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Petrology of the mantle rocks from the Muslim Bagh Ophiolite, Balochistan, Pakistan

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Abstract

The Muslim Bagh ophiolite comprises two main blocks; the Jang Tor Ghar Massif and Saplai Tor Ghar Massif, and possesses an almost complete ophiolite sequence. A thick mantle section, comprising foliated peridotite, grades into transition zone dunite. The foliated peridotite is mainly harzburgite with minor dunite which occurs within harzburgite and contains podiform chromite deposits. The transition zone comprises residual dunite with impregnations of wehrlite/pyroxenite, and is formed by predominantly mantle processes at its base and crystal fractionation at the top. The chromite in the mantle dunites is mostly podiform and vein-like in shape. The mantle rocks are porphyritic, with harzburgite poor in modal clinopyroxene and dunite poor in pyroxene, indicating that the peridotites are residues after melt extraction. This residual nature is further confirmed by the higher Cr # in spinel and Mg # in orthopyroxene and olivine from the foliated peridotite, suggesting their derivation by higher degree of partial melting from a depleted mantle source. The petrology of peridotite and the presence of huge chromite deposits in Muslim Bagh dunites suggest that it is formed from processes within a supra-subduction zone tectonic setting.

Keywords: Mantle section; Foliated peridotite; Dunite; Partial melting; Melt–rock reaction; Chromite.

1. Introduction

The Muslim Bagh ophiolite is regarded as a fragment of Late Cretaceous oceanic lithosphere, and composed of oceanic crust and upper mantle (Mahmood et al., 1995; Sawada et al., 1995; Kakar, 2011). The ophiolite has a partially to completely serpentinized thick mantle section consisting of foliated peridotite and a dunite rich transition zone. The foliated peridotite sequence is harzburgite-type (Nicolas, 1989) although minor lherzolite has also been reported from the basal section of the mantle sequence (Mahmood et al., 1995). A complete ophiolitic sequence, such as that of the Muslim Bagh, represents an excellent opportunity to investigate mantle processes at a spreading centre.

The Muslim Bagh mantle section and plutonic rocks were described as intrusive, and the associated volcanics as extrusive sequence by previous workers (HSC, 1960; Van Vloten, 1967; Bilgrami, 1964; Shah, 1974). More detailed mapping and geological understanding of the area has resulted from its economic potential in high grade chromite ore. As a result, the whole Muslim Bagh ophiolite has been mapped at scales between 1: 10,000 and 1:24,000 and compiled in the excellent maps of Rossman et al. (1971). This study is an initial report of the ongoing detailed work on the petrology of mantle rocks from the Muslim Bagh ophiolite and throws light on their nature and processes of formation.

2. Regional setting

The Muslim Bagh region is divided into three thrust-bounded geological terranes (Fig. 1). In the south, and tectonically lowermost, is the Calcareous belt of the Indian passive continent margin. This Zone consists mainly of limestones, sandstones and mudstones ranging in age from Early Jurassic to Paleocene that are overlain unconformably by Eocene to recent sediments (Warraich et al., 1995). This belt is overthrust by the Suture Zone that comprises the Muslim Bagh Ophiolite (see next section) which is also thrust over the Bagh Complex (Mengal et al., 1994). The Bagh complex consists of Triassic to Jurassic sedimentary rocks, Cretaceous igneous rocks, Cretaceous pelagic to hemipelagic sediments, and a small amount of mélange (Mengal et al., 1994). The Bagh Complex is divided into seven units, with each unit forming an individual thrust sheet (Kojima et al., 1994; Menga1 et al., 1994).

The Flysch Belt lies to the north of the Suture Zone and has Nisai Formation (Eocene) rocks at its base that unconformably overlie the ophiolite. These are succeeded by immature Oligocene turbidites of the Khujak Formation (Qayyum et al., 1996), Miocene–Pliocene arenites and conglomerates of the Multana Formation, and the lacustrine Pleistocene Bostan Formation (Fig. 1). Recently, Kasi et al. (2012) revised the stratigraphy of the area and renamed the Flysch belt as Pishin Belt; consisting of sandstones, mudstones, claystones and conglomerates, ranging in age from Miocene to Pleistocene.

3. The Muslim Bagh ophiolite

Muslim Bagh ophiolite, the largest fragment of the Zhob Valley ophiolites, occurs south-southeast of the Muslim Bagh town (Fig. 1). Other than the small fragments, the Muslim Bagh ophiolite comprises mainly two massifs; the Jang Tor Ghar Massif (JTGM west) and Saplai Tor Ghar Massif (STGM east) (Bilgrami, 1964; Fig. 1). Both blocks structurally overlie a series of metamorphic rocks with inverted metamorphic gradients. The JTGM is a tectonic klippe mainly composed of a refractory upper mantle section; here called foliated peridotites that occupy an area of about 150 km^2. The STGM shows a nearly complete ophiolitic sequence (Penrose Conference, 1972) ranging from foliated peridotite at the base through Mantle–Crust Transition Zone in middle, to the crustal rocks at top (Fig. 1). Many outcrops of dunite have large concentration of chromite deposits, which are mined in the area.

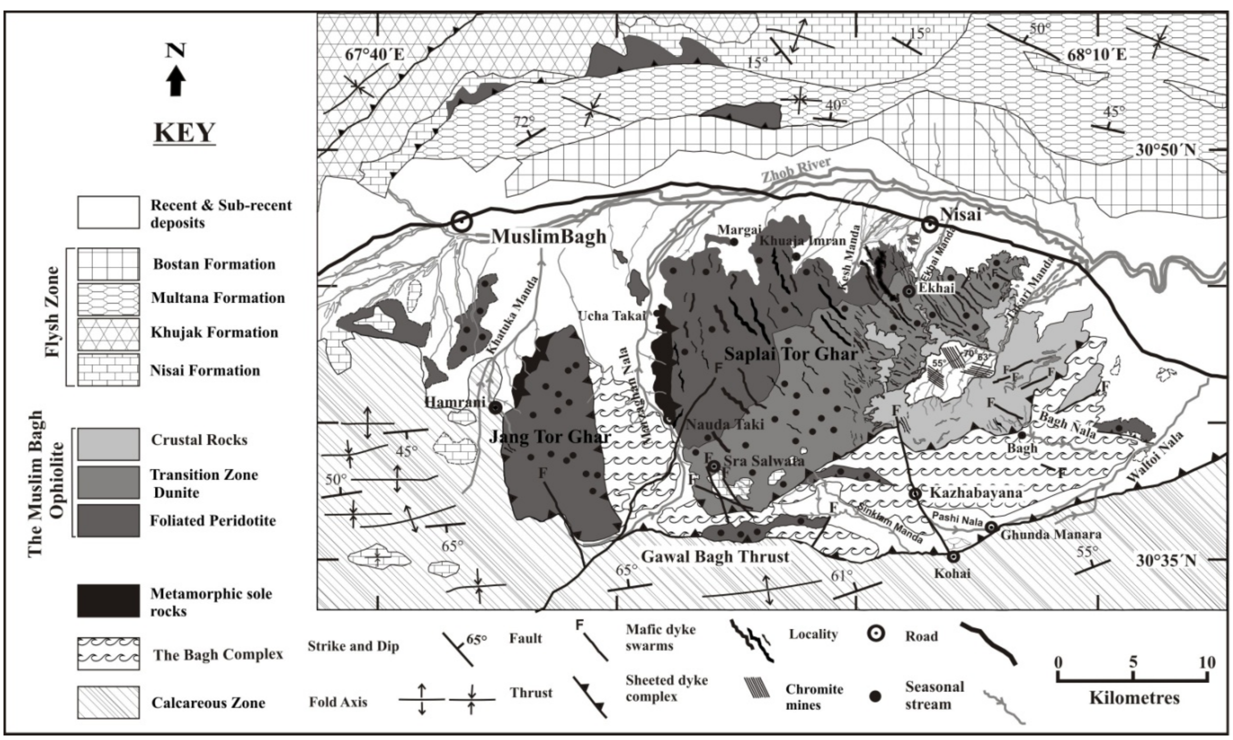

Fig. 1. Geological Map of the Muslim Bagh ophiolite and surrounding rocks units modified after HSC (1960), Siddiqui et al. (1996) and this study.

One of the striking features of the Muslim Bagh ophiolite is the presence of swarms of mafic dykes (3-15 metres thick), cross cutting the ophiolite at all structural levels. The crust of the Muslim Bagh ophiolite is only exposed in STGM and consists of cumulate dunite, wehrlite and pyroxenite at the base, overlain by the layered and foliated gabbro. The gabbroic section passes into a sheeted dyke complex dominated by hydrothermally-altered dolerite dykes with locally preserved chilled margins. The Sheeted dyke complex is intruded in its lower and middle sections by plagiogranite. The sheeted dykes, gabbros, mafic dykes and plagiogranite have geochemical signatures indicative of formation in a supra-subduction zone setting (Khan et al., 2007; Kakar, 2011).

4. The mantle section

The mantle section of the Muslim Bagh ophiolite is sub-divided into foliated peridotites and mantle–crust transition zone. The foliated peridotite has also been called as tectonite or ultramafic tectonite (Ahmad and Abbas, 1979; Siddiqui et al., 1996).

4.1. Foliated peridotite

This section represents the upper mantle segment of oceanic lithosphere and is found in both the massifs of the ophiolite. The JTGM is comprised of only foliated peridotites, while the STGM shows a well-developed foliated peridotite stratigraphically overlain by the dunite rich transition zone (Fig. 1).

The JTGM is essentially composed of harzburgite and dunite, but lherzolite has also been reported from the lowermost part of the massif (Mahmood et al., 1995). In the lower part of the mantle sequence harzburgite: dunite ratio is 70:30 (Siddiqui et al., 1996), but this is reversed in the upper part which is exposed in the STGM. These rocks are intensely sheared, occasional1y foliated, and show partial to complete serpentinization (30 to 100%, according to (Mahmood et al., 1995). Several mafic dykes were also observed in the western part of the massif. The foliated peridotite grades downward into basal peridotite displaying mylonitic to porphyroclastic textures. The Basal peridotite mylonites are exposed in the north-western part of the STGM (Fig. 1) and are characterized by a prominent dunite / harzburgite compositional banding. The thickness of the individual bands varies from a centimentre to many centimetres (Fig. 2a). These bands are parallel to the foliation in the basal mylonitic rocks.

The foliated peridotite in the STGM comprises harzburgite, depleted harzburgite and dunite which are commonly serpentinized. Relatively fresh peridotite is exposed only in the basal section of the Massif. Other than the harzburgite, lherzolite is also reported especially from the region of Nauda Taki area (Fig. 1). The STGM is rich in chromite deposits and is intruded by mafic dyke swarms and gabbroic intrusions (Fig. 1). Serpentinization in the peridotite is abundant in areas containing dunite bodies. In the peridotite, foliation and lineations are marked by elongated spinel and orthopyroxene grains (Fig. 2b). The dunite present in the mantle section is either interlayered with harzburgite (Fig. 2c) or occurs within the harzburgites as irregular or larger bodies (Fig. 2d) with predominantly podiform chromite deposits (e.g., Bilgrami, 1963; Rossman et al., 1971), ranging in size from less than a metre to many metres.

4.2. Mantle–crust transition zone

The mantle-crust transition zone (hereafter called the transition zone) of the ophiolite generally ranges from 3 to 5 km in thickness (Fig. 1). Its base consists of thick dunite with chromite, wehrlite/pyroxenite and gabbro occurring as discontinuous bands or lenses (cf. Benn et at., 1988; Nicolas, 1989; Boudier and Nicolas, 1995). In Muslim Bagh ophiolite this zone is exposed only in STGM and is characterized as dunite sequence which is readily recognized in the field by the absence of foliation, with intercalation of minor harzburgite in the lower part and of wehrlite/pyroxenite in the upper part. A good example of this transition zone is well exposed in the south of Nisai (Fig. 1) where it extends between the depleted harzburgite at the base and the gabbros at the top. This transition zone dunite (Fig. 2e) grades downwards into depleted harzburgite with a simultaneous decrease in the orthopyroxene fraction and enriched by the dykes/sills/veins of gabbros, anorthosite and pyroxenite in the upper part (Boudier and Nicolas, 1995; Mahmood et al., 1995).

The transition zone dunite in the Muslim Bagh ophiolite is thicker (2000–3000 m) (Siddiqui et al., 1996; Fig. 1) compared to those reported from the other ophiolites around the world; Semail, Oman (300–700 m) (e.g. Nicolas, 1989; Boudier and Nicolas, 1995; Nicolas et al., 1996), and Troodos, Cyprus (300 m) (e.g. Moores and Vine, 1971; Robinson et al., 2003). The transition-zone in Muslim Bagh ophiolite may have been formed by a combination of processes such as crystal fractionation, and mantle processes such as partial melting and melt–rock interaction (e.g., Malpas, 1978; Elthon et al., 1982; Zhou et al., 1996, 2005).

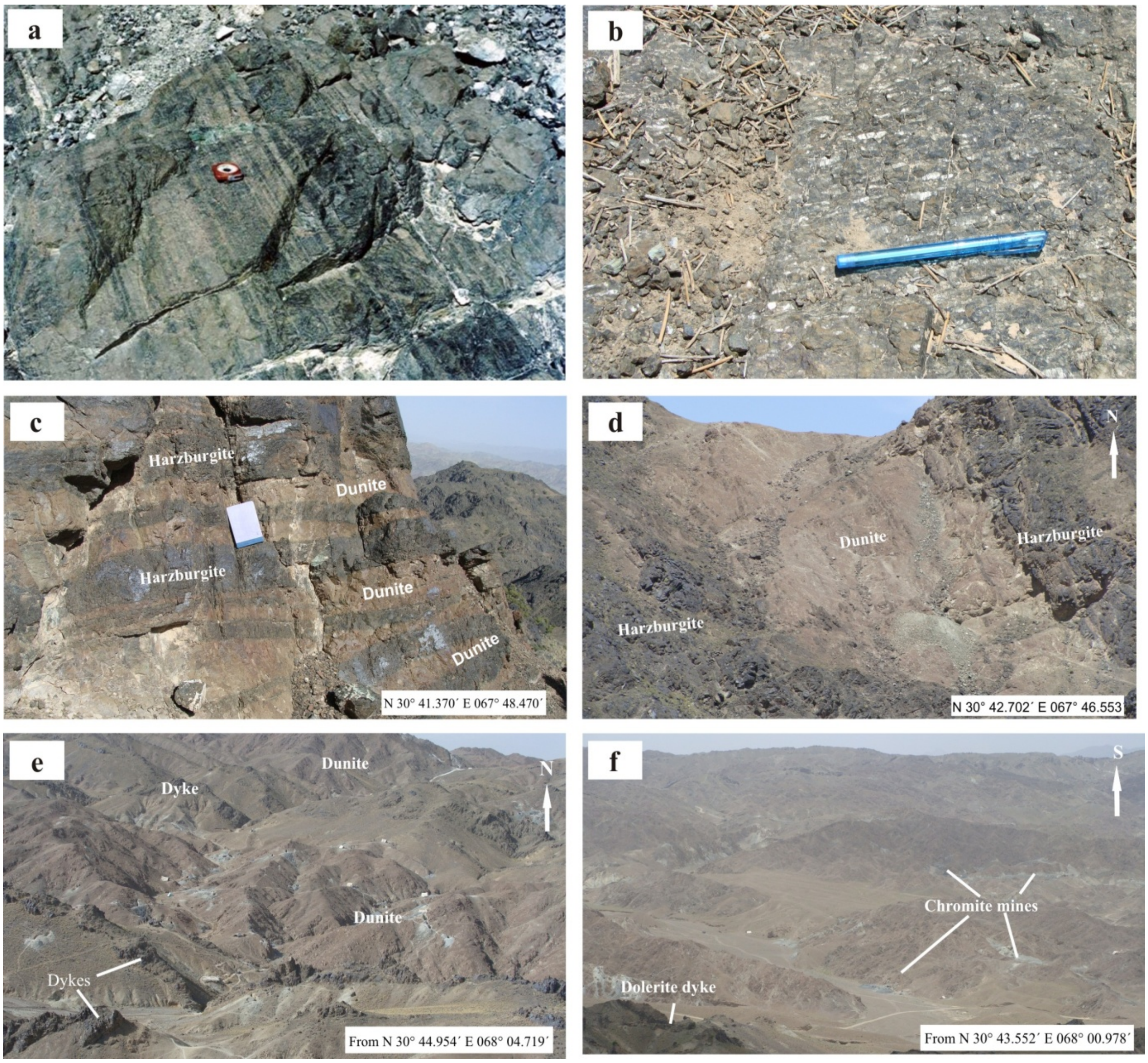

Fig. 2(a). Banding of dunite and harzburgite in the lower mylonitic peridotite, Jang Tor Ghar Massif;
(b). Elongated orthopyroxene grains in the foliated peridotite section of the mantle rocks;
(c). Layering of dunite and harzburgite in the foliated peridotite, Jang Tor Ghar Massif;
(d). Lager dunite bodies surrounded by harzburgite in the foliated peridotite, Jang Tor Ghar Massif;
(e). View of transition zone, showing chromite mines in dunite along with dolerite dykes, Nisai area, Saplai Tor Ghar Massif;
(f). A view showing a thick section of the Transition zone in Bunglay and Kharara Teza area, Saplai Tor Ghar Massif.

4.3. Petrography

Petrographically, the rocks of the mantle section are divided into lherzolite, harzburgite, depleted harzburgite, dunite, serpentinite and minor pyroxenite-wehrlite.

The lherzolite forms thin layers and is found in immediate contact with metamorphic sole rocks in both the STGM and JTGM (Fig. 1). They can be easily recognized in the field since they have a porphyroclastic to mylonitic, medium-grained texture and are less serpentinized than the harzburgite (Fig. 3a). Fresh surfaces of the lherzolite are greenish black and the rock breaks with sharp edges due to its hardness. The clinopyroxene is mainly diopside. The rocks are composed of olivine 70%, orthopyroxene 15%, clinopyroxene (mainly diopside [En $_{47-49}$] 5% to 10%), and spinel 2%. The clinopyroxene is locally altered to amphibole.

Harzburgite, which is generally serpentinized, forms massive bodies and is the most common rock type in the mantle section of the Muslim Bagh ophiolite. It can be easily recognized on fresh surface as greenish black, but the weathered surfaces are dark brown. It is generally coarse-grained and shows autoclastic, hypidiomrophic granular texture in relatively fresh varieties, while granoblastic texture predominates in altered varieties (Fig. 3b). The primary minerals include orthopyroxene (enstatite and bronzite) and olivine, with spinel as an accessory.

The enstatite (En $_{90-92}$) is euhedral to subhedral while the olivine (Fo $_{91-93}$) is subhedral to anhedral (Siddiqui et al., 1996). The olivine is partially to completely replaced by antigorite and iddingsite and the orthopyroxene is generally replaced by antigorite, bastite and chlorite. Chrysotile veinlets are common and generally cross-cut the groundmass. Small euhedral to subhedral crystals of chrome spinel or, locally, magnetite are scattered throughout the groundmass. The modal composition of the harzburgite is orthopyroxene (25-35%), olivine (5-10%), serpentine (56-60%) and chrome spinel (3-6%). The clinopyroxene is present in minor amounts (2%; Siddiqui et al., 1996). Depleted harzburgite (with low modal orthopyroxene) is found further up section in STGM, just before the base of the dunite rich zone. The depleted harzburgite comprises 10-20% olivine, 70-80% serpentine, ~5% orthopyroxene and 2% spinel. In some thin sections, a few grains of clinopyroxene were also observed.

Dunite is the second most abundant rock type in the mantle section and is medium to coarse grained and shows a granoblastic texture. Olivine is found as relict cores surrounded by a mesh of serpentine (Fig. 3c-d). Minor diopside and enstatite are also observed in some dunites. The olivine (Fo $_{92-94}$) is partially to completely replaced by antigorite or occasionally altered to iddingsite. Chrysotile veinlets generally cross cut the groundmass. The estimated mineral proportions are: 0-15% olivine, 75-80% serpentine, 2-3% clinopyroxene, 1-2% orthopyroxene and 2-3 % spinel (Siddiqui et al., 1996).

The dunite from the transition zone shows granoblastic texture. The olivine generally ranges in composition from Fo $_{89}$ to Fo$_{92}$. Diopside and spinel are also found as accessory minerals in the dunites. In many respects the dunite of this zone is similar to those found in the foliated peridotite. The modal composition is 15-20% olivine, 65-70% serpentine, 3-5% diopside and 2-3% spinel (Siddiqui et al., 1996).

About 80–90% of the peridotite in the study area is serpentinised. Serpentinites are massive and light green to brownish green. They are composed of more than 90% serpentine, the remaining being opaque oxides (spinel and magnetite) and olivine (Mahmood et al., 1995). The principal minerals developed during serpentinisation are antigorite and lizardite. Iron oxides are present in the form of microcrystalline material in the fractures and along the joints/fractures of olivine grains. Olivine is found as relict cores surrounded by serpentine, and bronzite relics in the serpentine may be partially to completely altered to bastite. Chromite, magnetite, and picotite are present in small amounts. The chromite occurs in the serpentine, whereas magnetite and picotite are present in the fractures in serpentine.

Wehrlite is medium-coarse-grained and shows granular porphyritic and hypidiomorphic texture (Fig. 3e). Granoblastic texture is also developed in some varieties. Large subhedral to euhedral grains of diopside (En_{43-48}) and anhedral granoblasts of olivine are embedded in a partially to completely serpertinised groundmass. The olivine (Fo_{73-89}) forms small enhedral crystals embedded in antigorite mesh. Occasionally enstatite (<2%) is also found in some of the wehrlites. Olivine is usually altered to antigorite while chrysotile occurs in the veinlets, cross cutting the groundmass. The modal composition of the rock is ~15% olivine, 50-55% serpentine; 20-30% diopside, 1-2% magnetite and 2% spinel (Siddiqui et al., 1996).

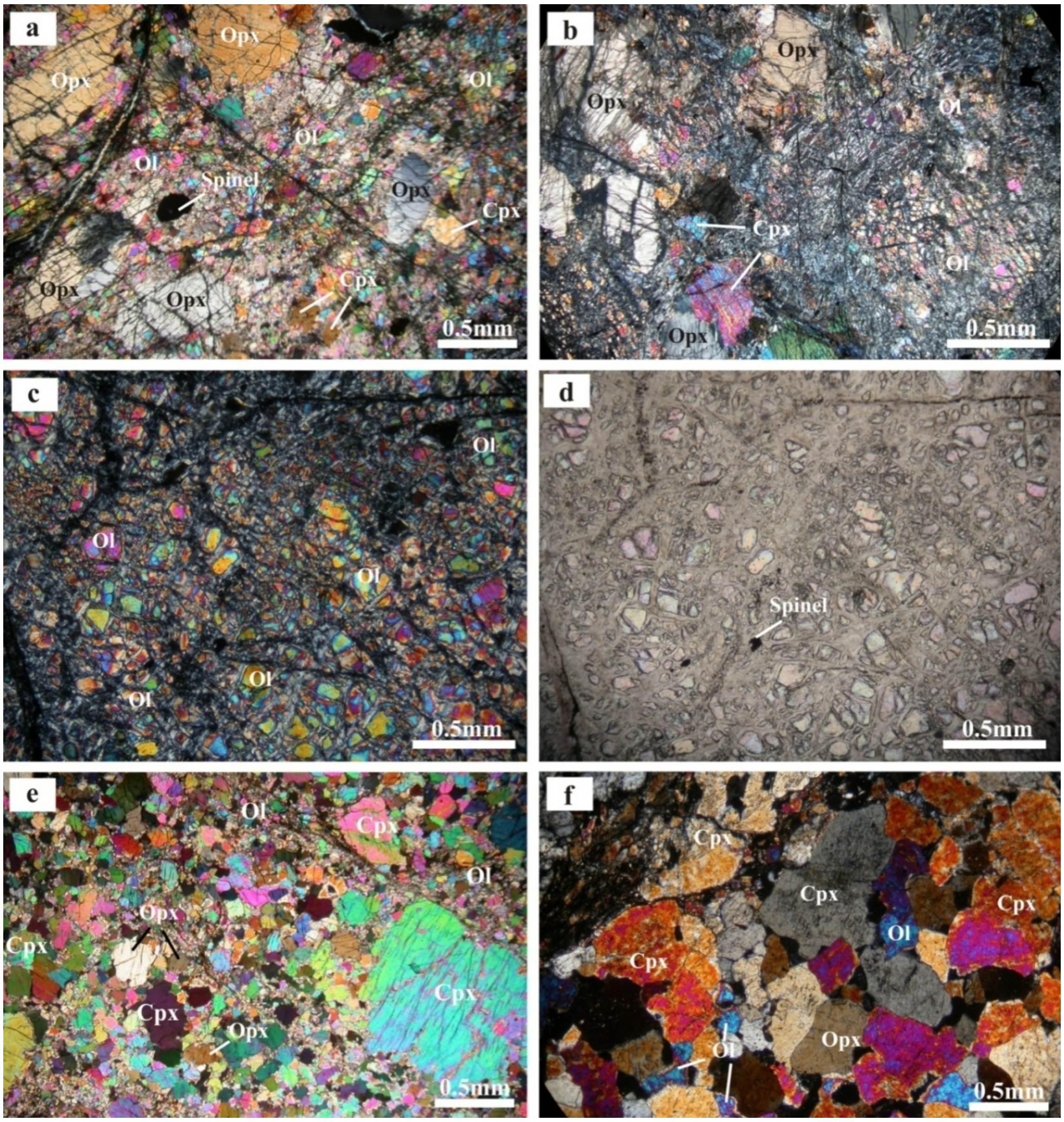

Fig. 3(a). Porphyritic to mylonitic texture in lherzolite showing large grains of orthopyroxene and some small grains of clinopyroxene embedded in the groundmass of olivine (XPL x 1.5);

(b). Hypidiomrophic granular and granoblastic textures in harzburgite showing subhedral grains of orthopyroxene and olivine in serpentine;

(c-d). Relict olivine grains embedded in a medium-fine-grained mesh of serpentine, c) XPL, d) PPL;

(e). Granular porphyritic and hypidiomorphic texture in wehrlite with large and small subhedral grains of clinopyroxene in the groundmass of clinopyroxene, orthopyroxene and olivine;

(f). Granular textures in pyroxenite. Mineral abbreviations are from Kretz (1983).

Pyroxenite is coarse-medium-grained, granular (Fig. 3f) and subpoikilitic in texture. Large euhedral to subhedral grains of diopside (En_{47-48}) and small anhedral grains of olivine comprise the subpoikilitic texture. Euhedral to subhedral enstatite is also occasionally found as phenocrysts. Olivine is partially serpentinised. Small euhedral to subhedral crystals of magnetite with minor spinel occur as accessories. The modal composition of pyroxenite is 60-70% diopside, 10-15% olivine, 2-3% enstatite, 5-7% serpentine and 2-3% opaque minerals (Siddiqui et al., 1996).

4.4. Mantle structures

On the basis of structural evidence, the mantle section can be divided into two broad domains:

1. The basal peridotite zone is a few hundred metres thick in both the JTGM and STGM, and is in faulted contact with sub-ophiolitic metamorphic sole rocks. This zone shows mylonitic microstructures which are formed at temperatures from 900–1000 °C (Nicolas, 1989; Mahmood et al., 1995), in response to ductile lithospheric deformation during the initiation of intra-oceanic subduction. They are also known as high-pressure, structures (Boudier and Coleman 1981; Mahmood et al., 1995).
2. Going upwards from these structures in both the Massifs, higher temperature microstructures predominate. These are the structures defined by two different flow fabric elements; the orthopyroxenes and spinel. These structures, therefore, formed during high-temperature deformation in the upper mantle during plastic flow conditions in a temperature range of 1200–1250 °C (Nicolas, 1989; Elitok and Druppel, 2008).

4.5. Chromite deposits

Following the classification of Thayer (1960), two distinct types of chromite deposits have been distinguished. The first type occurs within stratiform igneous complexes such as the Bushveld, South Africa (e.g., Cameron, 1977; Mondal, and Mathez, 2007) and Stillwater, USA (e.g., Spandler et al., 2005). The second type of chromite deposits is found within ophiolite complexes (e.g., Robinson et al., 1997).

The mantle section in the Muslim Bagh ophiolite contains economic deposits of chromite (Fig. 4a). This chromite occurs as pods, lenses and ball like bodies within dunite bodies of foliated peridotite in the ophiolite massifs and as tabular and lenticular bodies in the transition zone dunites of the STGM. The transition zone chromite bodies are larger in size and lower in grade compared to those found in the dunite of the lower foliated peridotite rocks of mantle section. Texturally the podiform chromite ores are classified into massive (Fig. 4b), disseminated, layered (Fig. 4c), nodular (Fig. 4d), anti-nodular, and brecciated varieties (e.g. Bilgrami, 1963).

5. Discussion

The mantle section of the Muslim Bagh ophiolite comprises foliated harzburgite and dunite with minor lherzolite. Harzburgite and dunite from the mantle section of ophiolitic complexes have often been referred to as depleted peridotite resulting from large degrees of partial melting of a lherzolite source (e.g., Nicolas, 1989; Baker and Beckett, 1999). Such residual mantle rocks are also likely to have been affected by magma–mantle interaction involving precipitation of orthopyroxene and olivine (e.g., Kelemen et al., 1992, 1995). Therefore, although some of the Muslim Bagh harzburgites may simply be residual from partial melting, many are also likely to be products of partial melting coupled with subsequent melt–peridotite interaction, and the dunite bodies are the pathways/porous reactive channels through which partial melts were transported (Kelemen et al., 1995; Edwards and Malpas, 1995; Braun and Kelemen, 2002; and Zhou et al., 1996, 2005).

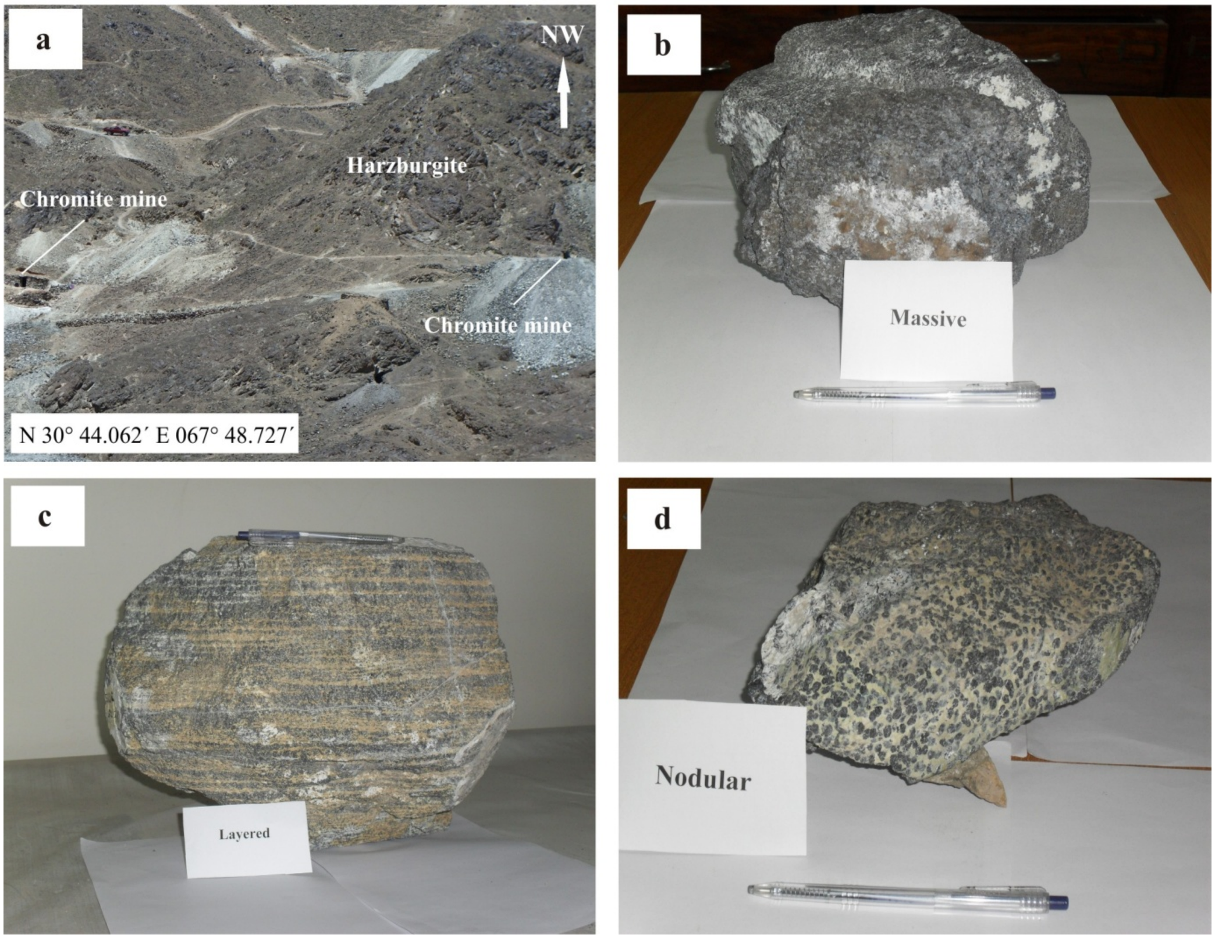

Fig. 4(a). A view of chromite mines in Sola area, Jang Tor Ghar Massif of Muslim Bagh ophiolite. Textural varieties of the chromite ore being mined have shown in b) Massive; c) Layered; d) Nodular.

The section from the lower foliated harzburgite/dunite to dominantly crustal rocks is marked by the transition zone whose origin and petrogenetic nature has also been debated. Several workers propose an origin by olivine fractionation and accumulation from picritic magma (cf., Coleman, 1977; Malpas, 1978; Elthon et al., 1982), while others propose a residual mantle origin (Nicolas and Prinzhofer, 1983; Boudier and Nicolas, 1995; Kelemen et al., 1995; Zhou et al., 1996). More recently, Suhr et al. (2003) and Zhou et al. (2005) suggested that it has formed by the process of mantle-melt reaction and that it is an integral part of the mantle sequence.

The nature and extent of some of the dunite, especially in the uppermost part of the transition zone in Muslim Bagh, are supportive of cumulate origin (Siddiqui et al., 1996). However, the Muslim Bagh transition zone also comprises residual dunite with impregnation of wehrlite and pyroxenite. Lenses and dykes/sills of gabbros and interstitial clinopyroxene and plagioclase are found everywhere in this zone. The presence of clinopyroxene and plagioclase is believed to be the result of magmatic impregnation and could represent a crystal-melt mixture. Furthermore, the lenses and dykes/sills of gabbros may have been injected laterally due to compaction (Benn et al., 1988). The uppermost cumulate part of the transition-zone dunites may have formed by crystal fractionation from crustal magma chambers during the first stage of evolution, (e.g., Malpas, 1978; Siddiqui et al., 1996), whereas the lower part may reflect the evidence of processes like high degrees of partial melting and extensive melt–rock interaction (Nicolas and Prinzhofer, 1983; Suhr et al., 2003; Zhou et al., 2005). In short, the transition zone appears to be formed by a combination of mantle and crustal processes and reflects predominantly mantle processes at its base with evidence of crustal processes in its uppermost parts.

The chromite concentrations occur in foliated peridotite and in the transitional dunite, are podiform and vein-like in shape and have been subjected to later deformation. Previous studies on compositional variations of chromite have suggested that high alumina chromites of Muslim Bagh (e.g., Siddiqui et al., 1996) are more likely to develop under higher pressure conditions (Irvine, 1967) and that they might represent either deeper mantle segregations (Hoshino and Anwar, 1989) or may have been formed by melt-rock interaction (Robinson et al., 1997; Zhou et al., 1996, 2005).

Petrographically, the Muslim Bagh mantle sequence harzburgites are poor in modal clinopyroxene and dunites poor in pyroxene, indicating that the peridotite is residual after significant melting (Mahmood et al., 1995; Siddiqui et al., 1996). The deformed relict primary minerals and the irregular shape of the spinel grains in the peridotite further indicate a residual mantle that has undergone high-temperature deformation under upper mantle plastic flow conditions (Nicolas, 1989; Mahmood et al., 1995; Ohara et al., 2002). The residual peridotite nature is further confirmed by the higher Cr and Mg # of accessory spinel and orthopyroxene and suggests their derivation by higher degree of partial melting of a depleted mantle source (Siddiqui et al., 1996; Arif and Jan, 2006).

Experimental studies on peridotite show that progressive melting of lherzolite rapidly eliminates clinopyroxene and gradually reduces the proportion of orthopyroxene (Mysen and Kushiro, 1977; Jaques and Green, 1980). As melting proceeds, forsterite and NiO contents of olivine, Mg# of pyroxene, and Cr # of spinel increases, and Al_2O_3 contents of the residual spinel and pyroxene and of the whole rock decreases (Dick and Bullen, 1984; Ohara et al., 2002). All these features indicate a residual upper mantle origin or a higher degree of partial melting (30-45%) of a depleted mantle source, for these rock suites (Mysen and Kushiro, 1977; Dick and Fisher, 1984).

6. Conclusions

The Muslim Bagh mantle section comprises foliated peridotite and transition zone dunite which are partially to completely serpentinised. The harzburgite in lower foliated peridotite may be residual from partial melting and/or a product of subsequent melt–mantle peridotite interaction and the dunites may depict the porous conduits for the partial melts. The transition zone is formed by a combination of mantle and crustal processes which reflect predominantly mantle processes at its base and crustal processes in its uppermost parts. Petrology, mineral chemistry of peridotite/chromite and the presence of chromite deposits in Muslim Bagh dunites suggest a supra-subduction zone tectonic setting for these rocks.

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