Petrogenesis of ophiolitic rocks from Indus Suture Zone, Ladakh Himalaya: Insights for Depleted Mantle beneath an intra-oceanic island arc complex

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1. Introduction

Mafic-ultramafic cumulate rock types are formed by slow crystallization of basaltic magma in shallow magma chambers overlying the mantle asthenosphere. Such rock types are found in different tectonic environments including oceanic lithosphere generated along the mid ocean ridges, subduction-related orogenic environments and non-orogenic complexes (Pal-Molnar et al., 2015, and references therein). Various petrological and geochemical features of mafic-ultramafic cumulate rock types are used to provide insights into their mantle sources, evolution of mantle derived melts and tectonic environment (Allahyari et al., 2014; Rahmani et al., 2020; Bhat et al., 2021b). In addition, they provide apparent information about the depth, size and thermal history of magma chambers as well as help to constrain various basalt differentiation models (Deng et al., 2015; Singh et al., 2017; Dey et al., 2018).

Parts of the ancient oceanic lithosphere have been emplaced along the continental margins in the form of ophiolite complexes during tectonic events of collision and obduction (Dilek and Furnes, 2014). These ophiolite complexes were originated either at mid-ocean ridges (MOR) or supra subduction zones (SSZ) including fore-arc and back-arc regions (Stern, 2004; Dilek and Furnes, 2014; Pearce, 2014; Saccani, 2015; Rahmani et al., 2020). Ophiolites are important source of information for understanding processes acting at mid-ocean ridges, subduction zones and marginal basins as well as to identify composition of parental magmas and mantle sources (Dilek and Furnes, 2019). Well-studied Mesozoic Neo-Tethyan ophiolite sequences are exposed in Kohistan Pakistan, Ladakh Himalaya India, Tibet and Myanmar along the NW-SE trending Indus Yarlung Tsangpo Suture (IYTS; Ahmad et al., 2008; Singh et al., 2017; Xiong et al., 2017; Bhat et al., 2017, 2019b; Buckman et al., 2018; Jadoon et al., 2019).

Although, good exposures of mantle peridotites, ultramafic cumulates, massive gabbros and basic volcanics are present in and around Kargil district of Ladakh. However, due to extreme weather conditions, high altitude, lesser accessibility and regional conflict, limited research work has been carried out on the petrology and geochemistry of these ophiolite components. Bhat et al. (2021b), on the basis of mineral and bulk-rock geochemistry, suggested that the Suru-Thasgam ophiolitic slice of western Ladakh originated at an intra-oceanic island arc within the Neo-Tethys Ocean. On the other hand, earlier workers reported mid-ocean ridge, ocean island and island arc affinity volcanics along the Indus Suture Zone (ISZ) near Chiktan and Shergol villages of Kargil district (Honegger et al., 1982; Rai, 1987; Robertson, 2000). In this paper, we report for the first time petrological, mineralogical and geochemical characteristics of various rock types including mantle peridotites, ultramafic cumulates, gabbros and basic volcanics along the ISZ Ladakh Himalaya. Based on the integrated mineralogical and geochemical data sets, present study is an attempt to understand the geological processes controlling genesis and possible tectonic affinity of these rock types.

2. Geological setting

2.1. Regional geology

Mesozoic age ophiolitic remnants of eastern portion of the Neo-Tethys Ocean are exposed along the IYTS (Fig. 1a; Dilek and Furnes, 2019; Bhat et al., 2021a and references therein). In Ladakh Himalaya, well-studied ophiolitic slices and associated ophiolitic melanges are exposed along the northwest to southeast trending ISZ such as Nidar ophiolitic complex towards eastern Ladakh (Ahmad et al., 2008), Spongtang ophiolitic complex towards southwestern Ladakh (Buckman et al., 2018), and Dras-Shergol-Suru ophiolitic slices towards western Ladakh (Radhakrishna et al., 1987; Bhat et al., 2017, 2019b). Recent studies based on the detailed whole-rock, mineral and isotope data proposed that these ophiolitic slices were evolved in a subduction zone tectonic setting in context of the Neo-Tethys Ocean (e.g., Ahmad et al., 2008; Buckman et al., 2018; Bhat et al., 2021a, 2021b). Towards western Ladakh (Fig. 1b), highly dismembered ophiolites are emplaced as thrust blocks over the Mesozoic Dras arc complex and are best exposed along the Dras-Kargil and Khangral-Chiktan road sections (Honegger et al., 1982; Reuber, 1989; Robertson, 2000; Bhat et al., 2019a, 2021b). Based on the limited data sets earlier workers proposed that these rootless bodies of ophiolites from western Ladakh represent substratum of Dras arc complex (e.g., Reuber, 1989; Robertson, 2000).

The Dras arc complex (Fig. 1b), with type section at Dras Village, forms a dominant litho-tectonic unit and represent part of the intra-oceanic island arc within the Neo-Tethys Ocean during Late Jurassic to Early Cretaceous Period (Bhat et al., 2019a, Walsh et al., 2021 and references therein). It comprises mafic to intermediate volcanics known as Dras volcanics with subordinate shallow-deep marine volcano-sedimentary assemblage of fore-arc apron known as Nindam Formation (Robertson and Degnan, 1994). To the north, this arc complex is thrust over the Ladakh Batholith and associated post-collisional molassic deposits of Indus Formation, while it is faulted against Late Permian continental shelf deposits of Lamayuru Formation and Indian passive margin Zanskar sedimentary sequence towards south. Also, discontinuous slivers of ophiolitic mélanges such as Sapi-Shergol-Wanlah-Urtsi mélange occur along this southern contact (Robertson, 2000; Robertson and Degnan, 1994). This arc complex is overlain by dismembered Late Jurassic to Early Cretaceous ophiolitic blocks such as mantle peridotites with minor gabbros in Suru Valley towards south of Kargil (i.e., Suru Valley ophiolite of Bhat et al., 2019b) and pyroxenites and gabbros near Thasgam Village towards east of Kargil (i.e., Thasgam ophiolitic slice of Bhat et al., 2021b). Reuber (1989) suggested that this oceanic lithosphere represent tectonically disrupted oceanic substratum of the Dras arc complex. However, Bhat et al. (2019b, 2021b), based on the mineral and whole rock geochemistry, suggested that these ophiolitic blocks evolved in an intra-oceanic subduction environment corresponding to Dras arc complex.

To the east of Kargil, from Pashkyum to Shergol, basic volcanics, minor gabbros and serpentinized peridotite blocks are associated with the Nindam Formation. Various previous workers have classified it as the ophiolitic mélange (e.g., Brookfield and Reynolds, 1981; Rai, 1987). However, this ophiolitic mélange is best exposed at the Shergol and Wanlah villages also known as Sapi-Shergol-Wanlah-Urtsi ophiolitic mélange sandwiched between Lamayuru Formation towards south and Nindam Formation towards north (e.g., Sinha and Mishra, 1994). The geochemistry of gabbros and serpentinized peridotites along the Sapi-Shergol ophiolitic mélange reflects subduction zone affinity (Bhat et al., 2017, 2019c) while the basic volcanics reflects island arc and ocean island geochemical characteristics (Sinha and Mishra, 1994).

Towards further east of Kargil, along the Khangral-Chiktan road section, isolated and limited outcrops of mafic volcanics and serpentinized peridotite blocks are associated with the flysch sequence of thinly bedded grey to greenish shales and greyish limestones of Nindam Formation, therefore giving a mélange like appearance at the outcrop. This forms a narrow east-west trending nearly 8 km thick zone thrust bound between Lamayuru Formation towards southwest and Indus Formation towards northeast. The volcanics are essentially basalt, andesite, and dacite while the peridotite blocks are serpentinized to varying degrees.

2.2. Field geology

For the present study, various rock samples were collected along the ISZ including mantle peridotites, ultramafic cumulates, gabbros and basalts. The studied rock samples were collected along the Khangral-Chiktan and Dras-Kargil road sections, respectively parallel to Chiktan Nala towards east of Kargil and Dras River towards southwest of Kargil (Fig. 1b). At Khangral-Chiktan road section, a well-defined ophiolitic mélange sequence is exposed along the Chiktan Nala (Rai, 1987), consisting serpentinized peridotites and greenschist grade metavolcanics intercalated with deep-sea sediments. These meta-basalts are considered equivalent to Dras volcanics by earlier workers (e.g., Honegger et al., 1982). The isolated dark green colored serpentinized peridotite blocks are exposed at Chiktan Village towards left-bank of the downstream Chiktan Nala and is associated with the sedimentary rocks of the ophiolitic mélange sequence (Fig. 2a). A minor unit of basalt showing spheroidal weathering with plagioclase feldspar grains of 0.5–1 cm across were also observed towards north of the ophiolitic mélange (Fig. 2b). Also, the greenschist grade metavolcanics of basalt to basaltic-andesitic composition are in contact with deep-sea sediments such as red-colored cherts (Fig. 2c). Besides, this mélange is dominated by sedimentary rocks such as thinly bedded greenish grey shales and occasional massive grey limestone.

Similarly, along the Dras-Kargil road section (Fig. 1b), good exposures of mafic-ultramafic rocks as faulted blocks are observed overlying the Dras arc complex. These undeformed medium to coarse grained dark colored ultramafic cumulates (Fig. 2d) and dark green colored gabbros (Fig. 2e) are exposed along the opposite banks of Dras River near Thasgam Village. In addition, good exposures of peridotites, gabbros are exposed in the vicinity of Dras Village (Fig. 2f).

3. Analytical methods

Relatively fresh and representative samples of mantle peridotites (two samples), ultramafic cumulates (five samples), gabbros (five samples) and basalts (eight samples) from the Kargil district, western Ladakh were selected for geochemical analysis. The crushed rock samples were milled to less than 200 mesh size using Retsch's Vibratory Disc Mill. Loss on ignition (LOI) values were determined by heating a separate aliquot of sample powder (5 gm) at 900 ^{o}C. Bulk-rock major oxide and some trace element (e.g., Cr, Ni, Co, Cu, Sc, V, Zn, Pb, Th, U, Rb, Sr, Ba and Zr) analysis were carried out on powder pellets using standard wavelength dispersive X-ray fluorescence (WD-XRF, Siemens SRS 3000) technique coupled with an automatic sample changer at the Wadia Institute of Himalayan Geology (WIHG), Dehradun, India following the procedure of Saini et al. (1998). Whereas, trace elements including rare earth elements (REE) were determined by Quadrupole-Inductively Coupled Plasma Mass Spectrometer (Q-ICPMS; Model: iCAPQ, ThermoFisher Scientific) with auto-sample changer at IUAC New-Delhi, India following the procedure of Kingson et al. (2017). Standard reference materials viz., MRG-1 (Mount Royal Gabbro, Canada), JB-1a (a Geological Survey of Japan basalt standard), and DG-H and AM-H (DG-H – Himalayan granite and AM-H – Himalayan amphibolite standard prepared by WIHG, Dehradun, India) along with couple of procedural blanks were also prepared with the studied sample batch. The analytical precision (relative standard deviation) for major elements is well below 1–2% for all samples including reference standards and < 5% for majority of trace elements therefore, demonstrating a high degree of machine accuracy and precision. The obtained major (anhydrous wt.%) and trace (ppm) element data of the studied rock samples is presented in Table 1, while the REE data and trace element ratios is presented in Table 2.

Mineral chemical analyses of olivine, orthopyroxene, clinopyroxene, plagioclase, amphibole and spinel from selected rock samples were performed at the Banaras Hindu University, Varanasi, using the electron probe micro analyzer (EPMA) CAMECA SX-Five instrument. The instrument was operated at an acceleration voltage of 15 kV and probe current of 20 nA. Well-calibrated natural silicates were used as standards and replicate analyses of individual points show an analytical error of <2%. EPMA results of studied minerals are presented in supplementary Tables S1 – S6.

4. Petrography

The petrographic study of the collected rock types from the Khangral-Chiktan and Dras-Kargil road sections of Kargil district are described in detail in the following sections.

4.1. Mantle peridotites

The mantle peridotites are dominantly composed of variable sizes of olivine (> 90 modal %), besides < 10 modal % of orthopyroxene, clinopyroxene, spinel, serpentine and oxides (Fig. 3a). Based on the observed mineralogy and texture these mantle peridotites are classified as dunites. Also, dark-brown vermicular spinel grains, commonly altered to iron oxide, occur between the silicate minerals. Along the fractures and grain boundaries, the iron oxide and serpentine are present as secondary mineral assemblage formed after the breakdown of olivine thereby reflecting low degree of serpentinization (< 10%). In addition, the presence of iron oxide along the margins and fractures of dark-brown spinel grains reflects alteration effects. Few euhedral-subhedral reddish-brown spinel grains are included in the associated silicate minerals indicating their early crystallization.

4.2. Ultramafic cumulates

Based on the constituent mineralogy and texture, the studied ultramafic rocks classify as cumulates of wehrlites and olivine-websterites. The wehrlites consist variable amounts of olivine (40-50 modal %), clinopyroxene (> 20 modal %), orthopyroxene (< 10 modal %) with < 10 modal % of oxide and serpentine. Whereas, olivine-websterites consist orthopyroxene (> 50 modal %), clinopyroxene (20-30 modal %) with < 20 modal % of olivine and oxide (Fig. 3b). At places, the inter-cumulus spaces are occupied by medium-grained subhedral olivine grains (Fig. 3b).

4.3. Gabbros

The gabbros are medium to coarse grained, commonly showing hypidiomorphic texture and classify as olivine-norite to hornblende-gabbro. The olivine-norite is composed of olivine (< 20 modal %) and plagioclases of bytownite-anorthite composition (> 60 modal %) with < 20 modal % of orthopyroxene (enstatite composition) and iron oxide (Fig. 3c). Similarly, the hornblende-gabbro consists plagioclase (> 55 modal %) of bytownite-anorthite composition and clinopyroxene (< 35 modal %) of diopside composition with < 20 modal % amphibole (hornblende-actinolite), orthopyroxene (enstatite) and iron oxide. Olivine shows replacement to oxide along the grain boundaries and fractures while plagioclase feldspar at places show zoning. The gabbros are fine to medium-grained and show ophitic to sub-ophitic textural relationship of constituent mineral grains. The constituent mineral grains include plagioclase (> 60 modal %) and clinopyroxene (20-30 modal %) with < 10 modal % of hornblende and oxide (Fig. 3d).

4.4. Basalts

The basalts are fine to medium grained, dominantly composed of subhedral megacrysts of plagioclase (anorthite to albite composition) with minor amount of clinopyroxene (diopside composition), embedded in a groundmass of plagioclase and clinopyroxene with minor development of chlorite (Fig. 3e). The constituent mineral assemblage shows porphyritic textural relationship and the plagioclase phenocrysts shows lamellar twinning. The metavolcanics (of basalts to basaltic-andesite composition) are fine grained, composed of clinopyroxene (i.e., diopside; < 0.2 mm size) and plagioclase (0.1–0.2 mm size) phenocrysts embedded in a groundmass of plagioclase and clinopyroxene with minor chlorite and iron oxide. The constituent mineral assemblage shows intergranular and ophitic textural relationship (Fig. 3f).

5. Results

5.1. Mineral Chemistry

5.1.1. Olivine

Representative analyses of olivine from the studied mantle peridotites, ultramafic cumulates and gabbros is presented in supplementary Table S1. The forsterite content of olivine ranges from $Fo_{89.1}$ to $Fo_{92.1}$ in mantle peridotites, $Fo_{87.8}$ to $Fo_{90.2}$ in ultramafic cumulates and Fo_{70} to $Fo_{74.2}$ in gabbros. Similarly, the Mg number (Mg# = 100 × Mg^{2+}/Mg^{2+}

+ Fe^{2+}) ranges from 89 – 93 in mantle peridotites, 88 – 92 in ultramafic cumulates and whereas, lower in 70 – 76 in gabbros. Also, the Cr_2O_3 content decreases from mantle peridotites (0.02 – 0.06 wt.%) to ultramafic cumulates (0.01–0.03 wt.%) while lower in gabbros (0.01–0.02 wt.%).

5.1.2. Orthopyroxene

Representative analyses of orthopyroxenes from various rock types are listed in supplementary Table S2. The orthopyroxenes in the studied rock types are of enstatite composition varying from $En_{96.5}$ $Fs_{7.5}$ $Wo_{0.4}$ to $En_{92.4}$ $Fs_{3.4}$ $Wo_{0.1}$ in mantle peridotites, En_{90} $Fs_{10.5}$ $Wo_{2.1}$ to $En_{88.2}$ $Fs_{9.2}$ $Wo_{0.6}$ in ultramafic cumulates and $En_{83.4}$ Fs_{29} $Wo_{1.5}$ to $En_{69.6}$ $Fs_{16.5}$ $Wo_{0.1}$ in gabbros (Fig. 4a). They are unzoned and highly magnesian with Mg# ranging from 96 to 98 in mantle peridotites, 90 to 94 in ultramafic cumulates and 71 to 83 in gabbros. Also, on the wollastonite-enstatite-ferrosilite ternary diagram of Morimoto et al. (1989) the orthopyroxenes of the studied rock types plots in enstatite field (Fig. 4a).

5.1.3. Clinopyroxene

Representative analyses of clinopyroxenes from the studied rock types are listed in supplementary Table S3. The clinopyroxenes in mantle peridotites and ultramafic cumulates have relatively uniform composition of En_{45-51} Fe_{1-2} Wo_{49-53} and En_{48-50} Fe_{45-48} Wo_{4-5} with Mg# of 96 to 99 and 90 to 94; respectively. Similarly, clinopyroxenes in gabbros and basalts shows compositional range of En_{45-46} Fe_{4-5} Wo_{49-50} and En_{44-46} Fe_{6-9} Wo_{45-48}, respectively. These clinopyroxenes show low-Ti characteristics (e.g., 0.1 to 0.2 wt.% in mantle peridotites, 0.4 to 0.7 wt.% in ultramafic cumulates, 0.2 to 0.3 wt.% in gabbros and 0.3 to 1.1 wt.% in basalts). Also, on the wollastonite-enstatite-ferrosilite ternary diagram of Morimoto et al. (1989) the clinopyroxenes of the studied rock types plots in the diopside field (Fig. 4a).

5.1.4. Spinel

Representative analyses of spinel grains, observed in mantle peridotites are shown in supplementary Table S4. These spinels are Al-rich (Al_2O_3 ranges from 51.5 to 57.3 wt.%) and Cr-depleted (Cr_2O_3 ranges from 10.8 to 15.5 wt.%). They show a wide compositional range with high Al# (Al number = $100 \times Al^{3+}/Cr^{3+} + Al^{3+} + Fe^{3+}$) ranging from 82 to 88 and Mg# ranging from 69 to 78 whereas, low Cr# (Cr number = $100 \times Cr^{3+}/Cr^{3+} + Al^{3+} + Fe^{3+}$) ranging from 11 to 17 (Table S4).

5.1.5. Plagioclase

Representative analyses of plagioclase from gabbros and basalts are presented in supplementary Table S5. In gabbros, plagioclases are Ca-rich (i.e., anorthitic) ranging in composition from $An_{91\text{-}84}$ $Ab_{16\text{-}9}$ $Or_{0.3\text{-}0.01}$ whereas, plagioclases in basalts show zoning of anorthite rich core ($An_{99\text{-}90}$ $Ab_{9.4\text{-}1}$ $Or_{0.7\text{-}0.3}$) to albite rich rim ($An_{5.6\text{-}2.3}$ $Ab_{97\text{-}94}$ $Or_{0.4\text{-}0.3}$). In a ternary diagram (Fig. 4b) of Deer et al (1992), the plagioclases in gabbros plots in bytownite-anorthite field whereas, plagioclases in basalts plots in anorthite and albite field.

5.1.6. Amphibole

The amphiboles are present in gabbros as secondary minerals formed due to the breakdown of pyroxenes. These amphiboles, with high Si content (i.e., SiO_2 ranges from 42.6 to 52.2 wt.%) and high Mg# (65–82) (supplementary Table S6), show compositional variation from tschermakite-hornblende to actinolite, defining a paragasitic trend as per Leakes (1978) classification diagram (Fig. 4c).

5.2. Alteration and element mobility

Although, the studied rock types of mantle peridotites, ultramafic cumulates, gabbros and basalts are mostly composed of primary mineral assemblage however, the presence of minor secondary mineral assemblage in some of the studied samples is consistent with possible post-magmatic elemental mobility. Therefore, before interpreting the geochemical data, it is critical to understand the effects of any post-magmatic alteration. The studied rock types have not undergone significant secondary alteration as inferred from their low LOI values (< 5 wt.% for most of the samples; Table 1). It is known that elements such as Al, Ti, Mn, HFSE (e.g., Nb, Th, Zr, P, Hf, Y etc.), most of the REE (except Ce and Eu) and transition metals (Cr, Ni, V, Sc) are among the least mobile elements during secondary processes of alteration and/or metamorphism in comparison with elements such as LILE (e.g., Sr, Rb, Ba, U, Pb) and LREE (e.g., Ce and Eu) (Cann, 1970; Floyd and Winchester, 1975). In mantle peridotites, major and trace element concentrations remain unaffected by low degree of serpentinization as observed by studied mantle peridotites (Deschamps et al., 2013; Verencar et al., 2021). We used SiO_2/MgO ratio as a proxy for element mobility in studied mantle peridotites. SiO_2/MgO ratio of the studied mantle peridotites is < 2.2 comparable to slightly serpentinized mantle peridotites (Peltonen et al., 1998). However, the MgO/SiO_2 ratio for the studied mantle peridotites (0.5 to 0.6) is lower than the primitive mantle (~ 0.8; McDonough and Sun, 1995) reflecting variable amount of Mg loss due to serpentinization. Similarly, we tested geochemical data of ultramafic cumulates, gabbros and basalts for possible element mobility by plotting such known selected and common susceptible trace elements against LOI values (Fig. 5). Elements like Rb, Sr, U, Th, Pb, Nb, La, Ce, and Eu do not show any correlation with LOI, reflecting pristine nature of the constituent elements. Besides, HFSE and REE have been largely used for petrogenetic interpretations.

5.3. Whole-rock geochemistry

The collected rock types from Kargil district have variable bulk-rock elemental concentrations with Mg# ranging from 91–92 in mantle peridotites, 75–60 in ultramafic cumulates, 56–71 in gabbros and 52–65 in basalts (with one sample ~39). Also, the lower concentration of alkalis (Na_2O + K_2O) in ultramafic cumulates (0.4–3.2 wt.%) is explained by the cumulative nature of these rocks (Kakar et al., 2013). In addition, the ultramafic cumulates have lower concentration of high-field strength elements (HFSE) such as Hf (0.02–0.1 ppm), Y (1–4 ppm) and Nb (0.3–1.1 ppm), reflecting presence of relatively high proportion of cumulus minerals as compared to inter-cumulus liquid as is also evident in petrography. The MgO concentration in the studied rock types is quite variable and ranges from highly magnesium in mantle peridotites (23.5–28.7 wt.%), ultramafic cumulates (10–12.6 wt.%) to less magnesium in gabbros (6.2–10.9 wt.%) and basalts (5.1–10.3 wt.%).

In Nb/Y versus SiO_2 and Zr/TiO_2 classification diagrams (after Winchester and Floyd, 1977), majority of the studied rock samples show sub-alkaline basalt nature with basalt to basaltic andesite compositional variation (Fig. 6a and 6b). However, one basaltic sample (i.e., CH28) shows alkali-basaltic characteristics and another sample (i.e., CH40) depicts dacitic composition. Similarly, in AFM ternary diagram of Beard (1986) (where A = Na_2O+K_2O; F = $Fe_2O_3^t$ and M = MgO), the studied mantle peridotites are consistent with ophiolitic mantle peridotite field whereas ultramafic rocks are consistent with arc-related ultramafic cumulate field (Fig. 6c).

The chondrite-normalized rare earth element (REE) patterns (normalization after Sun and McDonough, 1989) of the studied rock types are shown in figure 7. The studied gabbros and basalts have higher concentration of total REE (∑REE = 36–90 and 27–129, respectively) compared to ultramafic cumulates (∑REE = 1.7–6.2) and mantle peridotites (∑REE = 0.5–1). The mantle peridotites reflect depleted REE-patterns (i.e., $(La/Yb)_N$ = 0.6–1.1) while ultramafic cumulates display depleted to enriched REE-patterns (i.e., $(La/Yb)_N$ = 0.6–3.2; Fig. 7a). Similarly, fractionated REE-patterns were observed in gabbros and basalts (Fig. 7a & 7b) with enriched light REE (LREE) patterns (i.e., $(La/Yb)_N$ = 1.6–4.1 and 1–12.3; respectively) and flat heavy REE (HREE) patterns (i.e., $(Sm/Yb)_N$ = 1.1–2.2 and 1.2–3.6; respectively). However, two basalt samples depict flat chondrite normalized REE-patterns

[$(La/Yb)_N$ = 1–3] similar to NMORB and one sample (i.e., CH28) depict enriched LREE-pattern [$(La/Yb)_N$ = 12.3] similar to OIB. Also, the studied gabbros and basalts display no meaningful Eu-anomaly (i.e., $Eu/Eu^* = Eu/(Sm^*Gd)^{1/2}$ = 0.8–1 and 0.7–1; respectively).

The Primitive Mantle (PM) normalized multi-element patterns of the studied rock types is shown in figure 8. These rock types display sub-parallel and coherent trends reflecting their pristine nature. The mantle peridotites and ultramafic cumulates display overall depleted patterns with positive spikes of LILE (e.g., Rb, Th, U, Pb and Sr) while negative spikes of Nb, La, Ce, Nd, Zr and Eu as compared to other trace elements (Fig. 8a). However, gabbros and basalts (Figs. 8b and 8c) display fractionated multi-element patterns with LILE enrichment (e.g., Rb, Ba, Th, U, K, Pb and Sr) and HFSE depletion (e.g., Nb and Nd).

5.4. Geothermometry

In mantle peridotites, the relationship between orthopyroxene and clinopyroxene was not clear whether they have formed in equilibrium. Similarly, it was petrographically observed that the spinel grains are variously altered and therefore, restricts the use of olivine - spinel pair for thermometry. Thus, it became difficult to establish the thermometry of the studied mantle peridotite samples. However, the equilibration temperatures for ultramafic cumulates were determined using two pyroxene (clinopyroxene-orthopyroxene) thermometry proposed by Wood and Banno (1973) and Wells (1977). Two-pyroxene thermometry results reflects the equilibration temperature of around 946 to 1056 °C after Wood and Banno (1973) and slightly lower equilibration temperatures of 834–959 °C after Wells (1977) for studied cumulate pyroxenites.

6. Discussion

6.1. Magma differentiation

The observed major and trace element concentrations can be explained either by alteration effects and/or cumulate nature of these rock types. The selected major and trace element concentrations of the studied ultramafic cumulates, gabbros and basalts are plotted against an assumed differentiation index i.e., MgO (Fig. 9). These rock types show coherent trends with an observed increasing concentration (i.e., negative correlation) of SiO_2, TiO_2, Na_2O, K_2O, Th, Zr and Rb, while as decreasing concentration of $Fe_2O_3^t$ and CaO/Al_2O_3 against MgO from ultramafic cumulates to more evolved rock types such as gabbros and basalts, therefore reflecting magmatic differentiation. These inter-element relationships are consistent with magmatic accumulation of olivine, clinopyroxene, orthopyroxene and plagioclase. The high CaO/Al_2O_3 ratios in ultramafic cumulates (0.7 to 1.4), gabbros (0.5 to 0.7) and basalts (0.3 to 1.1) clearly indicates the accumulation of Ca-rich clinopyroxene and plagioclase as observed petrographically. Also, the Cr, Ni and $Fe_2O_3^t$ concentration decreases markedly from cumulates to basalts consistent with fractionation of olivine, spinel and clinopyroxene. Further, in AFM ternary diagram (Fig. 5c), the studied samples of basalts, gabbros, ultramafic cumulates and mantle peridotites reflect a trend concordant with highly magnesian nature of parental magmas.

6.2. Petrogenetic characteristics

Geochemical variation observed in the studied rock types could be explained either by mantle heterogeneity or by mantle metasomatism (Saccani 2015; Bhat et al., 2021b). For the petrogenetic characteristics in terms of source and depth/degrees of partial melting of the studied rock types, we have focused on the least mobile major and trace elements as discussed in previous section (Deschamps et al., 2013; Bhat et al., 2021a). Ophiolitic mantle peridotites represent the residual mantle from which the oceanic crust has been extracted (Brandl et al., 2017). The peridotites having either mid-ocean ridge and/or subduction zone affinity puts implications on the upper mantle heterogeneity, fluid/melt metasomatism, and fluid/melt rock interaction (Verencar et al., 2021). The higher concentration of mantle compatible elements (e.g., MgO and Cr) while lower concentration of mantle incompatible elements (e.g., TiO_2, Al_2O_3, La, Ce, Nb etc.) observed in the studied mantle peridotites as compared to PM are similar to highly depleted harzburgites and dunites probably reflect their residual nature (Aldanmaz et al., 2020; Verencar et al., 2021 and references therein). The above inference could be further explained in terms of Al_2O_3/SiO_2 and MgO/SiO_2 ratios. Melting residues have higher MgO/SiO_2 and lower Al_2O_3/SiO_2 ratios whereas, partial melts have lower MgO/SiO_2 and higher Al_2O_3/SiO_2 ratios. The Al_2O_3/SiO_2 and MgO/SiO_2 ratios of the studied peridotites are similar to 0.02 and 0.51, respectively. These ratios are lower relative to Shergol peridotites (0.05–0.06 and 1.09–1.2) and Suru Valley peridotites (0.04–0.06 and 0.7–0.9) from western Ladakh (Bhat et al. 2019b) and highly depleted mantle residual harzburgites (i.e., $Al_2O_3/SiO_2 \sim 0.02$ and $MgO/SiO_2 \sim 1.1$; after McDonough and Sun, 1995). In Al/Si versus Mg/Si diagram (Fig. 10), the studied mantle peridotites show lower Al/Si and higher Mg/Si ratios analogous to refractory mantle residual peridotites such as Shergol and Suru Valley peridotites, western Ladakh. Whereas, ultramafic cumulates, gabbros and basalts shows higher Al/Si and lower Mg/Si ratios comparable to Shergol cumulates and partial melts therefore reflects their derivative nature (Fig. 10). Previous workers suggested that the Shergol and Suru Valley peridotites reflect residual mantle peridotites leftover after earlier partial melting event (e.g., Bhat et al., 2017, 2019b, 2021a).

Various incompatible trace element ratios (e.g., Ti/Y, Ce/Yb, Nb/Y, Zr/Nb, LREE/MREE and LREE/HREE) are widely used to decipher the source characteristics of magmatic rocks (Aldanmaz et al., 2008). Such trace element ratios of the studied gabbros and basalts in comparison to NMORB, EMORB and OIB have been compiled in Table 3. These trace element ratios of the studied gabbros and few basalt samples (e.g., CH34, CH40, CH19, CH20 and CH24) are comparable to EMORB whereas, basalt samples e.g., CH30 and CH36 are analogous to NMORB and one basalt sample i.e., CH28 is comparable to OIB (Table-3). For instance, the Ce/Yb ratio of the studied gabbros (6–23) is much higher compared to that of NMORB ~2.5, but much closer to EMORB ~6.3. Similarly, the Zr/Nb ratio in CH30 and CH36 basalt samples (19–32) is higher compared to that of EMORB (~9), however is similar to NMORB (~33).

The chondrite normalized REE-patterns (Fig. 7) and PM-normalized multi-element patterns (Fig. 8) of the studied rock types reflect their derivation from subduction zone magmas (Shervais et al., 2004). We compared the chondrite normalized REE-patterns of these rock types to other Neo-Tethys ophiolitic rock types. The chondrite-normalized REE-patterns of the studied mantle peridotites are comparable to subduction related Shergol ophiolitic mantle peridotites (data after Bhat et al., 2017), Suru Valley ophiolitic mantle peridotites (data after Bhat et al., 2019b) and Spongtang ophiolitic mantle peridotites (data after Jonnalagadda et al., 2022) from Ladakh Himalaya and also with mantle peridotites from Naga Hill ophiolite (data after Verencar et al., 2021), Indo-Myanmar range, NE India (Fig. 11a). Similarly, the chondrite-normalized REE-patterns of the studied ultramafic cumulates are comparable with Naga Hill ophiolitic mantle peridotites (data after Verencar et al., 2021) from NE India (Fig. 11b). Further, the chondrite-normalized REE-patterns of the studied gabbros (Fig. 11c) are comparable to Shergol ophiolitic gabbros (data after Bhat et al., 2019c) and Suru-Thasgam ophiolitic gabbros (data after Bhat et al., 2021b). While as, basalt samples CH34 and CH40 (Fig. 11d) are analogous to Dras arc basalts (data after Bhat et al., 2019a) and sample CH28 is analogous to Shergol ophiolitic mélange OIB (data after Sinha and Mishra, 1994). Such geochemical characteristics reflect melting of a metasomatized mantle wedge with active participation of subducted slab components including subducting slab fluids originated from the dehydration of the down-going oceanic crust and slab melts generated from subducted sediments (Shervais et al., 2004). Similar petrogenetic processes have been earlier explained for other mafic-ultramafic rock types from Ladakh ophiolites (Ahmad et al., 2008; Bhat et al., 2019c, 2021b), Nagaland-Manipur ophiolites (Singh et al., 2017; Verencar et al., 2021), Naga Hill ophiolites (Dey et al., 2018) and Sabzevar ophiolite NE Iran (Rahmani et al., 2020).

Experimental studies have shown that the sediment-derived aqueous solutions are enriched in fluid-mobile trace elements such as LILE, Pb and U, while sediment-derived melts are enriched in fluid-insoluble trace elements such as LREE and Th besides fluid-mobile trace elements (Zheng and Hermann, 2014). Therefore, the addition of sediment-derived melts to the mantle wedge has a considerable role in transporting the water-insoluble elements from subducting slab to the mantle wedge (Plank and Langmuir, 1998). Fluid-immobile trace elements and their ratios such as Th, Yb, Zr, Th/Nb and Ba/Th are least affected by different degrees of partial melting and fractional crystallization, therefore are commonly used to determine the contributions of subduction-derived components to the mantle source. Because of their complex geochemical behavior, Ba and Th are respectively used as indexes of fluid-derived contribution and sediment-derived melt contribution in the context of subduction zone magmatism (Johnson and Plank, 1999). In order to determine the subduction component contribution to the mantle source of the studied rock types, Th versus Yb (supplementary Fig. S1a) and Th/Nb versus Ba/Th (supplementary Fig. S1b) ratios are plotted. In these plots it is clear that the magma source of these rock types was influenced by adding both aqueous fluid and sediment-derived melt.

The studied rock types are characterized by fractionated REE-patterns and the LREE enrichment increases with degree of differentiation (Fig. 7) reflecting the possible role of fractional crystallization. However, highly incompatible REE concentrations (e.g., La, Sm, and Yb) are unaffected by fractional crystallization processes therefore, are effectively used to decipher the nature of mantle source and partial melting degrees (Aldanmaz et al., 2008).

According to Aldanmaz et al. (2000), partial melts from a spinel-lherzolite mantle source will follow a melting trend subparallel to mantle array defined by depleted to enriched source compositions. However, partial melts from a garnet-lherzolite mantle source will follow a more steeply sloping trend subparallel to Sm/Yb ratio. In Sm/Yb versus La/Sm diagram (Fig. 12a), the studied samples plot along the spinel-lherzolite mantle source, with melt derivation by 5 to 30% partial melting of a depleted mantle source. Similarly, in La/Yb versus Dy/Yb plot (Fig. 12b; after Meddah et al., 2017) the studied rock types depict variable La/Yb ratio for a constant Dy/Yb ratio contends for a partial melting of 5 to 30% occurring in the spinel peridotite mantle source.

Thus, from the above discussion, it is evident that the studied rock types were evolved in a subduction zone environment, similar to other Neo-Tethyan ophiolites such as pyroxenite cumulates from Nagaland-Manipur ophiolite, NE India (Singh et al., 2017; Verencar et al., 2021), gabbros from Shergol ophiolitic slice, western Ladakh (Bhat et al., 2019b), mafic-ultramafic cumulates from Sabzevar ophiolite, Iran (Rahmani et al., 2020), gabbros and pyroxenites from Suru-Thasgam ophiolitic slice, western Ladakh (Bhat et al., 2021b) and other Neo-Tethyan ophiolites (Dilek and Furnes, 2019).

6.3. Geodynamic implications

We correlated the studied mantle peridotites, ultramafic cumulates, gabbros and basalts from western Ladakh with the neighboring consanguineous and well-studied Mesozoic age ophiolitic rock types of SSZ affinity along the IYTS such as mantle and cumulate peridotites from Naga Hill ophiolite, NE India, mantle and cumulate peridotites from Shergol ophiolite, western Ladakh, Suru-Thasgam ophiolitic gabbros, Shergol ophiolitic melange gabbros and OIB and Dras arc volcanics. Earlier workers proposed that the Dras volcanics (U-Pb zircon ages of 160±3 and 156±1 Ma; Walsh et al., 2021), Shergol and Suru-Thasgam ophiolitic rock types, besides Spongtang ophiolite (U-Pb zircon age of 136 Ma;

Buckman et al., 2018) and Nidar ophiolite (Sm-Nd mineral and whole rock age of 140±32 Ma; Ahmad et al., 2008) from other parts of Ladakh, are analogous to an intra-oceanic island-arc (IOIA) ophiolite complex within the Neo-Tethys Ocean (Bhat et al. 2021b and references therein).

In order to put constraints on the paleo-tectonic environment of the studied rock types, various tectono-magmatic discrimination diagrams based on mineral and whole-rock geochemistry are commonly employed (Stern, 2004; Wang et al., 2013; Nouri et al., 2017; Bhat et al., 2021b). The orthopyroxenes in the studied mantle peridotites and ultramafic cumulates are low in Al_2O_3 (< 1.41 and < 5 wt.%; respectively) and TiO_2 (e.g., < 0.15 and < 0.19 wt.%; respectively) but high in Mg# (e.g., 96–98 and 90–94; respectively, Table S2), comparable to SSZ ultramafic pyroxenes (Bhat et al., 2021b). Also, the presence of Mg-rich clinopyroxenes (i.e., Mg# = 96–99 in mantle peridotites and 90–94 in ultramafic cumulates) and Mg-rich olivines (Mg# = 89–93 in mantle peridotites and 88–92 in ultramafic cumulates) also suggest SSZ tectonic affinity (Parlak et al., 2020; Bhat et al., 2021b). Therefore, the Mg-rich olivines, orthopyroxenes and clinopyroxenes in the studied mantle peridotites and ultramafic cumulates are comparable to subduction zone rock types and differ from the rock types formed in mid-ocean ridge tectonic setting which are relatively MgO depleted (Hebert, 1982). Besides, the presence of low-Ti clinopyroxenes in the studied gabbros and basalts (< 0.3 and < 1.1 wt.%; respectively) comparable to Nidar and Shergol ophiolitic gabbros, Ladakh Himalaya (Ahmad et al., 2008; Bhat et al., 2019c) reflect their derivation from depleted mantle sources (Nayak and Pal, 2021). In addition, island arc and SSZ related igneous rocks have plagioclases with higher An-content (Beard, 1986; Parlak et al., 2000) commonly attributed to higher water content and higher CaO/Na_2O ratio in melts (Panjasawatwong et al., 1995). The studied gabbros have An-rich plagioclase compositions (e.g., An_{91} to An_{84}) comparable to Nidar ophiolitic gabbros, eastern Ladakh (Ahmad et al., 2008), Naga Hill ophiolites, eastern India (Abdullah et al., 2018), and Suru-Thasgam pyroxenites, western Ladakh (Bhat et al., 2021b). Also, these gabbros have amphiboles of pargasitic composition (Fig. 4c) correlative to island arc affinity rocks (Bhat et al., 2021b and references therein).

Further, the studied rock types have variable mineral compositions relative to low-pressure MORB-type parental magma (Elthon et al., 1982). The MORB low-pressure (~1 atm.) crystallization sequence starts with olivine crystallization followed by plagioclase prior to pyroxene crystallization with lower Mg# of coexisting clinopyroxene and olivine < 82 (Elthon et al., 1982; Pearce et al., 1984). In the studied rock types, the presence of both the clinopyroxene and orthopyroxene with high Mg# of coexisting olivines and clinopyroxenes (Fig. 13a) reflects their high-pressure crystallization phase relationship comparable to Suru-Thasgam pyroxenite cumulates from western Ladakh (Bhat et al., 2021b) and Bay of Island ophiolite and Mersin (Turkey) ophiolite cumulates (Elthon et al., 1982; Elthon, 1991; Parlak et al., 2020) formed at the base of island arc. Thus, the high-pressure crystallization phase relationship seems to be well-matched with the studied rock types along the ISZ. Similarly, in Al_2O_3 versus SiO_2 plot (Fig. 13b), the clinopyroxene compositions of the studied rock types reflect sub-alkaline nature and dominantly plots in arc tholeiitic field in Al versus Ti plot (Fig. 13c) similar to western Ladakh ophiolitic gabbros (Bhat et al., 2019c) and pyroxenites (Bhat et al., 2021b). However, few basalt compositions (e.g., CH36) plot in MORB field reflecting their MOR tectonic affinity.

The chondrite normalized REE-patterns (Fig. 7) of the studied rock types varies from depleted to LREE enriched pattern concomitant to their generation in an island arc tectonic setting. Similarly, the PM-normalized multi-element patterns (Fig. 8) of the studied rock types reflect negative anomalies at Nb and P with relative enrichment of LREE and LILE such as Rb, Ba, U, Th, Sr, and Pb conformable to an island arc tectonic affinity. In Th/Yb versus Nb/Yb tectono-discrimination diagram (after Pearce, 2008), mantle derived basaltic melts correspond to MORB-OIB array are unrelated to subduction, whereas those plotting above it are envisaged to be derived from a subduction-modified mantle. The studied rock types have higher Th/Yb ratio relative to Nb/Yb ratio therefore, depict an arc-array above the MORB-OIB mantle array augmenting a subduction zone environment (Fig. 14a). Similarly, in V versus Ti/1000 discriminating plot (after Shervais, 1982), V/Ti ratio acts as a suitable proxy for paleo-tectonic affiliation spanning over boninite, island-arc, mid-ocean ridge, back-arc and ocean island domains (Shervias, 1982; Pearce, 2014; Furnes and Safonova, 2019). Majority of the studied samples fall in the arc-tholeiite field thereby attesting their subduction affinity (Fig. 14b). Also, in AFM diagram of Beard (1986), the studied ultramafic rock types plots in arc-related mafic-ultramafic cumulate field, whereas gabbros and basalts plots in arc-related non-cumulate field (Fig. 5c). Therefore, on the basis of mineral and whole-rock geochemistry, present study proposes that the mantle peridotites represent metasomatized mantle wedge peridotites in the context of Neo-Tethys Ocean whereas, ultramafic cumulates and gabbros reflect high pressure fractionation sequences comparable to modern-day island-arc tholeiitic sequences.

7. Conclusions

The present whole-rock and mineral geochemical study on mantle peridotites, ultramafic cumulates, gabbros and basalts from the western Ladakh yield the following conclusions:

(1) Geochemically, the studied rock types show sub-alkaline tholeiitic characteristics with basalt, basaltic-andesite to dacite compositional variation.

(2) The mantle peridotites depict depleted chondrite normalized REE-patterns [$(La/Yb)_N$ = 0.6–1.1] while as ultramafic cumulates depict depleted to enriched REE-patterns [$(La/Yb)_N$ = 0.6–3.2]. Similarly, fractionated patterns are observed in gabbros [$(La/Yb)_N$ = 1.6–4.1] and

basalts [$(La/Yb)_N$ = 1.0–12.3]. However, basalt samples depict flat and enriched chondrite normalized REE-patterns similar to NMORB, EMORB and OIB geochemical characteristics.

(3) The presence of Mg-rich olivines, orthopyroxenes, clinopyroxenes and Ti-poor clinopyroxenes in mafic-ultramafic cumulates and gabbros reflect their derivation from previously depleted mantle source therefore exhibit close similarity to other subduction related Neo-Tethyan ophiolites.

(4) Our results suggest that the ultramafic cumulates and gabbros were formed by fractionation from tholeiitic melts at high pressure and temperature in an island arc tectonic setting.

(5) The present mineralogical and geochemical study suggests that the studied rock types formed as part of an oceanic crust in an intra-oceanic subduction system contemporaneous to Dras-Suru-Thasgam ophiolitic slices of western Ladakh.

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Figure Captions:

Fig. 1. (a) Regional tectonic setting of the Himalayan-Tibetan orogen where the study area is shown with a rectangle and (b) Geological map of western Ladakh, NW India (modified after Reuber, 1989) showing sample locations.

Fig. 2. Field photographs of (a) serpentinized peridotite, (b) spheroidal weathering of basalt, and (c) mafic volcanics along the Khangral-Chiktan road section and (d) wehrlite, (e) hornblende-gabbro and (f) peridotite along the Dras-Kargil road section.

Fig. 3. Photomicrographs under crossed polarized light showing; (a) dunite with olivine (Ol), orthopyroxene (Opx), clinopyroxene (Cpx), serpentine (Srp) and spinel (Sp) grains, (b) proto-granular texture of olivine-websterite consisting orthopyroxene (Opx) and clinopyroxene (Cpx) and subordinate olivine (Ol), (c) olivine-norite consisting olivine (Ol), orthopyroxene (Opx) and plagioclase (Pl) with minor hornblende (Hbl), (d) gabbro showing equigranular texture with grains of plagioclase (Pl), clinopyroxene (Cpx), hornblende (Hbl) and oxides, (e) basalt showing phenocrysts of plagioclase (Pl) and clinopyroxene (Cpx), and (f) porphyritic basalt showing phenocrysts of plagioclase (Pl) and clinopyroxene (Cpx) in a quenched matrix of plagioclase and clinopyroxene.

Fig. 4. Plots of (a) chemical variability of pyroxenes from mantle peridotites, ultramafic cumulates, gabbros and basalts shown in Wollastonite-Enstatite-Ferrosilite pyroxene ternary classification diagram after Morimoto et al. (1989), (b) chemical variability of plagioclase from gabbros and basalts in Ab-An-Or feldspar ternary classification diagram after Deer et al. (1992) and (c) chemical composition of amphibole from gabbros in the Leakes (1978) classification diagram.

Fig. 5. Binary plots of selected trace elements against loss on ignition (LOI) values in studied rock types from western Ladakh.

Fig. 6. Classification scheme based on (a) Nb/Y versus SiO_2 and (b) Nb/Y versus Zr/TiO_2 diagrams (after Winchester and Floyd, 1977) and (c) AFM ternary diagram (after Beard, 1986) for the studied rock types.

Fig. 7. Chondrite normalized REE-patterns of; (a) mantle peridotites and ultramafic cumulates, (b) gabbros and (c) basalts from the western Ladakh. Normalizing values are after Sun and McDonough (1989).

Fig. 8. Primitive Mantle (PM) normalized multi-element patterns of; (a) mantle peridotites and ultramafic cumulates, (b) gabbros, and (c) basalts from western Ladakh. Normalizing values are from Sun and McDonough (1989).

Fig. 9. Selected major and trace elements against MgO in studied rock types from western Ladakh.

Fig. 10. Al/Si versus Mg/Si plot of studied rock types in comparison to Shergol and Suru Valley residual mantle peridotites and Shergol cumulate peridotites.

Fig. 11. (a) Chondrite-normalized (after Sun and McDonough, 1989) REE-patterns of (a) mantle peridotites, (b) ultramafic cumulates, (c) gabbros and (d) basalts in comparison to other ophiolitic rock types.

Fig. 12. (a) La/Sm versus Sm/Yb diagram with melting curves obtained using nonmodal batch melting modeling after Bezard et al. (2011), and (b) La/Yb versus Dy/Yb diagram (after Meddah et al., 2017 and reference therein) where the models of batch melting of spinel and garnet peridotite sources are from Thirlwall et al. (1994).

Fig. 13. Various mineral chemistry discrimination diagrams (a) Mg# of coexisting olivine and clinopyroxene from the studied rock types, where field of ophiolitic mafic-ultramafic cumulates is after Parlak et al. (2020) whereas, field of low-pressure (1 atm.) MORB-type

magma is after Elthon et al. (1982), (b) Al_2O_3 versus SiO_2 of clinopyroxene compositions after Le Bas (1962), and (c) Ti versus Al after Beccaluva et al., (1989) of clinopyroxene compositions from the studied rock types.

Fig. 14. Tectono-magmatic discrimination plots of (a) Th/Yb versus Nb/Yb (after Pearce, 2008) and (b) Ti/1000 versus V (after Shervias, 1982) for the studied rock types. NMORB: Normal Mid Oceanic Ridge Basalt, EMORB: Enriched Mid Oceanic Ridge Basalt, OIB: Ocean Island Basalt and BAB: Back Arc Basalt.