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ARTICLE

Geochemistry and fore-arc evolution of upper mantle peridotites in the Cryogenian Bir Umq ophiolite, Arabian Shield, Saudi Arabia

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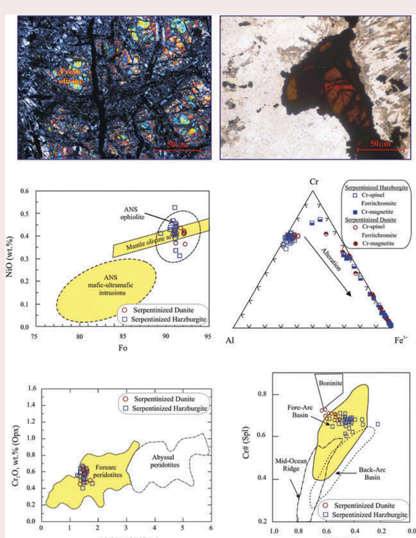
ABSTRACT

The Bir Umq ophiolite is one of the most important ophiolitic successions in the Arabian Shield, and represents an excellent case for the study of the tectonomagmatic evolution of the earliest Precambrian events in the juvenile part of the Arabian-Nubian Shield (ANS). It is a dismembered ophiolite, which includes a serpentinized peridotite with small amounts of gabbro and mélange, and is overlain by the Sumayir formation. The mantle section of the Bir Umq ophiolite has been pervasively sheared and folded during its emplacement and is extensively serpentinized, carbonated and silicified, resulting in the common development of magnesite and listwaenite along the shear zones. Listwaenite occurs in the form of upstanding ridges due to its resistance to erosion. Antigorite is the main serpentine mineral, which, however, has low amounts of lizardite and chrysotile, indicating that the present serpentinites formed by prograde metamorphism. The ophiolitic rocks of Bir Umq have undergone regional metamorphism up to the greenschist to amphibolite facies. The presence of mesh and bastite textures indicates harzburgite and dunite protoliths. The serpentinized peridotite preserves rare relicts of primary minerals such as olivine, pyroxene and Cr-spinel. The serpentinized ultramafics of Bir Umq have high Mg# [molar Mg/(Mg+Fe^{2+}); 0.90–0.93), low CaO, and Al_2O_3 contents similar to that of the environment of the suprasubduction zone. Additionally, they are characterized by the depletion of some compatible trace elements (e.g., Nb, Sr, Ta, Zr, Hf and REE), but show a wide variation in the Rb and Ba. Moreover, they are enriched in some elements that have affinities for Mg-rich minerals such as Ni, Cr, V, and Co. Fresh relics of olivine have high Fo (av. 0.91) and NiO (av. 0.42) contents, similar to those in the mantle olivine. The fresh Cr-spinel has high Cr# (0.68) and low TiO_2 content (av. 0.11), similar to those in modern fore-arc peridotites. The composition of both orth- and clinopyroxenes confirms the fore-arc affinity of the studied ultramafics. The present study indicates that the protoliths of the serpentinized ultramafics of Bir Umq have high partial melt degrees, which is consistent with the characteristics of ultramafic rocks formed in a subarc environment (fore-arc) within a suprasubduction zone system.



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Supplemental data for this article can be accessed here.

1. Introduction

The oceanic crusts of the Earth have different composition, thickness, and origin. Understanding the composition and origin of the oceanic crusts and lithosphere stands as an important focus of many petrologic and geochemical researches. Ophiolites are widespread in Saudi Arabia, which represents the part of the northwest Arabian-Nubian Shield (ANS).The ANS is an outstanding natural laboratory for examining the evolution and origin of mantle-derived juvenile crust. It represents the most widely exposed and best-preserved continental crust of juvenile character developed during the Neoproterozoic age on the Earth (Patchett and Chase 2002). Ophiolites of the ANS represent fractions of an oceanic lithosphere that were tectonically emplaced onto continental margins upon the closure of the Mozambique ocean and the collision between East and West Gondwana (e.g. Stern 1994; Dilek and Ahmed 2003; Johnson *et al*. 2003; Kusky *et al*. 2003; Azer and Stern 2007; Khalil *et al*. 2014; Gahlan *et al*. 2015; Obeid *et al*. 2016). Neoproterozoic ophiolites of the Arabian Shield have undergone multiple stages of metamorphism, deformation, and alteration (Al-Shanti and Gass 1983; Nassief *et al*. 1984; Ahmed and Hariri 2008). Most of these ophiolites are dismembered and not preserved as typical ophiolite successions. Available data about the ophiolitic rocks in the Arabian shield differ in quantity and quality. Moreover, most of the ophiolitic rocks in the Arabian Shield have not been studied in sufficient detail to define their tectonic setting and origin.

The study of ultramafic rocks associated with ophiolitic rocks can help to determine the tectonic setting and origin of ophiolites. Previous studies on the Neoproterozoic ophiolitic rocks of the Arabian Shield generated much controversy concerning their origin and tectonic setting (e.g., Bakor *et al*. 1976; Nassief *et al*. 1984; Pallister *et al*. 1988; Dilek and Ahmed 2003; Stern *et al*. 2004; Ahmed *et al*. 2012; Habtoor *et al*. 2017). Due to fractional crystallisation, alteration and metamorphism, the bulk chemistry of the Arabian ophiolites is less valuable in the study of petrogenesis. By contrast, relict primary minerals such as olivine, pyroxene and spinel can be used to characterize the geodynamic setting of the completely serpentinized ultramafic rocks (e.g., Dick and Bullen 1984; Bonatti and Michael 1989; Barnes and Roeder 2001; Khalil *et al*. 2014).

The Bir Umq ophiolite is one of the most important Precambrian oceanic lithosphere occurrences in the Arabian part of the ANS. However, published studies of the Bir Umq ophiolite are quite few (Al-Rehaili 1980; Al-Rehaili and Warden 1980; Pallister *et al*. 1988; Dilek and Ahmed 2003), with the character of its parent protolith and its tectonic interpretation remain poorly constrained. This is the first detailed field works, petrographical, geochemical and mineralogical investigations of the mantle section of the Bir Umq ophiolite. Although its upper mantle peridotite units are extensively serpentinized, however, the new mineral chemistry data from relict olivine, clinopyroxene, orthopyroxene and Cr-spinel phases make a valuable contribution to our understanding of petrogenetic evolution of the studied ophiolite. In terms of the tectonic setting of the formation of the Bir Umq ophiolite, the present work provides additional constraints supporting the forearc origin. We believe this contribution is scientifically valuable in understanding the evolution of the ANS.

2. Geologic setting

The Arabian Shield formed in the Neoproterozoic time and consists of well-defined tectonostratigraphic terranes separated by sutures that typically contain ophiolites. Ophiolitic rocks are the oldest oceanic fractions in the Arabian shield and identify the sutures between converging plates of the lithosphere. The Bir Umq ophiolite in the western side of Saudi Arabia is part of a major Neoproterozoic thrust and folded belt (Figure 1) that contains information on some of the earliest crust-forming events in the Neoproterozoic evolution of the ANS. It is located at the northeastern end of the Bir Umq-Nakasib suture, which extends 600 km in a southwesterly direction across the ANS (Johnson *et al*. 2003; Ali *et al*. 2010; Azer *et al*. 2013).

The Bir Umq area lies between longitude 23° 54\\& 24° 00\\N and latitude 40° 54\\and 41° 09\\E. It forms a low-relief landform and is dissected by many faults belonging to the Najd fault system. The Neoproterozoic rocks of the mapped area consist of ophiolitic rocks, Mahd Group and granodiorite (Figure 2(a)).

The Bir Umq ophiolite is a dismembered ophiolitic succession (838 and 764 Ma) which includes mainly serpentinized peridotite with small outcrops of gabbro and mélange in the south, and overlain in the north by the Sumayir formation. The structural trend of the ophiolite is ENE-WSW. However, it is also broadly folded following a north-south axis trending approximately through the town of Bir Umq. At its southern margin, the faults are steep north-dipping reverse faults(50°-70°). The shear fabrics and the down-dip plunge of stretching lineations indicate an early phase of top-to the south reverse dip-slip movement on a south-vergent thrust along the major faults, while later movement included dextral and sinistral horizontal shears (Blasband 2006).

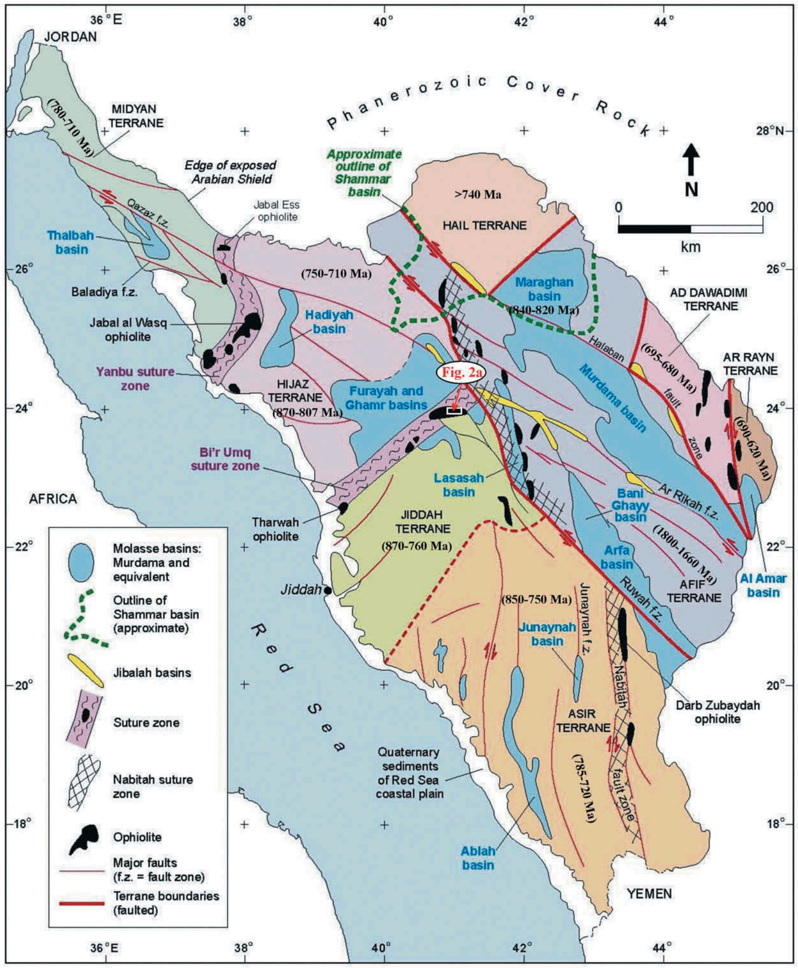

Figure 1. Regional tectonic map of the Arabian Shield showing the ophiolite belts in western Saudi Arabia (after Nehlig *et al.* 2002) showing terrane ages from Kröner *et al.* (1991), Pallister *et al.* (1988), Agar *et al.* (1992), Whitehouse *et al.* (2001), Dilek and Ahmed (2003), Hargrove *et al.* (2006a, 2006b). The location of the studied area (Figure 2a) is indicated.

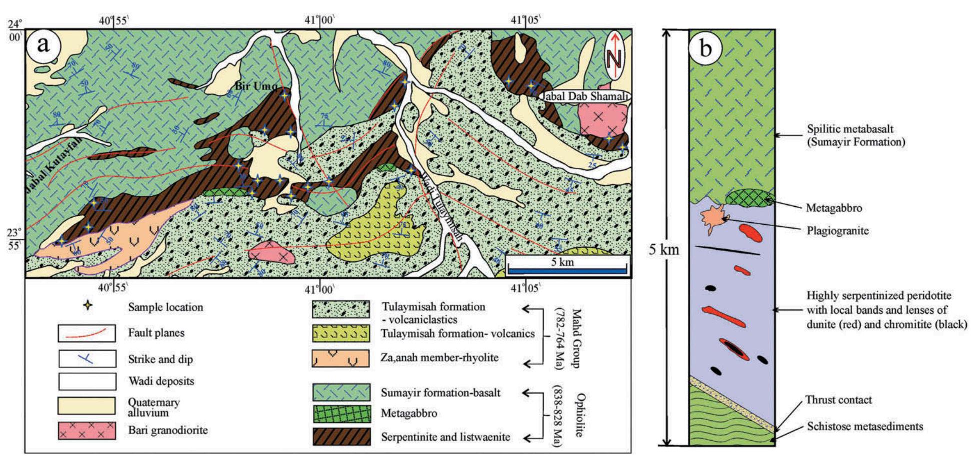

Figure 2. (a) Detailed geologic map of the Bir Umq area, modified after Kemp *et al.* (1982), geochronology after Dunlop *et al.* (1986) and Pallister *et al.* (1988); and (b) tectono-stratigraphic columnar section of the Bir Umq ophiolite.

The ultramafic rocks with minor presence of gabbro, plagiogranite, and ophiolitic mélange are concentrated close to Bir Umq, forming a chain of discontinuous hills with moderate relief. Serpentinized harzburgite is the dominant rock type in the mantle section of the study area, while serpentinized dunite occurs as bands and lenses within harzburgite as well as envelopes around chromitite pods (Figure 2(b)). The peridotite at Bir Umq was pervasively sheared and folded (Figure 3(a)) during the ophiolite emplacement and/or during subsequent orogenic events. It is extensively serpentinized, carbonated, and silicified, which results in the common development of magnesite and listwaenite along shear zones (Figure 3(b)).

Ophiolitic mélange of Bir Umq ophiolite occurs as discontinuous outcrops in the subvertical shear zones or the serpentinites tectonically resting on top of it that may represent an obduction-related mélange. The Bir Umq ophiolitic mélange consists of blocks of serpentinite, spilitic basalt, dolerite, and gabbro a few to several hundred metres across in a sheared serpentinite matrix (Figure 3(c)). The ophiolitic metagabbro exposed only at few localities and is isotropic gabbro with thin horizons of layered gabbro. It crops out as a thin (<50 m) sheet separated from the serpentinites by the fault zone, and as several scatter masses that are faulted against serpentinites. It grades from pyroxene-rich to hornblende-rich type and diorite. Also, small deformed gabbro has rodingite margins, indicating intrusion prior to latest serpentinization; therefore, it was probably formed during a late phase of ophiolite magmatism. Plagiogranite is found cutting serpentinized and carbonated peridotite to the south of Bir Umq, and yields zircon ages of 780–760 Ma, thus constraining the minimum age of the ophiolite emplacement (Pallister *et al*. 1988).

Along shear zones and thrust planes, the serpentinite is extensively sheared and intermingled with magnesite, talc–carbonate, and chlorite- and tremolite-rich rocks. Magnesite occurs as cryptocrystalline patches or fracture fillings. The contacts of talc-carbonate rocks are generally marked by major shear zones or fault planes. They are abundant along N–S shears as small dissected exposures of talc and magnesite.

Listwaenite occurs as upstanding ridges along shear zones and fault planes that are resistant to erosion (Figure 3(d)). In a few outcrops, the listwaenites are stained by iron oxide, which gives the rock its characteristic reddish brown colour. A few veinlets and irregular pockets of magnesite are observed in the sheared ultramafic rocks. The magnesite veinlets generally are concordant with the foliation in the sheared serpentinites. Small serpentinite rock fragments are observed within the magnesite.

The Sumayir formation crops out at the northeastern end of the Bir Umq suture and is extensively

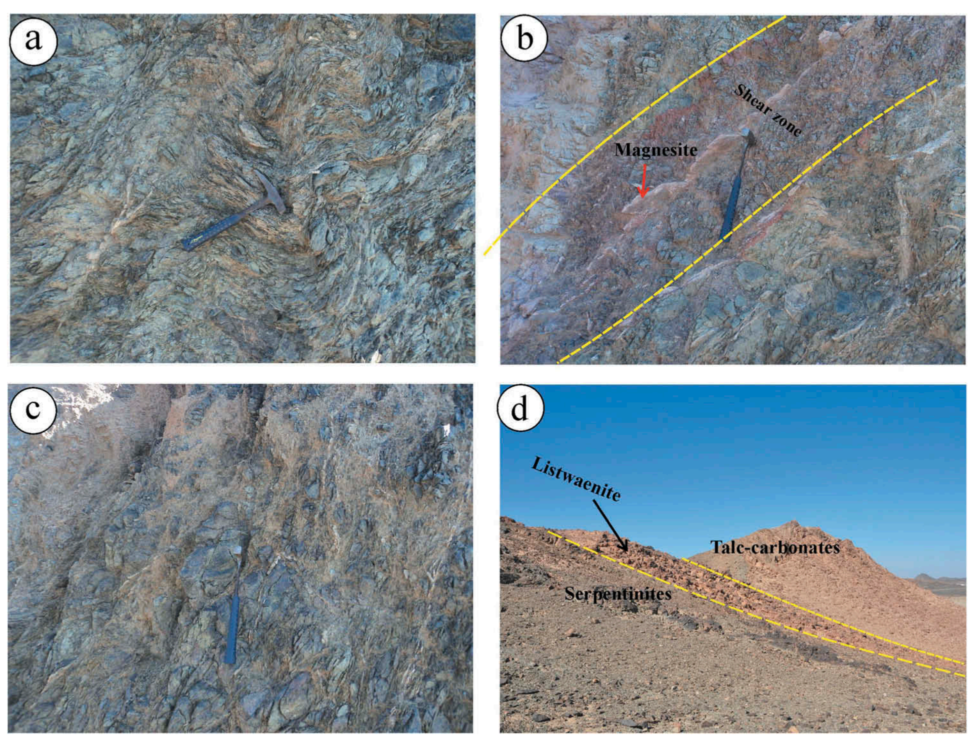

Figure 3. (a) Strongly folded serpentinite; (b) magnesite vein within a shear zone; (c) blocks of serpentinite within an ophiolitic mélange; and (d) ridge of listwaenite along shear.

covered by alluvium deposits. It represents members of the Bir Umq ophiolite. It consists of ~ 1.5 km thick succession of spilitic metabasalt, chert and metatuff (Al-Rehaili and Warden 1980; Kemp *et al*. 1982; Pallister *et al*. 1988; Johnson *et al*. 2002). The metabasalts of Sumayir formation yields a Rb-Sr whole-rock isochron of 831 ± 47 Ma (Dunlop *et al*. 1986).The rocks of the Mahd group are the most common rocks in the mapped area. The Mahd Group pertains to an island arc volcanic system It include metabasalt, metaandesite, and the felsic varieties (metadacite, metarhyodacite and metarhyolite) associating their metapyroclastics (conglomerate and tuffs) (Kemp *et al*. 1982; Roobol 1989; Hargrove 2006). Felsic volcanics and their pyroclastics are most common in the lower part of the group that overlain by basalt and andesite with andesitic breccia and tuff. The top of the Mahd Group include epiclastic breccias and conglomerates, sandstone, siltstone, and local limestone. The Bari granodiorite intrudes the Mahd group and the metabasalt of Sumayir Formation. It is overlain by Quaternary alluvium. The Bari granodiorite consists of medium -to-fine-grained biotite granodiorite that grades to tonalite.

There are some age constrains for the Neoproterozoic rocks in the study area. The ages of Bir Umq ophiolite and associated intrusions range between 838 and 764 Ma (Dunlop *et al*. 1986; Pallister *et al*. 1988). U-Pb zircon model age of 838 ± 10 Ma is obtained from diorite in the ophiolite close to the Bir Umq fault (Pallister *et al*. 1988). Ophiolitic metagabbro of Bir Umq yield a composite Sm-Nd isochron age of 828 ± 47 Ma, while metabasalt yields a Rb-Sr whole-rock isochron of 831 ± 47 Ma (Dunlop *et al*. 1986). Plagiogranite cutting serpentinized and carbonated peridotite of Bir Umq gave single-point zircon model ages of 764 ± 3 Ma and 782 ± 5 Ma that is interpreted to be the minimum age of ophiolite emplacement (Pallister *et al*. 1988). The Bari granodiorite has a SHRIMP crystallisation age of 776 ± 6 Ma (Hargrove 2006).

3. Petrography

All the ultramafic rocks in the Bir Umq area are highly serpentinized and altered to admixture of serpentines and their derivations. Based on the petrographic studies, the studied rocks are distinguished into serpentinites, listwaenite, talc-carbonate rocks, and magnesite. The detailed petrographic characterization of the rock types is presented below.

3.1. Serpentinites

Based on the petrographic studies, the serpentinized ultramafic rocks can be recognized into massive and sheared serpentinites. Both types have the same mineralogical composition, but in the sheared type the minerals are organized in parallel arrangement, producing a schistose texture. They are mainly composed of serpentine minerals with variable amounts of carbonates and talc with minor Cr-spinel, magnetite, amphiboles, sulphides, and chlorite. Despite the high degree of serpentinization, few relics of primary minerals can be recognized, including Cr-spinel, olivine, and pyroxene. Serpentine minerals include mainly antigorite with small amounts of chrysotile and lizardite. Antigorite mostly occurs as interpenetrating fine scales and as fibro lamellar aggregates exhibiting plumose structure (Figure 4(a)). Chrysotile occurs as cross-fibres filling veinlets within the antigorite(Figure 4(b)).

The ultramafic protoliths of the studied serpentinized peridotite are the harzburgite and the dunite, as indicated by the abundance of bastite and mesh textures, respectively. The bastite texture developed from the orthopyroxene and is characterized by magnetite striations along cleavage planes of the original crystals (Figure 4(c)). The serpentine minerals formed from the olivines and are characterized by a meshed texture (Figure 4(d)).

Olivine fresh relicts occur as highly strained anhedral crystals with kink bands similar to the olivines of deformed mantle tectonites from ophiolites They are dissected by network veins of serpentine, forming interlocking textures (Figure 4(e)). The fresh relics of both orthopyroxene and clinopyroxene are recorded in the serpentinized peridotite. The fresh relicts of orthopyroxene show a weak undulatory extinction and plastic deformational features such as kink structures and strain lamellae (Figure 4(f)). The orthopyroxene represents by enstatite which is mostly replaced by bastite. The clinopyroxene is represented by augite, which is transformed along its margins and cleavage planes into amphiboles and serpentines. Cr-spinel occurs mostly in the form of disseminated anhedral to subhedral crystals, but in rare occasions it has amoeboid and skeletal shapes. It is either light brown or dark brown to black in colour. Few Cr-spinel crystals are highly fractured and stretched due to strong shearing and deformation stress (Figure 5(a)). They are weakly to moderately altered to ferritchromite along the margins and cracks (Figure 5(b)),with rare films of dark Cr-magnetite.

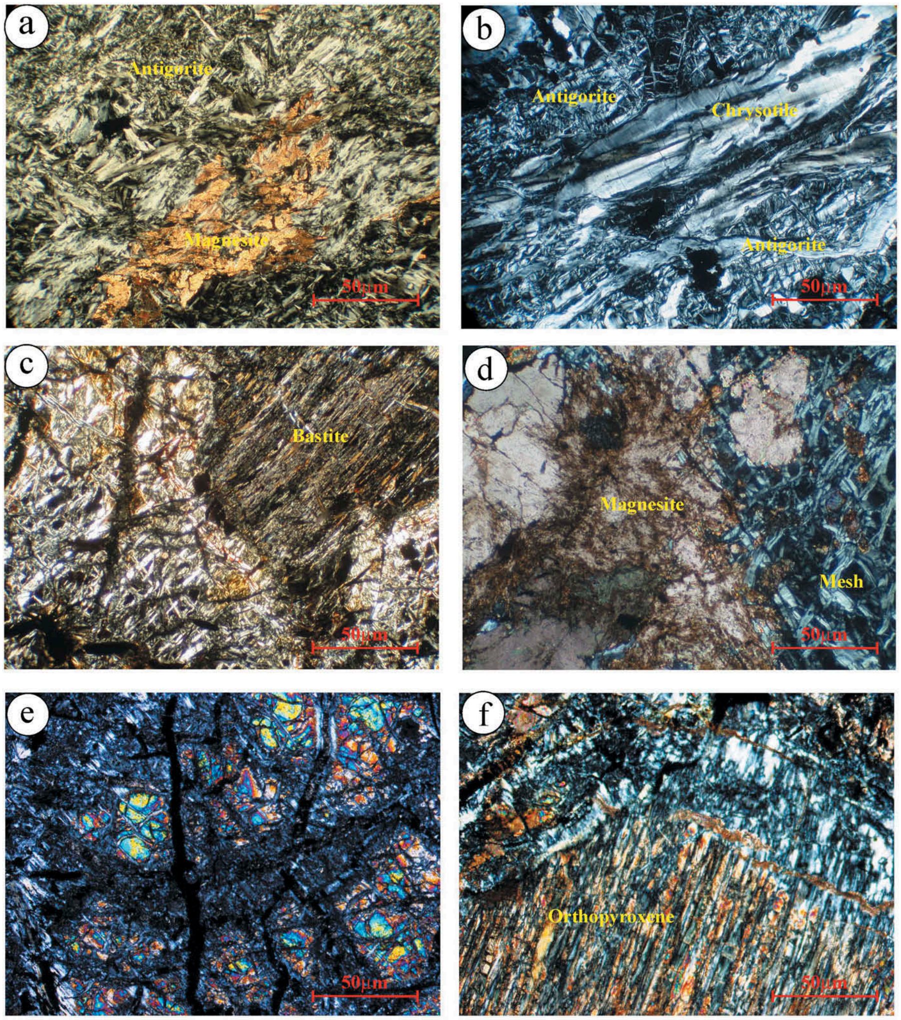

Figure 4. Photomicrographs showing petrographic textures under crossed nicols. (a) interpenetrating fine scaly and fibrolamellar aggregates of antigorite; (b) chrysotile fibres filling veinlets within the antigorite; (c) The bastite texture developed after orthopyroxene; (d) mesh texture after olivine and disperse crystals of magnesite; (e) fresh olivine relicts within a matrix of serpentine minerals; (f) fresh relicts of orthopyroxene within a matrix of serpentine minerals.

Carbonates occur as sparse crystals, patches, and fine aggregates which are mostly represented by magnesite (Figure 4(d)). Magnetite occurs as fine isolated grains or as streaks outlining the original crystals of pyroxene and their cleavage planes, giving a schiller structure. Also, it appears as a filling in the core of altered olivine or as veinlets. In rare cases, it undergoes martitization to bright-coloured haematite. Few secondary amphiboles are observed, including tremolite-actinolite and anthophyllite. The tremolite-actinolite occurs as fibrous aggregates (Figure 5(c)) embedded in the serpentine matrix or as veinlets of strong birefringence. Anthophyllite occurs as colourless wipes of moderate birefringence and parallel extinction (Figure 5(c)). The formation of anthophyllite reveals the beginning of another phase of alteration. Few accessory amounts of sulphides are recorded in a few samples, especially in those close to the shear zones. They are mainly pentalendite with minor gersdorffite. Pentalendite is commonly altered to garnerite and Ni-magnetite. Talc occurs as flaky or fibrous crystals developed after serpentine and, in turn, partially replaced by carbonate. It shows high interference colours and parallel extinction, and is more common in the serpentinite samples extracted close to the shear zones. Chlorite occurs as fine irregular flakes randomly distributed throughout the other constituents, or as rims around Cr-spinels. The latter is Cr-rich chlorite (kämmererite) and shows

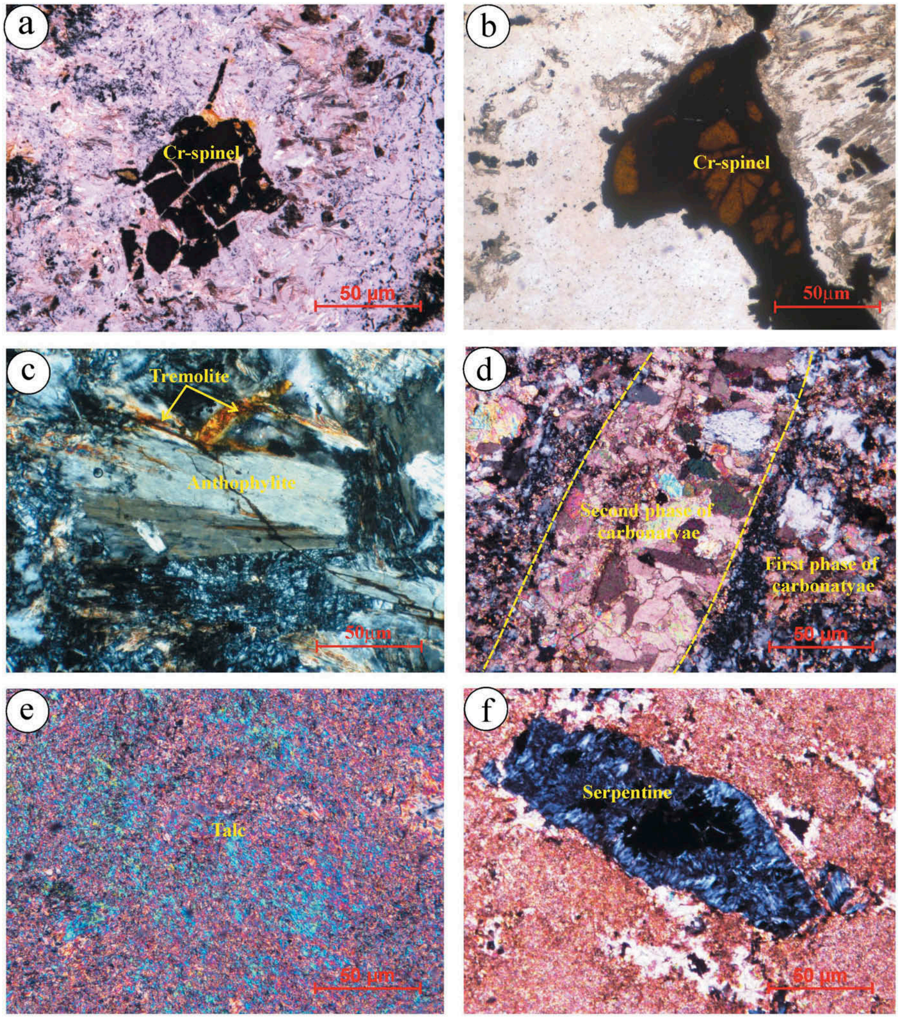

Figure 5. Photomicrographs showing petrographic textures under crossed nicols, except (a) and (b) under reflected light. (a) fractured Cr-spinel crystal; (b) Cr-spinel crystal altered along the margins and cracks to ferritchromite; (c) large crystal of anthophyllite and fibrous of tremolite-actinolite within serpentine matrix; (d) carbonate veinlet filling fractures within listwaenite; (e) fine dense microcrystalline aggregates of talc; and (f) rock fragments of serpentinite within talc.

an anomalous blue interference colour. This is the first record of kämmererite in the ophiolitic rocks of the Arabian Shield.

3.2. Listwaenite

The listwaenite is a fine-grained rock which can occur either as a massive rock with a porous texture, or as a sheared rock with a semi-schistose texture. It has different colours, such as brownish black, yellowish brown, and reddish brown. Quartz (45–55%) and carbonates (40–60%) are the essential minerals in the listwaenite. Minor amounts of serpentine, chlorite, chromite, and Cr-rich sericite (fuchsite) are also present. Quartz occurs in the form of fine-to medium-grained clusters or as wave-like thin veinlets. It shows a perfect undulate extinction. Carbonates occur in two phases. The first phase is represented by fine- to medium-grained aggregates or patches with pronounced twinkling and strong birefringence. The carbonates belonging to this phase are often stained with iron oxides with polysynthetic twinning. They have undergone different degrees of deformation, which are reflected by the presence of kink banding and by the subsequent fragmentation and recrystallization into fine-grained aggregates. The second phase is represented by the occurrence of carbonate veinlets filling fractures(Figure 5(d)). In some parts, carbonate veinlets are associated with quartz, which indicates a later replacement of carbonate by quartz.

3.3. Talc-carbonates

Talc-carbonates are fine-grained rocks exhibiting a schistose texture. They range in colour from brownish yellow to greenish grey-coloured rocks, and are composed essentially of carbonates and talc with minor amounts of serpentine, quartz, chlorite, and opaques. Carbonates occur as sparse patches, clusters, lenses, and veinlets embedded in a very fine talc matrix. Talc forms fine dense microcrystalline fibrous and platy aggregates with parallel arrangement (Figure 5(e)). It is colourless and has low relief, strong birefringence, and straight extinction, but it is sometimes stained by yellow limonitic materials. Opaque minerals include Fe-Ti oxides and Cr-spinel. The former occurs as fine anhedral disseminated crystals and is sometimes arranged along schistosity planes. Cr-chromite crystals occur as fine-grained deformed crystals scattered through the rock. Quartz occurs as scattered anhedral fine-grained crystals or in the form of veinlets cutting throughout the rock. It exhibits a wavy and undulate extinction. Few rock fragments of serpentinite are observed within the talc (Figure 5(f)).

3.4. Magnesite

Magnesite is a massive and cryptocrystalline rock consisting mainly of magnesite (> 95 vol.%) with minor amounts of calcite, dolomite, and serpentine minerals. Rare Cr-spinel and iron oxides are observed in a few samples. Some magnesite crystals are stretched, while others are re-crystallised, providing evidence of shearing. Cr-spinel crystals are highly altered into ferritchromite and Cr-magnetite. Dolomite and calcite are coarser than the magnesite, and fill cavities and vugs.

4. Mineral chemistry

Chemical compositions of different representative minerals were determined using a JEOL JXA-8500F electron microprobe at Washington state university(WSU). The analytical conditions were 15 kV accelerating voltage and 20 nA beam current along with mixes of suitable natural and synthetic mineral standards were applied for calibration. The analytical precision and detection limits of the analyses performed at WSU are listed on the website of the laboratory (https://environment.wsu.edu/facilities/geoanalytical-lab). The minerals identified in the Bir Umq ophiolite comprise olivine, pyroxenes, Cr-spinel, amphibole, and chlorite. The complete data set of the microprobe analyses is given in the online version (Supplementary Tables 1S-7S).

4.1. Olivine

Fresh relicts of olivine crystals are analysed from serpentinized ultramafic rocks of the Bir Umq ophiolites. Microprobe analyses and the calculated structural formulae of these olivine relics based on 4 oxygens are reported in Supplementary Table1S.Their composition showed little variability, with SiO_2 ranging from 40.73 to 41.73 wt. %., MgO contents ranging from 48.77 to 51.72 wt. %, and NiO contents ranging between 0.32 and 0.53wt.%, with negligible amounts of TiO_2 (<0.05 wt. %), Al_2O_3 (<0.02 wt. %), Cr_2O_3 (<0.06 wt. %), and CaO (<0.05 wt. %). The olivine of the serpentinized dunite have relatively higher Fo (91–92; av. 92) than those of the serpentinized harzburgite (Fo = 89–92; av. 91).

The analysed olivines are homogeneous (unzoned) forsterite, which indicates relatively stable conditions during crystallisation of olivine and formation of ophiolitic mantle section. The analysed olivines have NiO and Fo contents mostly similar to those of the olivine in the mantle array (Takahashi *et al*. 1987, Figure 6(a)). They compare well with the olivines from ophiolitic rocks of the ANS, but they have higher NiO and Fo than the mafic-ultramafic intrusions of non-ophiolitic origin (e.g., Khudeir 1995; Helmy and El Mahallawi 2003; Azer and El-Gharbawy 2011; Azer *et al*. 2016, 2017).

4.2. Pyroxenes

Orthopyroxene is analysed from the serpentinized harzburgite and dunite, while clinopyroxene is analysed only from the serpentinized harzburgite. The analysed pyroxenes and their structural formulae are presented in Supplementary Tables 2S and 3S.According to the pyroxene nomenclature of Morimoto *et al*. (1988), the analysed orthopyroxene is mainly enstatite, whereas the clinopyroxene ranges in its composition from diopside to augite. The enstatite contents of orthopyroxenes range from 89 to 92%. Both the orthopyroxene and the clinopyroxene of the Bir Umq ultramafics have low Al_2O_3 contents, in the range of 1.26–1.78 wt.%, while the Cr_2O_3 content ranges from 0.40 to 0.67wt.%. The orthopyroxenes in dunite have high Mg# (av. 0.93) than those in the harzburgite (av. 0.92). The clinopyroxene has higher Mg# (av. 95)than that in orthopyroxene (av. 92). The high Mg# values of both pyroxenes are similar to those of the residual mantle harzburgites (e.g., Jan and Windley 1990; Arai 1992). The low TiO_2contents (< 0.2%) of the clinopyroxene indicate its non-alkaline character (Le Bas 1962).

On the Al_2O_3vs. Cr_2O_3 discrimination diagram, the orthopyroxene has the characteristics of primary mantle orthopyroxene of depleted harzburgites (Figure 6(b)), but differs from secondary orthopyroxenes in regionally

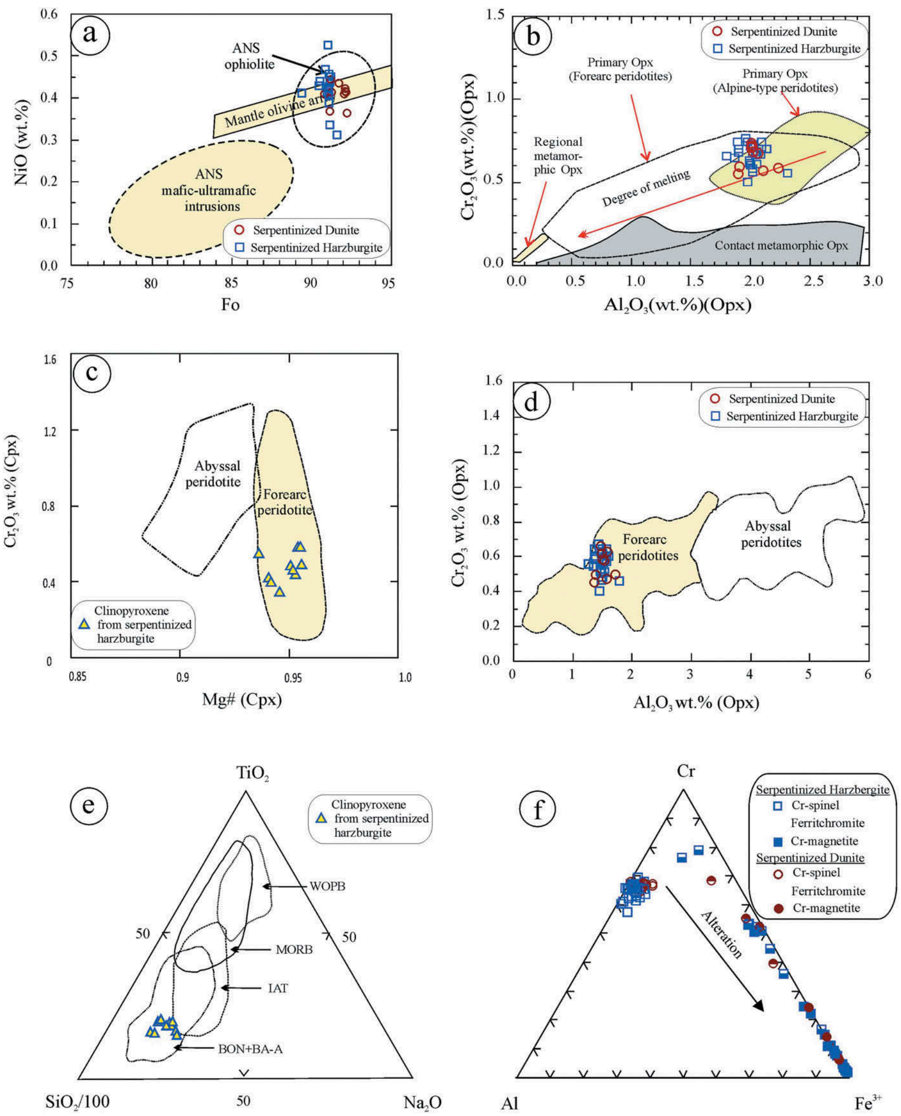

Figure 6. (a) NiO vs. Fo of olivine in the Bir Umq serpentinized harzburgite and dunite [mantle olivine array after Takahashi *et al.* (1987); field of mafic-ultramafic intrusions from Khudeir (1995), Ahmed *et al.* (2008), Azer *et al.* (2017); field of ANS ophiolites based on data from Khalil *et al.* (2014), Gahlan *et al.* (2015), Ahmed and Habtoor (2015), Obeid *et al.* (2016); Gahlan *et al.* (2018) and Azer *et al.* (2019)]; (b) Al_2O_3 vs. Cr_2O_3 of orthopyroxene (adapted from Obeid *et al.* 2016); (c) Mg# vs. Cr_2O_3 of clinopyroxene compared to fore-arc peridotite field from Ishii *et al.* (1992), and abyssal peridotite field (Hamlyn and Bonatti 1980; Johnson *et al.* 1990); (d) Al_2O_3 vs. Cr_2O_3 of orthopyroxenes, with fore-arc peridotite fields after Ishii *et al.* (1992) and abyssal peridotite field from Johnson *et al.* (1990); (e) TiO_2–Na_2O–SiO_2 diagram for clinopyroxene (Beccaluva *et al.* 1989: WOPB = within-ocean plate basalts, MORB = mid-ocean ridge basalts, IAT = island arc tholeiites and BON+BA-A = boninites + basaltic andesites and andesites from intra-oceanic fore-arcs); and (f) Cr–Al–Fe^{3+} plot of chromian spinels and their alteration products.

or thermally metamorphosed ultramafic rocks. The high Mg# and low Cr_2O_3 content of clinopyroxene, and the low content of Al_2O_3 of orthopyroxene consistently point to fore-arc peridotites (Figure 6(c,d)). The clinopyroxene has a chemical composition similar to that of boninite (Figure 6(e)). In general, boninite is characteristic of intra-oceanic fore-arcs (e.g., Bédard 1999; Beccaluva *et al.* 2004; Dilek *et al.* 2008; Dilek and Thy 2009), supporting a fore-arc setting for the ultramafic rocks of Bir Umq.

4.3. Cr-spinel

The analyses of Cr-spinels and their structural formulae based on 4 oxygens are given in Supplementary Tables 4S and 5S. Some Cr-spinels display zoning from fresh Cr-spinel core to altered rims. The alteration products of Cr-spinel are presented mainly in the form of ferritchromite with Cr-magnetite (Table 5S). On the Al–Cr–Fe^{3+} triangular plot (Figure 6(f)), the fresh Cr-spinels plot close to the Cr–Al join. Meanwhile, ferritchromite and Cr-magnetite plot along or close to the Cr–Fe^{3+} join, reflecting an increase in

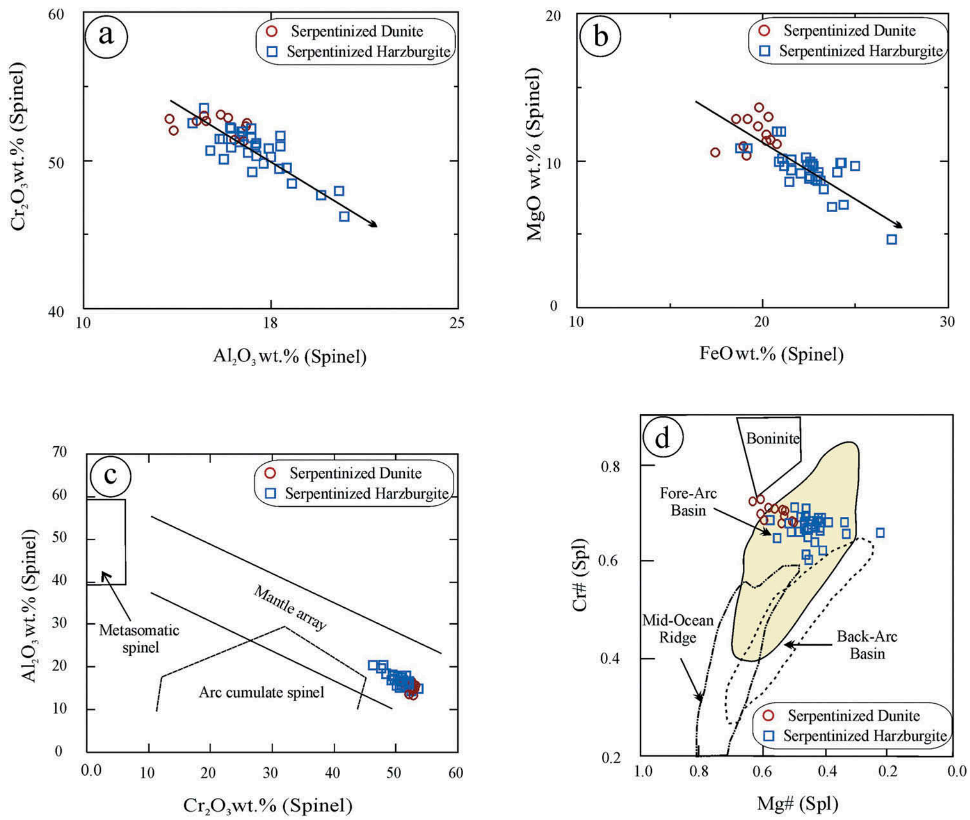

Figure 7. (a) variation diagram showing decrease of Cr_2O_3 with increase of Al_2O_3 in fresh relicts of Cr-spinel; (b) variation diagram showing decrease of MgO with increase of FeO in fresh relicts of Cr-spinel; (c) Cr_2O_3 vs. Al_2O_3 diagram for fresh relicts of Cr-spinel (after Franz and Wirth 2000); (d) Cr# vs. Mg# diagram for fresh Cr-spinels (after Stern *et al.* 2004).

Fe_2O_3 and a loss in Al_2O_3 and Cr_2O_3 due to alteration and metamorphism. Al_2O_3 of the fresh Cr- spinel cores correlates negatively with Cr_2O_3, whereas FeO correlates negatively with MgO (Figure 7(a,b)).

The fresh Cr-spinel in serpentinized dunite has concentrations of Cr_2O_3 (Cr# = 0.68–0.73; av. 70) and MgO (Mg# = 0.51–0.64; av. 0.57) that are significantly higher than those found in Cr-spinels in harzburgite (Cr# = 0.60–0.71; av. 0.67 and Mg# = 0.23–0.58, av. 0.45). All the analysed primary Cr-spinels have low Fe^{3+}# [$(Fe^{3+})/(Fe^{3+}$+ Cr+Al)] < 0.08. A similar feature is observed in the Cr-spinels of the serpentinites in the Eastern Desert of Egypt (e.g., Khalil *et al.* 2014; Gahlan *et al.* 2015).Ferritchromite and Cr-magnetite are rich in FeO, but depleted in Al_2O_3, MgO, and Cr_2O_3. MnO contents in the ferritchromite are higher than in fresh Cr-spinel and Cr-magnetite.

The compositions of fresh Cr-spinel fall within the spinel mantle array (Figure 7(c)) of Franz and Wirth (2000).The fresh Cr-spinels have high Cr# (>0.6) and low TiO_2 (≤ 0.4 wt.%), indicating that the ultramafic rocks of Bir Umq are a depleted residual after high-degrees of partial melting (e.g., Uysal *et al.* 2012). They have Cr# and Mg# values consistent with those of fore-arc peridotites (Figure 7(d)), and similar in this regard to those of ANS ophiolites (e.g., Stern *et al.* 2004; Azer and Stern 2007; Khalil *et al.* 2014; Obeid *et al.* 2016; Gahlan *et al.* 2018).

4.4. Secondary minerals

The analysed secondary minerals include amphiboles and chlorite. The chemical compositions and structural formulae of these minerals are listed in Supplementary Tables 6S and 7S. The chemical formulae of the amphiboles were calculated on the basis of 23 oxygen atoms in the anhydrous total using the 13-CNK method of Leake *et al.* (1997). The amphibole is classified as tremolite according to the amphibole classification of Leake *et al.* (1997). The low TiO_2 content (<0.1wt. %) of the tremolite indicates that they are secondary, and formed at the expense of pyroxenes. The tremolite also has low contents of Al_2O_3 (0.8–3.8wt. %), Na_2O (0.3–0.9wt. %), and Cr_2O_3 (0.1–0.4 wt. %).

Both green chlorite and violet-coloured Cr-bearing chlorite (kämmererite) are analysed. The analysed chlorites display wide chemical variations in SiO_2, Al_2O_3, Cr_2O_3, and FeO. The chlorite in the aureoles around chromian spinels are Cr-bearing chlorite (kämmererite; 2.68 to3.63 wt. % Cr_2O_3) and Mg-rich (20.99–23.37 wt. % MgO) with respect to the disseminated chlorite (Cr-poor and Fe-rich). Using the classification scheme of Hey (1954), the chlorite in the aureoles around chromian spinel is classified as ripidolite, whereas the disseminated chlorite is mostly pycnochlorite. The temperatures for chlorite formation calculated according to the calibrated geothermometer equation by Kranidiotis and MacLean (1987) are listed in Supplementary Table 7S. The inferred temperatures for the formation of disseminated chlorite ranges between 224 and 320°C, with an average of 271°C, while the temperature of kämmererite is in the range 285–319°C, with an average of 300°C, suggesting that the two chlorites represent different hydrothermal stages.

5. Whole-rock compositions

Based on the petrographic studies, 20 samples with minimal effects of hydrothermal alteration were selected for Whole-rock XRF analyses at Peter Hooper GeoAnalytical Lab, Washington State University, USA. The highly carbonated samples were not analysed to avoid misinterpretation because they are highly affected by alteration. The samples are crushed and homogenized to pebble size, and subsequently pulverized by an agate grinding bowl. Concentrations of major and trace elements were determined by X-ray fluorescence (ThermoARL X-ray Fluorescence Spectrometer). Based on the duplicate analyses of samples, the analytical precision is better than 1% (2σ) for most major elements, and better than 5% (2σ) for most trace elements (except V, Cr, Ni and Sc). The complete XRF procedure and its analytical precision and detection limits are fully documented in Johnson *et al.* (1999). Additionally, they listed on the laboratory website (https://environment.wsu.edu/facilities/geoanalytical-lab).

Whole rock geochemical data and the normative compositions for the studied serpentinized ultramafic rocks of the Bir Umq ophiolite are shown in Supplementary Tables 8S and 9S. Due to the high

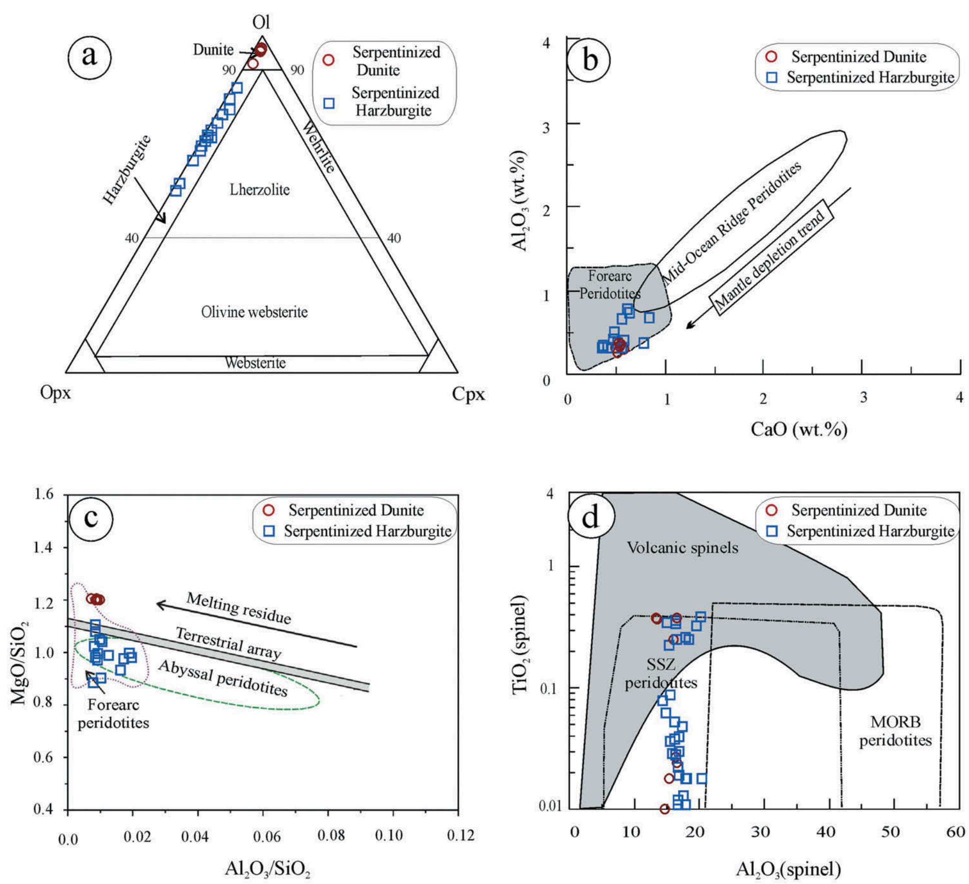

Figure 8. (a) Nomenclature of Bir Umq serpentinized ultramafic rocks based on Ol-Opx-Cpx normative composition (after Coleman 1977); (b) Al_2O_3vs.CaO diagram for serpentinized ultramafic rocks of Bir Umq (Ishii *et al.* 1992); (c)MgO/SiO_2 versus Al_2O_3/SiO_2 diagram for the Bir Umq ultramafic rocks [terrestrial array after Jagoutz *et al.* (1979) and Hart and Zindler (1986); primitive and depleted mantle values from McDonough and Sun (1995) and Salters and Stracke (2004); abyssal peridotites field after Niu (2004); field of fore-arc peridotites after Pearce *et al.* (2000) and Parkinson and Pearce (1998)]; (d)TiO_2 versus Al_2O_3 discrimination diagram (after Kamenetsky *et al.* 2001).

serpentinization of the Bir Umq ultramafic rocks, it is not suitable to conduct modal percentage analyses of the mafic minerals for use in the classification scheme of Streckeisen (1976). Therefore, the ultramafic rocks were classified using the whole-rock chemistry based on the normative compositions of the ultramafic rocks (Supplementary Tables 9S). The normative proportions of olivine, orthopyroxene, and clinopyroxene classify the serpentinized ultramafic rocks mainly as harzburgites and, less commonly, as dunite (Figure 8(a)).

The serpentinized ultramafic rocks are rich in MgO (36.15–40.48 wt. % in harzburgite and 42.46–43.26 wt. % in dunite). Additionally, they are poor in Al_2O_3 (< 1.0 wt. %), CaO (0.37–0.84 wt. %), and Na_2O (<0.03 wt. %). The low CaO contents are consistent with low clinopyroxene abundance and absence of plagioclase, as indicated by the low Al_2O_3 and by microscopic investigation. The concentration of iron falls within a narrow range (Fe_2O_3 = 6.76–8.14 wt. %). The serpentinized harzburgite are rich in SiO_2 and depleted in MgO compared to the serpentinized dunite. All the analysed samples have high LOI values (11.45–14.67 wt. %), which indicate the hydrous nature of the serpentinized ultramafics.

The analysed ultramafic rocks show high Mg# [Mg/(Mg + Fe)], from 0.90 to 0.92 in the harzburgite, and from 0.92 to 0.93 in the dunite. The analysed ultramafic rocks show wide variations in their trace element contents (Supplementary Table 8S). They are commonly enriched in Cr (1110–3188 ppm), Ni (1967–2920 ppm), and Co (89–121 ppm).

6. Discussion

The ophiolitic peridotites can be used as indicators of the mantle deep-seated processes taking place under the Arabian Shield. A strong controversy is still ongoing about accepting a reliable model to explain the tectonic history of the ophiolitic ultramafic rocks in the Arabian Shield (e.g., Ahmed and Habtoor 2015; Neary and Brown 1979; Ledru and Auge 1984; Nassief *et al*. 1984; Quick 1990; Ahmed and Hariri 2008; Ahmed and Surour 2016). In fact, this dispute is due to the insufficiency of detailed field studies and the shortage of mineralogical and petrological data. To better understand the petrogenetic and geotectonic history of the Bir Umq ultramafic rocks, we herein combined all the information obtained regarding their field relationships, petrography, mineralogy, and geochemistry. Then, we integrated the obtained results with the available geological and geochemical data on the ultramafic rocks from the ANS.

6.1. Metamorphism and alteration

The ultramafic rocks throughout the Arabian Shield have undergone various degrees of deformation, metamorphism, and alteration. The alteration of the ophiolitic rocks of the Arabian Shield may have occurred before, during, or after emplacement. Serpentinization of the ultramafic members of all the Arabian Shield ophiolites is extensive and is often accompanied by a carbonatization, reflecting the activity of CO_2 in the serpentinizing fluids. Along sheared zones and thrusted planes, they are largely transformed into talc-carbonate rocks, magnesite, and listwaenite. The origin of the fluids causing the carbonate alteration remains to be elucidated. Obviously, the predominance of carbonate alteration of the Arabian Shield ophiolitic ultramafics suggests a huge flux of CO_2-rich fluids derived from the mantle dehydration that occurred during the Neoproterozoic time. The various degrees of low-temperature alteration are indicated by high loss on ignition (LOI) for the serpentinized harzburgite and dunite of the Bir Umq ophiolite (11.45–14.67 wt. %). The mineral assemblage observed in the Bir Umq ophiolite (serpentine–magnetite–actinolite–chlorite) is consistent with low-grade greenschist- amphibolite facies metamorphism.

Serpentine minerals may form by hydration of primary mafic phases or by recrystallization of earlier serpentine phases during prograde metamorphism. The most common prograde reaction product is antigorite, while lizardite is a characteristic product of a retrograde reaction. The essential serpentine mineral in the Bir Umq serpentinized ultramafic rocks is antigorite, with lower amount of chrysotile and lizardite, which indicates that serpentinites formed under prograde metamorphism (e.g., Deer *et al*. 1992; Derbyshire *et al*. 2013).

Ferritchromite formation can occur at temperatures as low as ~500°C (Kimball 1990; Mellini *et al*. 2005), which indicates greenschist facies metamorphism (Evans and Frost 1975; Suita and Strieder 1996) or lower amphibolite facies metamorphism (Suita and Strieder 1996; Mellini *et al*. 2005). Ferritchromite in fore-arc peridotites can form due to a short-lived heating phase during the exhumation of mantle peridotite during closing of ocean basins, in which the remaining assemblage may remain at greenschist facies (Saumur and Hattori 2013; Azer *et al*. 2019). High Fe^{3+} in the ferritchromite and Cr-magnetite rims around fresh relics of Cr-spinel in Bir Umq ophiolite suggest increasingly oxidizing conditions during metamorphism, whereas low Fe^{3+} contents in the primary Cr-spinel indicate melt extraction and equilibration at relatively low oxygen fugacity (e.g., Mellini *et al*. 2005; González-Jiménez *et al*. 2009; Anzil *et al*. 2012).

In the Bir Umq ophiolite, the observation that ferritchromite surrounds Cr-chromian spinel with sharp compositional gaps indicates a dominantly upper greenschist facies metamorphism with excursions to lower amphibolite facies metamorphism (Evans and Frost 1975; Frost 1991; Suita and Strieder 1996; Barnes and Roeder 2001). Moreover, the presence of ferritchromite rims suggests that the host-rocks have undergone a prograde alteration at higher temperature (>500°C) and under oxidizing conditions (e.g., Farahat 2008; González-Jiménez *et al*. 2009). The present data suggest that the temperature of prograde metamorphism of the Bir Umq ultramafic rocks was near or below 500°C.

The presence of kämmererite around primary relics of chromian spinel reflects a further, lower-temperature episode of alteration at ~300°C, according to the chlorite thermometry results discussed above. The high Cr content of kämmererite (Table 7S) suggests its formation during the alteration of Cr-spinel to ferritchromite. Most Cr and Fe enter into ferritchromite during alteration of Cr-spinel, whereas Al and Mg are released to the surrounding silicate minerals. Then, the excess Cr and Al react with serpentine minerals to produce kämmererite (Azer and Stern 2007; Gahlan *et al*. 2018).

6.2. Geodynamic setting and petrogenesis

Ophiolites represent remnants of ancient oceanic crust and upper mantle, which are tectonically emplaced onto continental margins due to closing of ocean basins. They show significant variations in their internal structure, geochemical characteristics, emplacement mechanisms, and tectonic environments (Dilek *et al*. 2008; Dilek and Furnes 2014). They represent a variety of tectonic settings, from the rift–drift and seafloor spreading stages to subduction initiation and terminal closure (Dilek and Furnes 2011, 2014; Furnes *et al*. 2014). Seafloor spreading in the suprasubduction zone is necessary for the formation of ophiolites in forearc during the early stage of subduction or in back-arc basins (e.g., Stern 2004; Azer and Stern 2007).

Ophiolitic rocks of the Arabian Shield have been studied from a long time because they represent an important lithology for the reconstruction of the geodynamic evolution of the Pan-African belt of the ANS. The tectonic environment of the Arabian Shield ophiolites was interpreted on the basis of major- and trace-element compositions (e.g., Ledru and Auge 1984; Nassief *et al*. 1984; Ahmed and Hariri 2008), which proved difficult due to the influence of fractional crystallisations and alterations. The tectonic settings and significance of the Arabian Shield ophiolitic rocks are still controversial. The published works about the petrological characteristics of the ophiolitic ultramafic rocks (mantle section) of the Arabian Shield indicate that it has evolved in a diversity of tectonic settings, including the mid-oceanic ridge and the suprasubduction zone settings (e.g., Ahmed and Habtoor 2015; Neary and Brown 1979; Quick 1990; Dilek and Ahmed 2003; Ahmed and Hariri 2008; Ahmed *et al*. 2012; Ahmed and Surour 2016). According to Dilek and Ahmed (2003), Neoproterozoic ophiolites within the Arabian Shield display a record of different ages and tectonic setting. They considered the ophiolites within the Yanbu and Bir Umq suture zones are the oldest (870–740 Ma) and formed in forearc oceanic crust. The youngest ophiolitic rocks (c. 627 Ma) in the Arabian Shield are recorded in the Nabitah-Hamdah fault zone within the Asir terrane. They are post-collisional in origin and have chemical compositions typical of mid-ocean ridge basalt similar to Ligurian-type oceanic crust developed in an intracontinental pararift zone (Dilek and Ahmed 2003).

The suprasubduction zone tectonic settings is the most adopted tectonic setting for the Arabian Shield ophiolites (e.g., Ahmed and Habtoor 2015; Nassief *et al*. 1984; Pallister *et al*. 1988; Stern *et al*. 2004; Johnson *et al*. 2004; Ahmed *et al*. 2012; Ahmed and Surour 2016). Nevertheless, there is still much controversy about the tectonic setting in which the Arabian Shield ophiolites were formed within the suprasubduction zone (fore-arc or back-arc basins). The petrographical studies of the ultramafic rocks of the Bir Umq ophiolite indicate the formation mainly of harzburgite, with minor dunite, which is similar to the composition of ultramafic tectonites formed in suprasubduction environments (Pearce *et al*. 1984; Qiu *et al*. 2007). The serpentinized ultramafic samples of Bir Umq are depleted in Al_2O_3 and CaO, similar to fore-arc peridotites (Figure 8(b)). They have similar MgO/SiO_2 (0.88–1.20) and Al_2O_3/SiO_2 (0.01–0.02) ratios to those of fore-arc peridotites (Parkinson and Pearce 1998; Pearce *et al*. 2000; Niu 2004). They are plotted at low Al_2O_3/SiO_2ratios (Figure 8(c)), similar to the fore-arc peridotite which underwent high degrees of partial melting.

In the highly serpentinized peridotite, the chemistry of relict minerals, particularly olivine, pyroxene and spinel, can be a useful tool to reflect the tectonic environment of the ultramafic rocks (e.g., Dick and Bullen 1984; Barnes and Roeder 2001; Ohara *et al*. 2002; Arif and Jan 2006; Uysal *et al*. 2012; Khalil *et al*. 2014; Obeid *et al*. 2016). The high Cr# (>0.6; Table 4S) of Cr spinels of the Bir Umq ultramafic rocks, combined with their low TiO_2 content (<0.4 wt. %), indicates that these rocks probably formed in suprasubduction zone tectonic setting. On the Al_2O_3 vs. TiO_2 diagram (Kamenetsky *et al*. 2001), the analysed fresh Cr-spinels are plotted in the suprasubduction zone peridotites (Figure 8(d)). The chemical compositions of fresh relicts of the primary minerals of the Bir Umq ophiolite also indicate its fore-arc setting. The Cr# ratio of the fresh Cr-spinel chromian spinel of the serpentinized ultramafics of Bir Umq is mostly >0.60, and is similar to those of modern fore-arc peridotites (Figure 7(d)).

The chemical compositions of the analysed orthopyroxene and clinopyroxene of the serpentinized ultramafics support the fore-arc setting for the Bir Umq ophiolite. They have Al_2O_3, MgO and Cr_2O_3 contents similar to those of the fore-arc peridotites (Figure 6(b–d)). Also, the clinopyroxene compositions of the present study plot in the boninite field (Figure 6(e)), which is characteristic for fore-arc of intra-oceanic arcs (e.g., Bédard 1999; Beccaluva *et al*. 2004).

The relicts of fresh primary olivines in the strongly serpentinized peridotites can provide insights into the tectonic setting under which the ultramafic protoliths were formed, viz. mid-ocean ridge setting or suprasubduction setting (Parkinson and Pearce 1998). Magma genesis in different tectonic settings reflects the different extents of melting, as the progressing of melting increases magnesian in residual olivines. An undepleted upper mantle should have olivines that are lower in magnesian than the residual mantle. The analysed olivine of the Bir Umq ophiolite is of Mg-rich nature (Fo >90),similar to the mantle olivines that represent the residual after extensive melting similarly to peridotite of fore-arc setting (Coish and Gardner 2004). In the fore-arc environment, depleted mantle is available beside water to reduce the high temperature of melting. Therefore, hydrous partial melting of depleted mantle leaves behind a residue of much depleted peridotite (Pearce *et al*. 2000).

The Mg# of the Bir Umq ultramafic rocks ranges from 0.91 to 0.93, indicating that they are mantle rocks (Bonatti and Michael 1989). The primitive mantle nature of the Bir Umq serpentinized ultramafics is supported by their Cr and Ni contents (Hart and Zindler 1986).Bulk rock ratios of MgO/SiO_2 (0.88–1.20) and Al_2O_3/SiO_2 (0.01–0.02) exhibited by the Bir Umq serpentinized ultramafics indicate their depleted nature, i.e. that they are residual materials that underwent high degrees of partial melting. Additionally, the high NiO contents of the olivines of the Bir Umq serpentinized peridotite are similar to those of the olivines of mantle rocks. The high Cr# values (av. 0.68) and low TiO_2 contents of the spinels of the Bir Umq ultramafic rocks may indicate either that they are residual mantle rocks that underwent high degrees of partial melting, or that they are associated with boninitic melts (Uysal *et al*. 2012).

6.3. Comparison with Arabian-Nubian Shield ultramafic rocks

The Bir Umq serpentinized ultramafics are mainly harzburgite with small amounts of dunite, which are similar to the Neoproterozoic ultramafic rocks of the ANS ophiolites (e.g., Azer and Stern 2007; Khalil *et al*. 2014; Obeid *et al*. 2016; Azer *et al*. 2019). Geochemically, the Mg# of the Bir Umq ultramafic rocks (0.91–0.93) is markedly higher than that of the peridotites of ANS layered mafic-ultramafic intrusions (Mg# = 77–87, Khudeir 1995; Helmy and El Mahallawi 2003; Azer and El-Gharbawy 2011; Habtoor *et al*. 2016; Azer *et al*. 2017), but is comparable to those of the ANS ophiolite peridotites (Mg# = 0.89–0.94, Khalil and Azer 2007). Also, Al_2O_3/SiO_2 ratios (0.012–0.021) of the Bir Umq ultramafic rocks are generally lower than those of peridotites of layered intrusions (Al_2O_3/SiO_2 = 0.03–0.21, Khudeir 1995; Helmy and El Mahallawi 2003; Azer and El-Gharbawy 2011; Habtoor *et al*. 2016; Azer *et al*. 2017), but are similar to those of peridotites of the ANS ophiolites(Al_2O_3/SiO_2 = 0.01–0.04, Khalil and Azer 2007; Khalil *et al*. 2014; Obeid *et al*. 2016), reflecting their depleted nature.

The NiO and Fo contents of the olivines of the Bir Umq ultramafic rocks are comparable to those of the peridotites of the ANS ophiolites, while they are markedly higher than those of the peridotites of the ANS layered mafic-ultramafic intrusions (Figure 6(a)). The Cr-spinels of the Bir Umq ultramafic rocks are sometimes zoned with ferritchromite rims, they are not accompanied by pleonast (green spinel), and have high Cr_2O_3 and low TiO_2 contents similar to those of the ANS ophiolite peridotites. (e.g., Khalil and Azer 2007; Farahat 2008; Ahmed *et al*. 2012). Collectively, the mineralogical, geochemical, and petrological characteristics of the Bir Umq ultramafic rocks suggest that these rocks are cognate to the ANS ophiolite ultramafic rocks rather than to peridotites of layered mafic-ultramafic. Based on the present data, the Bir Umq ophiolites appear to represent a fragment of oceanic lithosphere formed during subduction initiation in a fore-arc setting above a subduction zone (Figure 9). Lithospheric mantle beneath the fore-arc-basin during subduction initiation was affected by high-degree partial melting and evolved to a depleted mantle melt source. The present results are consistent with other ophiolites of the ANS (e.g. Stern *et al*. 2004; Azer and Stern 2007; Khalil *et al*. 2014; Obeid *et al*. 2016 and many others).

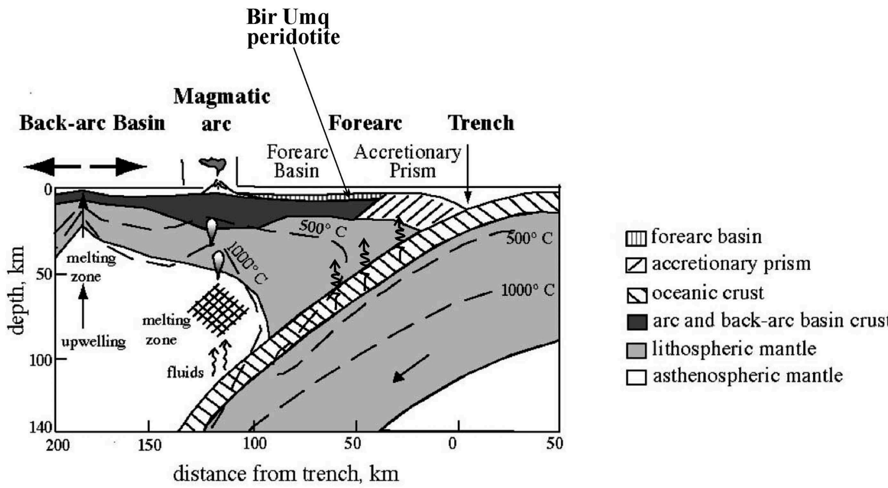

Figure 9. Cross-section showing the tectonic setting of Bir Umq ophiolite in the fore-arc environment above subduction zones (adopted from Azer and Stern 2007).

7. Summary

- The ophiolite of Bir Umq is one of the most remarkable Neoproterozoic ophiolitic massifs within the Arabian Shield. It represents a part of an incomplete ophiolitic section that was tectonically enclosed within – or thrusted over – island arc assemblages. It consists of a lower succession of serpentinized ultramafic rocks with small amounts of gabbro, plagiogranite, and mélange overlain by the spilitic basalt of the Sumayir formation. Along fault planes and shear zones, the ultramafic rocks are altered into assemblages of talc-carbonate, magnesite, and listwaenite.
- The Bir Umq mantle section is mainly constituted by serpentinized harzburgite with minor dunite, and abundance of mesh and bastite textures. Few fresh relicts of olivine, pyroxenes, and Cr-spinel are observed. The fresh cores of Cr-spinel are surrounded by ferritchromite and Cr-magnetite rims.
- The primary olivines have high Fo (89–92) and NiO (0.32–0.53 wt.) contents, which are consistent with those of residual mantle olivines that underwent high degrees of partial melt extraction. Pyroxenes have low Al_2O_3 and TiO_2 contents, similarly to those of depleted harzburgites. The fresh cores of Cr-spinel have high Cr# (>0.6) and low TiO_2 (<0.4).
- Bir Umq serpentinized ultramafics have high Mg#, Ni, Cr, and Co, and low Al_2O_3, CaO, and Al_2O_3/SiO_2 ratios, similarly to highly-depleted residual mantle rocks of fore-arc setting.

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Disclosure statement

No potential conflict of interest was reported by the author.

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Highlights

- Serpentinized ultramafics of Bir Umq have relict primary mantle minerals such as olivine, pyroxenes and chrome spinel.
- Texture, mineral and whole-rock chemistry show harzburgite and dunite protolith.
- Fresh relics of olivine have high Fo and Ni contents, similar mantle olivines.
- Serpentinized ultramafics of Bir Umq have chemical composition similar to the suprasubduction zone environment.
- Protoliths of the serpentinized ultramafics of Bir Umq have high partial melt degrees consistent with the ultramafic rocks formed in a fore-arc setting

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