Neoproterozoic (835–720 Ma) Serpentinites in the Eastern Desert, Egypt: Fragments of Forearc Mantle

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ABSTRACT

Most Neoproterozoic ophiolites of the Arabian-Nubian Shield show compositions consistent with formation in a suprasubduction zone environment, but it has not been clear whether this was in a forearc or back-arc setting. Ophiolitic serpentinites are common in the Eastern Desert of Egypt, but their composition and significance are not well understood. Here we report new petrographic, mineral, chemical, and whole-rock compositional data for serpentinites from Wadi Semna, the northernmost ophiolitic serpentinites in the Eastern Desert, and use these to provide insights into the significance of other Eastern Desert serpentinite locales. The Wadi Semna serpentinites are composed essentially of antigorite, chrysotile, and lizardite, with minor carbonate, chromite, magnetite, magnesite, and chlorite, and they were tectonically emplaced. The alteration of chrome spinel to ferritchromite was accompanied by the formation of chloritic aureoles due to the release of Al from spinel. Major-element compositions indicate that, except for the addition of water, the serpentinites have not experienced extensive element mobility; these were originally CaO- and Al_2O_3-depleted harzburgites similar to peridotites from modern oceanic forearcs. High Cr# (Cr/(Cr + Al)) in the relict spinels (average = 0.69) indicates that these are residual after extensive partial melting, similar to spinels in modern forearc peridotites. These characteristics of Wadi Semna serpentinites also typify 22 other Eastern Desert serpentinite localities. We infer that Eastern Desert ophiolitic serpentinites, except perhaps Gebel Gerf, originated by forearc seafloor spreading during subduction initiation associated with the closing of the Neoproterozoic Mozambique Ocean.

Online enhancements: tables.

Introduction

The Arabian-Nubian Shield (ANS) may be the largest tract of juvenile continental crust of Neoproterozoic age on Earth (Patchett and Chase 2002). According to Stern (1994), the ANS formed through four major tectonomagmatic episodes between about 900 and 550 Ma. The breakup of Rodinia in early to mid-Neoproterozoic time was followed by seafloor spreading to open the Mozambique Ocean, attended by formation and accretion of fringing arc and back-arc basins (~870–690 Ma). Fragments of East and West Gondwanaland collided at ~610 Ma, culminating in E-W crustal shortening and escape tectonics, including development of the NW-SE-trending left-lateral Najd shear system. The ANS stabilized as a craton before the development of an extensive peneplain in mid-Cambrian times (~520 Ma) and was exhumed in the Neogene as a consequence of Red Sea rifting and flank uplift.

The abundance of ophiolites and ophiolitic mélanges is a distinctive part of the ANS, sufficiently so that Stern (2004) referred to this region as an "ophiolite graveyard." The abundance of ophiolites is strong evidence that this crust was generated by plate-tectonic processes (Price 1984; Pallister et al. 1988; Berhe 1990; Stern et al. 2004). Nevertheless, the significance of ANS serpentinites is controversial because some researchers contest that these are ophiolitic and those who agree that they are ophiolitic do not agree on their tectonic significance. Interpretations are further complicated because ANS ophiolitic complexes are variably dismembered, deformed, and altered. These complications are particularly severe for serpentinized ultramaf-

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ics, which are the most important and distinctive lithology of dismembered ANS ophiolites and mélanges. Serpentinites are usually aligned along NW-trending Najd shear zones (in the northern ANS, where this study focuses) or along N-S upright folds and shear zones (in the southern ANS). In the central ANS, ophiolites are less disrupted and define clear suture zones (Abdelsalam and Stern 1997).

Ophiolitic ultramafics of Neoproterozoic age are common in the central and southern sectors of the Eastern Desert of Egypt (fig. 1*A*), where they occur as highly altered serpentinites and talc-carbonate (listwaenite; Johnson et al. 2004) rocks enclosing rare relicts of fresher peridotite. These ophiolites were first described by Rittmann (1958), but it was not until the Wadi Ghadir ophiolite was described that the significance of Egyptian ophiolites was appreciated (El Sharkawy and El Bayoumi 1979). Since then, the serpentinites of Egypt have generally been interpreted as parts of tectonically emplaced oceanic lithosphere (Shackleton et al. 1980; Ries et al. 1983; El Gaby et al. 1984, 1988; Abu El Ela 1996; and many others).

Ophiolites of the northern ANS are generally interpreted to have been generated in suprasubduction zone tectonic settings (Bakor et al. 1976; Nasseef et al. 1984; Pallister et al. 1988; Stern et al. 2004); similar interpretations hold for Egyptian ophiolites (Abu El Ela 1990; Khudeir and Asran 1992; El-Sayed et al. 1999; Ahmed et al. 2001; Abdel Aal et al. 2003; El Bahariya and Arai 2003; Farahat et al. 2004; Azer and Khalil 2005). Seafloor spreading necessary to form suprasubduction zone ophiolites occurs in forearcs during the infant arc stage of subduction initiation or in back-arc basins (Pearce 2003; Stern 2004). Most researchers infer a back-arc basin setting for Egyptian ophiolites (Khudeir and Asran 1992; El-Sayed et al. 1999; Ahmed et al. 2001; Abdel Aal et al. 2003; El Bahariya and Arai 2003; Farahat et al. 2004; El Gaby 2005); a forearc setting is rarely considered, partly because the hypothesis of forearc spreading during subduction initiation is relatively new (Shervais et al. 2004; Stern 2004). Assessments of tectonic setting for ANS ophiolites in general and Eastern Desert ophiolites specifically focus mostly on the trace-element composition of lavas and rarely consider the abundant serpentinites. Stern et al. (2004) recognized that ANS ophiolitic ultramafics are mostly harzburgitic, containing magnesian olivines and spinels (Cr#; molar Cr/(Cr + Al) mostly >0.60), comparable to spinels from modern forearcs and distinctly higher than spinels from mid-ocean ridge (MOR) and back-arc basin peridotites. However, the review of Stern et al. (2004) was incomplete for Egyptian ophiolitic serpentinites and is updated here.

Akaad (1996, 1997) and Akaad and Abu El Ela (2002) classified Eastern Desert serpentinites into (1) allochthonous serpentinites, including boudins in Hafafit-type gneisses and mélanges, and (2) flow-intruded serpentinites. The former appear as allochthonous bodies within arc assemblages, whereas the latter intrude the surrounding schists. Ahmed (2005) rejected an ophiolite interpretation and, because he inferred high-grade metamorphism near contacts, considered Eastern Desert serpentinites to have originated as intrusions of ultramafic magma. This interpretation is not generally accepted, even though it must be recognized that Alaska-type layered igneous intrusions, including ultramafic rocks, exist in the Eastern Desert (e.g., Dixon 1981; Farahat and Helmy 2006). In general, the intrusive appearance of Eastern Desert serpentinites can be attributed to the different structural positions of the serpentinites in the surrounding rocks, coupled with the fact that the serpentinites are much weaker and easier to deform than are the rocks that enclose them. Our results do not support a magmatic, intrusive origin for Egyptian serpentinites but indicate that they are parts of variably dismembered ophiolitic complex.

This article reevaluates the significance of Eastern Desert ophiolitic serpentinites. Most studies of these have concentrated on their geology, petrography, and bulk chemistry. However, information about their protoliths is scarce because of pervasive alteration; nevertheless, much can be learned with careful work. In this contribution, we show how this can be accomplished. We first present new field and geochemical data for the serpentinites of Wadi Semna. We then integrate these results with published whole-rock, spinel, pyroxene, and olivine compositional data for Eastern Desert serpentinites. This synthesis yields new constraints on the tectonic setting of Egyptian Neoproterozoic serpentinites and ophiolites.

Wadi Semna Serpentinites

Field Observations. The Wadi Semna study area lies in the extreme northern part of the central Eastern Desert (fig. 1*A*) and is occupied by multiply deformed serpentinites, metasediments, and metavolcanics along with ~600-Ma Hammamat sediments and younger gabbro (fig. 1*B*). Metasediments are dominated by pebbly metamudstones that constitute the matrix of the ophiolitic mélange. Primary structures such as sedimentary layering are preserved. Layering is characterized by alternation

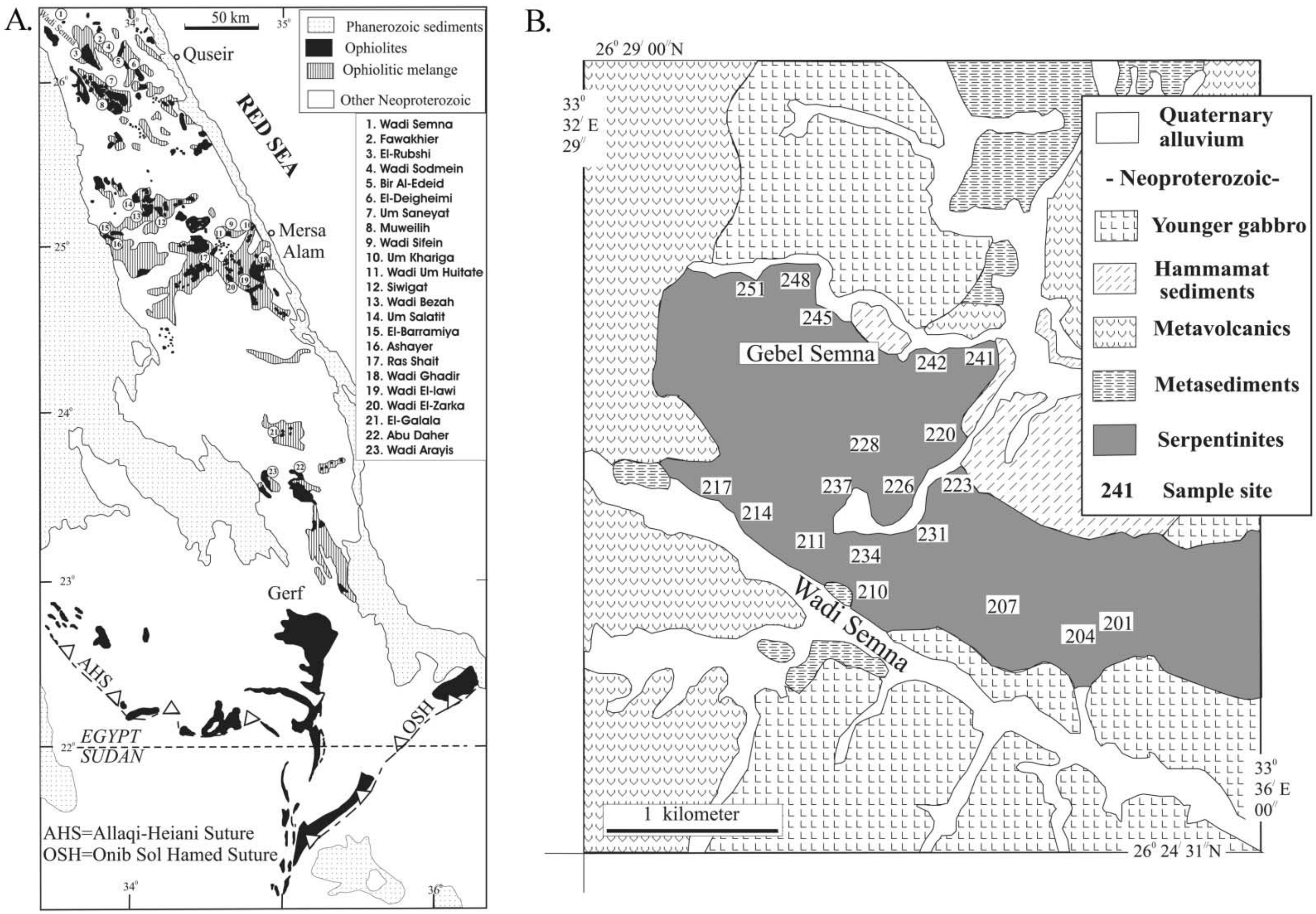

Figure 1. *A*, Distribution of ophiolitic rocks in Eastern Desert of Egypt (modified after Shackleton 1994). Localities of the serpentinite bodies (in which the chemical analyses of chrome spinels are available) are shown on the map. *B*, Geological map of Wadi Semna area (modified after Bakhit 1994).

of lighter and darker beds of silt and clays. Metavolcanics are metapyroclastics and metamorphosed flows of andesite, rhyodacite, and trachyte, interpreted as components of a Neoproterozoic arc (Bakhit 1994). Banded iron formation is associated with the meta-andesite. Ophiolitic lavas, sheeted dikes, and gabbro are missing.

Wadi Semna serpentinites define a WNW-oriented belt that is ~1–1.5 km wide. Contacts between the serpentinites and metavolcanics are faulted; these faults may have formed first during ~700-Ma ophiolite obduction and were then overprinted by ~600-Ma Najd shearing (Fowler and Osman 2001). Sometimes serpentinites are thrust over the associated metapyroclastics. The serpentinites are generally massive but became sheared and foliated near the contacts, where serpentinite is replaced by talc-carbonate rocks along shear zones. Away from the marginal shear zones, relicts of less serpentinized harzburgite locally show transitional relationships with the serpentinites. Thin magnesite veinlets are observed within the sheared serpentinites. The foliation of the intensively sheared serpentinite is NW-SE, parallel to the schistosity of the surrounding metavolcanics. The serpentinites are unconformably overlain by a small (~1 km across) outcrop of Hammamat sediments and are intruded by younger gabbro.

Petrography. Wadi Semna serpentinites include massive and sheared varieties, partly serpentinized harzburgite, and subordinate talc-carbonate. Further petrographic details are given below.

Massive Serpentinites. Petrographic and x-ray diffractogram studies indicate that the massive serpentinites are composed essentially of antigorite, chrysotile, and lizardite, with minor carbonate, chromite, magnetite, magnesite, and chlorite. Chrysotile occurs as cross-fiber veinlets traversing the antigorite matrix, which indicates that chrysotile formed late under static conditions (fig. 2*A*). Massive serpentinite preserves psuedomorphs and original textures of orthopyroxene and olivine, indicating that the protoliths were harzburgite and dunite. Orthopyroxene has been replaced by bastite with magnetite trains that define cleavage planes of the original orthopyroxene (fig. 2*B*). Original olivine is indicated by serpentine mesh texture and relicts coated with iron oxides (fig. 2*C*). Magnesite occurs as sparse crystals and fine aggregates. Chlorite occurs as small aggregates in an antigorite matrix or as aureoles around altered chrome spinels as well as coating bastite and mesh textures, indicating that chlorite formed after serpentinization. Kämmererite (chromian chlorite) is observed in a few aureoles as faintly pleochloric flakes, from violet to deep violet in color.

Opaque minerals in the massive serpentinites are mainly chrome spinels and magnetite. Chrome spinels occur as blood-red grains with rounded, subrounded, and irregular outlines. Sometimes, chrome spinels are replaced by ferritchromite and Cr-magnetite (fig. 2*D*). Ferritchromite is usually surrounded by irregular, faintly pleochloric aureoles of chlorite. Magnetite is represented by primary and secondary types. Primary magnetite occurs as fine, euhedral to anhedral grains (0.05–0.15 mm across), whereas secondary magnetite coats the olivine relicts, fills veinlets in chrome spinel grains, and defines the cleavage planes of the original orthopyroxene in bastite texture.

Partly Serpentinized Harzburgite. Partly serpentinized harzburgite occurs as minor bodies within the massive serpentinite. It consists essentially of serpentine minerals together with variable amounts of pyroxene, olivine, talc, and opaques. Pyroxenes are mainly cumulus orthopyroxene and minor augite surrounded by intercumulus primary olivine (fig. 2*E*). Pyroxene and olivine are variably serpentinized.

Sheared Serpentinites. Sheared serpentinites have the same composition as the massive varieties, but the serpentine minerals are commonly aligned producing schistosity (fig. 2*F*). Magnesite occurs as sparse crystals or as veinlets and pockets. Magnesite veinlets are monominerallic and cryptocrystalline, with sharp contacts with the enclosing serpentinites. Similar magnesite veins in Egyptian serpentinites are interpreted to have been produced after near-surface serpentinization (Salem et al. 1997; Ghoneim et al. 1999, 2003). Opaque minerals in the sheared serpentinites are mostly brecciated and rarely elliptical in shape.

Talc-carbonates. Talc-carbonate rocks are associated with serpentinites. Carbonates occur as anhedral clusters and veinlets of mainly magnesite and less common calcite and dolomite. Talc forms very fine, dense microcrystalline aggregates replacing serpentine minerals. Talc-carbonates associated with the sheared serpentinites are fine grained and foliated. The occurrence of carbonate implies significant calcium mobility, and sampling for this study avoided these rocks.

Analytical Techniques. Chemical composition of serpentines, chrome spinels, and chlorites was determined using an electron microprobe at the Geology and Metallogeny Laboratory, Orléans, France. Nineteen representative whole-rock samples were analyzed for major and trace elements, using x-ray

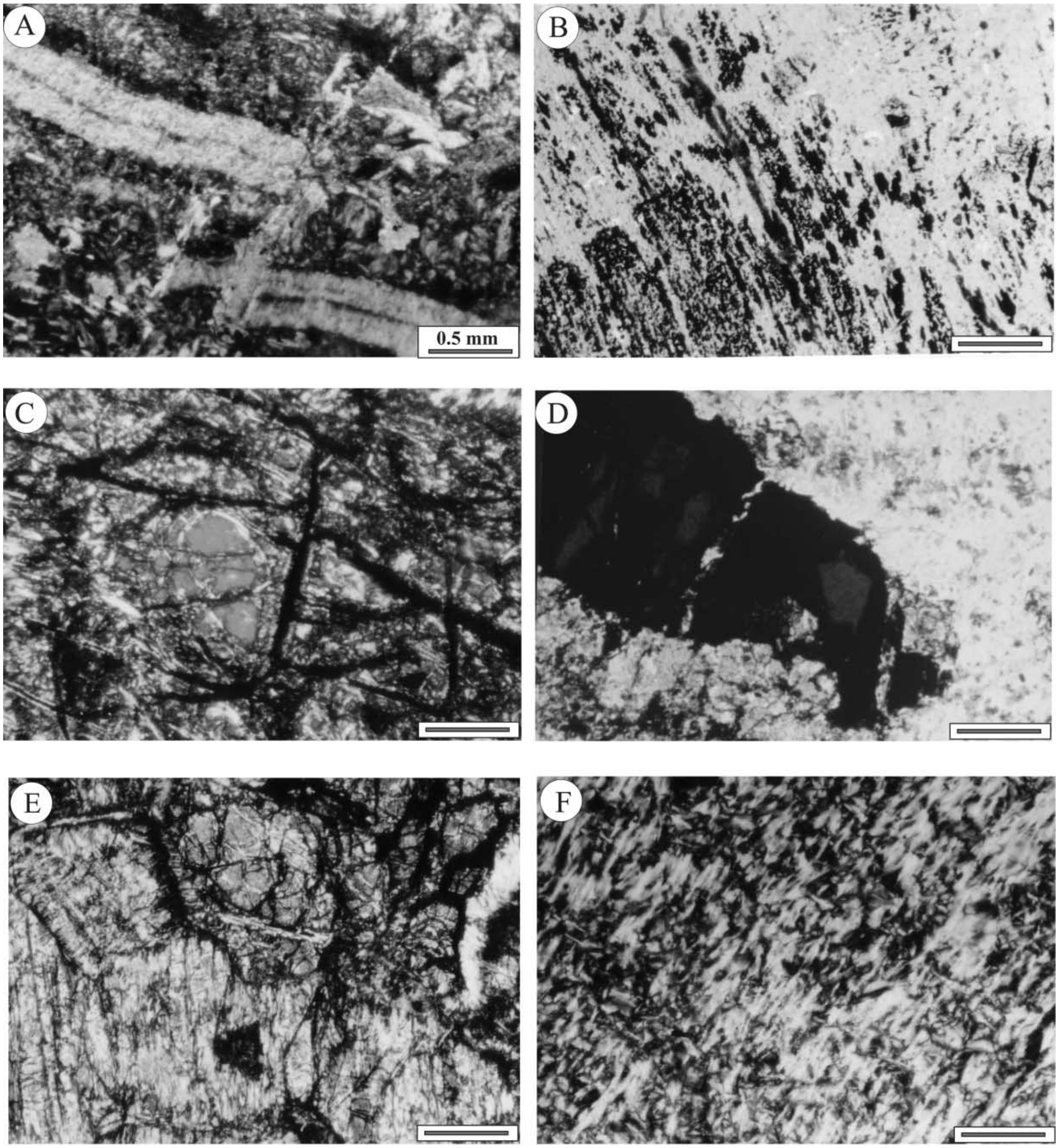

Figure 2. *A*, Chrysotile veinlets dislocated due to movement (crossed nichols). *B*, Pseudomorphic bastite showing magnetite trains that define cleavage planes of orthopyroxene (plane light). *C*, Fresh relicts of olivine in highly serpentinized peridotite (crossed nichols). *D*, Chrome spinel in the serpentinites (plane light). Note that chrome spinels (*gray*) are altered to ferritchromite and Cr-magnetite (*black*). *E*, Partly serpentinized peridotite showing cumulus orthopyroxene surrounded by intercumulus olivine (crossed nichols). *F*, Sheared serpentinite showing schistosity texture (crossed nichols). All scale bars are 0.5 mm.

fluorescence spectrometry on fused-glass discs and pressed powder pellets, respectively, at the Saudi Geological Survey, Jeddah, Saudi Arabia. The precision was generally better than ±5% for major oxides and most of the trace elements, as indicated by the duplicate analyses of rock standards. Loss on ignition (LOI) was determined by heating powdered samples for 1 h at 1000°C.

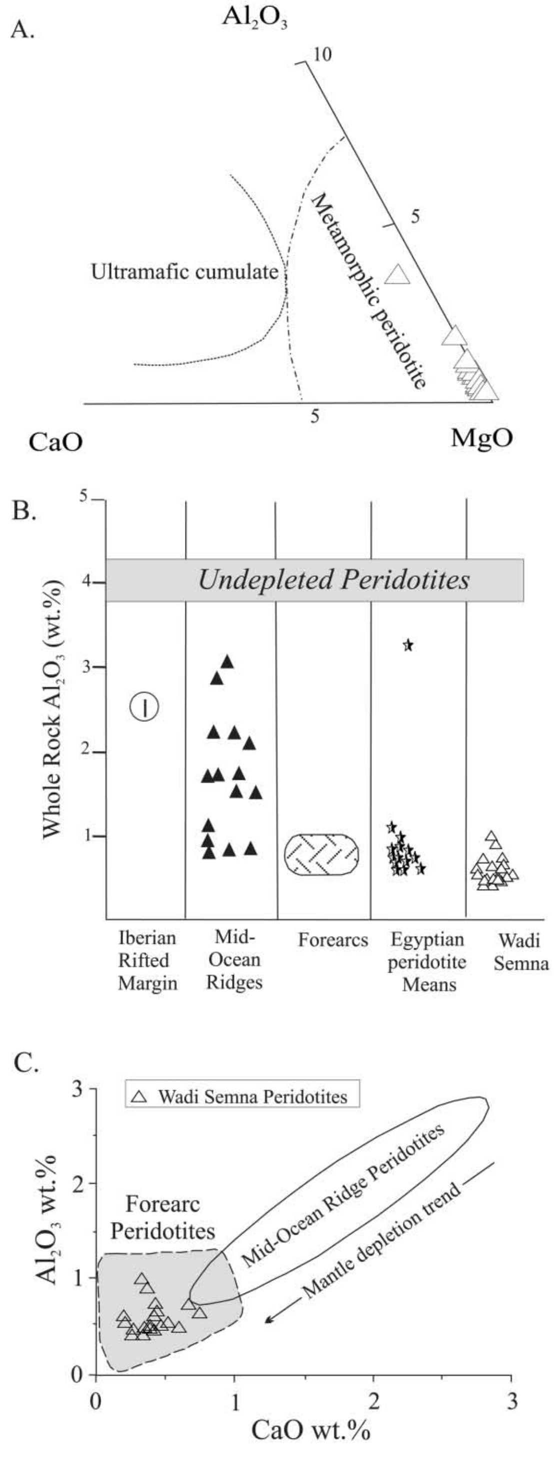

Figure 3. *A*, Al_2O_3-MgO-CaO diagram for the studied serpentinites (Coleman 1977). *B*, Whole-rock Al_2O_3 content in Wadi Semna serpentinites and other Egyptian Neoproterozoic peridotites compared with peridotites from other tectonic settings (modified after Bonatti and Michael 1989). The means of different localities in the Eastern Desert of Egypt are calculated on the basis of data from Abu El Ela (1990, 1996), Awad and Moussa (1997), El-Sayed et al. (1999), Khalil (2000), Bakhit (2001), El Bahariya and Arai (2003), Azer and Khalil (2005), A. E. S. Khalil and M. K. Azer (unpub. data), and this study. *C*, Al_2O_3 versus CaO diagram, comparing Wadi Semna serpentinites with peridotites from other tectonic settings (after Ishii et al. 1992).

Some samples of massive serpentinites were subjected to x-ray diffraction analysis to determine their mineralogical compositions. Powder diffraction patterns of the samples were obtained with Cu radiation with secondary monochrometer. The scanning speed was $2\theta = 1^\circ$/min at constant voltage 40 kV and 40 mA using a Brukur D_8 advanced x-ray diffractometer.

Whole-Rock Compositions. Representative chemical analyses of Wadi Semna massive serpentinites are given in table A1. (Note: all tables are available in the online edition or from the *Journal of Geology* office.) All samples contain abundant water and carbonate, with LOI ranging from ~12.5% to 16%, averaging 14.1%. Mean compositions of Wadi Semna serpentinites are 38.32 ± 0.81 wt% SiO_2, 37.66 ± 0.96 wt% MgO, 0.58 ± 0.16 wt% Al_2O_3, 7.89 ± 0.36 wt% total Fe as Fe_2O_3, and 0.40 ± 0.14 wt% CaO. This is a relatively restricted range and suggests that elemental redistribution associated with serpentinization was limited. This is also reflected in the high and relatively constant Mg# ($=100$ molar Mg/(Mg + Fe)), which ranges from 89 to 91.3 (mean $= 90.5 \pm 0.5$), similar to that of modern oceanic peridotites (Bonatti and Michael 1989). These results indicate that mobility of Mg and Fe at a scale larger than a hand specimen was limited, an inference further supported by the very low K_2O (~0.01%) and Na_2O contents (mean $= 0.11\%$). Ca metasomatism is a common concern in Egyptian serpentinites because of pervasive carbonate alteration (Stern and Gwinn 1990), but the low and restricted range of CaO in the Wadi Semna massive serpentinites (mean $= 0.40\% \pm 0.14\%$) suggests that this was limited in the samples we have analyzed. On the Al_2O_3-MgO-CaO diagram (fig. 3*A*), the Ca-depleted nature of the serpentinites is clear, and they plot within the field of metamorphic peridotites associated with ophiolites (Coleman 1977).

Petrographic and geochemical data indicate that addition or subtraction of elements other than water and perhaps silica was very limited for massive Wadi Semna peridotites, encouraging us to compare

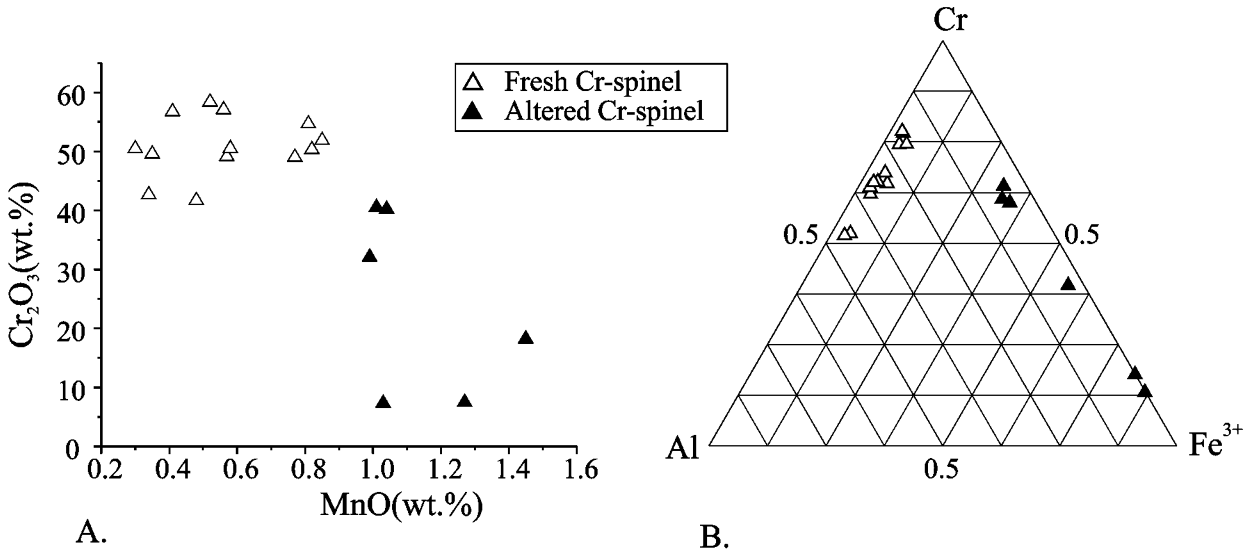

Figure 4. Fresh and altered Cr spinels in Wadi Semna serpentinites. *A*, Cr_2O_3 versus MnO plot of fresh (Mn-poor) and altered (Mn-rich) chrome spinels. *B*, Cr-Al-Fe^{3+} plot of Wadi Semna chrome spinels and their Al-poor alteration products.

these compositions with those of peridotites from modern tectonic settings. The very low abundance of alumina (0.58% ± 0.16% Al_2O_3) plots in the field of oceanic trench peridotites as defined by Bonatti and Michael (1989; fig. 3*B*). Similarly, the low mean CaO (~0.40%) suggests affinities with very depleted oceanic peridotites (Bonatti and Michael 1989), further supporting an interpretation that the protoliths were poor in clinopyroxene. Moreover, on the Al_2O_3 versus CaO diagram, the Wadi Semna serpentinites are depleted in Al_2O_3 and CaO, similar to harzburgites recovered from modern intra-oceanic forearcs (fig. 3*C*).

As expected for peridotites, the most important trace elements are Ni and Cr. Mean Cr and Ni contents (corrected for hydration) are high (2841 and 3027 ppm, respectively). The next most abundant trace element is Co (~134 ppm), followed by Zn and V (both ~43 ppm) and Sr and Zr (both ~12–13 ppm).

Mineral Chemistry. *Serpentine Minerals.* The composition of Wadi Semna serpentine minerals is relatively simple and deviates little from ideal compositions. Representative chemical analyses of the serpentine minerals are given in table A2. They contain 42.35–44.36 wt% SiO_2, 38.10–41.80 wt% MgO, 0.11–1.5 wt% Al_2O_3, 1.19–3.23 wt% FeO, and 0.03–0.64 wt% Cr_2O_3. The serpentine minerals form after retrograde hydrothermal alteration of ultramafic rocks or by prograde metamorphism of preexisting serpentinite (Deer et al. 1992). Lizardite is the most common retrograde product, while antigorite is the most common prograde reaction product. Our petrographic studies, as well as x-ray diffraction data (not shown here), revealed that the serpentine minerals of Wadi Semna serpentinites are mainly antigorite with subordinate chrysotile and lizardite. This indicates that parent minerals were first retrogressed to form chrysotile and lizardite. Progressive metamorphism recrystallized these minerals into antigorite.

Spinel. Chromite, along with scattered relicts of olivine and pyroxene, is the only mineral from the original ultramafic rock that routinely retains its original igneous composition in the serpentinites. In completely serpentinized ultramafic rocks containing no other relicts of primary silicate minerals, the composition of unaltered spinel is extensively used as a petrogenetic indicator (e.g., Dick and Bullen 1984; Barnes and Roeder 2001). Representative chemical analyses of accessory spinels and their alteration products from Wadi Semna serpentinites are listed in table A3. Fresh spinels contain high Cr_2O_3 (41.8–58.4 wt%) and the Cr# (molar Cr/(Cr + Al)) ranges from 0.54 to 0.80, with an average of 0.69. Altered spinel rims are represented by ferritchromite and Cr-magnetite; the former is more common. Relative to fresh chrome spinels, ferritchromite is enriched in Fe and Mn and depleted in Al, Mg, and Cr (fig. 4*A*). On a Cr-Al-Fe^{3+} diagram (fig. 4*B*), the altered spinels lie along the Cr-Fe join, reflecting loss of Al_2O_3 and Cr_2O_3 and addition of Fe_2O_3. Fresh chrome spinels have <0.1 (molar) Fe^{3+} and low TiO_2 content (<0.16 wt%) and are compositionally similar to podiform chromite (Leblanc et al. 1980).

Chlorite. Microprobe analyses of chlorites are given in table A4. Chlorite aureoles around altered spinels are generally rich in Cr_2O_3 (kämmererite), whereas matrix chlorites are impoverished in Cr_2O_3. The formation of chloritic aureoles around ferritchromite can be attributed to the dissolution of chrome spinels giving rise to ferritchromite rims. Ferritchromite retains Cr and Fe, whereas Al and Mg are released to coexisting silicate minerals. Excess Al reacts with serpentine minerals to produce chloritic aureoles. The presence of kämmererite indicates that chromium released from chrome spinels and ferritchromite enters into chlorite structure, where Cr substitutes for Al. On compositional fields for chlorites defined by Hey (1954), the matrix chlorites plot within the pennite, clinochlore, and ripidolite fields, while aureole chlorites plot in the clinochlore and sheridanite fields, reflecting their Fe-poor composition (fig. 5).

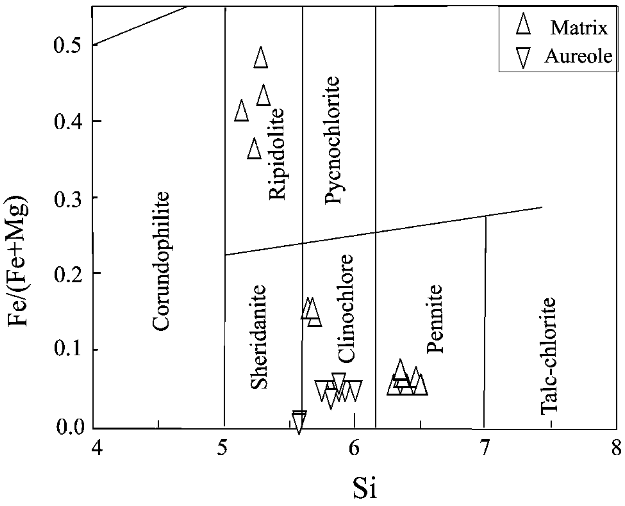

Figure 5. Chlorites in Wadi Semna serpentinites. Note Fe-poor nature of chlorites in aureoles around altered spinels. Fields after Hey (1954).

Tectonic Setting and Petrogenesis. As noted in the "Introduction," most recent studies of Egyptian ophiolites infer formation in a suprasubduction zone setting and conclude that this happened in a back-arc basin. In fact, suprasubduction zone ophiolites can form by seafloor spreading either in forearc or back-arc environments (Pearce 2003), and forearc ophiolites are much easier to emplace than back-arc basin ophiolites (Stern 2004). According to Pearce et al. (1984), ultramafic tectonite of MOR ophiolites includes both harzburgite and lherzolite together with subordinate dunite, while ultramafic tectonite in suprasubduction ophiolites is mainly harzburgite (80%–90%) with less dunite, lherzolite, and pyroxenite. Wadi Semna serpentinites are very poor in clinopyroxene and were derived mainly from harzburgite and subordinate dunite, like peridotites of suprasubduction zone ophiolites. The major-element characteristics of Wadi Semna serpentinites also reflect a depleted ultramafic protolith, consistent with a suprasubduction zone interpretation. Moreover, accessory fresh chrome spinels plot in the field of depleted mantle peridotite, close to the boninite field (fig. 6*A*), indicating a suprasubduction setting (Dick and Bullen 1984; Bonatti and Michael 1989).

Back-arc basin peridotites contain accessory chromite with Cr# ≤0.55, similar to those of MOR peridotites (Dick and Bullen 1984; Ohara et al. 2002; Ohara 2006). Only a few spinels with Cr# greater than that have been reported from the anomalously depleted 15°20′N region of the Mid-Atlantic Ridge (Bonatti et al. 1992; Silantyev et al. 1996) out of more than a thousand abyssal peridotites analyzed to date (H. B. Dick, pers. comm. 2006). The reason for this is fundamental, reflecting the limiting of mantle melting to the exhaustion of clinopyroxene, at which point spinels contain Cr# of 0.55 (Dick and Fisher 1984). Ophiolitic peridotites, however, commonly have spinel Cr# that exceed this value, indicating mantle melting considerably beyond exhaustion of clinopyroxene. This is attributed to the role of water in mantle melting above a subduction zone (Dick and Bullen 1984). Similarly, forearc peridotites typically contain accessory spinels with high Cr# (up to 0.80; Ohara and Ishii 1998; Stern et al. 2004). If we adopt these criteria, the spinels of Wadi Semna serpentinites are most similar to those in peridotites from modern forearcs. Moreover, on the Cr# versus Mg# diagram, fresh accessory chrome spinels plot close to the field of forearc peridotites recovered from the Mariana Trench (fig. 6*B*). Also, on a modification of the Cr# versus Mg# diagram (fig. 6*C*; Stern et al. 2004), the fresh chrome spinels of Wadi Semna plot mainly within the forearc field, while the altered spinels plot in the upper right-hand corner of the diagram.

Wadi Semna serpentinites are characterized by high Ni and Cr contents, further indicating that the protoliths were depleted peridotites. This is probably the same depletion responsible for high Cr# (>0.7) spinel. Such extensive depletion is due to extraction of a large melt fraction, greater than that

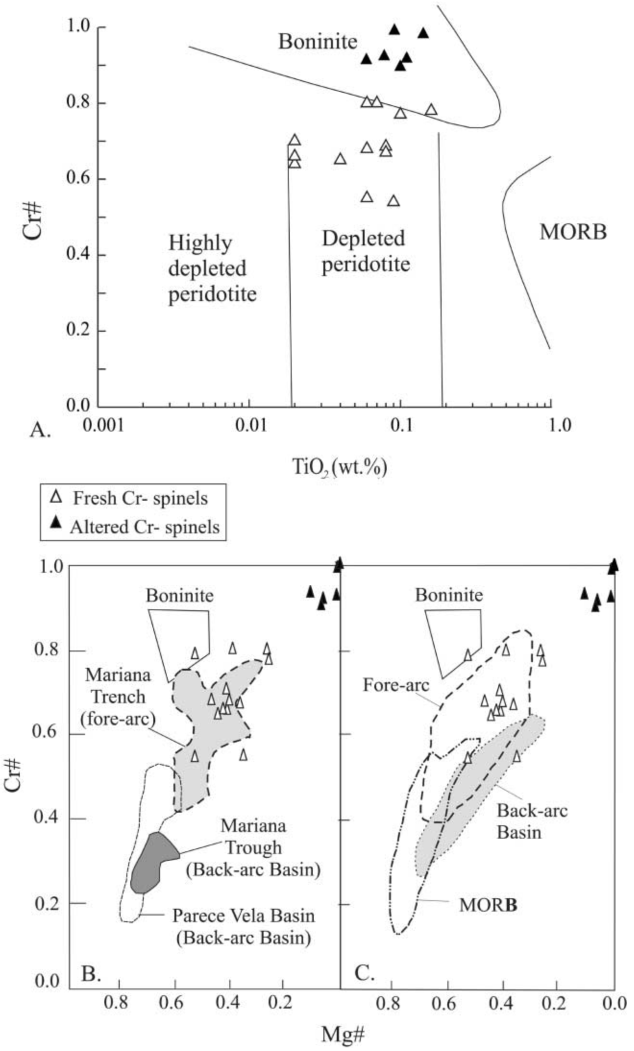

Figure 6. *A*, Cr# versus TiO_2 diagram for the analyzed accessory chrome spinels (fields after Dick and Bullen 1984; Jan and Windley 1990; Arai 1992). *B*, Cr# versus Mg# for the analyzed spinels and their alteration products (modified by Proenza et al. 2004; after Dick and Bullen 1984). *C*, Cr# versus Mg# for the analyzed spinels and their alteration products (adopted from Stern et al. 2004). *MORB* = mid-ocean ridge basalt.

typical for mid-ocean ridge basalt (MORB) or back-arc basin basalt. Extensive melt depletion can occur either in the mantle wedge beneath arcs or perhaps in upper mantle associated with hotspot plumes (e.g., Pearce et al. 1984; Ishiwatari et al. 2003). Such depleted peridotites form most commonly in fore-arc regions as a subduction zone begins to form. The high Cr# and low Ti chrome spinels as well as depleted whole-rock composition of Wadi Semna serpentinized peridotites are consistent with such an interpretation. Accordingly, we suggest that the Wadi Semna serpentinites are fragments of oceanic lithosphere that formed in a forearc environment as part of a suprasubduction zone ophiolite. This result is consistent with inferences for other ANS ophiolites based on spinel compositions (Stern et al. 2004). The proposed model for the tectonic setting of Wadi Semna serpentinites is shown diagrammatically in figure 7*B*–7*D*. We show that such an interpretation is generally applicable to the ophiolitic rocks of the Eastern Desert of Egypt.

Discussion: Tectonic Setting of Formation of Eastern Desert Ophiolitic Peridotites

Controversy continues concerning the tectonic environment in which ANS 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 forearc during subduction initiation. Magmas with boninitic affinities are reported from the Neoproterozoic ANS (Wolde et al. 1993; Yibas et al. 2003; Katz et al. 2004; Teklay 2006). Because Phanerozoic boninites appear to be restricted to a forearc setting (e.g., Hawkins et al. 1984; Murton 1989; Johnson and Fryer 1990; Stern and Bloomer 1992; Bédard 1999; Beccaluva et al. 2004), it can be inferred that boninites in the ANS also formed in a forearc.

The available radiometric ages for Eastern Desert ophiolitic rocks are listed in table A5. Egyptian ophiolites formed over an interval of ~105 million years (Zimmer et al. 1995), although there are only two ages for ophiolites from the central Eastern Desert, the focus of our study, and these are ~746 and ~788 Ma. These ages are slightly older than or overlap with the island arc stage (~770 to ~720 Ma; Stern and Hedge 1985).

Boninitic affinities of some Eastern Desert ophiolitic rocks have recently been recognized (e.g., El-Sayed et al. 1999; Abdel Aal et al. 2003); these authors inferred a back-arc or an interarc basin origin based on chemical compositions of the ophiolitic rocks. This interpretation conflicts with the observation that most boninites are now found in the forearcs of intraoceanic arcs. This is supported by the fact that clinopyroxene compositions of most Egyptian boninitic samples plot in the field characteristic for intraoceanic forearc regions (fig. 8). When interpreting the tectonic setting of Neoproterozoic ophiolitic rocks on the basis of major- and trace-element compositions of metavolcanic rocks encounters difficulties due to the effects of fractional crystallization and alteration, even when these problems are minimized, it can be very dif-

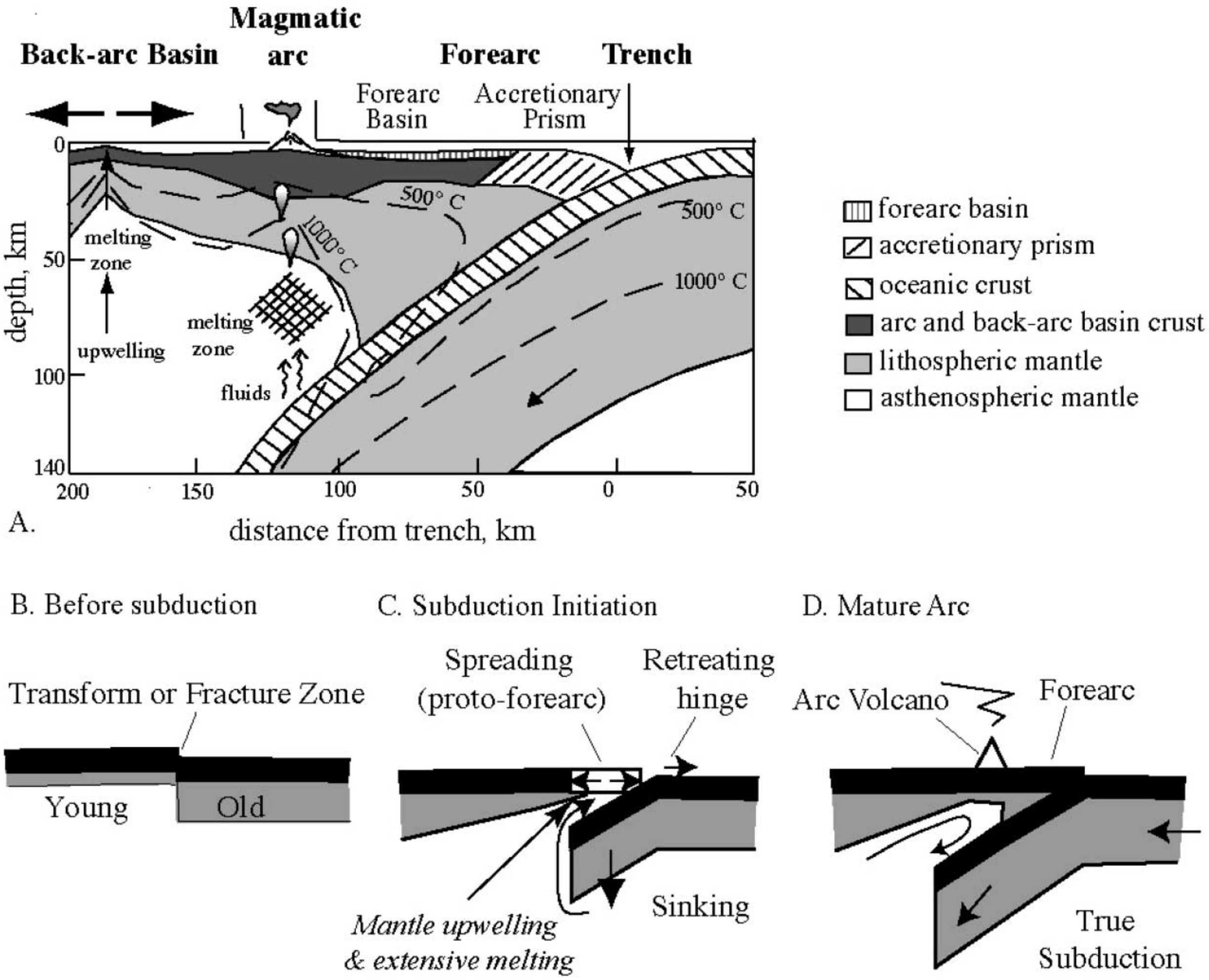

Figure 7. Cartoons showing the tectonic setting of Wadi Semna and other Egyptian serpentinites based on spinel compositions in peridotites. *A*, Cross section through a mature convergent margin showing isotherms (*dashed lines*) and zone of melting beneath the arc and back-arc basin (modified after Stern 2002). Note presence of cold lithosphere beneath forearc and complete absence of melting beneath the forearc of a mature convergent margin. *B–D*, Cartoons from Stern (2004) showing formation of a subduction zone, from collapse of a transform margin (*B*) to lithospheric subsidence associated with asthenospheric upwelling and extensive melting (*C*), leading to the formation of very depleted boninites and forearc peridotites, ultimately leading to the formation of a mature convergent margin (*A*, *D*). Spinel compositions of Egyptian peridotites are consistent with formation in *C*.

ficult to distinguish forearc and back-arc lavas on a basis of chemical compositions.

We have shown that spinels in peridotites retain their original igneous chemistry (with easily recognized exceptions, as discussed earlier). For this reason, composition of spinels in peridotites is a robust petrogenetic—and thus tectonic—indicator (e.g., Dick and Bullen 1984; Barnes and Roeder 2001). Our study of Wadi Semna peridotites and spinels consistently and unequivocally points to a forearc setting of formation. We expand on this approach to identify the tectonic setting of the ophiolitic serpentinites of Egypt in terms of spinel compositions.

The ranges and averages of Cr# in spinels from serpentinites and associated chromitite lenses from 23 different localities in the Eastern Desert (fig. 1*A*) are summarized in tables A6 and A7, respectively. We exclude spinels affected by alteration and extreme enrichment or depletion in Cr_2O_3, Al_2O_3, and $FeO_{(t)}$. We recognize that there is a bias toward serpentinites of the central Eastern Desert, which are much better sampled and studied than those of the southern Eastern Desert (fig. 1*A*); future studies of

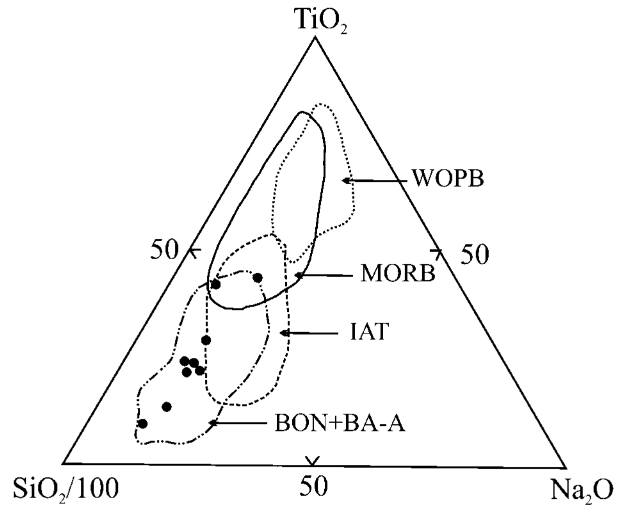

Figure 8. TiO_2-Na_2O-SiO_2 diagram for Egyptian boninitic pyroxenes (adopted from Abdel Aal et al. 2003; after Beccaluva et al. 1989). *WOPB* = within-ocean plate basals; *MORB* = mid-ocean ridge basalts; *IAT* = island-arc tholeiites; *BON+BA-A* = boninites + basaltic andesites and andesites from intraoceanic forearcs.

peridotites from the southern Eastern Desert and especially the Allaqi-Heiani-Gerf-Onib-Sol Hamed suture zone are needed.

Chemical analyses of chrome spinels in the serpentinized peridotites and the associated chromitite lenses are plotted on Cr# versus Mg# diagrams (fig. 9*A*–9*C*). These diagrams show that the spinels in chromitite lenses (podiform chromites; fig. 9*B*) have compositions that are significantly more magnesian on average than chromites disseminated in serpentinites (fig. 9*A*). The disseminated spinels are more affected by alteration and metamorphism than are those in the chromitite lenses. Altered spinels lie near the upper right corner of the diagram (fig. 9*C*), reflecting loss of Al and Mg to form chlorite aureoles as well as increase in ferric iron. The greater effect of alteration and metamorphism on the accessory spinels compared with those in the lenses is attributed to the proximity of disseminated spinels to nearby minerals containing Si needed to combine with Al and Mg released from the spinels to form chlorite.

Figure 9*D* shows that mean concentrations of Al and Ca in Eastern Desert serpentinites are similar to those expected for forearc harzburgites, with a couple of noteworthy exceptions. This result is similar to inferences based on Al contents alone (fig. 3*B*).

Data for two Eastern Desert serpentinites indicate that compositions of relict olivines are Mg rich, similar to olivines in forearc peridotites, suggesting that they are residual after extensive melting. Fo contents in relict olivines are >88, similar to those in other ANS ophiolites (Stern et al. 2004). Fo contents range from 91.3 to 93.0 in olivine from serpentinites from the Abu Daher area (Khudeir 1995), while in Um Khariga serpentinites, Fo is ~91 (A. E. S. Khalil and M. K. Azer, unpub. data). Compositions of coexisting olivine and spinels in Eastern Desert ophiolitic serpentinites further support a forearc setting for these ophiolites (fig. 10). Further analyses of coexisting relict olivines and spinels are needed to evaluate whether this is generally the case or unusual.

One exception to the general observation that Eastern Desert ophiolites have a forearc origin is the Gerf ophiolite, the largest and most complete ophiolite in the ANS. According to Zimmer et al. (1995), the Gerf ophiolite is an N-MORB-type ophiolite, which suggests a different tectonic setting for some ophiolites in southern Egypt, outside of the area we studied. It may be that ophiolites in the southern Eastern Desert have a different tectonic setting than do the central Eastern Desert ophiolites we have discussed. Testing this hypothesis requires further chemical, chronological, and isotopic studies of Egyptian ophiolitic rocks, especially those associated with the Allaqi-Heiani-Gerf-Onib-Sol Hamed suture in the far south. Further studies are also needed to understand ANS ophiolitic peridotites in Arabia and Sudan.

With the exception of the Gerf ophiolite, all studies of Egyptian ophiolites recognize the transitional geochemical character of lavas, between those of island arcs and MORB (e.g., El-Sayed et al. 1999; Abdel Aal et al. 2003; Farahat et al. 2004; Stern et al. 2004), and on this basis, a back-arc environment of formation is often inferred. Os-isotopic studies of chromites from Eastern Desert ophiolitic peridotites also are interpreted as forming in a supra-subduction zone environment (Ahmed et al. 2006). We agree that these transitional compositional features are due to the hydrous nature of magmatism and the effect of adding components from the subduction zone into the overlying mantle wedge. We also agree that Eastern Desert ophiolitic melts were generated in a strongly extensional intraoceanic arc, but the peridotite compositions do not support a back-arc basin environment of formation. Back-arc basin peridotites and spinels are similar to MOR peridotites and spinels; neither are as depleted as Egyptian serpentinites and associated spinels. There is much better agreement between the Egyptian data and the composition of modern forearc

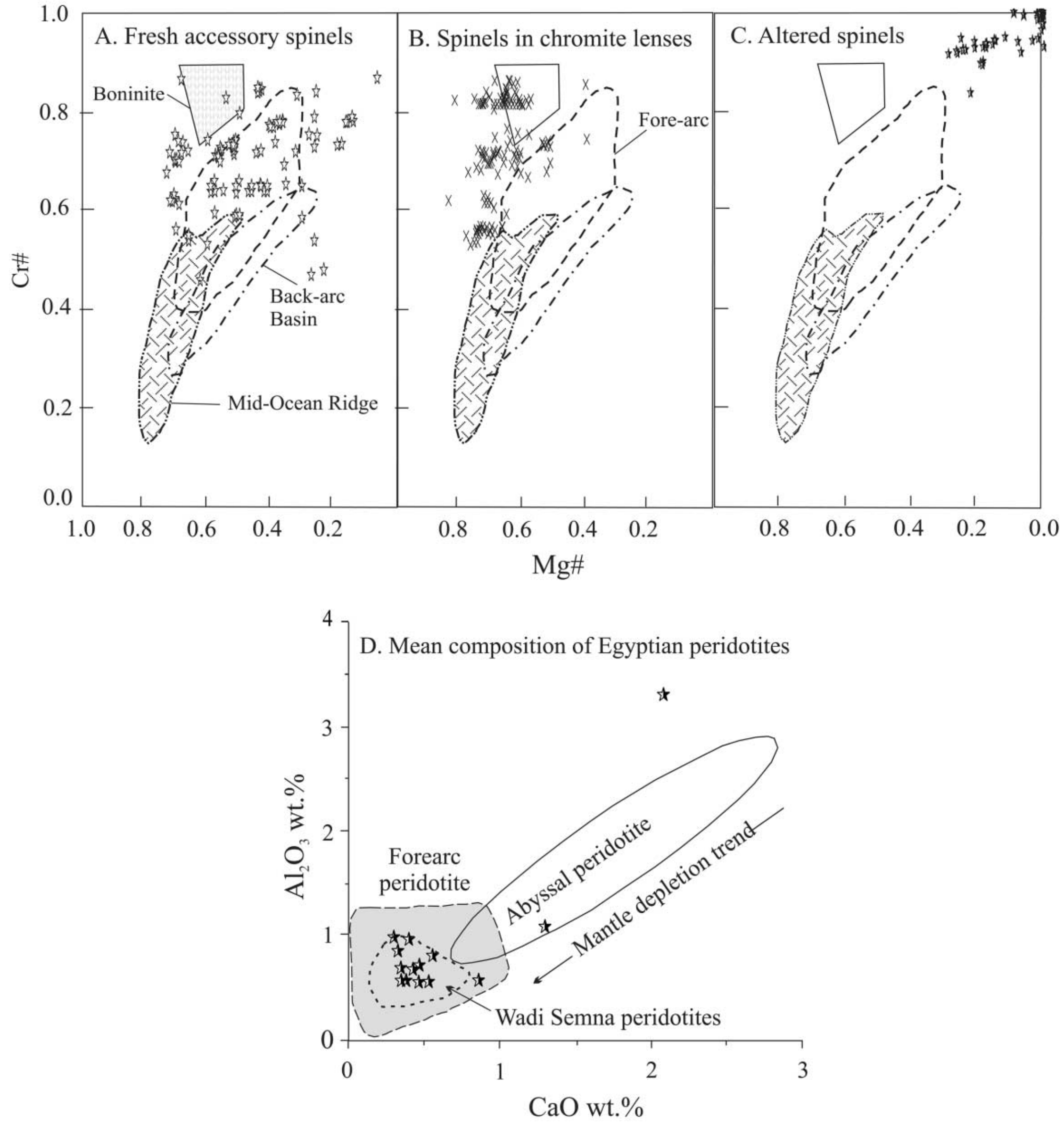

Figure 9. Cr# versus Mg# diagram for the Egyptian spinels in serpentinites (after Stern et al. 2004). The field boundaries are from Dick and Bullen (1984), Bloomer et al. (1995), and Ohara et al. (2002). *A*, Fresh accessory spinels. *B*, Spinels in the chromitite lenses. *C*, Alteration products of accessory spinels. *D*, Al_2O_3 versus CaO diagram showing the mean composition of the Eastern Desert serpentinites in comparison to forearc harzburgites (after Ishii et al. 1992).

peridotites and spinels, so we prefer a model that shows Egyptian ophiolitic peridotites mostly formed in a forearc during the beginning of subduction (fig. 7*C*) over a model where most Egyptian ophiolitic peridotites formed in a back-arc basin (fig. 7*A*).

Summary

The serpentinites of Wadi Semna define the northernmost ophiolitic serpentinites in the Eastern Desert of Egypt. Relatively fresh relics of partly serpentinized peridotites, showing gradational bound-

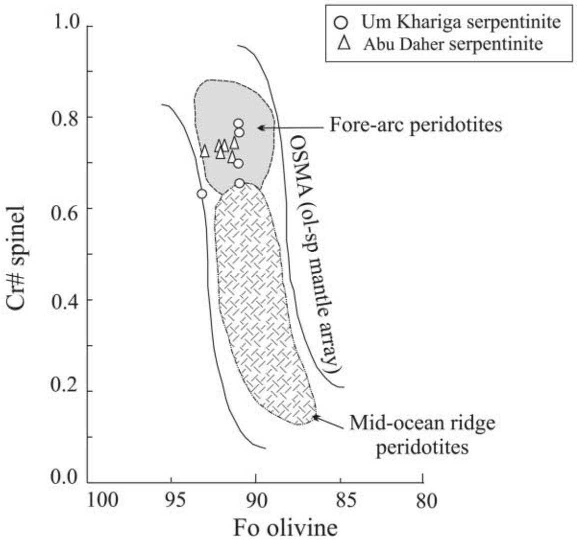

Figure 10. Cr# in spinels against Fo in coexisting olivine of serpentinites in Egypt (fields after Arai 1994). Chemical analyses of Abu Daher are adopted from Khudeir (1995), while those of Um Khariga are adopted from A. E. S. Khalil and M. K. Azer (unpub. data).

aries with the completely altered serpentinites, are observed. The absence of thermal effects of the serpentinites on the enveloping country rocks as well as their association with thrust faults indicate that the serpentinites were tectonically emplaced.

Wadi Semna serpentinites show a prevalence of mesh and bastite textures, suggesting derivation from harzburgite and dunite. The predominance of antigorite over other serpentine minerals indicates that the parent minerals were first retrogressed to form chrysotile and lizardite. Then, progressive metamorphism recrystallized these minerals into antigorite, probably during obduction. Four different spinel compositions are distinguished, namely, (1) magmatic chrome spinels, (2) hydrothermal altered chrome spinels (ferritchromite), (3) primary magnetite, and (4) metamorphic, synserpentinization magnetite. The alteration of chrome spinels to ferritchromite must have been related to serpentinization. The formation of chloritic aureoles around ferritchromite can be attributed to the dissolution of chrome spinels giving rise to ferritchromite rims. Ferritchromite retains Cr and Fe (Cr-magnetite), whereas Al and Mg are fixed in the coexisting silicate minerals. Excess of Al reacts with serpentine minerals, producing chloritic aureoles. The presence of kämmererite indicates that chromium released from chrome spinels and ferritchromite enters into chlorite structure where Cr substitutes for Al.

The chemical characteristics of the primary chrome spinels in Wadi Semna serpentinites are similar to those of modern forearcs. High Cr# in the analyzed chrome spinels (average = 0.69) indicates that these are residual after extensive partial melting. Therefore, the serpentinites of Wadi Semna represent a fragment of oceanic lithosphere that formed in a forearc environment; that is, they belong to an ophiolitic mantle sequence formed in a suprasubduction zone.

In the Eastern Desert of Egypt, chrome spinels disseminated in serpentinized rocks are usually more affected by alteration and metamorphism than are those from chromitite lenses. This feature can be attributed to greater subsolidus element redistribution with silicate phases in serpentinites than chromitite lenses. On the basis of the available data, the ophiolitic rocks in the Eastern Desert of Egypt, except Gebel Gerf, originated by forearc seafloor spreading during subduction initiation. The transitional geochemical characters between island arcs and MORB for the Egyptian ophiolites can be attributed to the transfer of large ion lithophile elements and volatile-rich components from the subduction zone into the overlying mantle wedge. The interpretation of a forearc setting for the ophiolitic rocks of Egypt is supported by the following: (1) the presence of sheeted dykes in some localities (El Sharkawy and El Bayoumi 1979; Nasseef et al. 1980), (2) the abundance of ophiolitic mélange, and (3) the occurrences of trench sediments as thin and highly foliated pelitic layers (Shackleton et al. 1980; Basta et al. 1983; Ries et al. 1983).

Ages of Egyptian ophiolites are similar to those of arc metavolcanic sequences in the Eastern Desert. It may be that the older ophiolites are more similar to modern MORB (e.g., Gebel Gerf). Further studies to understand the age and composition of ultramafic rocks along the Allaqi-Heiani-Gerf-Onib-Sol Hamed suture are needed to answer this question.

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