Arabian Journal of Geosciences (2018) 11: 313
https://doi.org/10.1007/s12517-018-3677-1

S. I. GEOLOGY OF AFRICA

Classification of the Neoproterozoic ophiolites of the Central Eastern Desert, Egypt based on field geological characteristics and mode of occurrence

Gaafar A El Bahariya[1]

Received: 16 February 2018 / Accepted: 12 June 2018 / Published online: 21 June 2018

Abstract

The present work presents new field observations on the geological characteristics of the Neoproterozoic ophiolites of the Central Eastern Desert (CED) of Egypt. Based on mode of occurrences, the investigated ophiolites appear to show characteristics of both MORB-type and SSZ-type ophiolites and classified from oldest to youngest into: (1) MORB intact ophiolites (MIO), (2) dismembered ophiolites (DO), and (3) arc-associated ophiolites (AAO). Ophiolite components include serpentinized peridotite and other metamorphosed ultramafics, metagabbros, sheeted dykes, pillowed and massive metabasalts, minor boninites, and pelagic sediments. The rocks of the MIO and DO were subjected to two main phases of deformation (D_1 and D_2) and metamorphism, whereas the AAO have been affected only by later phase of deformation (D_2). Compositional variation of chrome spinel in blocks of metamorphosed ultramafic and serpentinite of dismembered ophiolites shows three distinct groups (G1, G2, and G3) based on their Cr#. Whereas G1 is similar to abyssal peridotites, G2 and G3 display mainly supra-subduction zone (SSZ) tectonic setting. The ophiolitic metagabbros display both N-MORB and supra-subduction zone tectonic setting (SSZ). The basaltic rocks of the MORB-intact ophiolites (MIO) and blocks of metabasalts in the mélanges display N-MORB affinity, whereas the basaltic rocks associated with arc volcanics display SSZ tectonic setting. Collectively, the investigated ophiolites of the Central Eastern Desert (CED) fall into two groups, MORB or BABB and SSZ ophiolites. They are spatially and temporally unrelated, and thus, it seems likely that the two types are not petrogenetically related. Ophiolites occur in different geological settings, and they represent change of the tectonic setting of the ophiolites from MORB to SSZ with time.

Keywords Neoproterozoic ophiolites · Geological characteristics · Mode of occurrence · Central Eastern Desert · Egypt · MORB · SSZ

Introduction

Ophiolites are remnants of ancient oceanic crust and upper mantle that were tectonically emplaced into continental margins during the closure of ocean basins (Coleman 1984; Dilek and Furnes 2011). They preserve the geological record of the evolutionary history of ocean basins from their rift–drift and seafloor spreading stages to the subduction initiation and final closure (Dilek and Robinson 2003). Subduction zone tectonic is the most important factor in the igneous evolution of ophiolites and their emplacement into continental margins (Dilek and Furnes 2014). Ophiolites are a distinctive association of rocks interpreted to have formed in a variety of plate tectonic settings, including oceanic spreading centers, back-arc basins, fore arcs, arcs, and other extensional magmatic settings (Hoeck et al. 2002; Kusky 2004; Dilek et al. 2000; Dilek and Furnes 2011).

The northern part of the East African Orogen is mostly juvenile crust of the Arabian-Nubian Shield (ANS) (Stern 2002; Stoeser and Frost 2006). It now appears that the oldest Neoproterozoic rocks in the ANS are ~ 870 Ma, from the Asir terrain of Arabia and the southern Red Sea Hills of Sudan (Kröner et al. 1992). Proterozoic ophiolites were first widely recognized in the ANS (Al-Shanti and Mitchell, 1976; Bakor et al. 1976; Ries et al. 1983; Kroner 1985) and reviewed by many workers (Stern et al. 2004; Johnson et al. 2004; Dilek and Ahmed 2003; El Bahariya 2006, 2007, 2008, 2012;

This article is part of the Topical Collection on *New Advances and Research results on the Geology of Africa*

Gaafar A El Bahariya
gbahariya@yahoo.com

[1] Geology Department, Faculty of Science, Tanta University, Tanta, Egypt

Farahat 2010; Kusky et al. 2011; Abd El-Rahman et al. 2012). They are of Neoproterozoic age and are aligned in discrete suture zones as in Arabia (Pallister et al. 1988). Also, in the south Eastern Desert of Egypt, the ophiolitic rocks occur along the suture zones such as Allaqi-Heini-Gerf suture (Shackleton et al. 1980; Kröner et al. 1987).

The Eastern Desert of Egypt constitutes the northwestern segment of the ANS, which marks the northern extension of the East African Orogen. The ANS is a major orogenic system that formed near the end of the Proterozoic as a result of the closure of the Mozambique Ocean and the collision between East and West Gondwana (Stern 1994; Kusky et al. 2003). However, the ANS may have been formed through amalgamation or accretion of intra-oceanic island arcs and collision of these arcs with a continental margin (e.g., Stoeser and Camp 1985; Abdelsalam and Stern 1996). The accretion processes led to the formation of suture zones marked by widespread ophiolitic rocks (Stern 1994). The Central Eastern Desert is dominated by two major tectonostratigraphic units (El-Gaby et al. 1988; Abdeen and Greiling 2005) namely lower infrastructure one, which composed of gneisses and migmatites that crop out in dome structure and overlying suprastructure unit includes the Neoproterozoic ophiolite complexes and island arc-related metavolcanic and metasedimentary rocks.

Reliable age data place the ophiolites of the Nubian Shield in the age range 850–740 Ma (Pallister et al. 1988; Kröner et al. 1992). Zimmer et al. (1995) obtained ages range between 720 and 770 Ma. The ages of the plagiogranite in the ophiolite of Wadi Ghadir (746 ± 19 Ma, Kröner et al. 1992) and ophiolitic gabbro of Fawakhir area (736.5 ± 1.2 Ma, Andresen et al. 2009) in the CED are compatible with the ~ 750 Ma crust-forming event proposed by Ali et al. (2009). Also, note that Ali et al. (2010) suggested two evolution stages for the ophiolite in the ANS (~ 810–780 and ~ 730–750 Ma) and indicate that accretion between the Gabgaba–Gebeit–Hijaz terrains to the south and the SE Desert–Midyan terrains to the north occurred as early as 730 Ma and no later than 709 ± 4 Ma.

Neoproterozoic ophiolites have long been the subject of research because they represent important elements for a reconstruction of the geodynamic evolution of the orogenic belts. Among these, the CED is recognized as one of the best preserved ophiolitic sequences of Nubian Shield, representing a key area for studying the genesis and tectonic evolution of the Neoproterozoic oceanic units. El Bahariya (2012) classified the Neoproterozoic ophiolitic mélange of the CED of Egypt into (i) tectonic mélange, (ii) olistostrome, and (iii) olistostromal mélange. The exotic blocks within the mélanges are mainly ophiolites.

Despite the advances made in the study of ophiolites, a careful assessment of the rocks in the field is a key in shedding light to unanswered petrological questions. Particular attention is therefore paid to the field observations and descriptions, mode of occurrence, and geological setting of these rocks. Published geochemical data on the ophiolites of the CED suggested the presence of both MORB and SSZ ophiolites (e.g., El Bahariya and Arai 2003; El Bahariya 2006, 2007, 2008; Abd El-Rahman et al. 2009a, b; Basta et al. 2011; Gamal El Dien et al. 2016). The purpose of this paper is to present comprehensive field work and new petrological data on the Neoproterozoic ophiolites of the Central Eastern Desert of Egypt in order to classify the ophiolites and to discuss and overview their petrogenetic and tectonic implications.

Mode of occurrence and ophiolite classification

Numerous ophiolite occurrences in the Central Eastern Desert (CED) of Egypt have been investigated (Fig. 1). Based on various modes of occurrences and geological characteristics, the ophiolites of the Central Eastern desert (CED) are classified and mapped (Fig. 2) from oldest to youngest into: (1) MORB intact ophiolites (MIO), (2) dismembered ophiolites (DO), and (3) arc-associated ophiolites (AAO).

MORB intact ophiolites

The MORB intact ophiolites (MIO) occur as nearly complete slightly deformed intact sequences of serpentinized ultramafics, metagabbros, and massive and pillowed metabasalts, together with subordinate sheeted dykes and pelagic sediments. The contact of these ophiolites with the surrounding rocks is commonly tectonic, but locally, the ophiolite unconformably overlain by mélange with a noticeable shearing.

Muweilih ophiolite occurrence

The Muweilih occurrence is traversed by Wadi El Muweilih and Wadi Hammuda rivers and comprises a sequence of intact ophiolite. The Muweilih serpentinites merge into the Hammuda metagabbros and further to the northwest into the Muweilih metabasalts (Fig. 2a). Muweilih serpentinites occur as huge lensoidal sheets and sheared masses trending NW-SE, and are tectonically overlain by the metagabbros. The latter forms an elongate mass trending NW-SE (Akaad and Noweir 1980). It is bounded on its south-western and north-eastern sides by serpentinites, along tectonic contacts and the NW by the metasediments of the Hammuda Formation in the northwest. Moreover, the Hammuda metagabbro is followed to the north and northwest by Muweilih metavolcanics and pillow lavas, which are extended outside the map area shown in Fig. 2a. The metagabbros comprise both massive isotropic metagabbros and layered metagabbros. The layering is well preserved, where coarse-grained light and medium-grained dark layers alternate. Muweilih metabasalts are tectonically

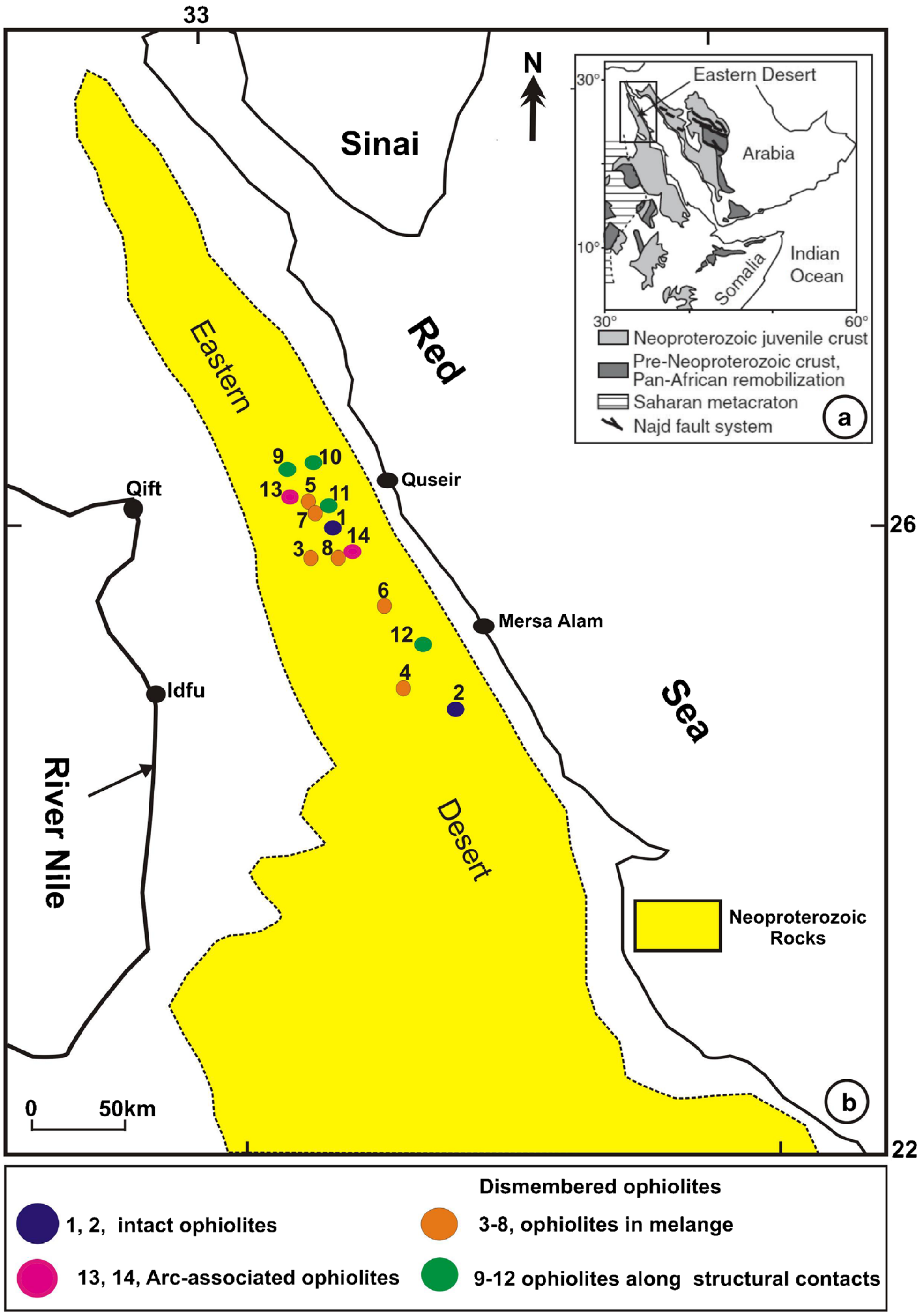


Fig. 1 Inset shows the outline of the Neoproterozoic Arabian-Nubian Shield (a) (Stern et al. 2006). Location map of the different ophiolite occurrences (b): 1 Muweilih intact ophiolites, 2 Ghadir intact ophiolites, 3 Kareim El Abiad, 4 Garf, 5 Um Esh, 6 Mubarak, 7 Muweilih Olistostrome, 8 Esel Olistosstrome, 9 Abu Meriewa, 10 Sodmine, 11 Um Saneyat, 12 Um Khariga, 13 El Sid, 14 Esel

overlain by volcaniclastic metasediments in the northeast and tectonically overlain by Muweilih conglomerate in the northwest with a noticeable thrusting and shearing along the contact (Fig. 3a). The massive rocks in places show columnar jointing and overlain by well-developed ellipsoidal pillows, 1–2 m in diameter most of which lack chilled crusts. Generally, the pillows show a closely packed ellipsoidal shape in a right-way up attitude and with very little interpillow material. The long axes of the pillows are oriented 40° NW and plunge up to 5° SE (Fig. 3b). Locally, the pillows are strongly deformed and elongated 30° NW and plunge 35° NW.

Ghadir ophiolite occurrence

Ghadir ophiolite is well exposed at the junction of Wadi El Beda and Wadi Saudi in the Wadi Ghadir area, where the ophiolitic sequence comprises small serpentinite sheets, layered gabbro at the base, followed by sheeted dykes

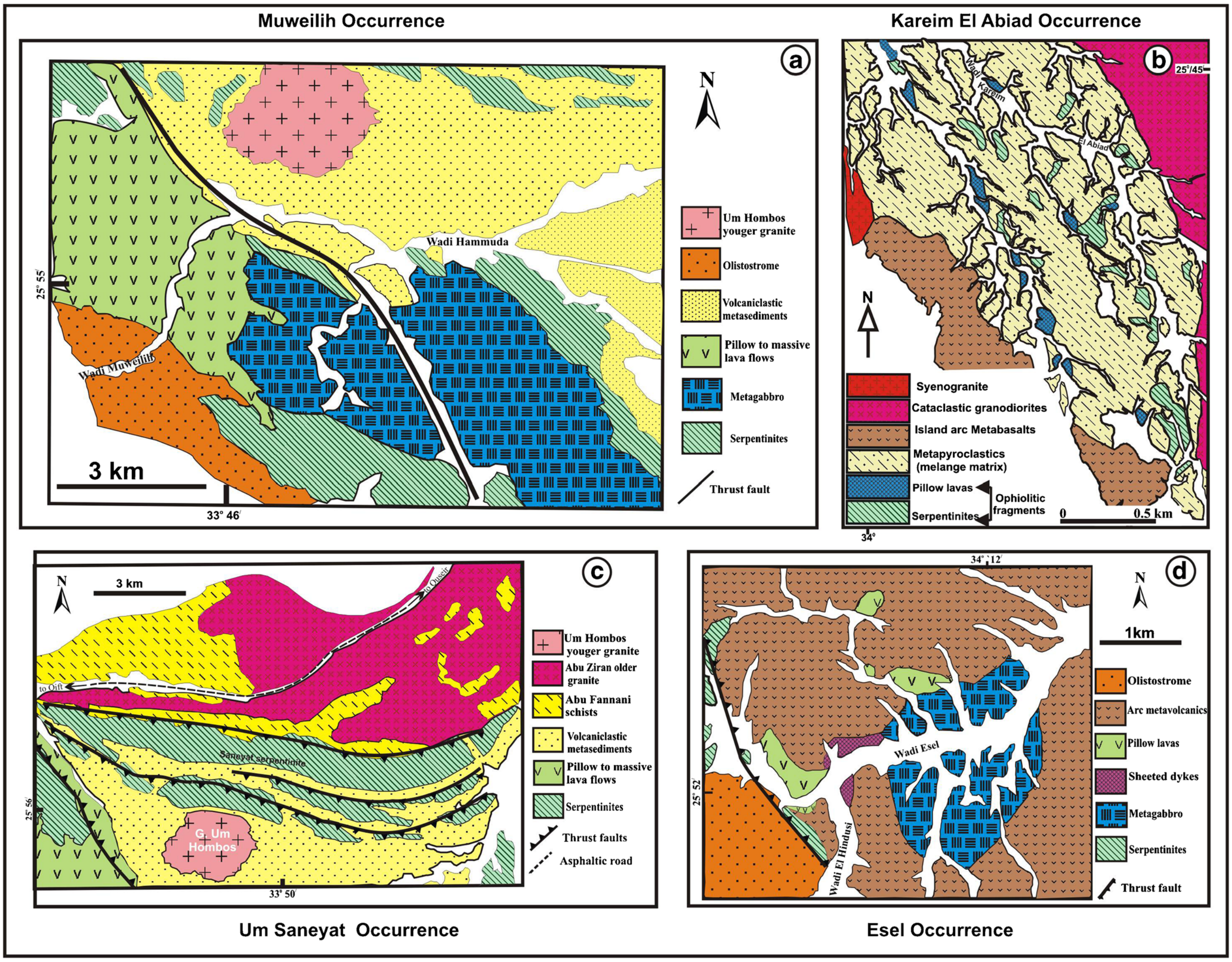


Fig. 2 **a** Representative geological maps of the Neoproterozoic ophiolites. **a** Muweilih MORB intact ophiolites. **b** Kareim El Abiad tectonic mélange (from El Bahariya 2012). **c** Um Saneyat occurrence (modified after Akaad and Noweir 1980). **d** Esel occurrence (modified after Abu El Ela and Aly 1990)

and pillow basalts, and then deep-sea sediments at the top (El Sharkawy and El Bayoumi 1979). Locally, serpentinite sheet occurs as thrust sheet over the pillow lava. The layered gabbro is rhythmically layered with plagioclase-rich leuco-layers alternating with dark layers both showing cumulate textures. The gabbroic complex encloses large pods of pegmatitic gabbro and less common anorthosite, trondhjemite, and plagiogranite. The mafic dikes are abundant in the area, merge into or cross-cutting the metagabbros and the pillow lavas as individual dike swarms (Fig. 3c). They vary in orientation, mainly striking N–E and NE–SW or NW–SE. The basalts consist of closely packed bulbous or oval pillows decreasing in size from base to top (Fig. 3d). They are composed mainly of pillow lavas along with minor isolated and broken-pillow breccias, and massive individual pillows (Fig. 3e) possess convex upper surface, holocrystalline core, and a peripheral zone rich in vesicles (Fig. 3f). The pillows range in size from 20 cm to 1.5 m across with a glassy, microcrystalline, vesicular sheath 2 to 8 cm thick depending on the size of the pillows.

Dismembered ophiolites (DO)

Dismembered ophiolites occur either as (i) ophiolite blocks in mélanges (Kareim El Abiad tectonic mélange, Garf tectonic mélange, Muweilih olistostrome, Esel olistostrome, Um Esh olistostromal mélange, and Mubarak oilstostromal mélange) or as (ii) ophiolites along structural contacts (Abu Meriewa occurrence, Sodmien Occurrence, Um Saneyat occurrence, and Um Khariga occurrence; Fig. 1).

Ophiolite blocks in mélange

It is noteworthy to mention that the ophiolite blocks in mélanges are only one of the different types of the

Fig. 3 Photographs showing the field observations of the MORB intact ophiolitic rocks at Muweilih and Ghadir occurrences. **a** Muweilih pillow lavas unconformably overly by Muweilh olistostrome with prominent shearing along the contact. **b** Closed-packed ellipsoidal pillow lavas from Muweilih occurrence displaying "right" way up" attitude. **c** Metagabbro (left) merge into sheeted dykes (right) with sharp contact (Looking E). **d** Closed-packed bulbous pillows from Ghadir occurrence (looking N). **e** Isolated and broken-pillow breccias and massive individual pillows (looking E). **f** Pillow possess convex upper surface, holocrystalline core, and a peripheral zone rich in vesicles (looking N)

classified Neoproterozoic ophiolites, since not all ophiolites are mélanges. The ophiolite blocks in mélange include serpentinites and metamorphosed ultramafic rocks, metagabbros, pillowed and massive metabasalts, and minor sheeted dykes and pelagic sedimentary rocks (e.g., El Bahariya 2012).

Tectonic mélange is recognized in Kareim El Abiad and Garf occurrences (Fig. 1). It contains mapabble to unmapabble exotic tectonically disrupted blocks, lenses, sheets, and slices of ophiolites set in a schistose matrix of metapyroclastics and volcaniclastics metasediments. Tectonic mélanges of Kariem El Abiad occur along a series of NW-SE thrusts and shear zones (Fig. 2b), with blocks of serpentinite (Fig. 4a), pillowed metabasalts and sheeted dykes blocks tectonically incorporated parallel to the general fabric of the sheared matrix. The Garf tectonic mélange forms a NW-SE trending belt with the ophiolitic serpentinites and pillowed metabasalts syntectonically incorporated and oriented along foliation planes of the sheared matrix of volcaniclastic metasedimentary rocks (Abu El Ela et al. 2013).

The olistostrome is reported in Muweilih and Esel occurrences (Fig. 1) and comprises lower chaotic succession of block-in matrix or clast-support and unorganized metaconglomerate and breccias (Fig. 4b) and upper interbedded succession of metaconglomerate, pebbly metagreywackes and metagreywackes. The ophiolitic components include metamorphosed ultramafics, metagabbros, metabasalts, and marble of variable sizes and shapes (e.g., Akaad et al. 1996a; El Bahariya 2012).

The olistostromal mélanges have been recognized in Um Esh and Mubarak occurrences. They are formed as olistostrome and subsequently disrupted by later tectonic emplacement of ophiolites. The Um Esh olistostromal mélange comprises tectonically oriented olistoliths, blocks, tectonic slices, sheets, and pebbles of ophiolites dispersed in a sheared volcaniclastic foliated matrix (Fig. 4c). The exotic ophiolitic components include metamorphosed ultramafic rocks, metabasalts, metagabbros, foliated amphibolites, and trondhjemite. The Mubarak olistostromal mélange is composed of ophiolitic blocks of serpentinites, metabasalts, and pelagic sediments set in a fine-grained sheared and schistose matrix of metagreywackes, metasiltstones, and schists (Akaad et al. 1996b). The clast-size ranges from pebbles to blocks and large olistoliths. Sheets of serpentinites are tectonically emplaced along NE-SW thrust (T_1) in conformity with the regional trend of the host matrix (Fig. 4d).

Ophiolites along structural contacts rather than in mélanges

The ophiolites are structurally controlled but do not represent a part of the mélange association of the Pan-African belt of Egypt. They are represented in this study by many occurrences including Abu Meriewa, Sodmine, Um Saneyat, and Um Khariga (Fig. 1). These ophiolites consist commonly of serpentinites and occur essentially along thrusts of different angles trending mainly in a NW-SE or NE-SE directions. Their contact with the country rocks is characterized by pervasive shearing and fragmentation.

Abu Meriewa ophiolite The Abu Meriewa ophiolite comprises a sequence of massive metabasalts and slices of serpentinite (Fig. 5a). The metabasalt forms a wedge elongated in a NW-SE direction bounded from above and below by two thrust faults and sandwiched between Hammamat molasse sediments and serpentinites (El Bahariya 2007). The metabasalts are part of a SW-dipping thrust sheet, traversed later by strike–slip fault.

Sodmeine ophiolite This is mainly represented by serpentinites, which form slices, lenses, and sheets trending NW-SE and tectonically thrusted up to the NE and sandwiched between metavolcanics and metapyroclastics (Fig. 5b). The serpentinites are well exposed along both sides of Qift-Quseir asphaltic road and along Wadi Sodmine and Wadi El-Haramiya. The serpentinites are generally massive but become sheared and foliated along the tectonic contacts with the adjacent metavolcanic rocks. Along shear zones, the serpentinite bodies are replaced by talc-carbonate rocks and include small pockets and veins of magnesite as well as chromitite lenses. Minor bodies of fresh perodotire relics, together with thin pyroxenite dykes, are encountered within the serpentinites (e.g., Akaad and Abu El Ela 2002).

Um Saneyat ophiolite The ophiolites are mainly metamorphosed ultramafics and serpentinites. They occur as elongate masses, isolated bodies, imbricate thrust sheets, and slices of variable thicknesses trending nearly E-W or NW (Fig. 2c). They are tectonically emplaced into the Abu Fannani schist and Abu Ziran granite to the north (Fig. 5c, d) or into the Hammuda metasediments to the south (Noweir 1968). These serpentinites occupy an old high angle E-W thrust dipping south (Akaad and Noweir 1972) and affected by the igneous intrusion of Um Hombos granite pluton to the south and southwest.

Um Khariga ophiolite The Um Khariga ophiolites occur as elongate dissected masses, sheets, and slices of serpentinites (Fig. 2c) emplaced along the high-angle thrust fault extending between the Sukkari metavolcanics and the Um Khariga metapyroclastics (Fig. 5e, f). The metamorphosed ultramafics include mainly serpentinites, together with minor talc carbonate, quartz carbonate, and siliceous rocks. They show conspicuous large and small compositional layering (Akaad et al., 1993).

Arc-associated ophiolites

The arc-associated ophiolites (AAO) are represented by El Sid ophiolite and Esel ophiolite (Fig. 1). They occur as intact massive to less deformed sequences in association with the arc metavolcanics. They are considered the youngest ophiolite sequences and composed of serpentinite, metagabbro, and pillowed and massive metabasalts, together with minor boninites and pelagic sediments. The rocks suffered only one phase of deformation (D_2) and show tectonic thrust contacts against the surrounding rocks. They are represented in this study by two occurrences, namely El Sid ophiolite and Esel ophiolite (Fig. 1).

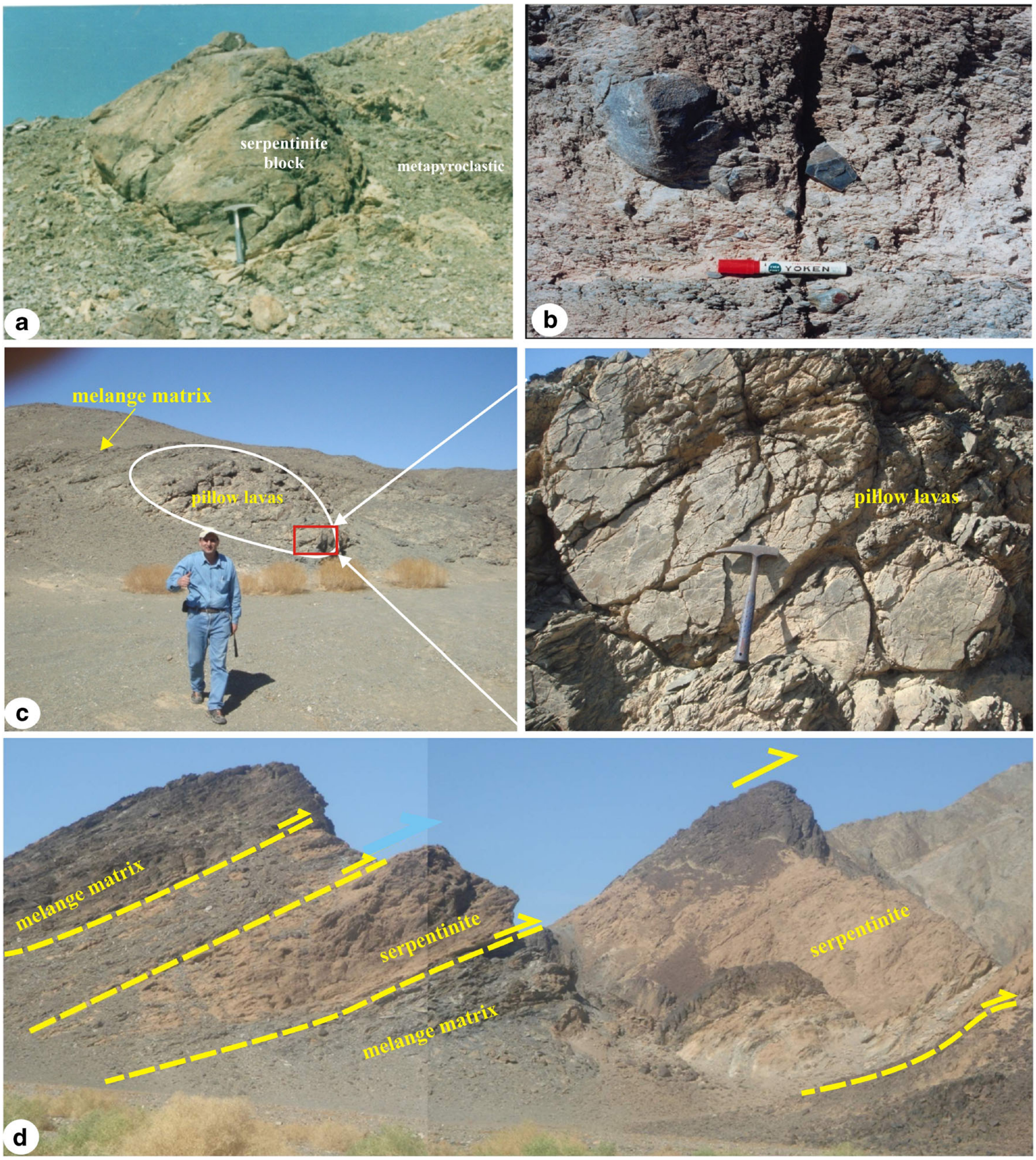


Fig. 4 Photographs showing the different blocks of ophiolites within mélanges. **a** Block of serpentinite tectonically emplaced within a sheared matrix of metapyroclastics (from El Bahariya 2012). **b** Metamorphosed ultramafic block-in matrix in Esel olistostrome. **c** Block of pillow lavas incorporated within sheared volcaniclastic matrix of Um Esh olistostromal mélange (left) and close-up view of the deformed pillow lavas (right). **d** Sheets and slabs of serpentinites tectonically incorporated within sheared volcaniclastic matrix of Mubarak olistostromal mélange (looking NW)

El Sid ophiolite

The El Sid ophiolite sequence occurs along Qift-Quseir road, nearly 80 km from Quseir City. It comprises a section of ophiolite, its base in the west and composed mainly of serpentinites and metagabbros, and its top to the east, which composed mainly of pillowed metavolcanics and pelagic sediments. The whole sequence is thrusted toward the NE over the Hammamt sediments to the east. It is intruded by post-tectonic younger granites. Many workers have studied the El Sid and Fawakhir ophiolites (e.g., El-Sayed et al. 1999; Garson and Shalaby 1976; Nasseef et al. 1980; Abd El-Rahman et al. 2009a). The ultramafic rocks are strongly serpentinized and crosscut by shear zones along which it is altered to talc and carbonates. Some pyroxenite bodies occur as irregular coarse-grained lenses within the serpentinite close to the ophiolitic gabbros**.** Occasionally, the contact between the serpentinite and the surrounding rocks is a tectonic fault

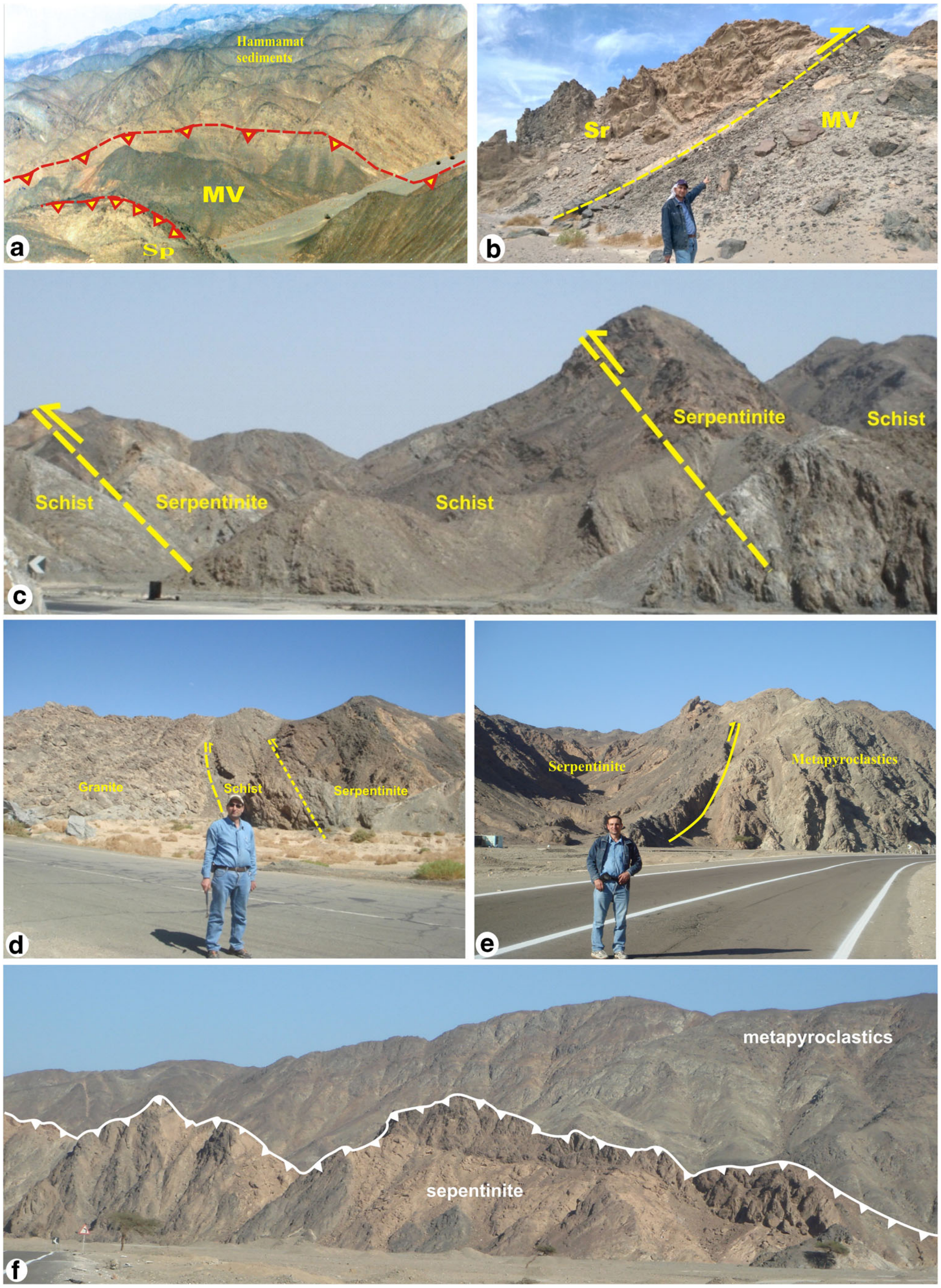


Fig. 5 Field photographs showing the ophiolite components along structural contacts rather than mélanges. **a** Blocks of serpentinites (SP) and Abu Meriewa metabasalts (MV) tectonically thrusted over the Hammamamt molasse sediments (Looking N). **b** Thrust sheet of serpentinite up to the NE over the metavolcanics of Sodmein ophiolite occurrence (looking N). **c**, **d** Um Saneyat imbricate thrusts of serpentinite sheets tectonically emplaced up to the N or nearly NW over Abu Fannani schists, and Abu Ziran granite (Looking E). **e**, **f** Sheets of serpentinite thrusted up to the NE over the Um Khariga metavolcanics and metapyroclastics (e looking NE; f looking SE)

striking NNW-SSE. El Sid metagabbro occurs as an elongate mass, extending across the Qift-Quseir road to the east of Fawakhir gold Mine (Noweir 1968). The metagabbro is bounded from the east by the metavolcanics and by the serpentinites in the western side and intruded by the Fawakhir granite. The transition from serpentinites to metagabbros is well exposed (Fig. 6a), but locally, the contact is strongly sheared. The metagabbro is massive, medium to coarse-grained, and has a grayish green to dark gray colors. Banding is occasionally observed, with altranation of coarse, medium, and fine-grained bands. Minor trondhjemites (Fig. 6b) usually occur as pockets, irregular masses, and veins within the normal gabbros. The metagabbro grades upwards into doleritic rocks with local preservation of sheeted dike features. NW-SE-oriented sheeted dikes are ~20 m thick on average and dip mostly to the NE (Fig. 6c). The metavolcanics are massive to pillowed and locally brecciated and associated with hyaloclastites and fine-grained red pellites (Fig. 6d). Pillow lavas are commonly spherical in shape and rarely ellipsoidal, with chilled margin and brecciated pillow structures (Fig. 6e, f, g, h). Some of these pillow lavas have a boninitic composition.

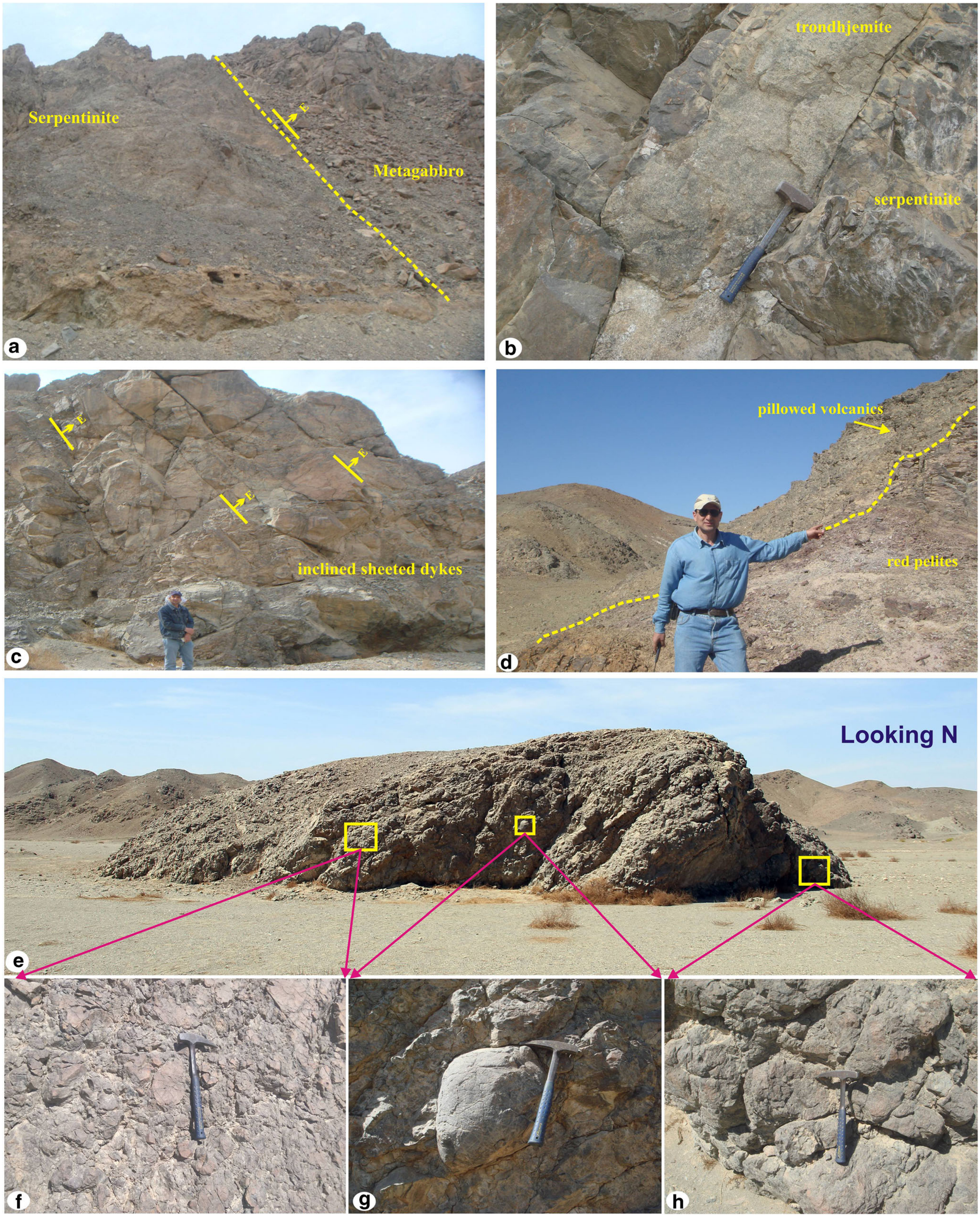


Fig. 6 Field photographs showing the El Sid arc-associated ophiolites components. **a** serpentinite merge into metagabbro (looking N). **b** Trondhjemite dyke-like intrusion within serpentinite. **c** Sheeted dykes of El Sid ophiolite (looking N). **d** Red pelagic pelites over pillow lavas of El Sid ophiolite at the entrance of Wadi Um Seleimat (looking E). **e** General view op pillow lavas along Qift-Qusier road (looking N). **f**–**h**) Nearly spherical pillow lavas of basaltic and boninitic composition of variable sizes

Esel ophiolite

The ophiolitic rocks of Wadi Esel include metamorphosed arc basaltic to basaltic andesite lavas and their corresponding pyroclastics. The ophiolite sequence comprises serpentinites, metagabbros, sheeted dykes, and pillow lavas (Fig. 2d). The ophiolitic metagabbros, sheeted dykes, and pillow lavas for a continuous succession are clearly exposed at Wadi Esel, while serpentinites occur as tectonic sheets, and lensoidal masses of various sizes, which are thrusted against the olsitostrome and arc metavolcanics and metapyroclastics (Fig. 7a; El Bahariya 2012). The metagabbros form an elongate oval mass, the larger axis is about 2.4 km, and its average width is ~ 1.6 km. Layered metagabbros (Fig. 7b) grade into sheeted dykes and finally grade into pillow lavas. The sheeted dykes cropout as small outcrop at the contact from the metagabbros and pillow lavas. They range in thickness from 0.6 to 1.5 m and stand with each other without any intervening older country rocks, where the contact between these dykes is hardly discernible, but occasionally, asymmetric chilled margins are observed (Fig. 7c). Some dykes occur within pillow lavas as feeders. The pillow lavas occur as four small masses and are characterized by the presence of the peculiar pillow structure. The pillows vary between 10 and 80 cm and have oval or spheroidal shape (Fig. 7d). They possess smooth rounded outlines and are usually smooth and convex upward, whereas their lower surfaces may conform to the pillows beneath. The pillows are separated from each other by thin films of basic tuffaceous matter. Most of the pillows are characterized by chilled margins. The pillows are tightly packed and contain very little interpillow matrix material, but some are brecciated and grade into tuffaceous pillows.

Petrographic features

The general petrographic description of the main ophiolite components is shown as follows:

Metamorphosed peridotite composed of serpentine, talc, carbonate, quartz, and relics of olivine, pyroxene, and chrome spinel (Fig. 8a). The serpentinite as a metamorphic product is common in all types of the classified ophiolites, whereas quartz carbonate and siliceous rocks (listwaenites) and talc carbonates are more restricted to the mélange type ophiolites (ophiolite blocks in mélanges). The serpentinites consist predominantly of antigorite, lizardite, and chrysotile, with subordinate talc, carbonate, chromite, chlorite, and magnetite (Fig. 8b). Talc carbonate rocks are composed of fine dense aggregates of talc enclosing clusters and rhombs of carbonates, with or without minor relics of antigorite.

The metagabbros are medium to coarse-grained and consist essentially of plagioclase, relics of pyroxene, together with amphibole. Iron oxides, epidote, sericite, chlorite, and calcite are secondary constituents. Short prismatic crystals of augite and/or long prismatic crystals of actinolite or actinolitic hornblende enclose tabular crystals of plagioclase in blasto-ophitic and blasto-subophitic textures, respectively (Fig. 8c).

The metabasalts show the following petrographic features:

1. Texturally, the metabasalts are aphyric to variably plagioclase-porphyritic (Fig. 8d); the groundmass is cryptocrystalline, intergranular (Fig. 8e), intersertal to ophitic or subophitic. The abundant phenocrysts and microphenocrysts are mainly of plagioclases. Some metabasalts contain sporadic relics of pyroxene and iron oxides. Pillow interior shows intergranular to ophitic and subophitic textures, whereas the pillow margin shows cryptocrystalline to intersertal textures. Variolitic, porphyritic, and intergranular textures are common characteristic for the metabasalts of MORB intact ophiolites and that of blocks in mélanges, whereas porphyritic and ophitic and subophitic textures with fresh pyroxene minerals are common in metabasalts of volcanic arc-associated ophiolites.
2. Vesicles vary from abundant to subordinate and finally to nearly absent or sporadic micro-vesicles. They vary in shape from circular to ellipsoidal and rarely irregular and are commonly filled by epidote, quartz, calcite, and chlorite (Fig. 8f). Amygdales increase in abundance from the interior to the margin of the pillow. There is a systematic increase in pillow vesicularity, volatile content, and vesicle size with decreasing depth of water at the site of emplacement at the time of eruption (e.g., Jones, 1969; Moore, 1965; Moore 1979), which suggests that both the highly vesicular metabasalts were extruded at shallow-water depths.

Structures and metamorphism

The ophiolitic components of the Central Eastern Desert of Egypt recorded two main deformational events (D_1 and D_2). The MIO and in part DO have been subjected to the two phases of deformation (D_1 and D_2), whereas the youngest AAO suffered only D_2.

D_1 structures include NW-SE thrusts (T_1) (Fig. 9a), tight to open isoclinal folds (F_1), together with axial planar foliation (S_1) (Fig. 9b). Both the intact ophiolites and the blocks within the mélange are deformed and elongated in a NW-SE direction, parallel to the schistosity of the matrix and to the regional trend of the mélange (L_1). These structures, together with an S-C fabric, commonly indicate a sinistral sense of shearing for D_1 (Fig. 9c, d).

The D_2 deformation is superimposed on the earlier deformation phase (D_1) as a consequence of transpression, which manifested by a NE-SW imbricate thrusts (T_2) and strike–slip faults. Deformational features and criteria of the D_2 event

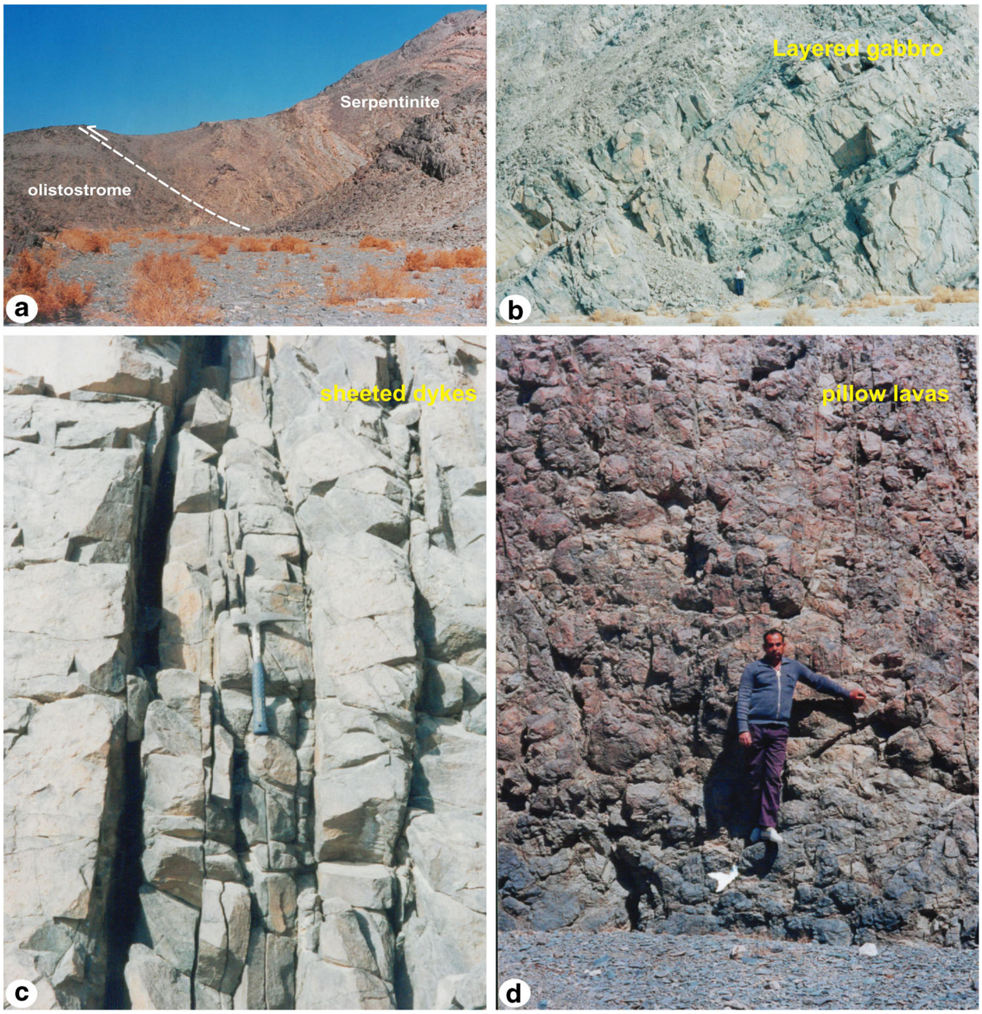


Fig. 7 Field photographs showing Esel arc-associated ophiolite components. **a** Serpentinite sheet thrusted up to the NW over Esel olistostrome (looking N). **b** Layered metagabbro of Esel ophiolite (looking N). **c** Sheeted dykes of Esel ophiolites (looking N). **d** Spherical and jointed pillow lavas of variable sizes at the top of the Esel ophiolite sequence (looking N)

include open folds (F_2) (Fig. 9e), drag folds along thrusts (T_2) (Fig. 9f), and shearing and crenulation foliations (S_2). The arc-associated ophiolites (AAO) and in part the ophiolite along structural contact rather than in mélanges were affected by this deformation, in which the rocks were thrusted (T_2), fragmented, and sheared (Fig. 9g). Shear sense indicators indicate dextral sense of shearing (Fig. 9h).

Strike slip faulting with dextral shearing during D_2 caused tectonic transportation and juxtaposition of the different components of the mélange. Slivers of serpentinite, silica-carbonate rock, and silicified rocks are tectonically occurring along the faults and shear zones during D_2. Chromite grains are elongated defining lineation (L_1), produced by thrusting (T_1) during the tectonic emplacement of the ophiolite blocks in mélanges (D_1). Later, thrusting and strike–slip faulting during D_2 led to fracturing of chromite grains.

The common mineral assemblage both in the ophiolite components and in the matrix of the mélange is dominated by biotite, chlorite, actinolite, actinolitic hornblende, hornblende, serpentine, carbonate, quartz, and fuchsite representing lower to upper greenschist facies regional metamorphism. Locally, the earlier regional metamorphism is superimposed by the effect of thermal metamorphism.

Two metamorphic events can be recognized in the ophiolitic serpentinites. The first event is greenschist facies regional metamorphism during deformational collisional phases (D_1 and D_2) and followed by hydrothermal and metasomatic metamorphism due to the obduction of ultramafic rocks along thrusts (T_2). Serpentinization process includes the formation of lizardite and chrysotile at temperatures less than 350 °C, whereas antigorite is apparently stable up to temperatures slightly above 500 °C (e.g., Barnes and O'Neil, 1969). Some talc-carbonate rocks were formed locally due to shearing along thrusts (T_2). In addition, the effect of hydrothermal and metasomatic addition of CO_2 is reflected in the formation of quartz-carbonate and talc carbonate rocks (e.g., Barnes et al. 1973; Bailey et al. 1964). The chromite shows slightly heterogeneous alteration along cracks and grain margins. Later, contact metamorphism locally took place after serpentinization due to the intrusions of granitic masses. This contact metamorphism may result in (i) the recrystallization of lizardite

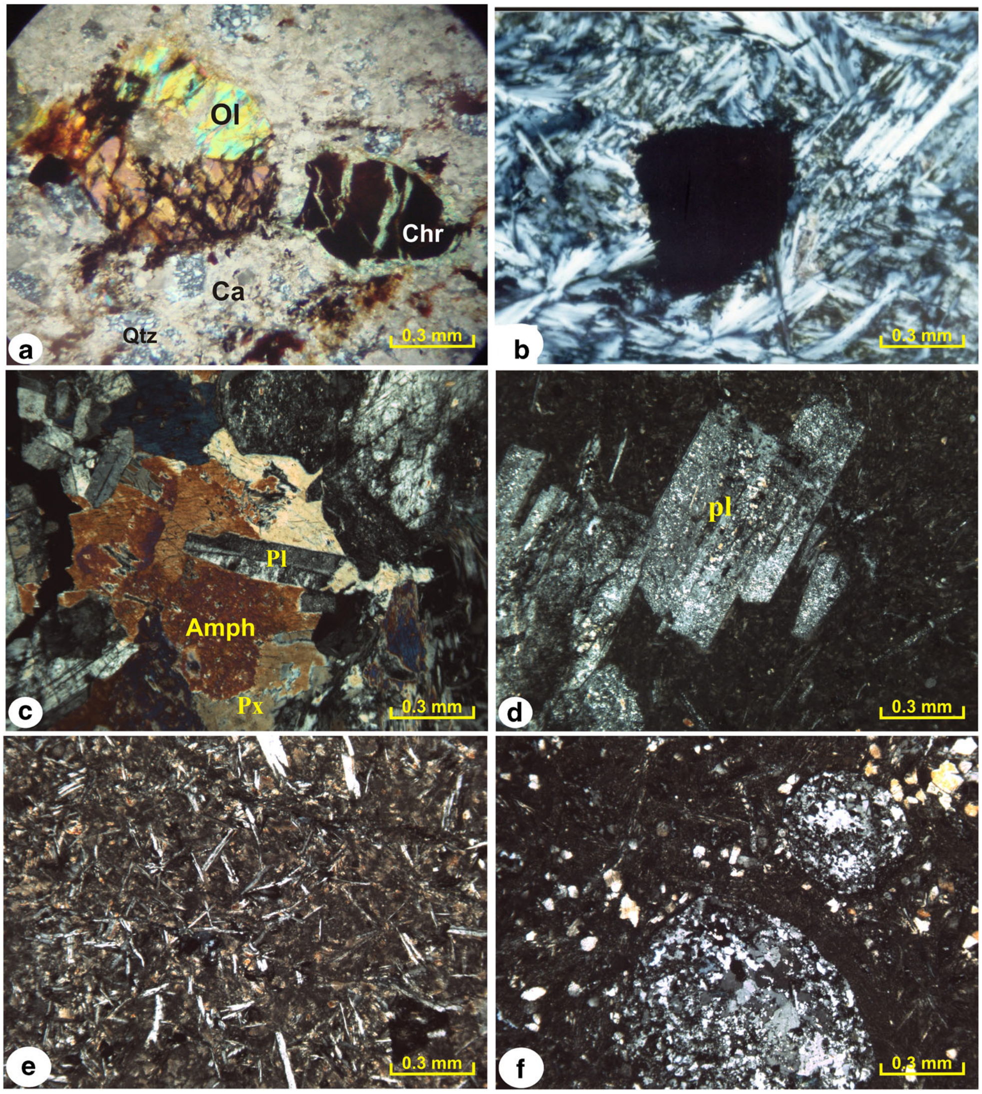


Fig. 8 Photomicrographs showing the petrographic features of ophiolites. **a** Metamorphosed peridotite with relics of olivine (0 l) and chrome spinel (Chr). **b** Serpentinite with chrome spinel relics. **c** Blasto-ophitic and subophitic metagabbro with plagioclase (Pl), amphibole (Amph), and relics of pyroxene (Px). **d** Porphyritic metabasalts. **e** Intergranular metabasalt. **f** Amygdaloidal boninitic metabasalt

to form antigorite; (ii) local addition of Si and Ca to form talc-bearing serpentinite, tremolite-bearing serpentinites, or talc carbonate rocks due to the hydration of a pyroxene-rich protolith; and (iii) release of magnetite and the alteration and metamorphism of chromite to form homogeneous Cr-magnetite or ferritchromite zones.

The ophiolitic gabbroic rocks underwent a regional metamorphism under lower or upper greenschist facies conditions (at 300–550 °C and lower to medium pressure of 1–3 kbar) (e.g., El Bahariya 2006). For examples, the metamorphic mineral assemblages of Muweilih metagabbro include actinolite, albite, chlorite, and epidote typical for the lower greenschist facies, whereas those for the El Sid ophiolite represented by actinolite, hornblende, albite, oligoclase, chlorite, and epidote favor upper greenschist metamorphic facies. The mineral assemblage observed in ophiolitic pillow lavas and massive metabasalts includes albite plagioclase, actinolite, and/or actinolitic hornblende, chlorite, epidote, biotite, and calcite, indicating a greenschist facies.

It is possible to differentiate between different ophiolites on the basis of deformation. The oldest MIO and in part DO have been subjected to the two phases of deformation (D_1 and D_2), whereas the youngest AAO suffered only D_2. Rocks of MIO and ophiolite blocks in mélanges show two styles of folding, penetrative foliation (S_1) and crenulation foliation (S_2), and elongation (L_1) and mylonitic lineation (L_2). Ophiolite sequence of AAO and in part ophiolite along tectonic contacts rather than in mélanges show only criteria of D_2 deformation manifested by tectonic emplacement along thrust faults (T_2), folding (F_2), and mylonitic lineation (L_2).

Geochemical characteristics

The geochemistry of ophiolite components is presented and discussed here based on compiled data from literature (e.g., Abu El Ela 1987; Akaad and Abu El Ela 1996; El Bahariya 2006, 2007, 2008; Abd El-Rahman et al. 2009a, b).

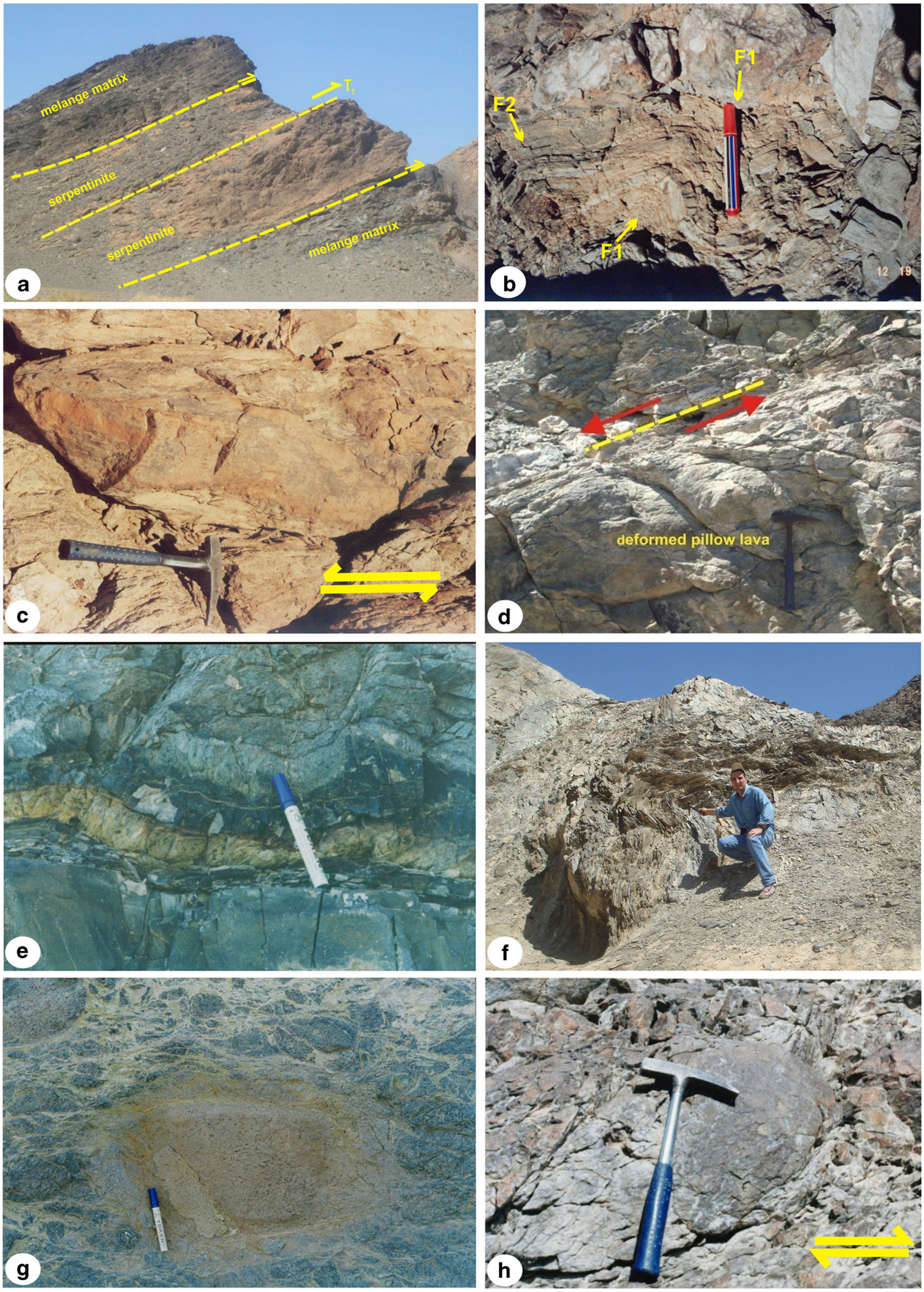


Fig. 9 Field photographs showing the deformational features during D_1 and D_2. **a** Sheet of serpentinite tectonically emplaced up to the NE along thrust faults (T_1) (looking NW). **b** F_1—folds superimposed by F_2 folds of metamorphosed ultramafic ophiolitic component. **c** Lensoidal block of metamorphosed ultramafics with sinisterly sense of shearing. **d** Deformed pillow lavas along shear zone with sinisterly shearing. **e** Open folds of serpentinite rocks. **f** Drag fold as a criteria for the tectonic emplacement of serpentinite along thrust fault (T_1). **g** Fragmented and brecciated serpentinites. **h** Deformed and fragmented pillow lavas

Metamorphosed ultramafics

Progressive melting of peridotites depletes Al relative to more refractory Cr in residual spinels, such that the Cr# of spinels (= 100Cr/Cr + Al) increases with melting (Dick and Bullen 1984). Bonatti and Michael (1989) used several parameters to distinguish between peridotites from different tectonic environments and that the most depleted peridotites are found in supra-subduction zone environments. The chrome spinels from the serpentinites and metamorphosed ultramafics of dismembered ophiolites have a wide range of Cr#, where the Cr# ranges from ~ 0.3 to 0.85 (El Bahariya and Arai 2003; El Bahariya 2008), and display both MORB and SSZ affinities (Fig.10a–d). They are classified into three groups (G1, G2, and G3) according to their Cr#. The chrome spinels of G1 are characterized by lower Cr# than the chrome spinels of the G2 and G3 (Fig. 10e). The G1 of these rocks are commonly having low Cr# showing lower degree of partial melting, and accordingly, they show similarity to abyssal peridotites. The Cr# of G2 and G3 spinels are similar to the range in arc and SSZ peridotites, implying a SSZ tectonic setting. Simultaneously, chromites associated with dunites are often significantly more Cr-rich (Cr# = 65–85) than those associated with harzburgite (e.g., Cr# ~ 50; Ahmed et al. 2001; El Bahariya and Arai 2003; El Bahariya 2008, 2012). The rocks have compositions ranging from relatively undepleted lherzolites to highly depleted harzburgites and display a diverse suite of geochemical signatures indicative of both anhydrous, mid-ocean ridge (MOR)-type and hydrous, supra-subduction zone (SSZ)-type melting regimes. The occurrence of both MOR and SSZ styles of melting regimes indicates that these ophiolites contain mantle residues from discrete stages of oceanic lithosphere generation (e.g., El Bahariya and Arai 2003; Ahmed et al. 2006; El Bahariya 2006, 2007, 2008; Khedr and Arai 2013; Azer 2014).

The ophiolitic metagabbros

On the Ti-V discrimination diagram (Fig. 11a), the ophiolitic metagabbros fall into two distinct groups: MORB-like group represented by Muweilih ophiolite occurrence and arc-type or boninite group represented by El Sid ophiolite occurrence (El Bahariya 2006). The Cr versus Y plot (Fig. 11b) can provide some information on the degree of partial melting (e.g., Pearce et al. 1984). The gabbroic rocks of MORB-affinity appear to be fractionated products as indicated by the comparatively lower Cr, Ni, and Mg contents, and by higher abundances of Al, Ti, P, Zr, and Y. Accordingly, they could have been derived by lower degree of partial melting of a slightly depleted source (e.g., Serri 1981) and bear similarities to those recovered from modern slow-spreading ridges or back-arc basins (e.g., Floyd et al. 2002). The arc-associated metagabbros show low abundances of Zr, Y, Ti, and Nb, which could have been generated by about 15–30% partial melting of a more depleted source. These gabbroic rocks show similarities with Josephine ophiolites (e.g., Harper 1984) and Troodos and Vourinos ophiolites which have island arc affinity or supra-subduction zone ophiolites (Pearce et al. 1984). On Fig. 11c, d, the ophiolitic metagabbros show compositional variations regarding MgO, TiO_2, and Zr and display two distinct chemical groups: a high-Ti, high-Zr, and low-MgO MORB-like group; and low-Ti, low-Zr, and high Mg arc-type group.

Ophiolitic metabasalts

The basaltic ophiolitic lavas can provide valuable clues about tectonic setting and the nature of melt generation. Ti-V diagram (Fig. 11a) shows the ophiolitic metabasalts to be related to two distinct geodynamic settings, namely Mid-Ocean Ridges (MOR) and intra-oceanic supra-subduction zones (SSZ). The chemical data of the pillowed metabasalts from MORB intact ophiolite (Muweilih and Ghadir occurrences) and dismembered ophiolites (Um Esh and Mubarak olistostromal mélange) appear to be closely comparable with those of MORB basalts and show similarities to back-arc basin basalts, reflecting lower degree of partial melting (compiled data from Akaad and Abu El Ela. 1996; Abd El-Rahman et al. 2009b; Basta et al. 2011; El Bahariya 2007, 2012). On the other hand, pillowed metabasalts and boninitic pillow lavas of the arc-associated ophiolites show similarity to the arc or SSZ volcanics implying a higher degree of partial melting (Fig. 11b) (data from Abd El-Rahman et al. 2009a).

On the constructed diagrams herein, the ophiolitic metabasalts and metagabbros show a compositional variation regarding their Ti, Mg, and Zr contents (Fig. 11c, d). With respect to their Ti contents, the metabasalts can be divided into high-Ti group, low-Ti group, and very low-Ti group. In general, the metabasalts of MORB affinity show high-Ti and Zr contents, relative to arc-like ophiolite metavolcanics (Fig. 11c). The pillow lavas with MORB-affinity can be further subdivided into high-Ti (most fractionated rocks), low-Mg and low-Ti, and high-Mg groups (Fig. 11d). It is noticed that Mg increases and Ti decreases from the south to the north of the CED. The low-Ti group can be further subdivided into low-Zr and high-Zr subgroups. The compositional variation within the MORB rocks appears to reflect the effects of low-pressure fractional crystallization (i.e., whereby TiO_2 and Al_2O_3 increased and MgO decreased). Marginal basin systems and most back-arc basin produce basalts essentially similar to depleted mid-ocean ridge basalts in their geochemistry (e.g., Saunders et al. 1980; Pearce et al. 1984).

Discussion and tectonic evolution

Classification of the CED Neoproterozoic ophiolites on the basis of filed geology

The present paper presents detailed geologic characteristics for the Neoproterozoic ophiolites based on field observations.

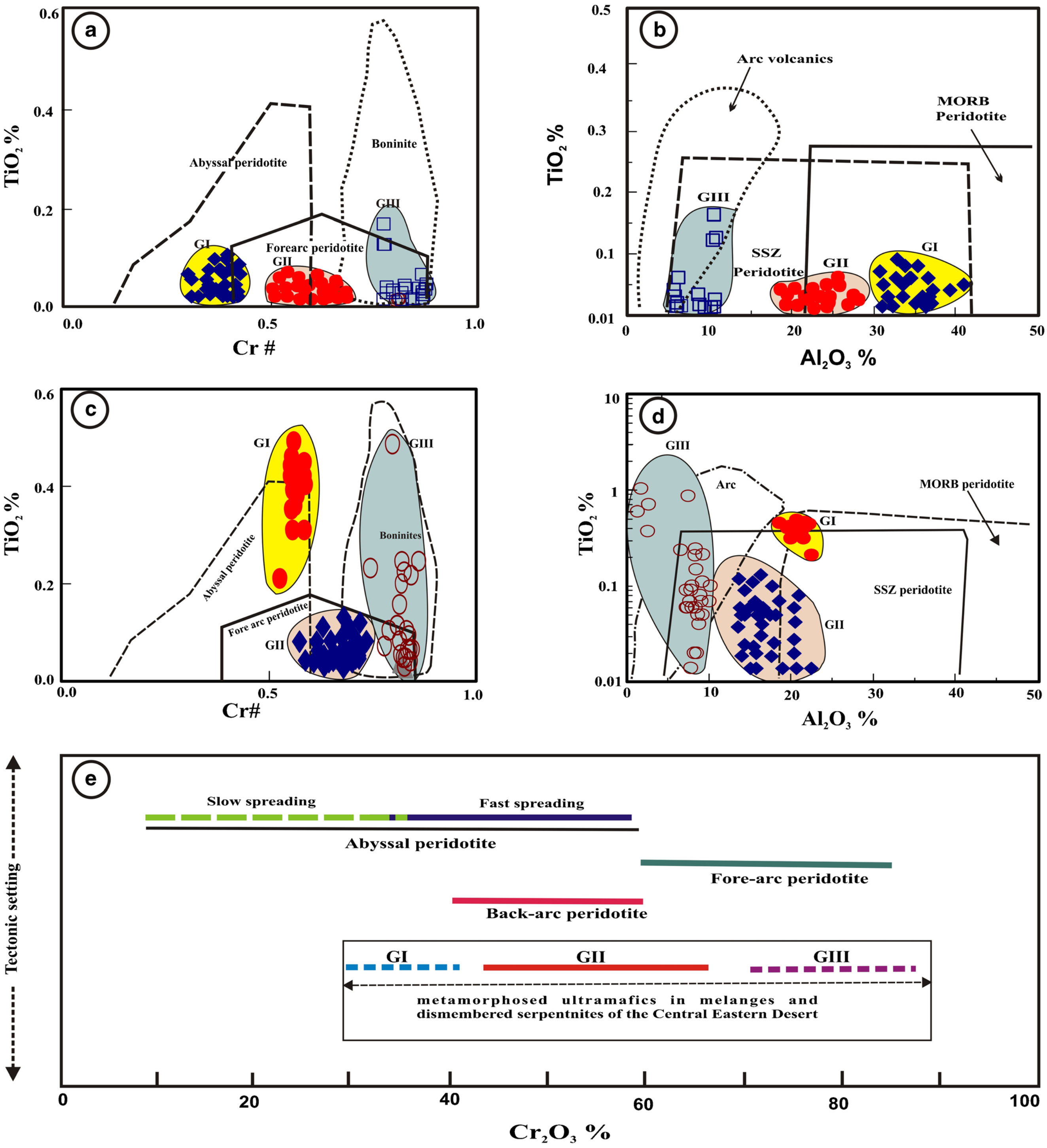


Fig. 10 TiO_2 vs. $Cr^{\#}$ and Al_2O_3 diagrams. **a**, **b** chrome spinels from ophiolitic blocks of metamorphosed ultramafics in mélanges (data from El Bahariya 2008, 2012). **c**, **d** Chrome spinels from serpentinite rocks along structural contacts rather than mélanges (data from El Bahariya and Arai 2003). **e** Ranges of Cr_2O_3 of whole Neoproterozoic chrome spinels in relation to peridotites from different tectonic settings (after Yong 1999; El Bahariya 2008). Fields of abyssal peridotite (Dick and Bullen 1984; Arai 1994), fore arc peridotite (Pearce et al. 2000), boninite (Ishikawa et al. 2002), and MORB and SSZ ophiolites (Kamenetsky et al. 2001)

The investigated ophiolites are classified into three groups from oldest to youngest: (i) MORB intact ophiolites (MIO), (ii) dismembered ophiolites (DO), and (iii) arc-associated ophiolites (AAO). The MIO have nearly a complete rock sequence of serpentinized peridotites, metagabbros, and massive and pillow lavas. Sheeted dykes are rarely reported, and the pillow forms are commonly ellipsoidal to bulbous. They are subjected to D_1 and D_2 and have the mineral assemblages

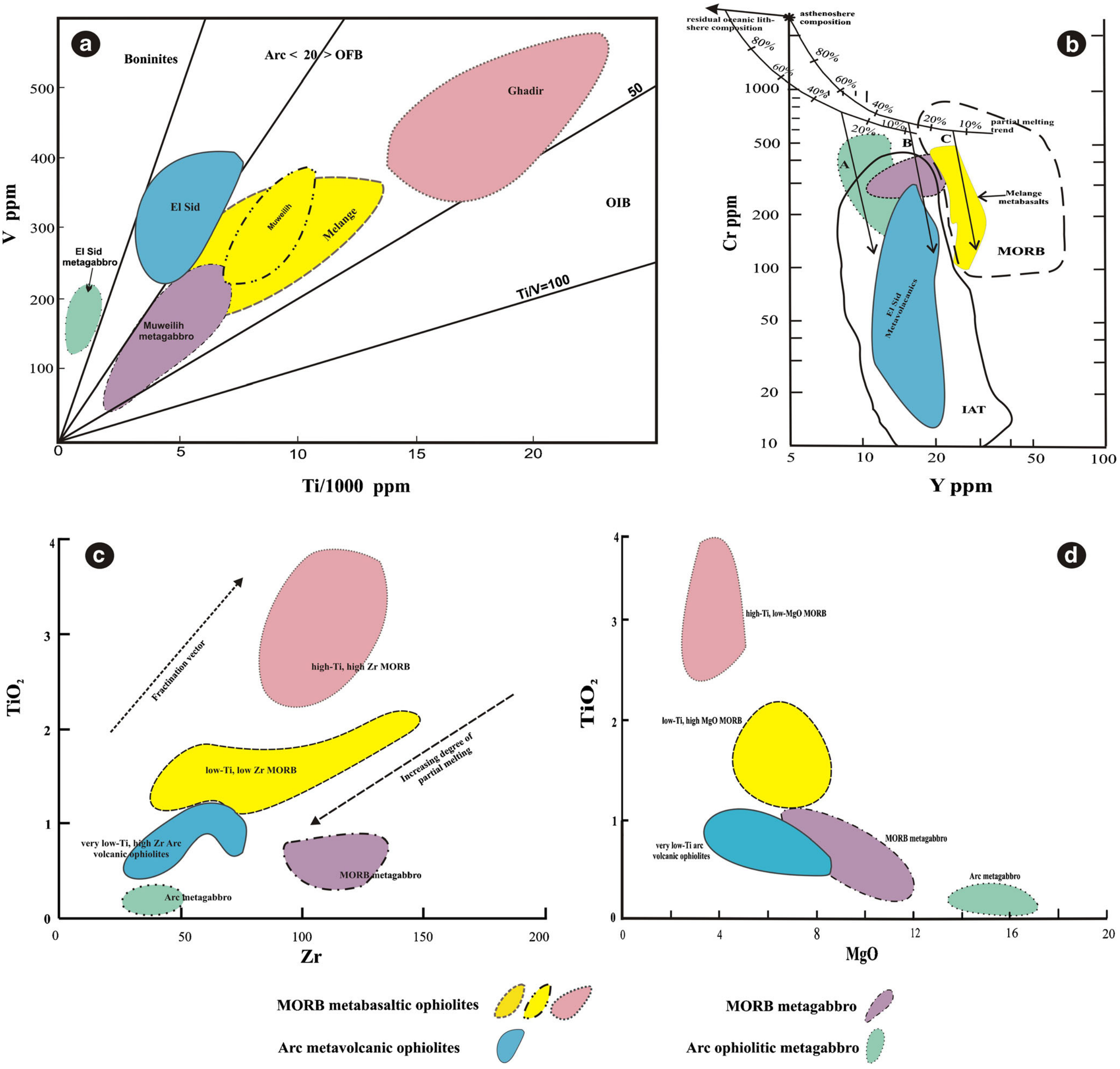


Fig. 11 Tectonic discrimination diagrams of the ophiolitic metabasalts and metagabbros. **a** Ti/1000 versus V diagram of Shervais (1982). **b** Cr versus Y discrimination diagram (Pearce et al. 1984). Diagrams based on compiled data from (Abu El Ela 1987; Akaad et al. 1997; El Bahariya 1988, 2006, 2007, 2008). Data of arc ophiolite metavolcanics from Abd El-Rahman et al. (2009a). **c**, **d** TiO_2 versus Zr and MgO constructed compositional variation diagrams for the ophiolitic metabasalts and metagabbros

of greenschist facies metamorphism. The DO on the other hand occur either as blocks of different sizes and shapes incorporated within a mélange matrix (with serpentinites, quartz carbonate, carbonate, and talc carbonate, together with pillow lavas as the common blocks) that underwent two phases of deformation D_1 and D_2 or as individual blocks and sheets of serpentinites, quartz carbonate, carbonate, and talc carbonate along tectonic faults rather than in mélanges which have been subjected in part to D_1 and D_2. They have been metamorphosed up to the upper greenschist facies metamorphism. Pillow forms in mélanges are commonly ellipsoidal and deformed. The AAO occur as nearly complete sequence of serpentinites, metagabbros, sheeted dykes, and pillow lavas in association with arc metavolcanics. Pillow forms are mainly spherical in shape, and some of which have boninitic composition. They are less deformed, which have experienced only one phase of deformation (D_2) and have mineral assemblages of greenschist facies metamorphism. They are not included as blocks and fragments in mélanges.

The different types of ophiolites fall geochemically and tectonically into two separate groups: relatively older group of high-to low-Ti ophiolites of MORB-like affinities formed in a back-arc tectonic setting (e.g., El Bahariya 2007; Abd El-Rahman et al. 2009b; Basta et al. 2011) and a younger group of very low-Ti ophiolites generated in a supra-subduction zone (SSZ) of for-arc tectonic setting (e.g., Beccaluva et al. 1984; Bortolotti et al. 2002; Abd El-Rahman et al. 2009a). Figure 12 summarizes the mode of occurrence and geological characteristics of the Neoproterozoic ophiolites of the Central Eastern Desert of Egypt.

MORB-ophiolites

The G1 of the ultramafics and serpentinites of the dismembered ophiolites (DO) show commonly low Cr# showing lower degree of partial melting, and accordingly, they show similarity to abyssal peridotites. The blocks of metabasalt and metagabbro in mélanges resemble to those of the MORB intact ophiolite (MIO), where the basaltic rocks of the MIO and DO especially those in mélanges exhibit N-MORB affinity. These different magmatic groups may have originated from fractional crystallization from different primary magmas, which were generated, in turn, from partial melting of mantle sources progressively depleted by previous melt extractions. The MORB ophiolite sequences are generated by 20% partial melting of an undepleted lherzolitic mantle source leaving, as a residue, depleted lherzolitic to harzburgitic mantle compositions. The generally low MgO, Cr, and Ni and high Zr contents for high-Ti group of MORB ophiolites are consistent with derivation of these rocks from an evolved magma. Moreover, the present work suggests the increase of the Mg of the MORB-type ophiolitic metabasalts from the south (Ghadir occurrence) to the north (Muweilih occurrence) in the Central Eastern Desert (El Bahariya 2007). The MORB or BABB ophiolites are inferred to have been formed in an intra-oceanic back-arc basin, which was subsequently disrupted via a thrusting and strike–slip faulting (e.g., Pearce 2003; El Bahariya 2012). This indicates localized compositional heterogeneities and/or variations in the Pan-African MORB-ophiolites.

SSZ ophiolites

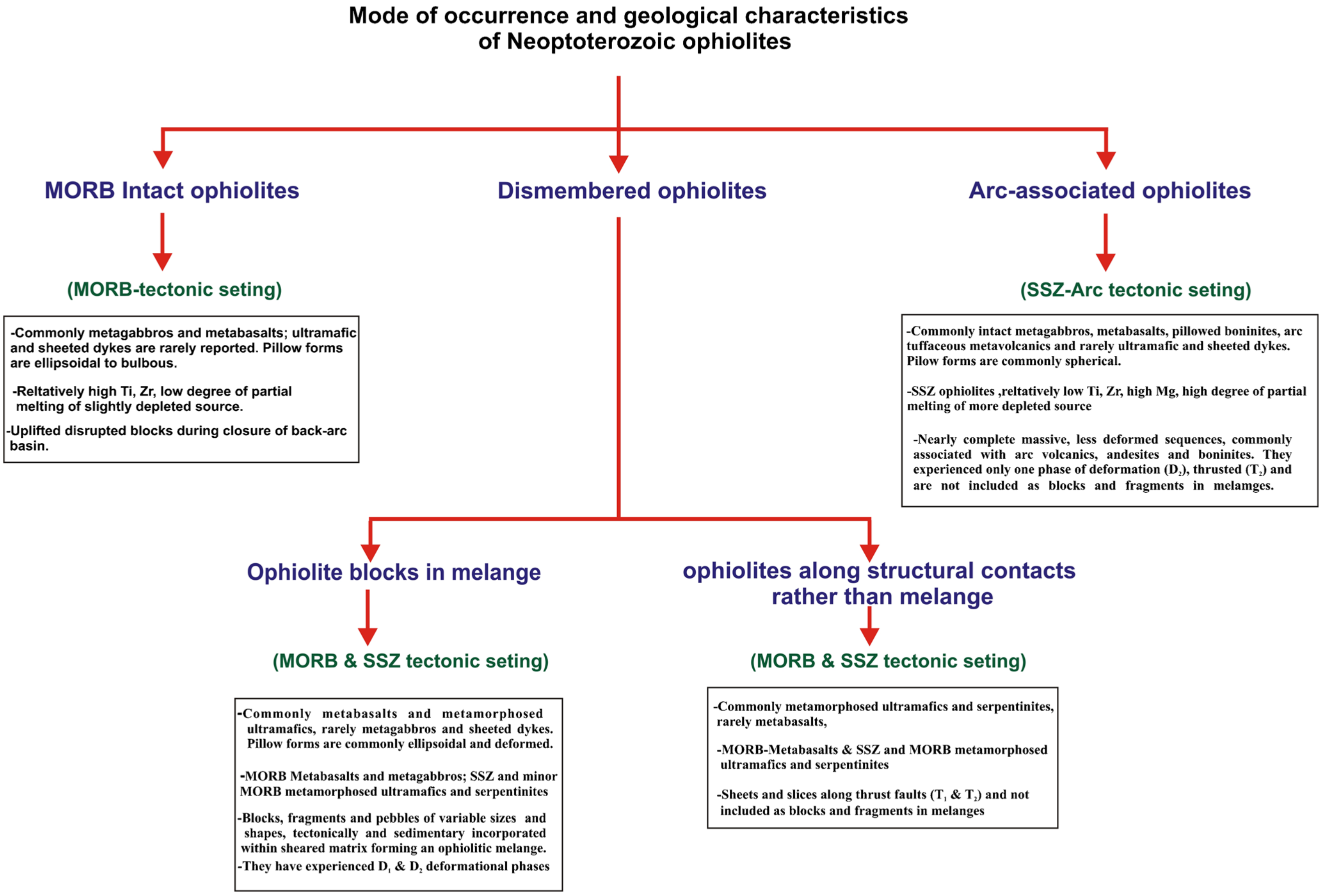
The G2 and G3 of the chrome spinels from metamorphosed ultramafics in mélanges and serpentinites have high Cr#, showing relatively high degrees of partial melting, and consequently, they show similarity to the arc peridotite or supra-subduction zone (SSZ) peridotites (e.g. El Bahariya 2008). The ophiolite metavolcanics and metagabbros of arc-associated ophiolites (AAO) show a geochemical affinity similar to island-arc basalts and low-Ti boninite. They represent a supra-subduction oceanic crust that formed in a fore arc tectonic setting (e.g. El Bahariya 2006; Abd El-Rahman et al. 2009a).

Moreover, the previous studies dealt collectively with the ophiolitic serpentinites of the CED as only one type of ophiolites showing a SSZ geochemical signature (e.g., El-Sayed et al. 1999; Ahmed et al. 2001; El Bahariya and Arai 2003; Azer and Stern 2007; Abd El-Rahman et al., 2012) and considered as fore-arc mantle fragments (e.g., Azer and Stern 2007; Khalil and Azer 2007). SSZ ophiolites with similar crustal architecture and geochemical features as in the Tethyan ophiolites are common in the Neoproterozoic record (Kusky 2004). The SSZ ophiolite with high MgO, low-TiO_2 contents and boninitic compositions, indicates enhanced degrees of melting of highly refractory mantle peridotites that is analogous to the earlier arc volcanism in the Eocene–Oligocene Izu–Bonin–Mariana system and the SSZ Tethyan ophiolites (e.g., Bloomer et al. 1995; Dilek and Thy 2009). The intense depletion of the lithospheric mantle led to the formation of depleted harzburgites.

Tectonic model and emplacement mechanism

The different geological settings of the Neoproterozoic ophiolites of the CED reflect variable palaeogeographic settings and subsequent tectonic events. They indicate compositional variations of the ophiolites from old MORB in the south to young SSZ in the north. On a regional scale, an island arc-marginal basin tectonic setting is suggested rather than an oceanic ridge for the CED ophiolites. Ophiolites with a back-arc origin have been documented in many areas of the Central Eastern Desert of Egypt (El Bahariya 2008; Abd El-Rahman et al. 2009a, b; Ali et al. 2009). The whole ophiolites appear to be formed through back-arc rifting, spreading, and subsequent record of subduction initiation and the development of new fore arc crust above this subduction zone. This consistency of having ophiolitic crustal rocks with an oceanic back-arc geochemical affinity and fore arc geochemical signature may indicate the evolution of the Neoproterozoic intra-oceanic island arc assemblage of the CED above an NW-dipping subduction zone (e.g., El Bahariya 2008; Abd El-Rahman et al. 2012).

The oceanic lithosphere of MORB-type and SSZ ophiolites is tectonically emplaced via subduction–accretion or collisional processes (e.g., Wakabayashi and Dilek, 2003). The spatial and temporal occurrence of volcaniclastic metasedimentary and metapyroclastic rocks with the MORB ophiolites suggests that they are formed in an intra-oceanic back-arc basin. The rocks of MORB intact ophiolites (MIO) may be considered as remnants of disrupted and uplifted MORB-type crust during closure of the back-arc basin in which they formed. They are tectonically emplaced onto the continental margin due to the closure of the back-arc basin and the subsequent arc-collision. On the other hand, the SSZ-like ophiolite is suggested to be formed in a fore-arc tectonic setting (represented by AAO) during the closing stages of the



-Commonly metagabbros and metabasalts; ultramafic and sheeted dykes are rarely reported. Pillow forms are ellipsoidal to bulbous.

-Reltatively high Ti, Zr, low degree of partial melting of slightly depleted source.

-Uplifted disrupted blocks during closure of back-arc basin.

-Commonly intact metagabbros, metabasalts, pillowed boninites, arc tuffaceous metavolcanics and rarely ultramafic and sheeted dykes. Pilow forms are commonly spherical.

-SSZ ophiolites ,reltatively low Ti, Zr, high Mg, high degree of partial melting of more depleted source

-Nearly complete massive, less deformed sequences, commonly associated with arc volcanics, andesites and boninites. They experienced only one phase of deformation (D_2), thrusted (T_2) and are not included as blocks and fragments in melamges.

-Commonly metabasalts and metamorphosed ultramafics, rarely metagabbros and sheeted dykes. Pillow forms are commonly ellipsoidal and deformed.

-MORB Metabasalts and metagabbros; SSZ and minor MORB metamorphosed ultramafics and serpentinites

-Blocks, fragments and pebbles of variable sizes and shapes, tectonically and sedimentary incorporated within sheared matrix forming an ophiolitic melange.

-They have experienced D_1 & D_2 deformational phases

-Commonly metamorphosed ultramafics and serpentinites, rarely metabasalts,

-MORB-Metabasalts & SSZ and MORB metamorphosed ultramafics and serpentinites

-Sheets and slices along thrust faults (T_1 & T_2) and not included as blocks and fragments in melanges

Fig. 12 Flow chart showing the mode of occurrence and geological characteristics of the Neoproterozoic ophiolites of the CED of Egypt

back-arc basin and emplaced as a result of the collision of the intra-oceanic arc with the continent. The ophiolite emplacement onto the margins was completed in the arc-back-arc-continent collision. SW-dipping subduction was proposed by El Ramly et al. (1984), in which the marginal basin and the island arc system were imbricated, from east to the west, and were then thrust onto the continental margin. Suture formation was assigned to the collapse of a marginal basin and an arc complex against an Andean margin to the west (e.g., El Bayoumi and Greiling 1984).

The dismembered ophiolites (DO) occur either as mélanges or imbricate and tectonically fragmented ophiolite slices. A back-arc or inter-arc basin origin is favored as the setting of the formation of the “ophiolitic mélange” through tectonic and/or concurrent sedimentary and tectonic processes (e.g., El Bahariya 2012). The exotic and native components in the mélange were juxtaposed due to compressional deformation during the back-arc basin closure (D_1) and subsequent arc–arc sutures, accompanied by obduction of arc-associated ophiolites (AAO) of SSZ affinity during D_2.

Ophiolites of mid-Neoproterozoic age are abundant in the Arabian-Nubian Shield (ANS) of NE Africa and Arabia. They range in age from 690 to 890 Ma and occur as nappe complexes marking suture zones between terrains that suggested two evolution stages for the ophiolite in the ANS ~ 810–780 and ~ 730–750 Ma (e.g., Ali et al. 2010). The results of age dating give age ranges of 694 ± 8 Ma for the youngest ANS ophiolite to 870 ± 11 Ma for the oldest (e.g., Yibas et al. 2003; Stern et al. 2004). The field geology and mode of occurrence indicate that these ophiolites formed at more than one time in accordance with the obtained age data (e.g., Stern et al. 2004; Ali et al. 2010).

The process of formation and tectonic stages of the ophiolite emplacement as well as ophiolite mélange formation are illustrated in Fig. 13 with the age dating giving by Stern et al. (2006) as reference:

1. Formation of oceanic back-arc basin floor of MORB-type (870–750 Ma); Intra-oceanic subduction within a pristine MORB-type lithosphere results in SSZ basaltic magmatism with IAT affinity (750–650 Ma)
2. The back-arc basin collapse and closure lead to uplifting and disruption of MORB-type ophiolites into remnant nearly intact uplifted ophiolite sequences, which unconformably overly by tectonic mélange and olistostrome
3. Contemporaneous to the back-arc basin closure, the slab sinking and inter arc spreading with generation of boninites and/or very low-Ti tholeiites. Subsequent

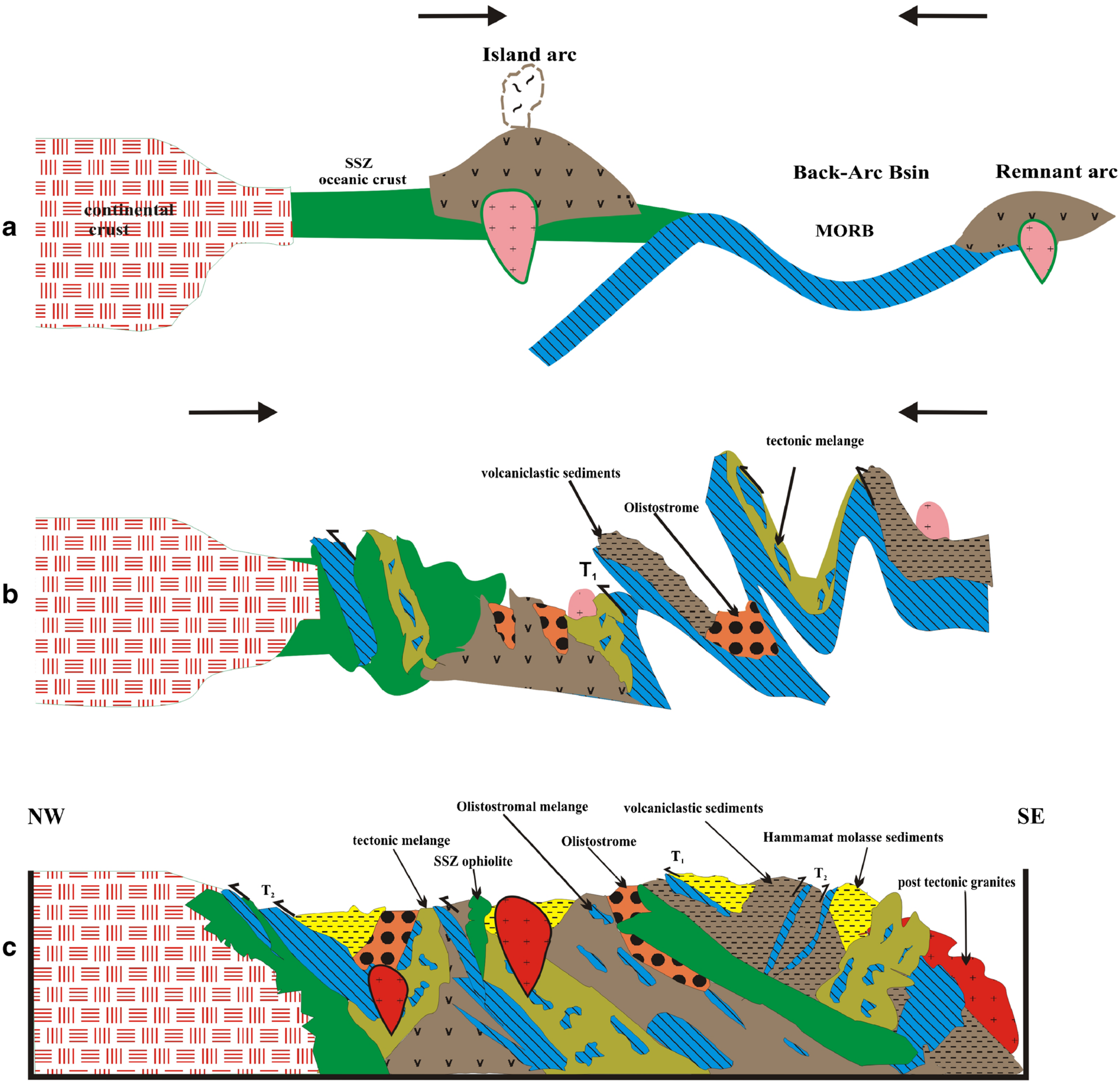


Fig. 13 Simplified tectonic model diagram illustrating the site of formation of ophiolites and processes of tectonic emplacement as a consequence of back-arc basin deformation and consequences collisional events during back-arc–arc-continent

convergence and arc collision causes large and relatively intact lithospheric sections of SSZ ophiolites to be obducted onto the continental margin as well as the fragmentation and mixing of mélanges to form olistostromal mélange.

The geological and geochemical features indicate a progressive evolution of the CED ophiolites of the Nubian Shield from initial MORB-like to IAT tholeiites to boninites through time. We suggest that MORB ophiolites are remnants of ocean floor of N-MORB type and became tectonically interstacked and obducted together with the SSZ-type ophiolites in a subduction zone environment. Many ophiolites in the northern Arabian-Nubian Shield are disrupted by NW trending strike–slip faults and shear zones of the Najd fault system (Sultan et al. 1988). The different types of ophiolites were brought together by tectonic stacking during the obduction and tectonic emplacement processes when collision of island arc complexes with the active margin of the African continent occurred during an accretion event − 600–700 Ma ago (e.g., Zimmer et al. 1995). Accretion/collision marking the culmination of the Pan-African Orogeny and continued shortening coupled with escape tectonics and continental collapse (Stern et al. 2006).

Summary and conclusion

Summary

From the foregoing, the following main points can be summarized:

Mode of occurrence:

1. Based on the mode of occurrence of the ophiolites and processes of ophiolite emplacement, the ophiolites of the CED of Egypt are classified and mapped from oldest to youngest into (1) MORB intact ophiolite (MIO), (2) dismembered ophiolites (DO), which classified into (i) ophiolite blocks in mélanges and (ii) ophiolites along structural contacts rather than mélanges; and (3) arc-associated ophiolites (AAO).
2. Metagabbros and metabasalts, which occur either as members of MORB intact ophiolites (MIO) or as blocks in mélanges, exhibit MORB or BABB affinity, whereas metagabbros and metavolcanics of arc-associated ophiolites (AAO) show arc or SSZ affinity.
3. Sheeted dykes are scarce among ophiolite components. Thickness and shape of pillow lavas vary with the type of ophiolites. Rocks of arc-associated ophiolites are generally massive and less deformed; pillow lavas of which are commonly of spheroidal shape and some of which are of boninitic composition.

Geochemistry:

1. The different types of ophiolites fall geochemically and tectonically into two separate groups: MORB-like ophiolites formed in a back-arc tectonic setting and SSZ ophiolites of fore-arc tectonic setting.
2. Almost all serpentinites and metamorphosed ultramafics are similar to SSZ ophiolites, but still some others, showing MORB affinity. The metamorphosed ultramafics and serpentinites with high Cr# may either indicate a SSZ tectonic setting or reflect dunite as a source rock rather than a tectonic setting.
3. Collectively, the ophiolites of the CED fall into two groups, MORB or BABB and SSZ ophiolites, which are spatially and temporally unrelated, and thus, it seems likely that the two types are not petrogenetically related. They had a progressive geochemical evolution from MORB-type back-arc basin oceanic crust in the south to fore arc of supra subduction zone setting in the north.

Deformation:

1. The MORB ophiolites (oldest) have been subjected to two phases of deformation (D_1 and D_2), whereas the SSZ-volcanic arc-associated ophiolites (youngest) suffered only D_2 deformation and not included as blocks in the mélange.
2. Although tectonized harzburgites and serpentinite rocks are of wide distribution among ophiolitic components, they seldom occur as a part of intact complete ophiolite sequences. This may be attributed to the mobility of serpentinites, and consequently, it is tectonically re-emplaced and squeezed during successive tectonics and deformation and contemporaneous igneous intrusions (e.g., Akaad 1997 and there in).

Conclusion

The ophiolites of the CED show significant variations in their internal structure and emplacement mechanisms and therefore mode of occurrence. They underwent multiple phases of deformation and metamorphism and successive tectonic emplacement as a consequence of collisional events. The ophiolites of the CED record the fundamental stages of the Neoproterozoic juvenile crust evolution from MORB to SSZ tectonic setting. They were emplaced onto the continental margin due to the closure of the back-arc basin and the subsequent arc-collision. Therefore, they depict distinct lithological association and mode of occurrence and deformational characteristics that could be deciphered that careful field investigation could be sued to classify these ophiolites into three distinct ophiolite types. The geochemical fingerprints of the rock associations of these ophiolites further corroborate this classification.

Although the discrimination between serpentinite of abyssal-type peridotites and those related to SSZ or arc ophiolites in the field are very interesting, the widespread occurrence of serpentinite rocks in different structural and geological settings needs further investigation. Detailed and extensive compositional and geochemical variations within ophiolites of MORB affinity and discrimination between arc-related ophiolites and island arc rocks are required.

Acknowledgements Field work was supported by the Tanta University, Egypt, which is gratefully acknowledged. I would like to express my sincere thanks to Prof. Dr. Ibrahim Khalaf, Menofia University, Egypt, and Prof. Dr. Bisrat Yibas, Council for Geoscience, Pretoria, South Africa, for their great efforts and constructive reviews to improve the manuscript. I am grateful to the guest editor Prof. Dr. Hamimi and Prof. Dr. Abdullah M. Al-Amri (Editor-in-Chief) for handling the manuscript and for their constructive editorial comments and help.

References

Abd El-Rahman Y, Polat A, Dilek Y, Fryer BJ, El-Sharkawy M, Sakran S (2009a) Geochemistry and tectonic evolution of the Neoproterozoic incipient arc-fore arc crust in the Fawakhir area, central Eastern Desert, Egypt. Precambrian Res 175:116–134

Abd El-Rahman Y, Polat A, Dilek Y, Fryer BJ, El-Sharkawy M, Sakran S (2009b) Geochemistry and tectonic evolution of the Neoproterozoic Wadi Ghadir ophiolite, Eastern Desert, Egypt. Lithos 113:158–178

Abd El-Rahman Y, Polat A, Dilek Y, Kusky TM, El-Sharkawy M, Said A (2012) Cryogenian ophiolite tectonics and metallogeny of the central Eastern Desert of Egypt. Int Geol Rev 54:1870–1884

Abdeen MM, Greiling RO (2005) A quantitative structural study of Late Pan-African compressional deformation in the central Eastern Desert (Egypt) during Gondwana assembly. Gondwana Res 8: 457–471

Abdelsalam MG, Stern RJ (1996) Sutures and shear zones in the Arabian-Nubian shield. J Afr Earth Sci 23:289–310

Abu El Ela AM (1987) Chemistry of pillow lava from Wadi Beriric, Wadi Mubarak district, central eastern desert, Egypt and its tectonic significance. Delta Journal of Science 11:803–830

Abu El Ela AM, Aly SM (1990) The ophiolite suite of Wadi Esel, Eastern Desert, Egypt. Proceedings of the Egyptian academy of Science 40: 27–39

Abu El Ela AM, El Bahariya GA, Abu Anbar MM, Masoud EL (2013) Geology and tectonic evolution of Neoproterozoic rocks around Wadi Garf, Eastern Desert, Egypt: emphasis on the petrochemistry of volcano-sedimentary association. Egypt J Geol 57:209–231

Ahmed AH, Arai S, Attaia AK (2001) Petrological characteristics of the Pan African podiform chromatite and associated peridotites of the Proterozoic ophiolite complexes, Egypt. Mineralium Deposita 36: 72–84

Ahmed AH, Hanghøj K, Kelemen PB, Hart SR, Arai S (2006) Osmium isotope systematics of the Proterozoic and Phanerozoic ophiolitic chromitites: in situ ion probe analysis of primary Os-rich PGM. Earth Planet Sci Lett 245:777–791

Akaad MK (1997) On the behavior of serpentinites and its implications. Geological Survey of Egypt 74:95

Akaad MK, Abu El Ela AM (1996) Geology and petrochemistry of the Muweilih submarine metabasalts, Qift-Quseir region, Eastern Desert, Egypt. Egypt J Geol 40(1):321–349

Akaad MK, Abu El Ela AM (2002) Geology of the basement rocks in the eastern half of the belt between latitudes 25o 30/ and 26o 30/ N, central eastern desert, Egypt. The Geological Survey of Egypt 78:1–118

Akaad MK, Noweir AM (1972) Some aspects of the serpentinites and their associated derivatives along Qift-Quesir road, Eastern Desert. Ann Geol Surv Egypt II:251–270

Akaad MK, Noweir AM (1980) Geology and lithostratigraphy of the Arabian Desert orogenic belt between Latudes 25° 35′ and 26° 30' N. Sym. On “Evolution and mineralization of Arabian-Nubian Shield”. Applied Geology, Jeddah Bulletin 3:127–135

Akaad MK, Abu El Ela AM, El Kamshoshy HI (1993) Geology of the region west of Mersa Alam, Eastern Desert, Egypt. Annals of the Geological Survey of Egypt 24:1–18

Akaad, M.K., Noweir, A.M., Abu El Ela, A.M., El Bahariya, G.A., 1996a. The Muweilih Conglomerate: Qift-Quseir road region, and the problem of the Atud Formation. Proceedings of Geological Survey, Egypt, Cenn. Conference 23–45

Akaad MK, Noweir AM, Abu El Ela AM (1996b) Geology of the Pan-African basement rocks of the Gabal al Hadid-Wadi Mubarak District, eastern desert, Egypt. Ann Geol Surv Egypt 73:1–78

Akaad MK, Noweir AM, Abu Ela AM, El Bahariya GA (1997) The Um Esh olistostromal mélange, Qift-Quseir region, central Eastern Desert, Egypt. Egypt J Geol 41:465–494

Ali KA, Stern RJ, Manton WI, Kimura J-I, Khamis HA (2009) Geochemistry Nd isotopes and U-Pb SHRIMP zircon dating of Neoproterozoic volcanic rocks from the central Eastern Desert of Egypt: new insight into the ~750 Ma crust-forming event. Precambrian Res 171:1–22

Ali KA, Stern RJ, Manton WI, Johnson PR, Mukherjee SK (2010) Neoproterozoic diamictite in the Eastern Desert of Egypt and northern Saudi Arabia: evidence of ~750 ma glaciations in the Arabian-Nubian shield. Int J Earth Sci 99:705–726

Al-Shanti A M S, Mitchell A H G., 1976. Late Precambrian subduction and collision in the Al Amar-Idsas region, Arabian Shield, Kingdom of Saudi Arabia. Tectonophysics 41–47

Andresen A, Abu El-Rus MA, Myhre PI, Boghdady GY, Coru F (2009) U-Pb TIMS age constraints on the evolution of the Neoproterozoic Meatiq gneiss dome. Eastern Desert, Egypt: International Journal of Earth Science 98:481–497

Arai S (1994) Compositional variation of olivine-chromian spinel in Mg rich magmas as a guide to their residual spinel peridotites. J Volcanol Geotherm Res 59:279–294

Azer MK (2014) Petrological studies of Neoproterozoic serpentinized ultramafics of the Nubian shield: spinel compositions as evidence of the tectonic evolution of Egyptian ophiolites. Acta Geol Pol 64(1):113–127

Azer MK, Stern RJ (2007) Neoproterozoic (835–720 Ma) serpentinites in the Eastern Desert, Egypt: fragments of fore arc mantle. J Geol 115: 457–472

Bailey EH, Irvin WP, Jones DL (1964) Franciscan and related rocks and their significance in the geology of western California. California Division of Mines and Geology Bulletin 183:177

Bakor AR, Gass IG, Neary CR (1976) Jabal al Wask, Northwest Saudi Arabia: an Eocambrian back-arc ophiolite. Earth Planet Sci Lett 30: 1–9

Barnes I, O'Neil JR (1969) The relationship between fluids in some fresh Alpine-type ultramafics and possible modern serpentization, western United States. Geol Soc Am Bull 80:1960–1974

Barnes I, O'Nell JR, Rapp JB, White DE (1973) Silica-carbonate alteration of serpentine: wall rock alteration in mercury deposits of the California coast ranges. Econ Geol 68:388–398

Basta FF, Maurice AE, Bakhit BR, Ali KA, Manton WI (2011) Neoproterozoic contaminated MORB of Wadi Ghadir ophiolite, NE Africa: geochemical and Nd and Sr isotopic constraints. J Afr Earth Sci 59:227–242

Beccaluva L, Ohnenstetter D, Ohnenstetter M, Paupy A (1984) Two magmatic series with island arc affinities within the Vourinos ophiolite. Contrib Mineral Petrol 85(3):253–271

Bloomer, S.H., Taylor, B., Macleod, C.J., Stern, R.J., Fryer, P., Hawkins, J.W., Johnson, L., 1995. Early arc volcanism and the ophiolite problem: a perspective from drilling in the western Pacific, In Taylor, B., and Natland, J., eds., Active margins and marginal basins of the western pacific: geophysical monograph, American Geophysical Union 88, p. 1–30

Bonatti E, Michael PJ (1989) Mantle peridotites from continental rifts to ocean basins to subduction zones. Earth Planet Sci Lett 91:297–311

Bortolotti V, Marroni M, Pandolfi L, Principi G, Saccani E (2002) Interaction between mid-ocean ridge and subduction magmatism in Albanian ophiolites. J Geol 110:561–576

Coleman RG (1984) The diversity of ophiolites. Geol Mijnb 63:141–150

Dick HJB, Bullen T (1984) Chromian spinel as a petrogenetic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contrib Mineral Petrol 86:54–76

Dilek, Y., Ahmed, Z., 2003. Proterozoic ophiolites of the Arabian shield and their significance in Precambrian tectonics. In Dilek, Y & Robinson, P.T. (eds) Ophiolites in Earth History. Geol Soc Lond, Spec Publ 218, 685–700

Dilek Y, Furnes H (2011) Ophiolite genesis and global tectonics: geochemical and tectonic fingerprinting of ancient oceanic lithosphere. Geol Soc Am Bull 123:387–411

Dilek Y, Furnes H (2014) Ophiolites and their origins. Elements 10:93–100

Dilek, Y., Robinson, P.T., 2003. Ophiolites in earth history: introduction. In: Dilek, Y., Robinson, P.T. (Eds.), Geological society, London Special Publications 218, 1–8

Dilek Y, Thy P (2009) Island arc tholeiite to boninitic melt evolution of the cretaceous Kizildag (Turkey) ophiolite: model for multi-stage early arc–forearc magmatism in Tethyan subduction factories. Lithos 113(1–2):68–87

Dilek, Y., Moores, E.M., Elthon, D., Nicolas, A., 2000. Ophiolites and oceanic crust: new insights from Field Stud and the Ocean Drilling Program Geological Society of America Special Paper 349. Boulder, CO, USA p552

El Bahariya, G.A., 1988. Geology of the district southwest of Gabal El Sibai, easterndesert, Egypt. Unpublished M Sc. Thesis, Tanta University, Tanta, 198 pp.

El Bahariya GA (2006) Petrology, mineral chemistry and metamorphism of two pan- African ophiolitic metagabbro occurrences, central Eastern Desert, Egypt. Egypt J Geol 50:183–202

El Bahariya GA (2007) Geology, compositional variation and petrogenesis of possible MORB-type ophiolitic massive and pillowed metabasalts from the Pan-African belt, eastern desert Egypt. Egypt J Geol 51:41–59

El Bahariya GA (2008) Geology, mineral chemistry and petrogenesis of Neoproterozoic metamorphosed ophiolitic ultramafics, central Eastern Desert, Egypt: implications for the classification and origin of the ophiolitic mélange. Egypt J Geol 52:55–82

El Bahariya, G A., 2012**.** Classification and origin of the Neoproterozoic ophiolitic mélange in the Central Eastern Desert of Egypt. n: Dilek, Y , Festa, A., Ogawa, Y. and Pini, G.A. (eds): Chaos and geodynamics: Melanges, Melange forming processes and their significance in the geologic record Special issue “mélanges” Tectonophysics, Part VI ophiolitic mélange, 357–370

El Bahariya, G.A., Arai, S., 2003. Petrology and origin of Pan-African serpentinites with particular reference to chromian spinel composition, Eastern Desert, Egypt: implication for supra-subduction zone ophiolite. The third international conference on the geology of Africa, Assiut, Egypt 1, 371–388

El Bayoumi, R.M.A., Greiling, R.O., 1984, Tectonic evolution of a Pan-African plate margin in southeastern Egypt—a suture zone overprinted by low angle thrusting? *in* Klerkx, J., and Michot, J., eds., African Geology: Tervuren, Belgium, p. 47–56

El Ramly MF, Greiling R, Kröner A, Rashwan AA (1984) On the tectonic evolution of the Wadi Hafafit area and environs, eastern desert of Egypt. Bulletin of King Abdelaziz University 6:113–126

El Sharkawy MA, El Bayoumi RM (1979) The ophiolites of Wadi Ghadir area Eastern Desert. Egypt Annals of the Geological Survey of Egypt IX:125–135

El-Gaby, S., List, F.K., Tehrani, R., 1988, Geology, evolution and metallogenesis of the Pan-African belt in Egypt, *in* El-Gaby, S., and Greiling, R.O., eds., The Pan-African belt of Northeast Africa and adjacent areas: Braun-Schweig (Vieweg); p. 17–68

El-Sayed MM, Furnes H, Mohamed FH (1999) Geochemical constraints on the tectonomagmatic evolution of the late Precambrian Fawakhir ophiolite, central Eastern Desert, Egypt. J Afr Earth Sci 29:515–533

Farahat ES (2010) Neoproterozoic arc–back-arc system in the Central Eastern Desert of Egypt: Evidence from supra-subduction zone ophiolites. Lithos 120:293–308

Floyd, P.A., Kryza, R., Crowley, Q.G., Winchester, J.A., Abdelwahed, M., 2002. Sleza ophiolite: geochemical features and realationship to lower Palaeozoic rift magmatism in the bohemian massif. In: Winchester, J. A., Pharaoh T. C., Verniers, J., (eds.): Palaeozoic amalgamation of Central Europe. Geological Society of London, Special Publication 201, 197–215

Gamal El Dien H, Hamdy M, Abu El-Ela A, Abu-Alam T, Hassan A, Kil Y, Mizukami T, Soda Y (2016) Neoproterozoic serpentinites from the Eastern Desert of Egypt: insights into Neoproterozoic mantle geodynamics and processes beneath the Arabian-Nubian shield. Precambrian Res 286:213–233

Garson, M.S., Shalaby, I.M., 1976, Pre-cambrian–lower Paleozoic plate tectonics and metallogenesis in the Red Sea region: geological Association of Canada, special paper, 14, 573–596

Harper GD (1984) The Josephine ophiolite, northwestern California. Geol Soc Am Bull 95:1009–1026

Hoeck V, Koller F, Meisel T, Onuzi K, Kneringer E (2002) The Jurassic south Albanian ophiolites: MOR- vs. SSZ-type ophiolites. Lithos 65:143–164

Ishikawa T, Nagaishi K, Umino S (2002) Boninitic volcanism in the Oman ophiolite: implications for thermal condition during transition from spreading ridge to arc. Geology 30:899–902

Johnson, P.R., Kattan, F.H., Al-Saleh, A.M., 2004. Neoproterozoic ophiolites in the Arabian shield: field relations and structure. In: Kusky, T.M. (Ed.), Precambrian ophiolites and related rocks. Developments in Precambrian Geology 13, 129–162

Jones JG., 1969. Pillow lavas as depth indicators. Am J Sci 267:181–195

Kamenetsky VS, Crawford AJ, Meffre S (2001) Factors controlling chemistry of magmatic spinel: an empirical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. J Petrol 42(4):655–671

Khalil AES, Azer MK (2007) Supra-subduction affinity in the Neoproterozoic serpentinites in the Eastern Desert, Egypt: evidence from mineral composition. J Afr Earth Sci 49:136–152

Khedr MZ, Arai S (2013) Origin of Neoproterozoic ophiolitic peridotites in south Eastern Desert, Egypt, constrained from primary mantle mineral chemistry. Mineral Petrol 107(5):807–828

Kröner A (1985) Ophiolites and the evolution of tectonic boundaries in the late Proterozoic Arabian–Nubian shield of Northeast Africa and Arabia. Precambrian Res 27:277–300

Kröner A, Greiling RO, Reischmann T, Hussein IM, Stern RJ, Durr S, Kruger J, Zimmer M (1987) Pan-African crustal evolution in the Nubian segment of northeast Africa. In: Kr ner A (ed) Proterozoic lithospheric evolution. American Geophysical Union, Geodynamics Series 17, Washington, DC, pp 237–257

Kröner A, Greiling RO, Reischmann T, Hussein IM, Stern RJ, Durr S, Kruger J, Kröner A, Todt W, Hussein IM, Mansour M, Rashwan AA (1992) Dating of late Proterozoic ophiolites in Egypt and Sudan using the single grain zircon evaporation techniques. Precambrian Res 59:15–32

Kusky, T.M., 2004. Precambrian ophiolites and related rocks. Developments in Precambrian Geology, 13, Edited by T.M. Kusky, Elsevier, p. 748

Kusky TM, Abdelsalam M, Tucker RD, Stern RJ (2003) Preface to special issue Precambrian research on the east African and related Orogens and the Assembly of Gondwana. Precambrian Res 123(2–4):81–85

Kusky TM, Wang LUDY, Robinson P, Peng Songbai P, Xuya H (2011) Application of the modern ophiolite concept with special reference to Precambrian ophiolites. Sci China Earth Sci 54(3):315–341

Moore JG (1965) Petrology of deep-sea basalt near Hawaii. Am J Sci 263:40–52

Moore JG (1979) Vesicularity and CO_2 in mid-ocean ridge basalts. Nature 282:250–253

Nasseef AO, Bakor AR, Hashad AH (1980) Petrography of possible ophiolitic rocks along the Qift-Qusier road. Eastern Desert, Egypt: Bulletin of King Abdelaziz University 3:157–168

Noweir, A.M., 1968. Geology of the Hammamat-Um Seleimat district, Eastern Desert, Egypt. Ph.D., Thesis, Assiut University p. 670

Pallister JS, Stacey JS, Fischer LB, Premo WR (1988) Precambrian ophiolites of Arabia: geologic settings, U-Pb geochronology, Pb-isotope characteristics, and implications for continental accretion. Precambrian Res 38:1–54

Pearce, J.A., 2003. Supra-subduction zone ophiolites: in: Dilek, Y., Newcomb, S. (Eds.), ophiolite concept and the evolution geological thought Bouder, Colorado. Geological Society of America Special Paper 373, 269–293

Pearce, J.A., Lippard, S.J., Roberts, S., 1984. Characteristics and tectonic significance of supra subduction zone ophiolites. In: Kokelaar, B.P., Howells, M.F. (Eds.), Marginal Basin Geology: Geological Society Special Publication 16, 77–94

Pearce JA, Barker PF, Edwards SJ, Parkinson IJ, Leat PT (2000) Geochemistry and tectonic significance of peridotites from the south sandwich arc-basin system, South Atlantic. Contrib Mineral Petrol 139(1):36–53

Ries RM, Shackleton RM, Graham RH, Fitches WH (1983) Pan-African structures, ophiolites and mélange in the Eastern Desert of Egypt: a traverse at 26^{o} N. J Geol Soc Lond 140:75–95

Saunders, A. D., Tarney, J., Marsh, N. G., Wood, D. A., 1980. Ophiolites as ocean crust or marginal basin crust: a geochemical approach, In Panayiotou, A. (ed.), Ophiolites-Proceedings of the International Ophiolite Symposium, Cyprus 193–204

Serri G (1981) The petrochemistry of ophiolitic gabbroic complexes: a key for the classification of ophiolites into low-Ti and high-Ti types. Earth Planet Sci Lett 52:203–212

Shackleton RM, Ries RM, Graham RH, Fitches WH (1980) Late Precambrian ophiolitic mélange in the Eastern Desert of Egypt. Nature (London) 285:472–474

Shervais JW (1982) Ti-V plots and the petrogenesis of modern and ophiolitic lavas. Earth Planet Sci Lett 59:101–118

Stern RJ (1994) Arc assembly and continental collision in the Neoproterozoic east African Orogen: implications for the consolidation of Gondwanaland. Annu Rev Earth Planet Sci 22:319–351

Stern RJ (2002) Crustal evolution in the east African Orogen: a neodymium isotopic perspective. J Afr Earth Sci 34:109–117

Stern, R. J.; Johnson, P. R.; Kröner, A., Yibas, B. 2004. Neoproterozoic ophiolites of the Arabian-Nubian shield. In Kusky, T M, ed Precambrian ophiolites and related rocks. Precambrian Geology 13, 95–128

Stern RJ, Avigad D, Miller NR, Beyth M (2006) Evidence for the snowball earth hypothesis in the Arabiannubian shield and the east African orogen. J Afr Earth Sci 44:1–20

Stoeser DB, Camp V (1985) Pan-African microplate accretion of the Arabian shield. Geol Soc Am Bull 96:817–826

Stoeser DB, Frost CD (2006) Nd, Pb, Sr, and O isotopic characterization of Saudi Arabian shield terranes. Chem Geol 226:163–188

Sultan M, Arvidson RE, Duncan IJ, Stern RJ, El Kaliouby BE (1988) Extension of the Najd shear system from Saudi Arabia to the central Eastern Desert of Egypt based on integrated field and land sat observations. Tectonophysics 7:1291–1306

Wakabayashi, J., Dilek, Y., 2003. What constitutes “emplacement” of an ophiolite?: mechanisms and relationship to subduction initiation and formation of metamorphic soles, in Dilek, Y and Robinson, PT, eds, Ophiolites in Earth History: Geological Society, London, Special Publication 218, 427–447

Yibas B, Reimold WU, Anhaeusser CR, Koeberl C (2003) Geochemistry of the mafic rocks of the ophiolitic fold and thrust belts of southern Ethiopia: constraints on the tectonic regime during the Neoproterozoic (900–700 Ma). Precambrian Res 121:157–183

Yong IL (1999) Geotectonic significance of detrital chromian spinel: a review. Geosci J 3(1):23–29

Zimmer M, Kröner A, Jochum KP, Reischmann T, Todt W (1995) The Gabal Gerf complex: a Precambrian N-MORB ophiolite in the Nubian shield, NE Africa. Chem Geol 123:29–51