Acta Geologica Polonica, Vol. 64 (2014), No. 1, pp. 113–127
DOI: 10.2478/agp-2014-0006

DE GRUYTER OPEN

Petrological studies of Neoproterozoic serpentinized ultramafics of the Nubian Shield: spinel compositions as evidence of the tectonic evolution of Egyptian ophiolites

MOKHLES K. AZER

Geology Department, National Research Centre, 12622-Dokki, Cairo, Egypt.
Email: mokhles72@yahoo.com

ABSTRACT:

Azer, M.K. 2014. Petrological studies of Neoproterozoic serpentinized ultramafics of the Nubian Shield: spinel compositions as evidence of the tectonic evolution of Egyptian ophiolites. *Acta Geologica Polonica*, **64** (1), 113–127. Warszawa.

The mafic-ultramafic rocks of the Gabal El-Degheimi area, Central Eastern Desert of Egypt, are parts of an ophiolitic section. The ophiolitic rocks are dismembered and tectonically enclosed within, or thrust over, island arc assemblages. Serpentinites, altered slices of the upper mantle, represent a distinctive lithology of the dismembered ophiolites. Some portions of the serpentinized rocks contain fresh relicts of primary minerals such as chromian spinel and olivine. The abundance of bastite and mesh textures suggests harzburgite and dunite protoliths, respectively, for these serpentinites. Some fresh cores of chromian spinel are rimmed by ferritchromite and Cr-magnetite. The development of alteration rims around chromian spinel cores indicates their formation during prograde alteration and under oxidizing conditions during lower amphibolite facies metamorphism. Fresh chromian spinels are characterized by high contents of Cr_2O_3 (48.92–56.74 wt. %), Al_2O_3 (10.29–20.08wt. %), FeO (16.24–28.46 wt. %) and MgO (4.89–14.02 wt. %), and very low TiO_2 contents (<0.16 wt. %). The analyzed fresh chromian spinels have high Cr# (0.62–0.79) characteristic of spinels in mantle peridotite that has undergone some degree of partial melting. The data presented here suggest that the mantle peridotites of the Gabal El-Degheimi area are similar to fore-arc peridotites of suprasubduction zone environments.

Keywords: Neoproterozoic; Serpentinite; Arabian-Nubian Shield; Chromian spinel; Fore-arc.

INTRODUCTION

The basement rocks of Egypt form the western part of the Arabian–Nubian shield (ANS). The ANS is the northern continuation of the Mozambique belt, and together, they have been referred to as the East African Orogen (Stern 1994). The ANS represents an excellent example of the Pan-African orogenic cycle, which has long been recognized as a period of major crustal accretion (Gass 1981; Kröner 1984; Kröner *et al*. 1991; Reischmann and Kröner 1994; Kusky *et al*. 2003). The ANS may represent the largest tract of juvenile continental crust of Neoproterozoic age on Earth (Patchett and Chase 2002). Ophiolites are key components of the ANS and are mostly nappes forming distinct belts between arc sequences and older cratons and microcontinents (Abdelsalam and Stern 1996). The ophiolitic rocks of the ANS are not all of the same age and formed over wide period of time (e.g. Kröner *et al.* 1992; Shackleton 1994; Zimmer *et al.* 1995; Loizenbauer *et al*. 2001; Ali *et al*. 2010). They have isotopic ages range from 890 to 690 Ma, documenting a 200 Ma year period of oceanic magmatism. All ANS ophiolites are strongly deformed, metamorphosed, and altered by silicification and carbonatization. Serpentinized ultramafics are a distinctive lithology of the dismembered ANS ophiolites and mélanges.

The ophiolites and ophiolitic mélanges are a distinctive part of the basement rocks of Egypt. They can provide important clues about the origin and evolution of the ANS. Nevertheless, the significance of the Egyptian ophiolites is controversial because they are variably dismembered, deformed, and altered. Serpentinized ultramafic rocks are the most important and distinctive lithology. Geological studies of the Eastern Desert ophiolites vary in quality and quantity. In the past, studies of the Egyptian ophiolites have focused on volcanic rocks for evaluating their tectonic setting and petrogenesis. The ophiolitic peridotites have been largely ignored until recently (Azer and Khalil 2005; Azer and Stern 2007; Farahat 2008; Hamdy *et al*. 2013; Khedr and Arai 2013), although the mantle peridotites provide complementary information about the petrogenesis and tectonic setting of the ophiolitic rocks.

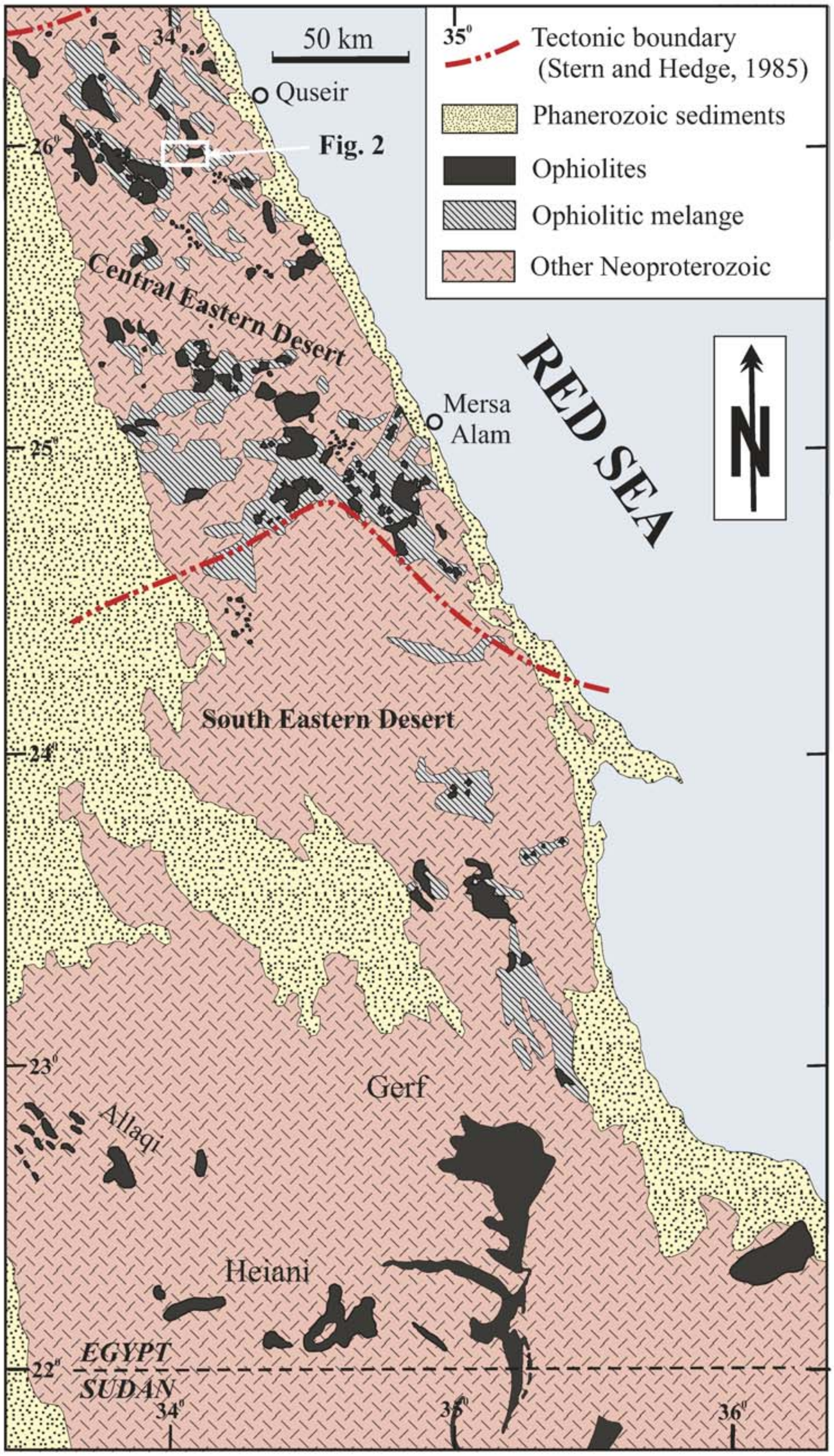
It is noteworthy that the ophiolitic peridotites in the Eastern Desert of Egypt are highly serpentinized and their primary silicates and primary textures have been altered during serpentinization. However, fresh relicts of chromian spinels and olivines are present in the Gabal El-Degheimi serpentinites. The primary chromian spinels can be used to infer the origin and tectonic setting of the serpentinites due to their ability to survive alteration and metamorphism. Here, I provide the first description of the different textures and mineral compositions of chromian spinels, produced under mantle conditions, from serpentinites of the Neoproterozoic ophiolites in the Gabal El-Degheimi area. Also, the compositions of the primary chromian spinels are used to deduce the petrogenesis and tectonic environments for the serpentinites.

REGIONAL GEOLOGY

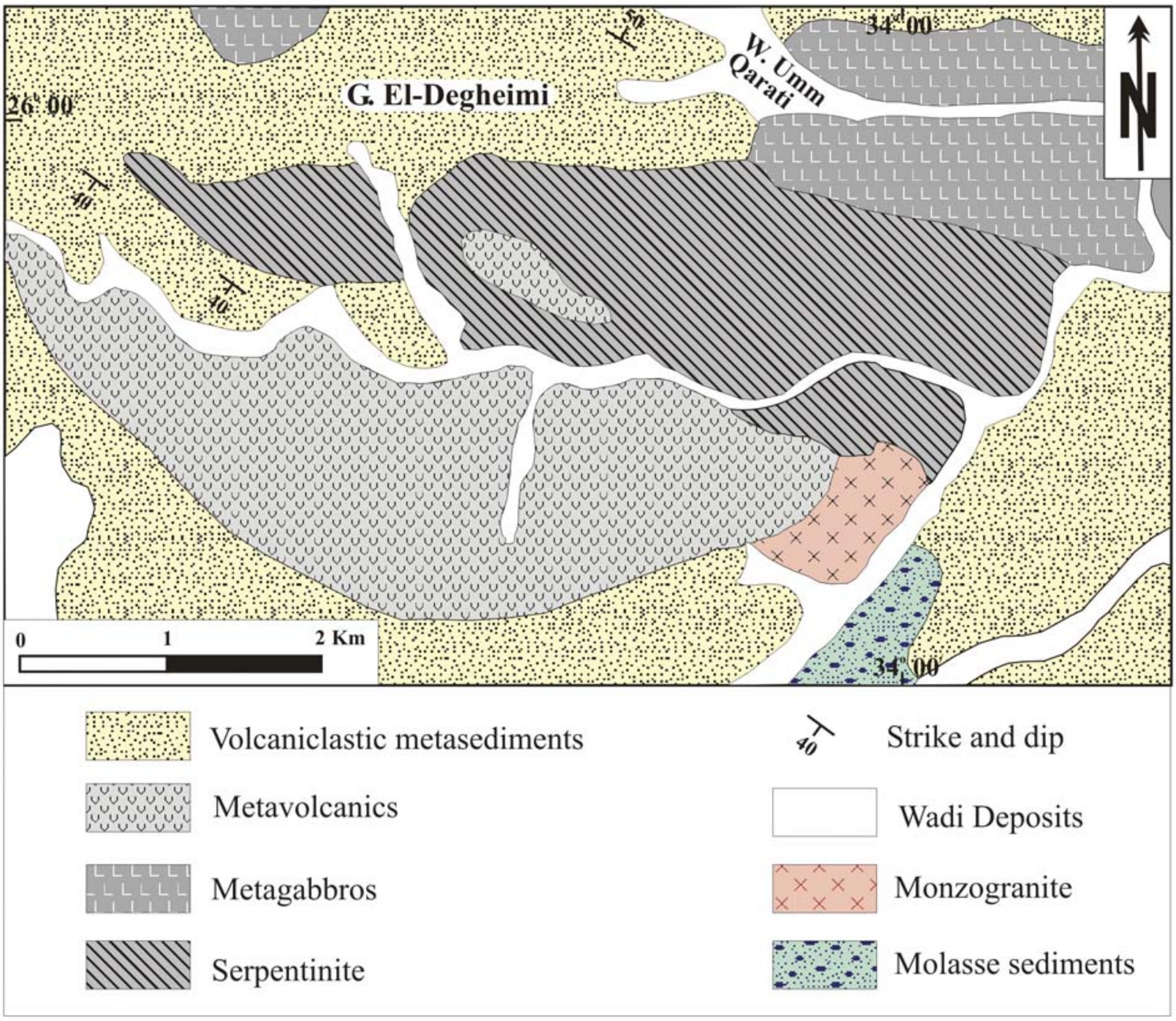
Neoproterozoic mafic-ultramafic complexes constitute one of the distinctive rock units in the Precambrian belt of Egypt. They have different ages and tectonomagmatic evolution and are differentiated into two main groups; thrust ophiolites and intrusions. The thrust ophiolites are generally dismembered, representing remnants of oceanic lithosphere that coexisted with the ANS Neoproterozoic intra-oceanic arcs. The intrusive mafic-ultramafic complexes form undeformed, small, elliptical outcrops and are commonly concentrically zoned or layered intrusions as well as dyke-like intrusions (Helmy and El Mahallawi 2003; Farahat and Helmy 2006; Azer and Gharbawy 2011; Azer *et al.* 2012). Neoproterozoic ophiolites are common in the central and southern sectors of the Eastern Desert of Egypt (Text-fig. 1), where they occur as tectonized bodies and mélanges of pillowed metabasalt, metagabbro, and variably altered ultramafic rocks (El Sharkawy and El Bayoumi 1979). The latter are mostly serpentinites with relicts of fresh ultramafic protoliths, but include abundant quartz-carbonates (listwaenite) and talc-carbonates (Osman 1995; Johnson *et al*. 2004; Zoheir and Lehmann 2011; Azer 2013).

In the Central Eastern Desert of Egypt, several isolated serpentinized ultramafic bodies occur and have been considered as remnants of ophiolites. Few previous studies have been carried out on the ophiolitic rocks of Gabal El-Degheimi area (Akaad and Abu El-Ela 2002; Abdel Karim *et al*. 2008), which comprises ophiolitic rocks, metavolcanic and volcaniclastic metasedimentary rocks of an island arc association, molasse sediments (Igla Formation) and monzogranite (Text-fig. 2). The ophiolites represent the oldest rock units in the mapped area (Akaad and Noweir 1980; Abdel-Karim *et al*. 2008). They are dismembered and include completely serpentinized peridotite, talc-carbonates, metagabbros and amphibolites. Serpentinites and metagabbros are tectonically enclosed within, or thrust over, the island arc assemblage. The metavolcanics of the island-arc association are represented mainly by calc-alkaline meta-andesite with minor metadacite and their pyroclastics; the volcaniclastic metasediments include metagreywackes, metamudstones, metasiltstones and metaconglomerates.

The serpentinites in Gabal El-Degheimi area form an elongated mass (6.3 km long, striking E-W) that is dissected by small wadis. In the eastern part of the mapped area the serpentinite is thrust over metagabbros and intruded by monzogranite. Trachyte plugs intrude the serpentinite in its western part. The trachyte plugs cannot be displayed in the map area at the present scale because they are very small. The serpentinite is generally massive, but becomes sheared and foliated along shear zones. It shows extreme alteration along thrust and shear zones into talc-carbonate rocks or quartz-carbonate rocks (listwaenite). The alteration products occur as scattered patches or sheet-like bodies along shear zones and fault planes. Calcite and magnesite veinlets cut through serpentinite.



Text-fig. 1. Distribution of ophiolitic rocks in the Eastern Desert of Egypt (modified after Shackleton 1994). The location of Figure 2 is indicated

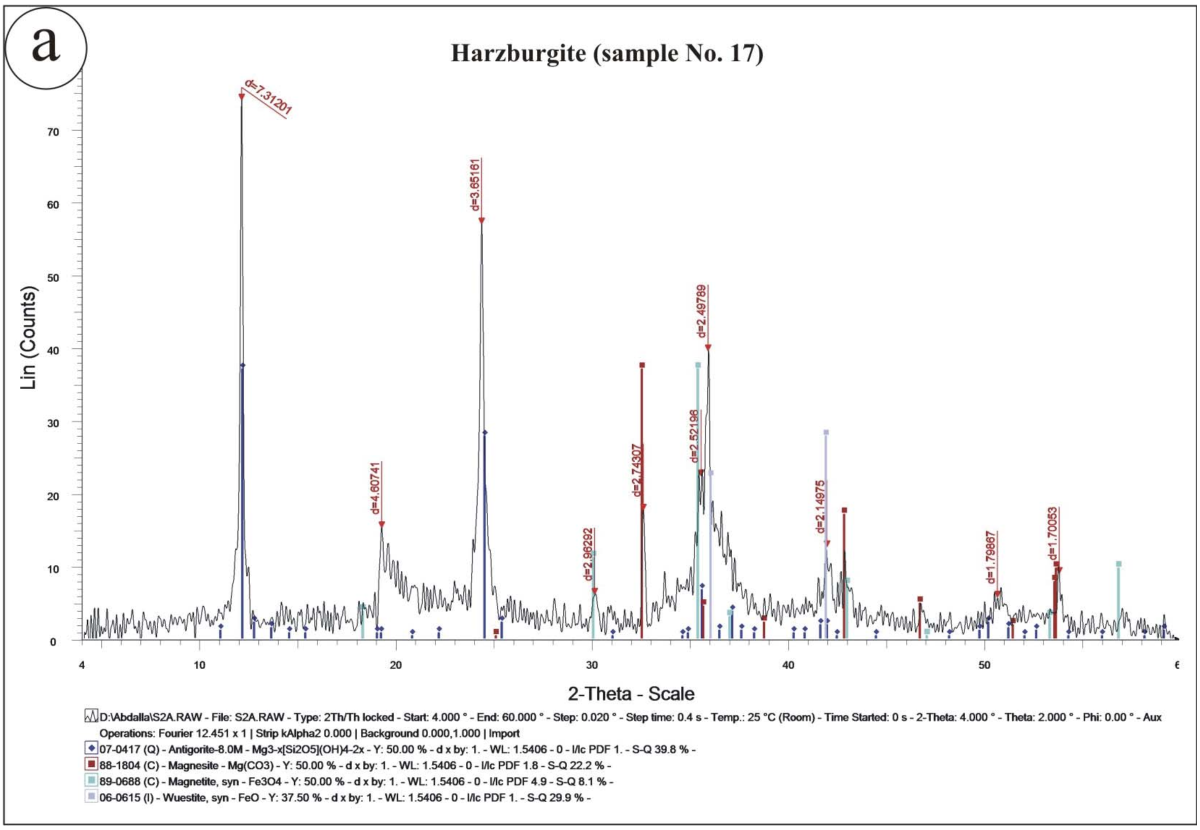


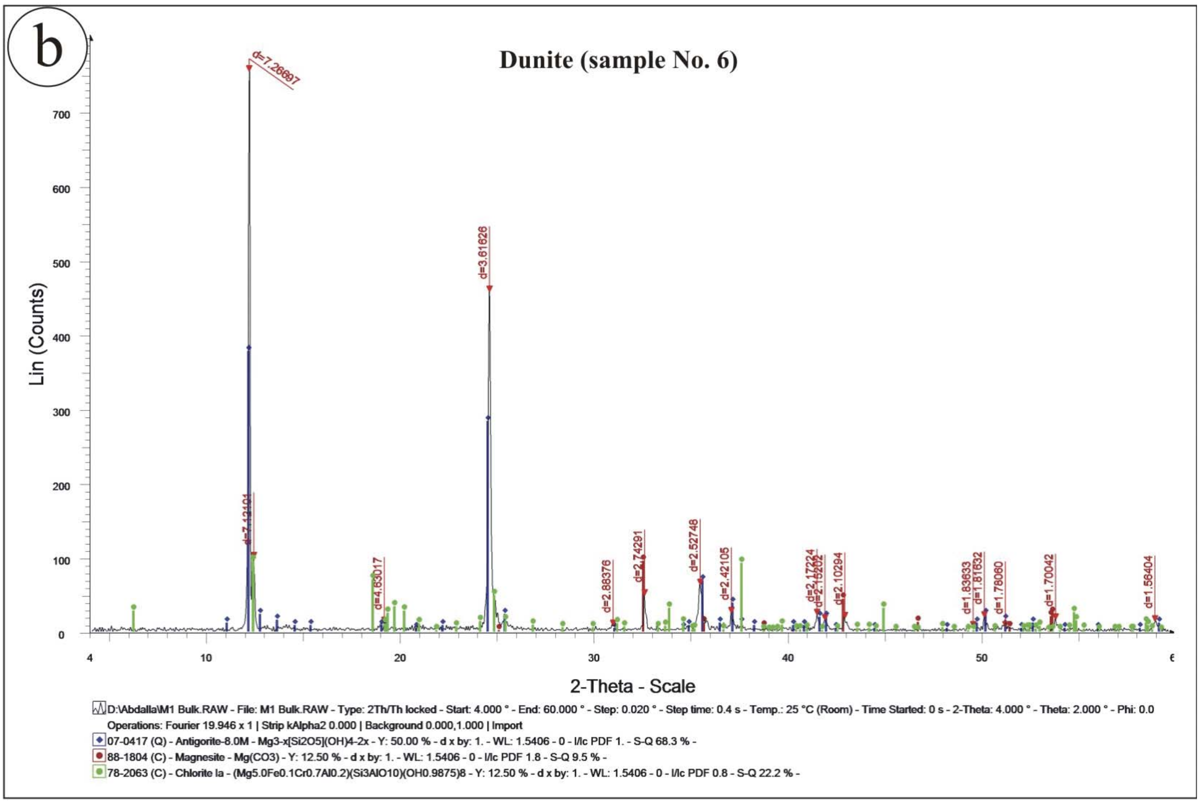
Text-fig. 2. Detailed geological map of the Gabal El-Degheimi area (after Akaad and Abu El Ela 2002)

PETROGRAPHY

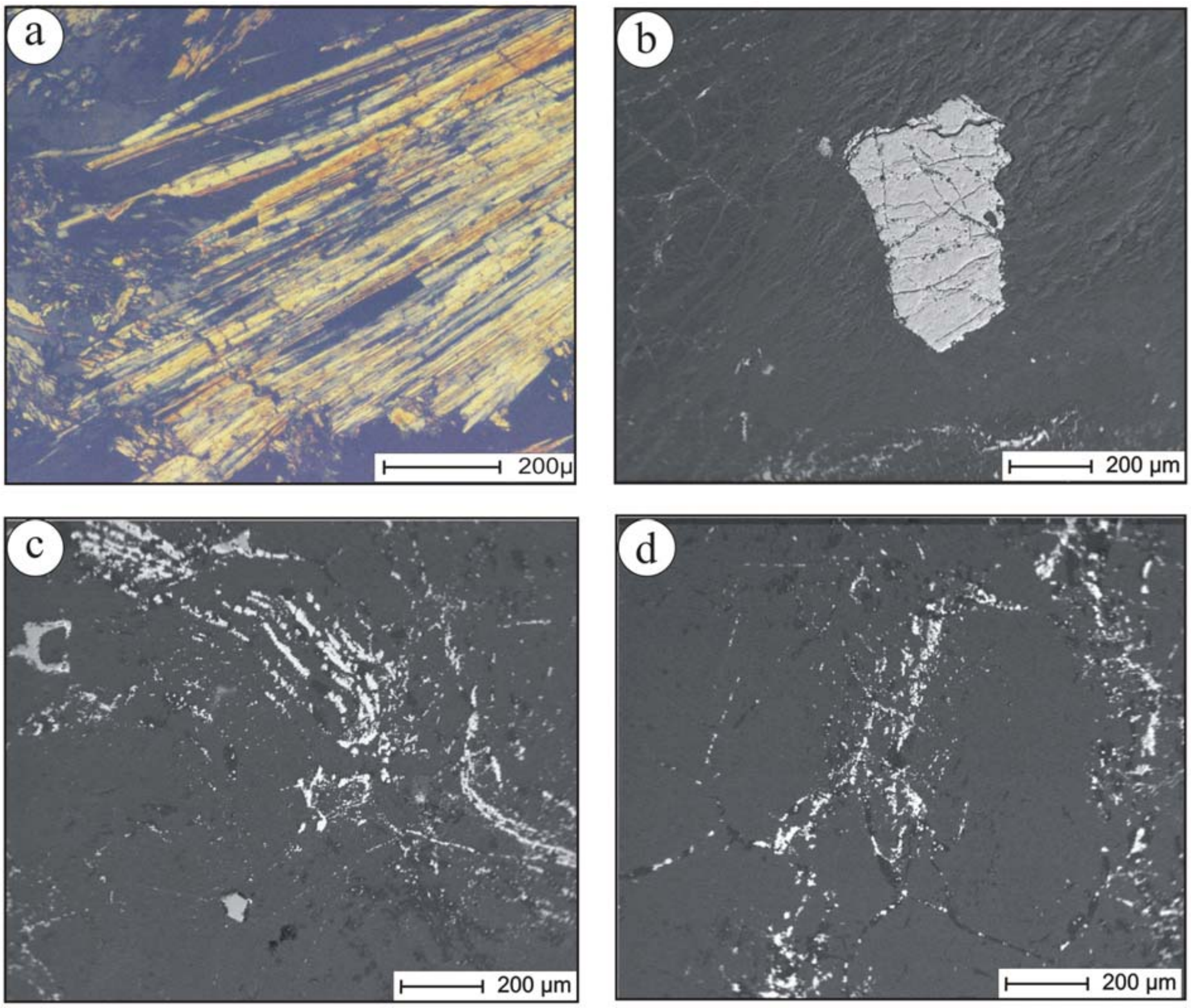
Petrographic studies were carried out on both thin and polished sections of the serpentinites. The mineral contents were determined by X-ray powder diffraction (XRD) and optical microscopy. The powder diffraction patterns of the samples were obtained with Cu radiation with secondary monochrometer. The scanning speed was $2\theta = 1$deg/min at constant voltage 40kV and 40mA using a BRUKER D8 advanced X-ray diffractometer at the central Metallurgical and Development Institute in Cairo, Egypt. Mineral identification was carried out using the data given in the American Standard Test Materials (ASTM) cards by measuring the d-values of the different atomic planes and their relative intensities. Representative XRD charts are given in Text-fig. 3.

All investigated ultramafic samples are almost completely serpentinized peridotites. They consist of serpentine minerals (>90 of the rock), brucite, chlorite, tremolite, talc, opaque minerals and carbonates together with fresh relics of olivine and chromian spinel. Petrographic and x-ray diffractogram studies indicate that the serpentine minerals are represented mainly by antigorite (Text-fig. 3a, b) with lesser amounts of lizardite. Antigorite occurs as platy aggregates with characteristic plumose texture. Lizardite is rare and occurs as elongated crystals forming a bundle-like form. The presence of bastite and mesh textures can be used to indicate harzburgite and dunite protoliths, respectively. Fresh olivine crystals are rare and form anhedral cracked crystals dissected by network veins of serpentine, forming interlocking textures. Carbonates occur as sparse crystals, patches and fine aggregates. Brucite appears as platy or fibrous crystals intermixed with serpentines as well as veinlets. A few chlorite flakes are commonly found around altered chromian spinel grains. Near the contact with monzogranite, an-





Text-fig. 3. a – Chart of X-ray diffraction analysis in the serpentinized harzburgite, and b – Chart of X-ray diffraction analysis in the serpentinized dunite



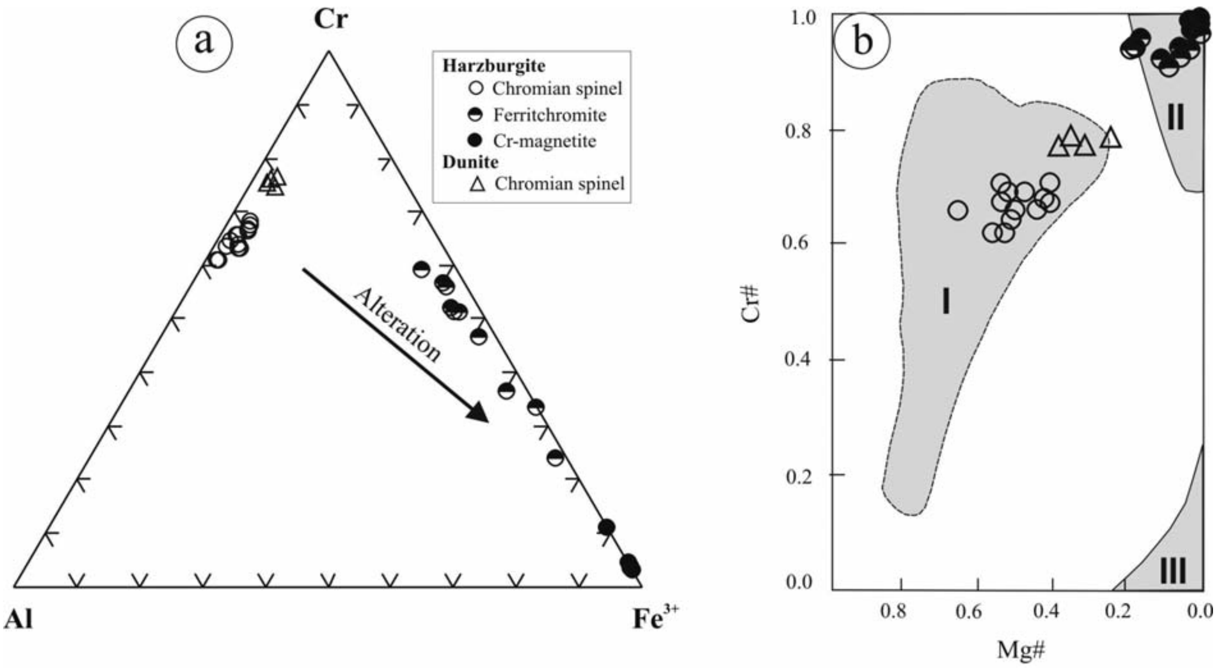
Text-fig. 4. a – long needles of anthophyllite near the contact with monzogranite (under crossed nichols), b – Backscattered-electron (BSE) image showing disseminated chromian spinel in the serpentinites, c – BSE image showing thin magnetite streaks and striations disposed along the cleavage planes of original orthopyroxene, and d – BSE image showing fine magnetite clusters surrounding olivine crystals

thophyllite and tremolite are observed within the serpentinites. Anthophyllite occurs as long thin needles (Text-fig. 4a), while tremolite exists as acicular bundles within antigorite serpentine groundmass.

Ore microscopy revealed that the serpentinites of Gabal El-Degheimi are poor in opaque minerals (4–5 % modally). They are mainly chromian spinels and magnetite as well as minor specks of pyrite. Chromian spinel occurs as disseminated subhedral crystals (Text-fig. 4b) and/or irregular grains of reddish brown colour in thin section, whilst in reflected light it is rimmed by magnetite with numerous interstices filled with serpentine minerals. Some chromian spinel crystals are zoned, or sometimes completely replaced by ferritchromite and/or Cr- magnetite. Magnetite occurs as disseminated crystals or veins cutting chromian spinel and to a lesser extent as very thin magnetite streaks and striations along cleavage planes in original orthopyroxene (Text-fig. 4c) or as fine opaque clusters surrounding olivine crystals (Text-fig. 4d). A few disseminated specks of pyrite are observed within the serpentinites, especially along shear zones.

MINERAL CHEMISTRY

The chemical compositions of chromian spinels were determined using an electron microprobe under operating conditions of 15 kV and 20 nA. Suitable synthetic and natural mineral standards were applied. The analyses were carried out at the Geology and Metallogeny Laboratory, Orléans, France. Chromites were



Text-fig. 5. a – Cr–Al–Fe^{3+} plot of chromian spinels and their alteration products, and b – Mg# vs. Cr# variation diagram (fields after Roeder 1994 and Mondal *et al.* 2001). Field I: Cr-spinels in mantle peridotites, field II: magnetite from metamorphic rocks, field III: magnetite from unmetamorphosed igneous rocks

analyzed in three samples (2 harzburgites and 1 dunite). Representative analyses of chromian spinels and its alteration products are presented in Table 1. Some chromian spinels display zoning from fresh chromian spinel cores to ferritchromite and Cr-magnetite rims, especially in the harzburgite. In the present study, only the unaltered chromian spinels of harzburgite and dunite have been used as petrogenetic indicators.

The fresh chromian spinels in the harzburgite have high contents of Cr_2O_3 (48.92–52.79 wt.%) and very low TiO_2 contents (<0.16 wt.%). They exhibit wide ranges of Al_2O_3 (14.69–20.08 wt.%), FeO (16.24–23.73 wt.%) and MgO (8.30–14.02 wt.%). In contrast, the chromian spinels in the dunite show limited compositional variation and are rich in Cr_2O_3 (54.92–56.74 wt.%) and FeO (23.03–28-28.46 wt.%) and depleted in Al_2O_3 (10.29–11.12 wt.%) compared to the chromian spinels in harzburgite. The harzburgite chromian spinels show either a continuous transition from Al- and Cr-rich cores towards rims enriched in Fe and Cr, or display an abrupt compositional change from chromian spinel cores to ferritchromite and Cr-magnetite (Table 1). Fresh chromian spinels in the harzburgite have lower Cr# (0.62 to 0.71) than the chromian spinels of dunite (Cr#: 0.77–0.79). On the other hand, the chromian spinels of harzburgite have high Mg# (0.41–0.66) than the chromian spinels of dunite (Mg#: 0.25–0.39). Ferritchromite is enriched in total iron and strongly depleted in Al_2O_3 and MgO. Furthermore, it is richer in MnO (1.0–1.46 wt. %) than chromian spinel (0.29–0.77 wt.%) and Cr-magnetite (0.07–0.09 wt.%).

The variability in chromite compositions from both fresh and altered rims is clearly shown on an Al–Cr–Fe^{3+} triangular plot (Text-fig. 5a). The altered phases (ferritchromite and Cr-magnetite) in the harzburgite plot along the Cr–Fe^{3+} join, reflecting the loss in Al_2O_3 and Cr_2O_3 and increase in Fe_2O_3 due to alteration and metamorphism. Meanwhile, the fresh chromian spinels in harzburgite and dunite lie along the Cr–Al join. All the fresh chromian spinels have Cr# and Mg# similar to those of mantle peridotites, while rims are similar to metamorphic spinel (Text-fig. 5b).

DISCUSSION

Ophiolitic rocks of Egypt have long been the subject of research because they represent important elements in the reconstruction of the geodynamic evolution of the Pan-African belt. Assessments of the tectonic setting of the Egyptian ophiolites have focussed mostly on the trace element composition of lavas and have rarely considered the abundant serpentinites. However, interpreting the tectonic setting of Neoproterozoic ophiolitic rocks on the basis of the bulk composition of metavolcanic rocks encounters difficulties due to the effects of fractional crystalliza-

Rock type	Harzburgite																
Sample No	17																
Spot no.	Single crystals			C1	R1a	R1b	C3	R3a	R3b	C4	R4a	R4b	C5	R5	C6	R6a	R6b
	#2	#15	#3	#6	#7	#8	#18	#19	#20	#31	#32	#28	#7	#8	#9	#10	#11
SiO_2	0.045	0.016	0,002	0.015	0.175	0.218	0	0.03	0.015	0.02	0.028	0.219	0.015	0.091	0	0.004	0.034
TiO_2	0.12	0.131	0,1	0.105	0.085	0.197	0.145	0.303	0.025	0.125	0.067	0.095	0.066	0.097	0.16	0.105	0.091
$Al2O_3$	16.61	18.255	15,347	17.39	1.41	1.293	19.95	0.036	0.015	17.245	2.045	1.631	14.725	0.785	20.08	0.047	0.044
Cr_2O_3	51.295	49.983	51,908	50.515	39.375	31.569	48.96	22.773	2.055	50.235	36.315	35.655	51.889	16.272	48.921	7.389	2.315
FeO	19.035	19.38	21,625	16.24	52.82	62.016	19.14	72.232	89.41	19.67	57.185	56.08	23.729	78.054	17.815	86.768	88.61
MnO	0.285	0.315	0,401	0.311	1.235	1.461	0.31	1.94	0.07	0.362	1.001	1.265	0.558	1.187	0.325	1.115	0.09
MgO	11.24	10.816	9,943	14.02	3.425	1.152	11.375	0.506	0.04	10.44	2.045	3.405	8.302	0.642	12.005	0.159	0.15
CaO	0.01	0.02	0,007	0.012	0	0.008	0.025	0.006	0.01	0.015	0.005	0.005	0.009	0.014	0.014	0.011	0
Total	98.64	98.916	99.333	98.608	98.525	97.914	99.905	97.826	91.64	98.112	98.691	98.355	99.293	97.142	99.32	95.787	91.334
Si	0.012	0.004	0.001	0.004	0.050	0.064	0.000	0.009	0.005	0.005	0.009	0.063	0.004	0.027	0.000	0.001	0.011
Ti	0.023	0.025	0.020	0.020	0.018	0.044	0.027	0.067	0.006	0.024	0.015	0.021	0.013	0.021	0.030	0.024	0.022
Al	5.041	5.507	4.695	5.162	0.478	0.447	5.904	0.013	0.006	5.274	0.698	0.552	4.570	0.273	5.944	0.017	0.016
Cr	10.444	10.1 15	10.653	10.058	8.963	7.334	9.719	5.317	0.509	10.306	8.310	8.107	10.802	3.804	9.715	1.758	0.575
$Fe^{3=}$	0.445	0.320	0.612	0.733	6.420	8.002	0.322	10.518	15.464	0.361	6.945	7.173	0.594	11.826	0.280	14.175	15.344
$Fe^{(ii)}$	3.654	3.828	4.082	2.687	6.297	7.237	3.697	7.321	7.970	3.907	6.895	6.314	4.631	7.463	3.462	7.666	7.938
Mn	0.062	0.068	0.088	0.066	0.301	0.364	0.066	0.485	0.019	0.080	0.245	0.308	0.124	0.297	0.069	0.284	0.024
Mg	4.316	4.127	3.848	5.264	1.470	0.504	4.258	0.223	0.019	4.039	0.882	1.460	3.259	0.283	4.496	0.071	0.070
Ca	0.003	0.005	0.002	0.003	0.000	0.003	0.007	0.002	0.003	0.004	0,002	0.002	0.003	0.005	0.004	0.004	0.000
Cr#	0.67	0.65	0.69	0.66	0.95	0.94	0.62	1.00	0.99	0.66	0.92	0.94	0.70	0.93	0.62	0.99	0.97
Mg#	0.54	0.52	0.49	0.66	0.19	0.07	0.54	0.03	0.00	0.51	0.1 1	0.19	0.41	0.04	0.56	0.01	0.01

C = Core

R = Rim

Table 1. Chemical composition of accessory chromain spinels from serpentinites of Gabal El-Degheimi area.

Rock type	Harzburgite											Dunite			
Sample No	25											6			
Spot no.	Single crystal	C1	R1	C2	R2a	R2b	C3	R3a	R3b	C4	R4	Single crystals			
	#2	#25	#26	#4	#5	#6	#8	#9	#10	#29	#30	#1	#6	#12	#23
SiO_2	0.001	0.008	0.18	0.018	0.178	0.073	0.023	0.408	0.175	0.017	0.177	0.002	0.01	0	0.005
TiO_2	0.1025	0.1055	0.075	0.062	0.088	0.043	0.035	0.093	0.015	0.044	0.072	0.06	0.092	0.08	0.04
Al_2O_3	15.408	14.687	1.755	16.781	1.522	0.023	16.255	2.548	0.015	17.107	1.555	10.867	10.289	11.12	10.615
Cr_2O_3	52.111	52.788	35.84	49.706	25.175	2.446	50.891	40.365	2.97	49.23	39.852	55.265	56.741	55.615	54.915
FeO	20.437	19.201	56.225	23.639	69.341	91.143	23.216	51.751	90.41	22.889	52.43	25.739	24.689	23.025	28.455
MnO	0.392	0.304	1.165	0.577	1.262	0.073	0.765	1.021	0.064	0.546	1.199	0.485	0.565	0.485	0.485
MgO	10.804	11.103	3.295	8.553	1.126	0.135	8.406	1.743	0.215	9.207	3.651	6.24	7.206	7.59	4.89
CaO	0.013	0.016	0.005	0.0101	0.018	0.003	0.018	0.012	0	0.005	0	0.007	0.014	0.015	0
Total	99.2685	98.2125	98.54	99.3461	98.877	93.939	99.661	98.019	93.864	99.104	98.936	98.665	99.642	97.93	99.405
Si	0.000	0.002	0.052	0.005	0,052	0.022	0.006	0.119	0.053	0.004	0.052	0.001	0.003	0.000	0.001
Ti	0.020	0.021	0.017	0.012	0,019	0.010	0.007	0.020	0.003	0.009	0.015	0.012	0.019	0.016	0.008
Al	4.687	4.515	0.592	5.150	0.521	0.008	4.995	0.877	0.005	5.233	0.524	3.492	3.272	3.560	3.427
Cr	10.634	10.885	8.139	10.234	5.777	0.591	10.490	9.324	0.718	10.102	9.016	11.914	12.104	11.942	11.893
Fe^{3+}	0.638	0.554	7.131	0.582	9.561	15.336	0.490	5.519	15.163	0.639	6.326	0.568	0.581	0.465	0.660
Fe^{2+}	3.773	3.634	6.373	4.566	7.268	7.951	4.572	7.124	7.942	4.329	6.221	5.301	4.990	4.764	5.858
Mn	0.086	0.067	0.283	0.127	0.310	0.019	0.169	0.253	0.017	0.120	0.288	0.112	0.129	0.112	0.113
Mg	4.158	4.318	1.411	3.321	0.487	0.061	3.267	0.759	0.098	3.563	1.557	2.537	2.899	3.073	1.997
Ca	0.004	0.004	0.002	0.003	0.006	0.001	0.005	0.004	0.000	0.001	0.000	0.002	0.004	0.004	0.000
Cr#	0.69	0.71	0.93	0.67	0.92	0.99	0.68	0.91	0.99	0.66	0.95	0.77	0.79	0.77	0.78
Mg#	0.52	0.54	0.18	0.42	0.06	0.01	0.42	0.10	0.01	0.45	0.20	0.32	0.37	0.39	0.25

C = Core

R = Rim

Table 1. Cont.

tion and alteration. Also, it is difficult to distinguish fore-arc and back-arc lavas on the basis of chemical composition alone.

The whole-rock composition of the highly serpentinized peridotite is of limited geochemical use but the chemistry of the preserved magmatic minerals, particularly olivine, spinel and pyroxene, reflects the crystallization conditions and the tectonic environment of the ultramafic parent rocks. In the completely serpentinized ultramafic rocks containing no relicts of primary silicate minerals, chromite is the only igneous mineral that retains most of its original composition.Therefore, the compositions of the primary chromian spinels are here used to deduce the petrogenesis and tectonic environment of the serpentinites in the Gabal El-Degheimi area.

Tectonic setting and petrogenesis

The ophiolites of Egypt are generally interpreted to have been generated in suprasubduction zone tectonic settings (e.g. El Sayed *et al*. 1999; Farahat *et al*. 2004; Azer and Stern 2007; Basta *et al*. 2011; Ahmed *et al*. 2012). In contrast, a MOR tectonic setting has been inferred for the origin of Gerf ophiolites in Egypt (Zimmer *et al*. 1995). Most researchers recognize the transitional geochemical character of the lavas, between those of island arcs and MORB, and on this basis, a back-arc environment of formation for the ophiolites is often inferred (e.g. El Sayed *et al*. 1999; Farahat *et al.* 2004; Abd El-Rahman *et al*. 2009; Basta *et al*. 2011). A fore-arc setting has rarely been considered for the ophiolites (Azer and Stern 2007; Khalil and Azer 2007; Abd El-Rahman *et al.* 2009; Hamdy *et al*. 2013; Khedr and Arai 2013; Azer *et al*. 2013).

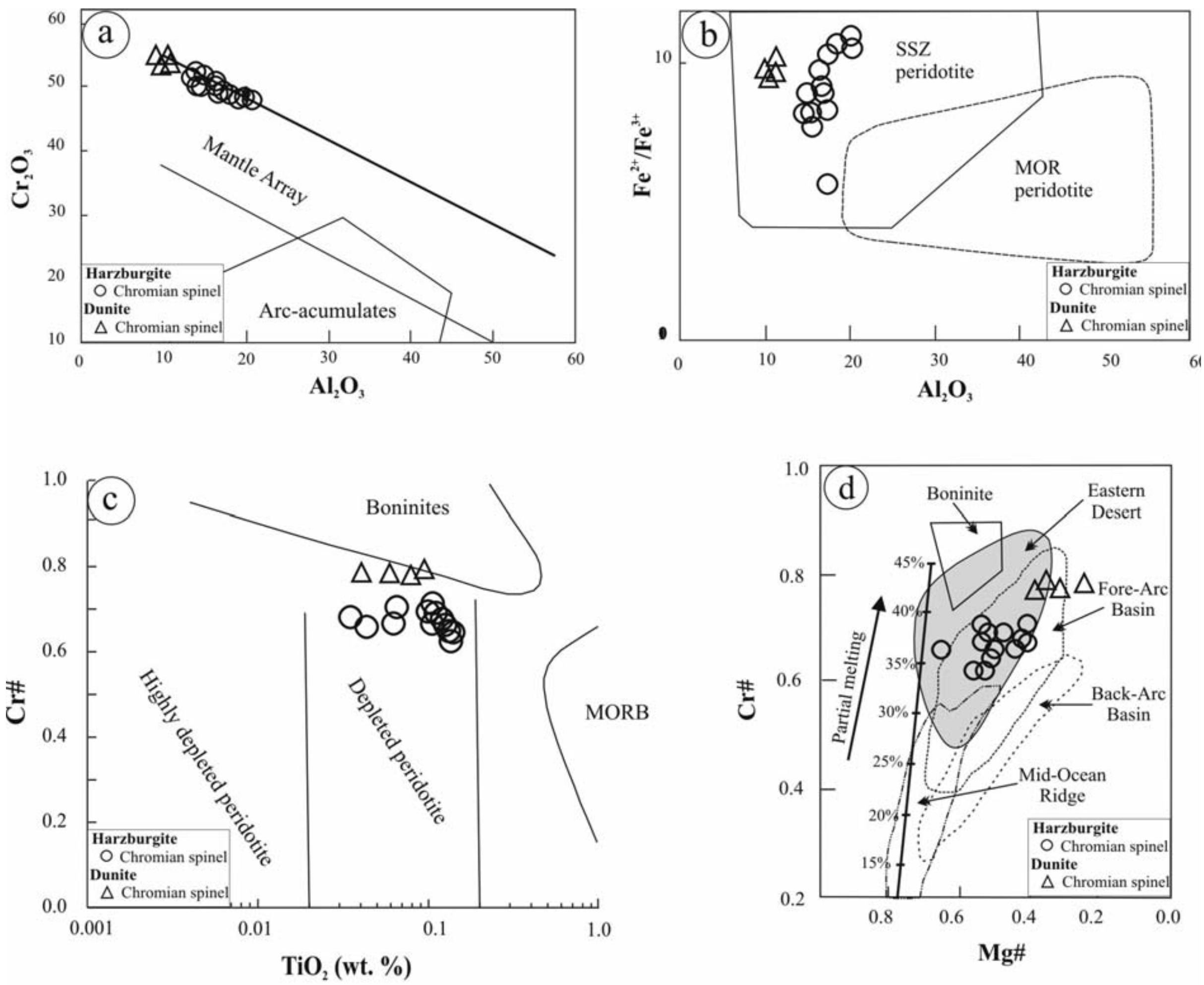
Controversy continues concerning the tectonic environment in which the Egyptian ophiolites formed. The abundance of immature and volcaniclastic sediments deposited on top of the ophiolites suggests formation at an intraoceanic convergent margin, either in a back-arc basin or a fore-arc during subduction initiation. Boninitic affinities of some Egyptian ophiolites have recently been recognized by some authors (e.g. El Sayed *et al*. 1999; Abdel Aal *et al.* 2003; Saleh 2006), and these authors inferred a back-arc or an inter-arc basin origin based on the chemical compositions of the ophiolitic rocks. However, this interpretation conflicts with the observation that most boninites are found in the fore-arcs of intraoceanic arcs (e.g. Murton 1989; Johnson and Fryer 1990; Bédard 1999; Beccaluva *et al.* 2004).

The chemical composition of accessory chromian spinel can be used to deduce the different tectonic settings of different igneous rocks (e.g. Barnes and Roeder 2001; Sobolev and Logvinova 2005; Arif and Jan 2006). Spinels from MOR and back-arc basin peridotites generally have Cr# <50 (Barnes and Roeder 2001; Ohara *et al*. 2002); whereas spinels in fore-arc peridotites generally have higher Cr# (up to 80) and those from boninites typically have Cr# of 70–90. Fresh chromian spinels in the serpentinites at Gabal El-Degheimi have chemical compositions that lie at the upper range of the mantle array (Text-fig. 6a). On the Al_2O_3 vs. Fe^{2+}/Fe^{3+} diagram (Text-fig. 6b), the compositions of fresh chromian spinels are akin to the supra-subduction zone (SSZ) peridotite field. The analyzed primary chromian spinels have low TiO_2 contents ranging from 0.04 to 0.16 wt.% with an average 0.09, which indicates a depleted mantle peridotite. The depleted nature of the studied serpentinites is further deduced by using the Cr# vs. TiO_2 diagram for the fresh chromian spinels (Text-fig. 6c). Overall, the high Cr# and low TiO_2 spinel as well as their depleted nature suggest an origin from a mantle wedge or a sub-arc mantle. The Cr# of Gabal El-Degheimi serpentinites is mostly >60 and similar to those of modern fore-arc peridotites and Egyptian serpentinites (Text-fig. 6d). Such a setting for the ophiolitic rocks in the Eastern Desert is supported by the fact that clinopyroxene and olivine compositions of most Egyptian ophiolites plot in the field characteristic of intraoceanic fore-arc regions (Abdel Aal *et al*. 2003; Khalil and Azer 2007). Also, the boninitic affinities of some Eastern Desert ophiolitic rocks support a fore-arc setting (e.g. El Sayed *et al*. 1999; Abdel Aal *et al.* 2003; Saleh 2006)

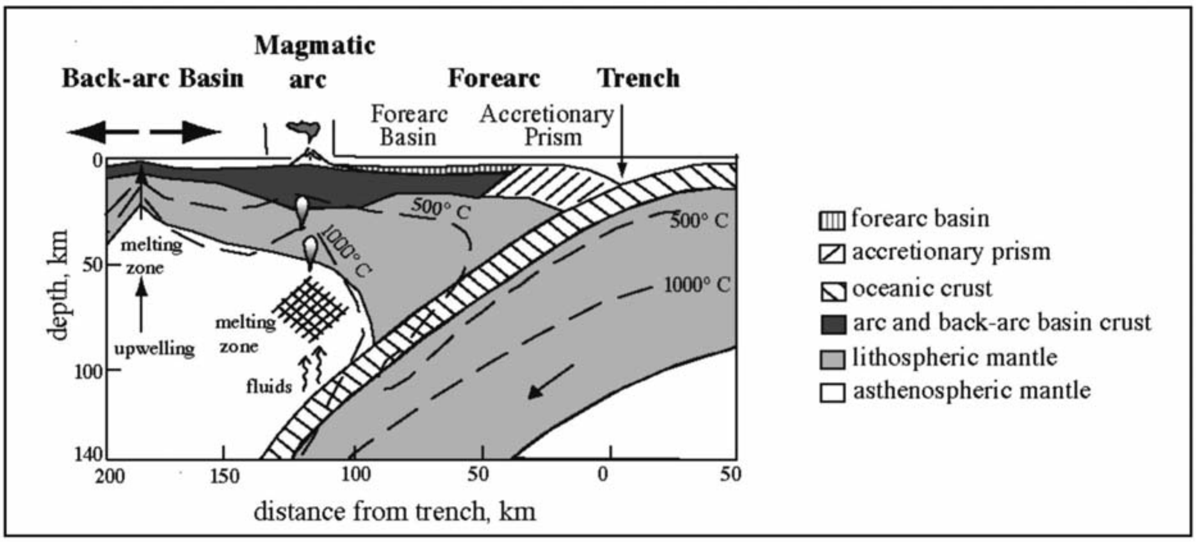
On the Cr# vs. Mg# plot, the fresh chromian spinels show a negative trend (Text-fig. 6d), reflecting a partial melting trend from harzburgite to dunite. Based on spinel compositions, the Gabal El-Degheimi serpentinized peridotites were formed by large amounts of melt extraction (~ 34–44%; Text-fig. 6d). The high degree of partial melting is consistent with fore-arc peridotites (Bonatti and Michael 1989) which have formed by 30 % partial melting. On the basis of the data presented here, the fresh chromian spinels from the serpentinized ultramafics of Gabal El-Degheimi area are similar to those of spinel of mantle peridotites that have gone some degree of partial melting in a fore-arc environment. The present results are comparable with those of ANS ophiolites which represent a fragment of oceanic lithosphere that formed in a fore-arc environment (Text-fig. 7).

Alteration of chromian spinel

All the Egyptian ophiolites are strongly deformed and metamorphosed to low-grade greenschist facies, but in some places they reach amphibolite grade (e.g. El-



Text-fig. 6. (a -) Plot of fresh chromian spinels on Al_2O_3 vs. Cr_2O_3 diagram (after Franz and Wirth 2000), (b -) Al_2O_3 vs. Fe^{2+}/Fe^{3+} diagram showing the fields of supra-subduction zone (SSZ) and mid oceanic ridge (MOR) peridotite (after Kamenetsky *et al*. 2001), (c -) Cr# vs. TiO_2 diagram for the analyzed fresh chrome spinels (fields after Dick and Bullen 1984; Arai 1992; Jan and Windley 1990), and (d -) Cr# vs. Mg# diagram for fresh chromian spinels (after Stern *et al*. 2004); the field boundaries are from Dick and Bullen (1984), Bloomer *et al*. (1995) and Ohara *et al.* (2002). The melting trend of experimental equilibrium (melting %) is from Hirose and Kawamoto (1995). Field for chromites in the Egyptian serpentinites of the Eastern Desert is adopted from Farahat *et al*. (2011)



Text-fig. 7. Cartoons showing the tectonic setting of Egyptian ophiolites in the fore-arc environment above subduction zones (after Azer and Stern 2007)

Sayed *et al.* 1999; Farahat 2008; Khedr and Arai 2013). The ultramafic rocks associated with the Egyptian ophiolites are largely converted to serpentinite or to mixtures of serpentine, talc, tremolite, magnesite, chlorite, magnetite, and carbonate. Under the effects of post-magmatic and/or metamorphic processes, the primary chromian spinels start to develop alteration products such as ferritchromite and Cr-magnetite (e.g. Barnes 2000; Mellini et al. 2005). These two secondary phases are usually attributed to the effects of low to medium grade metamorphism up to lower amphibolite facies (Thalhammer *et al*. 1990; McElduff and Stumpfl 1991). In Egyptian ophiolites, the alteration of chromian spinels to ferritchromite may have started during the late magmatic stage but it is mainly due to the much later serpentinization and tectonism (Khudeir *et al*. 1992; Khalil and Azer 2007). Farahat (2008) attributed the formation of chromian spinel cores followed by ferritchromite and Cr-magnetite rims to formation at transitional greenschist-amphibolite to lower amphibolite facies.

The ferritchromite in the serpentinites is enriched in total iron and strongly depleted in Al_2O_3 and MgO (Text-fig. 5a), reflecting the loss in Al_2O_3 and Cr_2O_3 and increase in Fe_2O_3 due to alteration and metamorphism. Very low Fe^{3+} contents in the fresh chromian spinels indicate relatively low oxygen fugacity conditions at their primary source (Murck and Campbell 1986), while high Fe^{3+} in the ferritchromite and Cr-magnetite rims suggesting an oxidative state during metamorphism (Anzil *et al*. 2012). Highly oxidising conditions favour the reaction of chromian spinel with serpentine to produce chlorite, ferritchromite and Cr-magnetite (Mellini *et al*. 2005; González-Jiménez *et al*. 2009). Therefore, the development of ferritchromite rims around chromian spinel cores indicates their formation during prograde alteration and under oxidizing conditions (González-Jiménez *et al.* 2009). This alteration should have taken place during lower temperature amphibolite facies metamorphism (Suita and Streider 1996). The minimum temperature of formation of ferritchromite is ~500°C (Mellini *et al*. 2005). The abundance of antigorite as the serpentine mineral, in the Gabal El-Degheimi serpentinites, suggests that it formed at 400−600 °C (Evans 2010) during an early stage of serpentinization at great depth.

Correlations with other late Neoproterozoic ultramafic rocks of the ANS

In this section, we aim to compare the serpentinized ultramafics of Gabal El-Degheimi with the ultramafic rocks of ANS (ophiolites and mafic-ultramafic intrusions) through comparing their petrological and mineralogical characteristics. The ultramafic rocks of the ANS ophiolites are essentially represented by harzburgites and dunites (e.g. Farahat *et al.* 2011; Azer *et al*. 2013). On the other hand, the ultramafic rocks of layered mafic-ultramafic intrusions show a wide variation in rock types, including wehrlite, dunite, lherzolite and pyroxenites with minor harzburgite. (Khudeir 1995; Helmy and El-Mahallawi 2003; Farahat and Helmy 2006; Helmy *et al*. 2008; Azer and El-Gharabawy 2011). The present study suggests harzburgite and dunite protoliths for the serpentinites of Gabal El-Degheimi due to the abundance of bastite and mesh textures, similar in this regard to the ophiolitic serpentinites of the ANS. The harzburgite in the mafic-ultramafic intrusions are characterized by the presence of green spinel (pleonaste) and primary intercumulus amphiboles (Khudeir 1995; Helmy *et al*. 2008) which have not been recorded in the present study.

Similar to those of the Gabal El-Degheimi serpentinites, spinels in the serpentinized peridotites of ANS ophiolites are mainly represented by chromian spinels (e.g. Azer and Stern 2007; Farahat 2008; Ahmed *et al*. 2012; Khedr and Arai 2013), whereas peridotites of the layered intrusions contain chromian spinels and green spinel (Khudeir 1995; Azer and El-Gharabawy 2011). The chromian spinels of ANS ophiolite ultramafic rocks display zoning from fresh chromian spinel cores to ferritchromite and Cr-magnetite rims (e.g. Khalil and Azer 2007; Farahat 2008; Ahmed *et al*. 2012; Khedr and Arai 2013). On the other hand, the chromian spinels of ultramafics in the mafic-ultramafic layered intrusions are not zoned (e.g. Ahmed *et al*. 2008; Azer and El-Gharabawy 2011). The chromian spinels of Gabal El-Degheimi ultramafic rocks are zoned with ferritchromite and Cr-magnetite rims. Also, they are not accompanied by green spinel and have high Cr#. The mineral composition of fresh chromian spinel in Gabal El-Degheimi is analogous to the fore-arc peridotites and serpentinized peridotites in the Eastern Desert of Egypt (Text-fig. 6d). This is consistent with the high Cr# (mostly >0.6) for spinels in ANS harzburgites, which are comparable to the forearc peridotites (Stern *et al*. 2004). Accordingly, the chromian spinels of the studied serpentinites are similar to the ophiolitic ultramafic rocks of the ANS rather than to ultramafics of layered mafic-ultramafic intrusions.

CONCLUSIONS

- The mafic-ultramafic rocks of the Gabal El-Degheimi area, Central Eastern Desert of Egypt, are dismembered ophiolites and tectonically enclosed within, or thrust over, island arc assemblages.

- Some portions of the serpentinized rocks contain fresh relicts of primary chromian spinel and olivine and others are extremely altered along thrusts and shear zones. The abundance of bastite and mesh textures suggests harzburgite and dunite protoliths.
- The primary chromian spinels are rimmed by ferritchromite and Cr-magnetite. The development of ferritchromite rims around chromian spinel cores points to formation during prograde alteration, under oxidizing conditions, at lower amphibolite facies metamorphism.
- The compositions of primary chromian spinels from the serpentinites of Gabal El-Degheimi have the characteristics of those derived from mantle that has experienced some degree of partial melting in a fore-arc tectonic environment.

Acknowledgements

The author would like to express deep gratitude to Dr. Peter R. Johnson and Dr. Ayman Maurce for their critical reading and valuable comments that improved this contribution. Also, the author would like to thank Dr. Saleh Gameel for helping in performing the microprobe analyses in France. Also, the author highly appreciates thoughtful review by Prof. Ray Macdonald, which improved the manuscript.

REFERENCES

Abd El-Rahman, Y., Polat, A., Dilek, Y., Fryer, B.J., El-Sharkawy, M. and Sakran, S. 2009. Geochemistry and tectonic evolution of the Neoproterozoic incipient arc-fore-arc crust in the Fawakhir area, Central Eastern Desert of Egypt. *Precambrian Research*, **175**, 116–134.

Abdel Aal, A.Y., Farahat, E.S., Hoinken G. and El-Mahalawi, M.M. 2003. Ophiolites from the Egyptian Shield: A case for a possible inter-arc origin. *Mitt. Osterr. Ges*., **148**, 81–83.

Abdel-Karim, A.M., Azzaz, S.A., Moharem, A.F. and El-Alfy, H.M. 2008. Petrological and geochemical studies on the ophiolite and island arc association of Wadi Hammariya, central Eastern Desert, Egypt. *The Arabian Journal for Science and Engineering*, **33**, 117–138.

Abdelsalam, M.G. and Stern, R.J. 1996. Sutures and Shear Zones in the Arabian–Nubian Shield. *Journal of African Earth Science*, **23**, 289–310.

Ahmed, A.H., Helmy, H.M., Arai, S., Yoshikawa, M., 2008. Magmatic unmixing in spinel rim late Precambrian concentrically-zoned mafic–ultramafic intrusions, Eastern Desert, Egypt. *Lithos*, **104**, 85–98.

Ahmed, A.H., Gharib, M.E. and Arai, S. 2012. Characterization of the thermally metamorphosed mantle-crust transition zone of the Neoproterozoic ophiolite at Gebel Mudarjaj, south Eastern Desert. *Lithos*, **142-143**, 67–83.

Akaad, M.K. and Abu El Ela, A.M. 2002. Geology of the basement rocks in the eastern half of the belt between latitudes 25⁰ 30′ and 26⁰ 30′ N Central Eastern Desert, Egypt. Geological Survey of Egypt, Paper, 78.

Akaad, M.K. and Noweir, A.M. 1980. Geology and Lithostratigraphy of the Arabian Desert orogenic belt of Egypt between Lat. 25⁰ 35′ and 26⁰ 30′ N. *Bull. Inst. Applied Geol., King Abdul Aziz Univ., Jeddah*, **3**, 127–135.

Ali, K.A., Azer, M.K., Gahlan, H.A., Wilde, S.A., Samuel, M.D. and Stern, R.J. 2010. Age of formation and emplacement of Neoproterozoic ophiolites and related rocks along the Allaqi Suture, south Eastern Desert, Egypt. *Gondwana Research*, **18**, 583–595.

Anzil, P.A., Guereschi, A.B. and Martino, R.D. 2012. Mineral chemistry and geothermometry using relict primary minerals in the La Cocha ultramafic body: A slice of the upper mantle in the Sierra Chica of Córdoba, Sierras Pampeanas, Argentina. *Journal of South American Earth Sciences*, **40**, 38–52.

Arai, S. 1992. Chemistry of chromian spinel in volcanic rocks as a potential guide to magma chemistry. *Mineralogical Magazine*, **56**, 173–184.

Arif, M. and Jan, M.Q. 2006. Petrotectonic significance of the chemistry of chromite in the ultramafic-mafic complexes of Pakistan. *Journal of Asian Earth Sciences*, **27**, 628–646.

Azer, M.K. 2013. Evolution and economic significance of listwaenites associated with Neoproterozoic ophiolites in south Eastern Desert, Egypt. *Geologica Acta*, **11**, 113–128.

Azer, M.K., Abu El-Ela F.F. and Ren, M. 2012. The petrogenesis of late Neoproterozoic mafic dyke-like intrusion in south Sinai, Egypt. *Journal of Asian Earth Sciences*, **54-55**, 91–109.

Azer, M.K. and El-Gharbawy, R.I. 2011. Contribution to the Neoproterozoic layered mafic-ultramafic intrusion of Gabal Imleih, south Sinai, Egypt: Implication of post-collisional magmatism in the north Arabian-Nubian Shield. *Journal of African Earth Sciences*, **60**, 253–272.

Azer, M.K. and Khalil, A.E.S. 2005. Petrological and mineralogical studies of Pan-African serpentinites at Bir Al-Edeid area. Central Eastern Desert, Egypt. *Journal of African Earth Sciences*, **43**, 525–536.

Azer, M.K., Samuel, M.D., Ali, K.A., Gahlan, H.A., Stern, R.J., Ren, M. and Moussa, H.E. 2013. Neoproterozoic ophiolitic peridotites along the Allaqi-Heiani Suture, South Eastern Desert, Egypt. *Mineralogy and Petrology,* **107**, 829-848.

Azer, M.K. and Stern, R.J. 2007. Neoproterozoic (835-720 Ma) serpentinites in the Eastern Desert, Egypt: Fragments of fore-arc mantle. *The Journal of Geology*, **115**, 457–472.

Barnes, S.J. 2000. Chromite in komatiites, 2. Modification during green-schist to mid-amphibolite facies metamorphism. *Journal of Petrology*, **41**, 387–409.

Barnes, S.J. and Roeder, P.L. 2001. The Range of Spinel Compositions in Terrestrial Mafic and Ultramafic Rocks. *Journal of Petrology*, **42**, 2279–2302.

Basta, F.F., Maurice, A.E., Bakhit, B.R., Ali, K.A. and Manton, W.I. 2011. Neoproterozoic contaminated MORB of Wadi Ghadir ophiolite, NE Africa: Geochemical and Nd and Sr isotopic constraints. *Journal of African Earth Sciences*, **59**, 227–242.

Beccaluva, L., Coltori, M., Giunta, G. and Siena, F. 2004. Tethyan vs. Cordilleran ophiolites: a reappraisal of distinctive tectono-magmatic features of supra-subduction complexes in relation to subduction mode. *Tectonophysics*, **393**, 163–174.

Bédard, J.H. 1999. Petrogensis of boninites from the Betts Cove ophiolite, Newfoundland, Canada: identification of subducted source components. *Journal of Petrology*, **40**, 1853–1889.

Bloomer, S.H., Taylor, B., MacLeod, C.J., Stern, R.J., Fryer, P., Hawkins, J.W. and Johnson, L. 1995. Early arc volcanism and ophiolite problem: A perspective from drilling in the Western Pacific. In: Taylor, B., Natland, J. (Eds), Active Margins and Marginal Basins of the Western Pacific, Geophysical Monograph, Vol. 88. American Geophysical Union, Washington, DC, pp. 1–30.

Bonatti, E. and Michael, P.J. 1989. Mantle peridotites from continental rifts to oceanic basins to subduction zones. *Earth and Planetary Science Letters*, **91**, 297–311.

Dick, H.B. and Bullen, T. 1984. Chromian spinel as a petrogenetic indicator in abyssal and Alpine-type peridotites and spatially associated lavas. *Contribution to Mineralogy and Petrology*, **86**, 54–76.

El Sayed, M.M., Furnes, H. and Mohamed, F.H. 1999. Geochemical constraints on the tectonomagmatic evolution of the late Precambrian Fawakhir ophiolite, Central eastern Desert, Egypt. *Journal of African Earth Sciences*, **29**, 515–533.

El Sharkawy, M.A. and El Bayoumi, R.M. 1979. The ophiolites of Wadi Ghadir area, Eastern Desert, Egypt. *Annals of the Geological Survey of Egypt*, **9**, 125–135.

Evans, B.W. 2010. Lizardite versus antigorite serpentinite: magnetite, hydrogen, and life (?). *Geology*, **38**, 879–882.

Farahat, E.S. 2008. Chrome-spinels in serpentinites and talc carbonates of the El Ideid-El-Sodmein District, central Eastern Desert, Egypt: their metamorphism and petrogenetic implications. *Chemie der Erde*, **68**, 193–205.

Farahat, E.S., El Mahalawi, M.M. and Hoinkes, G. 2004. Continental back-arc basin origin of some ophiolites from the Eastern Desert of Egypt. *Mineralogy and Petrology*, **82**, 81–104.

Farahat, E.S. and Helmy, H.M. 2006. Abu Hamamid Neoproterozoic Alaskan-type complex, south Eastern Desert, Egypt. *Journal of African Earth Sciences*, **45**, 187–197.

Farahat, E.S., Hoinkes, G., Mogessie, A. 2011. Petrogenetic and geotectonic significance of Neoproterozoic suprasubduction mantle as revealed by the Wizer ophiolite complex, Central Eastern Desert, Egypt. *International Journal of Earth Sciences*, **100**, 1433–1450.

Franz, L. and Wirth, R. 2000. Spinel inclusions in olivine of peridotite xenoliths from TUBAF seamount (Bismark Archipelago/Papua New Guinea): evidence for the thermal and tectonic evolution of the oceanic lithosphere. *Contributions to Mineralogy and Petrology*, **140**, 283–295.

Gass, I.G. 1981. Pan-African (Upper Proterozoic) plate tectonics of the Arabian-Nubian Shield. In: Kröner, A. (Ed.), Precambrian plate tectonics, Elsevier, Amsterdam, 387–405.

González-Jiménez, J.M., Kerestedjian, T., Proenza, J.A. and Gervilla, F. 2009. Metamorphism on chromite ores from the Dobromirtsi ultramafic Massif, Rhodope Mountains (SE Bulgaria). *Geologica Acta*, **7**, 413–429.

Hamdy, M.M., Harraz, H. Z. and Aly, G.A. 2013. Pan-African (intraplate and subduction-related?) metasomatism in the Fawakhir ophiolitic serpentinites, Central Eastern Desert of Egypt: mineralogical and geochemical evidences. *Arabian Journal of Geosciences*, **6**, 13–33.

Helmy, H.M. and El Mahallawi, M.M. 2003. Gabbro Akarem mafic-ultramafic complex, Eastern Desert, Egypt: a Late Precambrian analogue of Alaskan-type complex. *Mineralogy and Petrology*, **77**, 85–108.

Hirose, K. and Kawamoto, T. 1995. Hydrous partial melting of lherzolite at 1GPa: the effect of H_2O on the genesis of basaltic magmas. *Earth and Planetary Science Letters*, **133**, 463–473.

Jan, M.Q. and Windley, B.F. 1990. Chromian spinel-silicate chemistry in ultramafic rocks of the Jijal complex, Northwestern Pakistan. *Journal of Petrology*, **31**, 667–715.

Johnson, L.E. and Fryer, P. 1990. The first evidence for MORB-like lavas from the outer Mariana fore-arc: geochemistry, petrography and tectonic implications. *Earth and Planetary Science Letters*, **100**, 304–316.

Johnson, P.R., Kattan, F.H. and Al-Saleh, A.M. 2004. Neoproterozoic ophiolites in the Arabian Shield. In: Kusky, T.M. (Ed), Precambrian Ophiolites and Related Rocks. Developments in Precambrian Geology, 13, Elsevier, 129–162.

Kamenetsky, V.S., Crawford, A.J. and Meffre, S. 2001. Factors controlling chemistry of magmatic spinel: an empirical study of associated olivine, Cr-spinel and melt inclusions from primitive rocks. *Journal of Petrology*, **42**, 655–671.

Khalil, A.E.S. and Azer, M.K. 2007. Supra-subduction affinity in the Neoproterozoic serpentinites in the Eastern Desert, Egypt: Evidence from mineral composition. *Journal of African Earth Sciences*, **49**, 136–152.

Khedr, M.Z. and Arai, S. 2013. Origin of Neoproterozoic ophiolitic peridotites in south Eastern Desert, Egypt, constrained from primary mantle mineral chemistry. *Mineralogy and Petrology,* **107**, 807-828.

Khudeir, A.A. 1995. Chromian spinel-silicate chemistry in peridotite and orthopyroxenite relicts from ophiolitic serpentinites, Eastern Desert, Egypt. *Bulletin of Faculty of Science, Assiut University*, **24**, 221–261.

Khudeir, A.A., El Haddad, M.A. and Leake, B.E. 1992. Compositional variation in chromite from the Eastern Desert. *Mineralogical Magazine*, **56**, 567–574.

Kröner, A. 1984. Late Precambrian plate tectonics and orogeny: a need to redefine the term Pan-African. In: Klerkx, J. and Michot, J. (Eds), African Geology, Teruren, 23–26.

Kröner, A., Stern, R.J., Linnabacker, P., Manton, W., Reischmann, T. and Hussein, I.M. 1991. Evolution of Pan-African island arc assemblages in the south Red Sea Hills, Sudan, and in SW Arabia as exemplified by geochemistry and geochronology. *Precambrian Research*, **53**, 99–118.

Kröner, A., Todt, W., Hussein, I.M., Mansour, M. and Rashwan, A.A. 1992. Dating of late Proterozoic ophiolites in Egypt and Sudan using the single grain zircon evaporation technique. *Precambrian Research*, **59**, 15–32.

Kusky, T.M., Abdelsalam, M., Tucker, R. and Stern, R. 2003. Evolution of the East African and Related Orogens, and the Assembly of Gondwana. *Special Issue of Precambrian Research*, **123**, 81–344.

Loizenbauer, J., Wallbrecher, E., Fritz, H., Neumayr; P., Khudeir, A.A. and Kloetzli, U. 2001. Structural geology, simple zircon ages and fluid inclusion studies of the Meatiq metamorphic core complex: Implications for Neoproterozoic tectonics in the Eastern Desert of Egypt. *Precambrian Research*, **110**, 357–383.

McElduff, B. and Stumpfl, E.F. 1991. The chromite deposits of the Troodos complex, cyprus: evidence for the role of a fluid phase accompanying chromite formation. *Mineralium Deposita*, **26**, 307–318.

Mellini, M., Rumori, C. and Viti, C. 2005. Hydrothermally reset magmatic spinels in retrograde serpentinites: formation of "ferritchromit" rims and chlorite aureoles. *Contributions to Mineralogy and Petrology*, **149**, 266–275.

Mondal, S.K., Baidya, T.K., Rao, K.N.G. and Glascock, M.D. 2001. PGE and Ag mineralization in a breccia zone of the Precambrian Nuasahi Ultramafic– mafic Complex, Orissa, India. *Canada Mineralogy*, **39**, 979–996.

Murck, B.W. and Campbell, I.H. 1986. The effect of temperature, oxygen fugacity and melt composition on the behavior of chromium in basic and ultrabasic melts. *Geochimica et Cosmochimica Acta*, **50**, 1871–1887.

Murton, B.J. 1989. Tectonic controls on boninite genesis. In: Saunders, A.D. and Norry, M.J. (Eds), Magmatism in the ocean basins. *Geological Society of London, Special Publication*, **42**, 347–377.

Ohara, Y., Stern, R.J., Ishii, T., Yurimoto, H. and Yamazaki, T. 2002. Peridotites from the Mariana Trough: first look at the mantle beneath an active back-arc basin. *Contribution to Mineralogy and Petrology*, **143**, 1–18.

Osman, A. 1995. The mode of occurrence of gold-bearing listvenite at El Barramiya gold mine, Eastern desert, Egypt. *Middle East Research Centre, Ain Shams University, Earth Sciences Series*, **9**, 93–103.

Patchett, P.J. and Chase, C.G. 2002. Role of transform continental margins in major crustal growth episodes. *Geology*, **30**, 39–42.

Reischmann, T. and Kröner, A. 1994. Late Proterozoic island arc volcanics from Gebeit, Red Sea Hills, north-east Sudan. *Geologische Rundschau*, **83**, 547–563.

Roeder, P.L. 1994. Chromite: from the fiery rain of chondrules to the Kilauea Iki lava lake. *Canada Mineralogy*, **32**, 729–746.

Saleh, G.M. 2006. The chromite deposits associated with ophiolite complexes, southeastern Desert, Egypt: Petrological and geochemical characteristics and mineralization. *Chinese Journal of Geochemistry*, **25**, 307–317.

Shackleton, R.M. 1994. Review of late Proterozoic sutures, ophiolitic me´langes and tectonics of eastern Egypt and north Sudan. *Geological Rundschau*, **83**, 537–546.

Sobolev, N.V. and Logvinova, A.M. 2005. Significance of accessory chrome spinels in identifying serpentinite paragenesis. *International Geological Review*, **47**, 58–64.

Stern, R.J. and Hedge, C.E. 1985. Geochronologic and isotopic constraints on Late Precambrian crustal evolution in the Eastern Desert of Egypt. *American Journal of Sciences*, **285**, 97–127.

Stern, R.J. 1994. Arc assembly and continental collision in the Neoproterozoic East African Orogen: implications for the consolidation of Gondwanaland. *Annual Reviews of Earth and Planetary Science*, **22**, 319–351.

Stern, R.J., Johnson, P.R., Kröner, A. and Yibas, B., 2004. Neoproterozoic ophiolites of the Arabian-Nubian Shield. In: Kusky, T.M. (Ed.), Precambrian Ophiolites and Related Rocks. In: Developments in Precambrian Geology, 13, 95–128.

Suita, M. and Strieder, A. 1996. Cr-spinels from Brazilian mafic-ultramafic complexes: metamorphic modifications. *International Geology Review*, **38**, 245–267.

Thalhammer, O.A.R., Prochaska, W. and Miihlhans, H.W. 1990. Solid inclusions in chrome-spinels and platinum group element concentrations from the Hochgrdssen and Kmubath Ultramafic Massifs (Austria). *Contributions to Mineralogy and Petrology*, **105**, 66–80.

Zimmer, M., Krner, A., Jochum, K.P., Reischmann, T. and Todt, W. 1995. The Gabal Gerf complex: a Precambrian N-MORB ophiolite in the Nubian Shield, NE Africa. *Chemical Geology*, **123**, 29–51.

Zoheir, B.A. and Lehmann, B. 2011. Listvenite-lode association at the Barramiya gold mine, Eastern Desert, Egypt. *Ore Geology Reviews*, **39**, 101–115.

Manuscript submitted: 21st July 2013
Revised version accepted: 17th October 2013