusive mafic rocks not slivers of deeper basement uplifted along faults.

On the map scale the Abu Furad amphibolites are quite complex (Fig. 8) and significantly thicker than any shear zones so far seen in the Abu Marawat or the metagabbro–diorites. Numerous peneconcordant dioritic, tonalitic, granodioritic and granitic intrusions showing varying intensities of foliation and other solid-state ductile structures cross-cutting magmatic foliations (Fig. 13) are features of the Abu Furad amphibolites in common with the shear zones described above. The Abu Maya diorite is an example of a larger intrusion into the Abu Furad amphibolites. This intrusion incorporates blocks of the Abu Furad amphibolite. The diorite is mainly unfoliated and postdates the magma reaction and migmatization features seen in the amphibolite blocks (Fig. 3c and d). In Section 4, the structural relations between the Abu Furad amphibolites and the hot shear zones in the metavolcanics and metagabbro–diorite complex are discussed and the significance of these zones is considered.

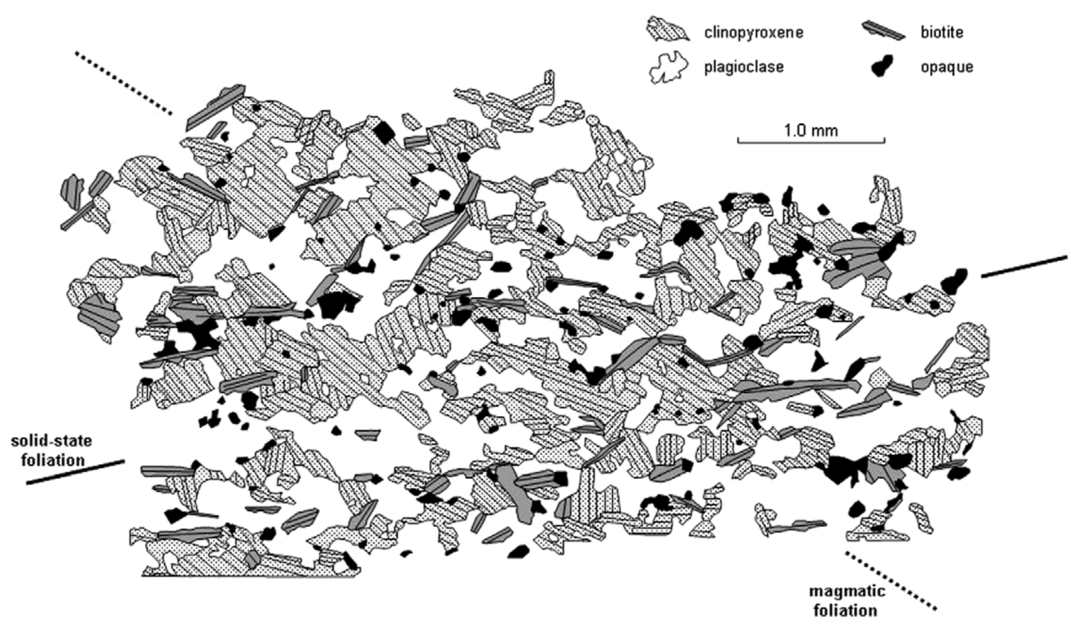


Fig. 13. Sketch of a photomicrograph of one of the Abu Furad amphibolites showing a magmatic foliation defined by the grain long axes and crystallographic *c*-axis of clinopyroxenes with partial pseudomorphous replacement by hornblende (both represented by stippled grains). The magmatic foliation is overprinted by a solid state foliation defined by chlorite pseudomorphs after biotite (grey grains). The chlorite–biotite also defines a subsidiary fabric parallel to the *c*-axis of the amphiboles and appears to have been a partial replacement of them. Elsewhere in this thin section, and generally for the Abu Furad amphibolites, the two fabrics are sub-parallel. Black grains are opaque phases.

4. Discussion

4.1. Origin and significance of the Abu Furad amphibolites

From the above descriptions it is clear that the Abu Furad amphibolites strongly resemble the hornblende schists of the hot ductile shear zones in the metagabbro–diorite complex and Abu Marawat metavolcanics. Features in common include: microstructures and textures; the association of S_1 foliations and L_1 lineations with ductile shearing; shear sense indicators showing consistent top-to-the-NW (normal) movement sense; numerous syn-shearing peneconcordant intrusions of gabbro, diorite, tonalite and granite; the spatial relations between these intrusions and medium grade metamorphism and other high temperature metamorphic features (gneissosity, migmatization, Fig. 5h). The obvious conclusion is that the Abu Furad amphibolites formed in hot multiply syn-kinematically intruded ductile shear zones with normal shear sense. The existence of rare hornfelsic textured rocks in the shear zones does not invalidate this model. Such rocks may be either xenoliths in the larger intrusions or result from the thermal effects of an intrusion into a temporarily inactive part of the shear zone.

The protolith of the Abu Furad amphibolites is mainly mafic metavolcanics with contributions also from metagabbro and metadiorite intrusions. The metavolcanic origin is supported by (a) the close relationship between low-grade metavolcanics and concordant strips of amphibolites in the Eastern Desert (El Ramly and Akaad, 1960); (b) the existence of banded iron metasediments within the Abu Furad amphibolites (Fig. 2a) – an association typical of the metavolcanics of the Eastern Desert (El-Gaby et al., 1990; Sabet et al., 1972); (c) the chemistry of the Abu Furad amphibolites is that of immature-arc tholeiites (Dardier and Al-Wakeel, 1998), or island arc tholeiites and calc-alkaline volcanics (Asran, 1992); (d) Hassan and Hashad (1990, p. 221)) noted that the basaltic metavolcanics of the CED seem to grade into amphibolites as the NED is approached.

Two further matters to consider regarding the Abu Furad amphibolites are: (1) why is the Abu Furad much thicker than the ~100 m wide zones in the metagabbro–diorite complex and metavolcanics? (2) what is the tectonic significance and scale of the shearing event? These points are discussed below, while the age of the shearing event is considered in Section 4.3.

(1) The ~100 m thick ductile shears in the metagabbro–diorite and metavolcanics are probably narrower splays connected to a much larger main detachment shear. The abundance of melt that passed along these distal shears argues that they must have been part of a larger magma plumbing system. The thicker Abu Furad amphibolites may represent a deeper or more proximal section of the shear system – most likely a portion of the main detachment shear zone. The actual thickness of amphibolites is approximately 1500 ± 200 m, with errors mainly due to the complex deformation associated with the intrusion of the Barud Tonalite and Bula granodiorite pluton.

(2) Having a normal sense of shear with no significant strike-slip component, these extensional ductile shears are not the equivalent of El-Gaby's (1994) Qena–Safaga Shear Zone. The shearing is compatible with a NW–SE regional extensional event. Top-to-the-NW shear sense indicators found in the El-Zarga metasediments have similar kinematics and therefore the extension has affected a significant thickness of the arc crust at the time from arc sediments to arc plutonites. The shear zones have tapped considerable volumes of gabbroic, dioritic and tonalitic melt of island arc affinity. Considering the scale of the extensional shear system and its syn-arc magmatic timing we suspect that these shears may be related to arc rifting.

The topics of arc-rifting, arc collisions and back-arc basins within the NED are quite controversial. Shimron (1984) and Furnes et al. (1985) pictured a back-arc basin existing north of the Kid Group arc volcanics in the Sinai. El-Gharbawi and Hassen (2001) also preferred a back-arc basin setting for Sinai metagabbro–diorites. Arc suturing in the Sinai, extending into the NED, has been interpreted by Garson and Shalaby (1976), Bakor et al. (1976), Vail (1985), Shackleton (1986), Blasband et al. (1997, 2000) and Brooijmans et al. (2003). The estimated age of arc collision there is between 750 and 650 Ma (Blasband et al., 2000). A significant number of workers, however, doubt the existence of marginal basins and arc sutures in the NED and Sinai. Reymer (1983, 1984) and Stern et al. (1985) challenged the finding of ophiolites in the Wadi Kid area. Stern (1994) showed post-orogenic rifts in the same location as Shimron's ophiolite suture, while Abdelsalam and Stern (1996) showed no sutures north of the Allaqi-Heiani suture in the Eastern Desert. Church (1988) warned that some ultramafic–mafic complexes may have a very different origin to ophiolites, some having formed in a fore-arc environment by rifting. Abdel-Rahman (1990) reassigned Shimron's (1984) possible ophiolitic outcrops in the NED to his GDT – a subduction-related intrusive association.

4.2. Intrusive magmatic character of the Barud Tonalite

The essentially igneous origin of the Barud Tonalite was recognized by Hume (1934) and Schürmann (1966). Schürmann also identified NED paragneisses derived from the greywacke-slate series. Belts of these paragneisses were viewed by Sabet et al. (1972) and Akaad et al. (1973) as remnants of a high temperature granitization event that yielded the nearby tonalites and other gneissic granitoids. A range of contacts from gradational to sharp between the granitoids and the paragneisses was interpreted in terms of increasing degrees of separation of the granite magma from its source. From this concept the classification of G1, Older or "grey" granites into autochthonous, parautochthonous and intrusive was derived (El-Gaby et al., 1990). Strike continuous slivers of amphibolite and other gneissic and migmatitic inclusions were described as "horizons" which survived the granitization process (Akaad et al., 1973). The Barud was thought to be ancient continental crust by Habib (1987a,b) and El-Gaby et al. (1990) and to extend to the northern limits of the NED.

Detailed examination of the field relations of the Barud Tonalite, especially its margins leads us to conclude that the gneissic banding in the Barud is essentially a magma flow-related schlieren feature. We find no evidence that these tonalites formed by in situ melting at the present crustal level of the NED. The tonalite intruded along and into a pre-existing NE-trending shear zone characterized by amphibolite and schists (the Abu Furad amphibolites). The shear zone xenoliths contain evidence for *earlier* syn-shearing magmatic activity, migmatization and magma contamination by xenoliths and enclaves (Fig. 3c, d, 8 and 9). The tonalite apophysis of the Barud in the SW of the area mostly lacks the complications of enclaves, xenoliths and magma contamination seen elsewhere. This may be because the apophysis has intruded into more massive metagabbro–diorite instead of foliated amphibolites. The shear zone was a conduit for a range of melt compositions. Under such conditions magma mingling to produce the observed enclave swarms is also to be expected. The continuity of some sheared amphibolite and migmatite slivers reflects not the survival of "horizons" from a granitization process, but the original orientation of the shear zone which is preserved as partial screens by tonalite pulses intruding along it, producing NE-trending magmatic foliations with steeply pitching flow lineations (Fig. 11e and f).

4.3. Structural history and tectonic interpretation of the Barud area

A model for the stages of development of the Barud area is presented in Fig. 14, and a rough estimate of the age of the events in this area is shown in Table 1, based on published geochronological data for rocks of the surrounding areas.

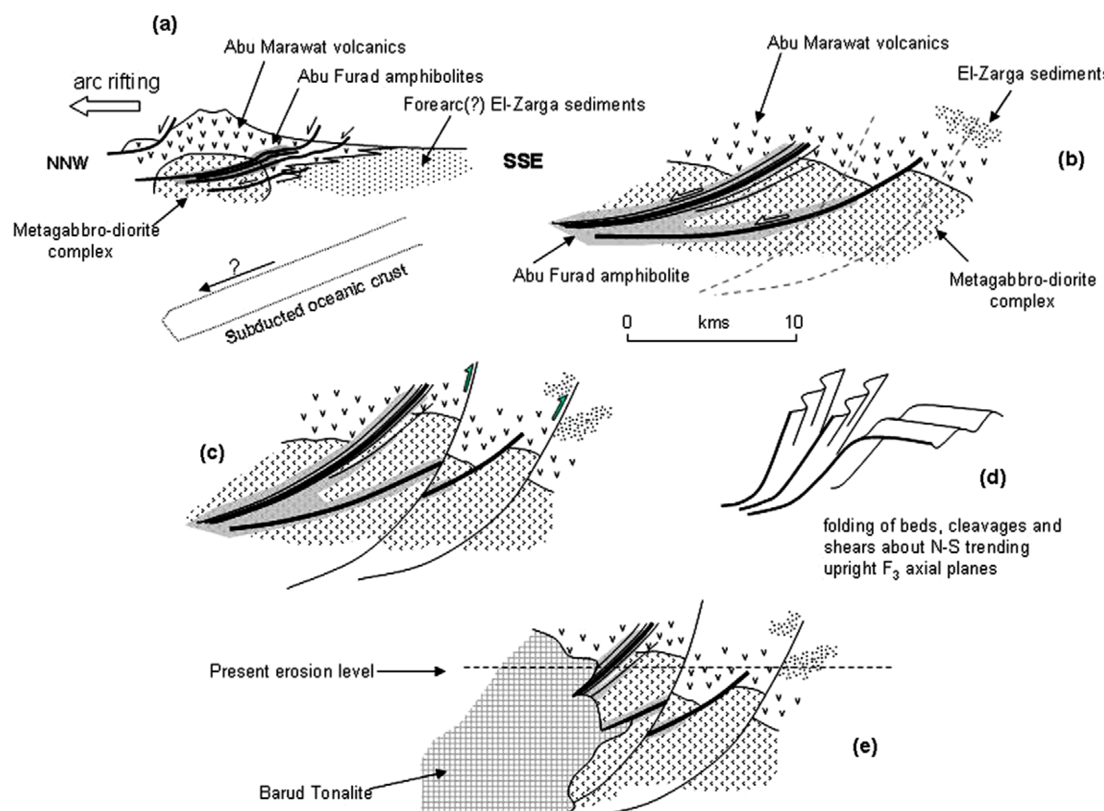


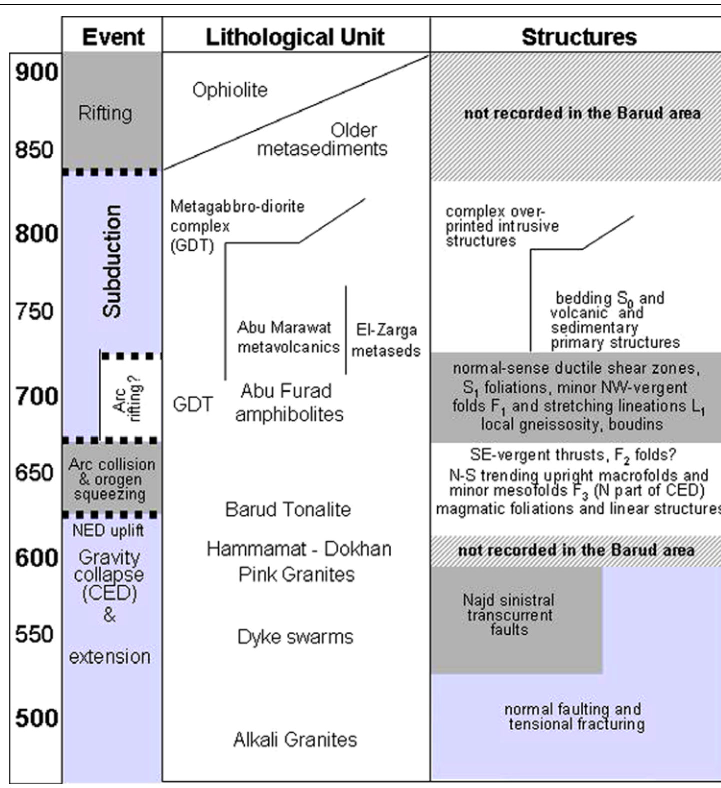
Fig. 14. Cartoon showing stages of the proposed tectonic development of the Barud study area. Approximate scale for (b), (c) and (e) shown. All figures are sketched looking towards the ENE. (a) The Abu Marawat volcanics erupt in an oceanic arc setting above a NNW dipping subduction zone. The El-Zarga sediments form in a forearc setting to the SSE of the arc axis. The metagabbro–diorite complex represents the main subduction-related intrusions (∼750–700 Ma). (b) Subduction-related arc extension generates a listric normal ductile shear system, which taps the magmas from the arc axis. Syn-kinematic intrusions of mainly diorites and gabbros but also tonalites into the active ductile shear zones produces the Abu Furad amphibolites and hornblende schists (∼700 Ma). (c) Arc collision generates listric SE-vergent thrusts that rotate the previous units to moderate to steep NW dips. The rotation effects decrease SE-wards (∼670 Ma). (d) The collision zone is further squeezed between E and W converging parts of Gondwana. This folds the thrust sheets about N–S trending axial planes with generally steep NW plunging axes (∼650 Ma). (e) Barud Tonalite is intruded in the final stages of the E–W squeezing (∼620 Ma).

The first stage presents the Abu Marawat metavolcanics as an island arc volcanic sequence lying above a northerly dipping subduction zone (Fig. 14a and b: ~750–700 Ma). There is no data bearing on the direction of subduction in the Barud area so we have opted to accept the northerly dipping subduction zone preferred by Habib (1987b) who included the Barud as part of a much larger area to the south. The abundance of sub-aerial silicic lavas in the Abu Marawat suggests that these volcanics were erupted from a mature arc, as also concluded by Habib (1987a) and Aly et al. (1991) for the metavolcanics south of the Barud area. El-Gaby et al. (1990) considered the metagabbro–diorites as typically intrusive into the metavolcanics. According to Abdel-Rahman (1990, 1995) the metagabbro–diorites are subduction-related arc axis plutons. Dardier and Al-Wakeel (1998) found that the arc metavolcanics and metagabbro–diorites of the Barud area have comparable chemistry. Alternatively the metagabbro–diorites may have back-arc affinities (Amstutz et al., 1984; Ghoneim et al., 1992; El-Gharbawi and Hassen, 2001). The El-Zarga metasediments in Fig. 14a are placed in a fore-arc setting, though other stratigraphic relations may be valid.

The first recognized structural tectonic event (Fig. 14a and b) was the development of a major low angle shear detachment zone with normal sense of shearing (~720–700 Ma), consistent with NW–SE crustal extension. This shear zone cut through the volcanics, sediments and metagabbro–diorites producing S_1 foliations, L_1 lineations and rare F_1 folds, and penetrated the arc core from which it tapped melts. Dioritic and tonalitic melts trickling along the hot active shear developed gneissic by a combination of magmatic, high temperature metamorphic and solid state deformation, and local melting effects.

Arc collision (Fig. 14c: ~670 Ma) produced large listric SE vergent thrusts that rotated the earlier units to

Table 1
Summarization of the Barud area main stratigraphic units, structural events and mesoscopic structures with our model of tectonic events and their inferred age, in the framework of the evolution of the North Eastern Desert



The basis of the inferred ages is as follows: Rifting and ophiolite formation (900–840 Ma) – Bentor (1985), Kröner et al. (1992), Stern (1994), Abdelsalam and Stern (1996). Subduction and island arc stage (840–690 Ma) – Stern (1979, 1981), Bielski (1982), Bentor (1985), El-Gaby et al. (1988), Stern (1994), Abdel-Rahman (1995, 1996), Abdel-Rahman and Doig (1987), Abdelsalam and Stern (1996). Arc suturing and collision of East and West Gondwana (690–620 Ma) – Stern and Hedge (1985), Stern (1994). Barud Tonalite (630 Ma) – Stern et al. (1984), Stern and Hedge (1985), El-Gaby et al. (1988), Moghazi (1999). Hammamat–Dokhan (610–590 Ma) – Stern (1979), Bielski (1982), Ressetar and Monrad (1983), Ries et al. (1983), Massey (1984 – in Willis et al. 1988), Stern and Hedge (1985), Abdel-Rahman and Doig (1987), Willis et al. (1988), Moghazi (1999), Wilde and Youssef (2000), Moghazi (2003). Gravity collapse (Sinai) (600–590 Ma) – Blasband et al. (1997, 2000). Younger Granites (590 Ma) – Fullagar and Greenberg (1978), Ressetar and Monrad (1983), Stern and Hedge (1985), Stern and Gottfried (1986), Hassan and Hashad (1990), Blasband et al. (1997), Moghazi (1999). Najd faulting (600–540 Ma) – Stern (1985), Stern (1994). Dyke swarms (550 Ma) – Stern and Hedge (1985), Stern and Gottfried (1986), Reymer (1986), Stern et al. (1988).

moderate dips to the NW. F_2 folds probably formed at this stage, and there may have been further steepening of the beds by back-rotation of the thrusts in the later stage of the collision. The steepened beds and foliations were then folded about approximately N–S upright axial planes (F_3 folds) during an E–W tectonic shortening event (Fig. 14d: ~640 Ma). This is most obvious in the southern half of the area but is much weaker in the northern part where the NE–SW trends of earlier ductile shear and listric thrusts are preserved. The SE-ward thrusting and N–S folding events in the Barud area are correlated with the SSE-ward thrusting and the N–S trending folds and thrusts, respectively, discovered by Habib et al. (1978) at Gabal El-Rubshi, immediately south of the Barud area. The E–W shortening associated with N–S trending folds may be related to the final collision between east and west Gondwana (Abdelsalam and Stern, 1996).

Intrusion of the voluminous Barud Tonalite (Fig. 14e: ~630 Ma) and the smaller Bula Granodiorite and Rabbah Trondhjemite followed the N–S folding. As shown in Fig. 2a, there are some prominent N–S to NW trending late fault structures intersecting the Bula Granodiorite and displacing the contact between the metagabbro–diorites and metavolcanics. These sinistral faults probably resulted from continued E–W shortening. We recognize them as Najd faults (~570–550 Ma) and suggest that the N-dipping normal shears in the Rabbah Trondhjemite intrusion are kinematically related to them. The latest Pan-African events in the area were the intrusions of the Abu Furad Granite and the dykes (~550–530 Ma).

4.4. Some consequences for the Qena–Safaga Line

Stern and Hedge (1985) proposed a popularly accepted threefold division of the Egyptian Eastern Desert into northern (NED), central (CED) and southern (SED) parts. The NED–CED boundary is generally represented as a straight, curved or complexly curvilinear N60E trending thrust (dipping NW) or dextral strike-slip fault (Stern and Hedge, 1985; Stern and Gottfried, 1986; Bennett and Mosley, 1987; Greiling et al., 1988a; El-Gaby et al., 1988, 1990; El-Gaby, 1994; Greiling et al., 1994) (Fig. 1). It is appropriate to make a brief comment on this feature since the NED–CED boundary passes through the Barud study area and our geological investigations provide some evidence bearing on the nature of this boundary.

The NED–CED boundary separates two regions with remarkable lithological and structural differences (Stern and Hedge, 1985). In the NED there are distinctly higher concentrations of granitoids and much reduced proportions of oceanic volcanic rocks and almost no ophiolitic materials compared to the CED. The NED shows traces of steeply dipping, E–W to NE–SW trending foliations and fold axial planes (Sabet et al., 1972; Dardir and Abu Zeid, 1972; Francis, 1972; Ghanem, 1972; Ghanem et al., 1973; Stern et al., 1984; El-Gaby et al., 1988; Abd El-Wahed and Abdeldayem, 2002), while the CED has a strong NW–SE structural trend for most of its northern half (Fig. 2 of Greiling et al., 1988b). The NED also lacks the gneissic domes (though reported in the Sinai – Blasband et al., 1997) and NW trending Najd fault systems of the CED, but has closely spaced NE-trending dyke swarms that are not well represented in the CED. El-Gaby et al. (1988) proposed that the differences between the NED and CED resulted from uplift of the NED along the Qena–Safaga Line, leading to the stripping away of the ensimatic cover rocks to expose the continental basement. The mechanism of uplift was suggested to be an oblique thrusting along the Qena–Safaga Line, with northeast-trending dextral component (El-Gaby, 1983).

Significant uplift of the NED is supported by crystallization depth estimates for NED granitoids (Helmy et al., 2004). The latter authors recently conducted a thermobarometric study of five calc-alkaline plutons, including parts of the Barud area, and concluded that these plutons had crystallized at original depths of up to 20 km. As noted by El-Gaby (1994), the time of uplift is constrained by the intrusion age of the gneissic granitoids (680–620 Ma – Stern and Hedge, 1985) and the deposition of Hammamat clastics (600–590 Ma – Willis et al., 1988) and Dokhan Volcanics (610–560 Ma – Ressetar and Monrad, 1983), which lie unconformably upon the granitoids. This places the uplift of the NED in the interval ~620–600 Ma. The post-orogenic NED pink granites are also high-level intrusions emplaced into Hammamat and Dokhan. Abdel-Rahman and Martin (1987) reported miarolytic cavities in NED leucogranites and estimated 4.5–8 km crystallization depths. These high level intrusions were not subsequently stripped away, nor have the Hammamat and Dokhan been later removed or deeply buried. This indicates a remarkable degree of lithospheric stability since the ~620–600 Ma uplift, apart from brittle extension associated with dyke swarms, some fault block rotation yielding northerly dips for the Hammamat and Dokhan (El-Gaby et al., 1988), and marginal uplift associated with Red Sea rifting.

The mapping of the Barud area presented in this paper demonstrates that the (originally) NE-trending, NW-dipping reverse faults that occupy the Qena–Safaga Line cannot be responsible for the uplift of the NED. These reverse faults have been affected by N–S folding, which *predates* the intrusion of the Barud Tonalite. The Barud Tonalite cuts across the reverse faulted boundary between the metagabbro–diorite complex and the Abu Marawat metavolcanics in the eastern part of the map area (Fig. 2a). The thrusts are interpreted to be related to the earlier event of arc accretion. It is clear that thrusting at the southern margin of the NED is not responsible for the ~620–600 Ma uplift of the NED.

Acknowledgements

The authors would like to thank the Chairman of the Egyptian Nuclear Materials Authority Prof. Hamdy Sadek for permission to use NMA facilities and vehicles in this project. We thankfully acknowledge the support, guidance and logistical assistance provided by Dr. Saleh Ammar at the NMA.

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