Whole Rock Geochemistry and Petrography of Pyroxenite Veins within Cumulate Dunite, Mawat Ophiolite: Implication for Classification and Petrogenesis, Kurdistan Region, NE Iraq

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Abstract
The Mawat ophiolite is situated in the Kurdistan region of Iraq. Pyroxenite veins are crossed cut ultramafic Mawat ophiolite. Petrographic study and new geochemical data suggest that Pyroxenite veins in ultramafic units can be classified into two main rock types: websterite and pyroxenite. The websterite veins have a width ranging from 10 to 25 cm and a length of 300 m inside dunite. The pyroxenite veins, on the other hand, have a width of up to 10 cm and extend for around 150 m along dunite rock. Their major element geochemical characteristics emphasized that the websterite has relatively higher contents of SiO₂ (49.01–53.02 wt%), CaO (15.3–19.35 wt%), Al₂O₃ (1.06–1.36 wt%), Σrare earth elements (1.09–2.09 ppm), and low MgO (21.07–23.06 wt%). Pyroxenite rock samples are characterized by relatively low SiO₂ (41.01–48.09 wt%), CaO (1.49–12.3 wt%), Al₂O₃ (0.65–1.29 wt%), Σrare earth elements (0.3–3 ppm), and high MgO (24.04–39.07 wt%). The result of Trace and rare earth elements suggests that pyroxenite veins are formed by partial melting from the extensively depleted mantle. The rare earth element in dunite normalized to chondrite shows a flat to concave trend, whereas chondrite normalized rare earth elements in pyroxenite rock samples are highly depleted (SmN/CeN ~2) and display a negative light rare earth elements trend in comparably flattened positive middle rare earth elements and heavy rare earth elements patterns. This suggests that the vein is generated from supra-subduction zone settings. The enrichment in Ba, Th, and U provides further constraints on re-fertilization mechanisms. The research samples even showed a wide range of high partial melting degrees from the mantle source.

Keywords: Websterite; Pyroxenite; Mawat ophiolite; Partial melting; Kurdistan region; Iraq

1. Introduction
Ophiolites have been identified in a variety of locations across the world. They have developed in a variety of tectonic environments. The tectonic setting of ophiolites may be generally divided into two categories: those that are subductional related and non subductional related (Dilek and Furnes, 2011). Ophiolites that were not formed as a result of subduction include continental margin, mid-ocean ridge (MOR), and plume types. The magmatism that formed these ophiolites occurred during periods of rifting and ocean floor spreading. Forearc, backarc, and island arc forms of ophiolites are classified as subduction-related or suprasubduction zone (SSZ) ophiolites (Dilek and Furnes, 2011; Monsef et al., 2018).

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All ophiolites are composed of mafic and ultramafic rocks. The previous research concluded that the mafic gabbroic rocks of Mawat ophiolite Complex (MOC) are thought to have an affinity for MORBs (Mirza and Ismail, 2007). The tholeiitic metagabbros found at the southern part of the MOC as a result of partially melted peridotite (Koyi et al., 2010), while chemistry and isotope data provide strong evidence that the Mawat area has undergone magmatic activity. They are associated with a deep mantle plume and are similar to OIB-type magma (Azizi et al., 2013). Al Humadi et al. (2022) demonstrates that the MOC is represent the supra-subduction zone ophiolites of the Alpine-Himalayan Orogenic Belt, which is situated above the subduction zone. It is classified as low-Ti boninitic magma that was formed by partial melting at the suprasubduction zone (Azizi et al., 2013).

The occurrence of ultramafic rock outcrops within the MOC (Fig. 1) is remarkable compared to other complexes, such as the Penjween Complex or the Zagros ophiolite in Iran. For instance, in the Kermanshah and Khoy regions, the main component of the ophiolite complex consists of ultramafic rocks (Allahyari et al., 2010; Saccani et al., 2013). The ultramafic rocks in Mawat (Fig. 2a) have various degrees of serpentinization and contain an abundance of chromite pods (Ismail et al., 2010; Mohammad, 2011).

Using petrochemistry could assist in identifying the origin of the mantle as well as provide significant understanding into processes such as melt extraction, partial melting, and interaction between melts and rocks in the upper mantle of the ancient oceanic lithosphere (Arai et al., 2007; Dilek and Thy, 2009). By analyzing these, we can determine the tectonic environment in which they formed (Piccardo and Guerrieri, 2011).

The harzburgite and dunite are cut by clinopyroxene dykes (Azizi et al., 2013; Mirza, 2008). Structure and texture of pyroxenite vein point to a melt rock process that created pyroxene at conditions close to peridotite solidus (Garrido & Bodinier, 1999). In addition to having a significant impact on the melting process and the creation of veins and fertilized mantles, their formation also affects the movement of melting through the shallow mantle. Geological, petrographic, and whole-rock geochemical studies were performed on dunite and pyroxenite vein rocks situated in the Sarshiw valley (Fig. 2b). These data allowed an assessment of the main rock types and origin of pyroxenite veins. A partial melting and refertilization mechanism are suggested for pyroxenite veins generation within the supra subduction zone.

2. Geological Setting

The Tertiary Zagros Orogenic Belt, striking from NW to SE, is an essential component of the Alpine-Himalayan orogenic belt, which encompasses much of southern Europe, southwest Asia, and the Middle East. The Zagros Orogenic Belt is a young continental convergence zone that extends from eastern Turkey to northern Iraq, across Iran to the Strait of Hormuz, and eventually into northern Oman (Moghadam and Stern, 2011).

The Zagros Mountains are Cenozoic age and are found in the interface between the Arabian and Eurasian plates (Fig. 1) as a result of the collision between the Eurasian and Arabian plates (Agard et al., 2005; Takin, 1972, Mohammad et al., 2014, Mohammad and Cornell, 2017; Mohammad and Qaradaghi, 2016, Mohammad et al.2020, Mohammad et al., 2023). The Zagros Mountains in Iraqi Kurdistan consist of five parallel structural areas that extend from northwest to southeast (Fig. 1). Such as the Sanandaj-Sirjan Zone (Shalair terrain), the crushed zone, the imbricate zone, the Zagros Fold Thrust Belts (High and Low Folded Zones), and the Mesopotamian Foredeep.
The vast majority of Neo-Tethyan ophiolites identified in the eastern Mediterranean are fragments of oceanic lithosphere that were formed by supra-subduction zones (SSZ). These findings have been supported by various studies conducted by Ali and Roustam (2021), Bağcı et al. (2005, 2006, 2008), Bağcı and Parlık (2009), Beyarslan and Bingöl (2000), Dilek et al. (1999, 2007), Dilek and Flower (2003), Dilek and Furnes (2009), Parlak et al. (1996, 2000, 2002, 2004, 2009, 2013), Pearce et al. (1984), Rızaoğlu et al. (2006), Robertson et al. (2006, 2007), Saccani and Photiades (2004), and Yalıınız et al. (1996). Ophiolitic remnants in Iraq constitute a part of the crushed zone between the imbricate zone and the Sanandaj-Sirjan Zone (Fig. 1).

The MOC is a constituent of the Neo-Tethyan Ophiolite Belt located in the Middle East. Aswad and Elias (1988) determined the age of the ophiolite by analyzing the process of magmatic crystallization, which yielded an age of around 101 ± 5 million years (K-Ar dating), 96 Ma U-Pb by Mohamamd and Qaradghi (2016). In terms of age, this ophiolite can be compared to the Iranian Ophiolites (Neyriz ophiolite, 93–98 Ma (Ghazi and Hassanipak, 1999), and Kermanshah ophiolite, 95–98 Ma (Hassanipak et al., 2002)) and Oman Ophiolite (Samail Ophiolite, 95 Ma (Tilton et al. 1981)).

The MOC covers 250 km² and consists of two thrust sheets, as shown in Fig. 2a. The Upper Cretaceous Mawat Ophiolite complex and the Late Cretaceous to Paleogene Walash-Nouprdan Groups are the most notable formations. The tectonic boundary between the two groups is indicated by highly deformed mylonitic gabbro (Azizi et al., 2013). The Mawat ophiolite shift 25 km southwest (Mohamamd et al., 2014). There are local thrust faults within the sequence units that suggest the ophiolite is...
Fig. 2. a) The geological map of the Mawat ophiolite complex MOC in the Kurdistan region of NE Iraq (Modified from Hama-Aziz, 2008). b) Google Earth image showing the location of the pyroxenite vein in the ultramafic rocks of the MOC. c) Geologic cross section of the Mawat ophiolite and associated units (Al-Qayim et al., 2012). d) The lithological sections are pseudo stratigraphic columns of the Mawat ophiolite modify after (Omer, 2023)

overturned. The series starts with thin and highly altered basalts at the lower part and extends up to a thickness of 2km. The uppermost layer consists of amphibolized gabbro, metagabbro, and green schist, which are associated with small intrusions of intermediate and acidic intrusions. These rocks overlay the metagabbros and serpentinized ultrabasic rocks (dunite, harzburgite, and lherzolite), as well as pyroxenite and chromite at the top (Mohammad and Cornell, 2017).

The most remarkable ultramafic outcrop within the complex is located in the central section of the complex, as seen in Fig. 2a. The pillow basalt is underlying by amphibolitized gabbro, mostly composed of cumulate gabbro; felsic minerals are segregated from the gabbro due to localized metamorphism and deformation. Upper gabbro has more diversity. The material exhibits significant distortion and
mylonization (Mohammad et al., 2016; Yara and Mohammad, 2018). Intermediate and acidic minor intrusions are associated with basic and ultrabasic masses (Mirza, 2008).

3. Sampling and Analysis Techniques

To further comprehend the petrogenesis of pyroxenite veins, 32 samples were collected at 35°50'53.99"N, 45°33'3.92"E in the eastern portion of the center of MOC, approximately 4 km south of the Rashakani village. The sample location is shown in Figure 2b, from contact blocks of host rock (dunite) and pyroxenite veins that crop out in the MOC. More than 60 polished thin sections prepared for petrographic study using transmit and reflected light optical microscopy at university of Sulaimani.

A total eleven samples were ground up into a fine powder at the University of Sulaimani's geology department to find out more about the geochemical features of the pyroxenite vein and hosted dunite found in the ophiolitic rocks of the Sarshew valley in the Kurdistan region of northeast Iraq. The samples were analysed at ALS Laboratory Group, SL (Spain) for abundant whole-rock major, trace, and rare earth elements. Fusion of lithium Li Borate prior to dissolving it in acid is the most effective quantitative analytical method for an extensive variety of rare earth and trace element analyses with an ICPMS. Method ME-MS81TM, combined with Method ME-ICP06 were selected for the major, trace and rare earth elements. In addition, including base metals from a second ICP-AES analysis using four-acid digestion from a single fusion. The results of the analyses of whole-rock geochemical data for 11 whole rocks are shown in Table 1.

4. Results

4.1. Petrography

4.1.1. Dunite

Dunite appears in the light olive green to grey olive green due to the existence of black olivine (Fig. 3a). It has a homogeneous lithological composition. Cumulate dunite consists mostly of olivine and small amounts of spinel, orthopyroxene and clinopyroxene (Fig. 3b). Olivine is the most common subhedral to anhedral mineral, displaying a size variation from 0.2 to 5.0 mm and an abundance above 85%. It is partially serpentinezed (Fig. 3c and d) along the cracks and grain boundaries to form a meshed texture (Fig. 3d). Serpentine is abundant at more than 5% and is often observed as colourless, flaky, anhedral, and sometimes as elongated blades with roughly parallel orientations (Fig. 3d). However, the olivine occasionally alters to talc (Fig. 3c), with an abundance of less than 5%. The presence of triple junctions (Fig. 3b) is evidence of equilibrium recrystallization.

The predominant accessory mineral that dominates in the dunite samples that were examined is chromite (Fig. 3c & d). It appears in the form of tiny subhedral crystals and has an abundance of more than 5%. They range in color from dark reddish brown to black and in shape from subhedral to anhedral

4.1.2. Pyroxenite

According to field observation two types of pyroxenite were determined; webistrite is dark gray to black color (Fig. 4a) and pyroxenite is thinner with gray to bluish gray color. Webistertite occurs as a layer (10-25 cm) that extends up to 250 metres within dunite (Fig. 4) wheal the pyroxenite is thinner (5-10cm) and associated with harzburgite (Fig. 5a) extend up to 200m long. They are characterized in sharp contact with their host rocks (Fig. 4a and 5b).
Fig. 3. a) field photography showing reverse faulted pyroxenite vein in dunite with disseminated chromite. b) Microphotograph of olivine (Ol) showing triple junction and straight sides. c) olivine (Ol) made mesh texture while altered to talc and serpentine, and some fractures filled with iron oxide and the chromite grains were spread out within the rock. d) altered olivine grains to serpentine and made sieve texture with scattered chromite in olivine aggregate.

Fig 4. Field photographs showing pyroxenite veins of the MOC: a) Webisterite vein's opposite walls fit together. b) Orthopyroxenite veins cutting dunite with light gray to bluish color.
Fig. 5. Field photography showing a) Pyroxenite vein within dunite deformed and cutting by thrust fault
d) Webisterite showing sharp contact with hosted dunite

Webisterite as a main vein rock with fine- to coarse-grained subhedral to anhedral and cataclastic texture (Fig. 6a). It is comprised mostly of pyroxene (clinopyroxene~35% and orthopyroxene~25%), with small amounts of olivine (~5%). Pyroxenes are variably altered into amphibole (~15%), serpentine and talc (~15%), in all samples investigated. The accessory minerals consist of plagioclase (~5%), chromite, sulfide and oxide minerals (Fig. 6b and c). Pyroxene crystals range from 0.3 to 1.5 mm, with megacrysts reaching more than 1 cm (Fig. 7a). Pyroxene crystals are sieved and xenoblastic with many tiny, euhedral inclusions that can increase grain size from the cores to the rims and partly transform into amphibole and talc (Fig. 6c); however, the laths or large crystals of tremolite-actinolite are occasionally embedded inside the crystals of clino and orthopyroxene (Fig. 6b). Pyroxene grains show variable amounts of pyroxene dissolution and replacement by serpentine (Fig. 6d). Plagioclase was detected as anhedral interstitial between pyroxene grains, referring to melt impregnation (Fig. 7a). Pyroxenite is characterised by fine to medium grain; the primary magmatic mineral assemblage is mainly of pyroxene (orthopyroxene ~20% and clinopyroxene ~15%) and olivine (~5%). Amphibole (~30%), serpentine (~20%), talc (~5%), and oxide (~5%) are the main secondary minerals. Accessory minerals are represented by chromite and sulfide. High tectonic movement in the area caused the rock demorflation and metamorphism. Pyroxenite is often serpentinized, and its minerals are replaced by serpentine minerals. Pyroxene is replaced by tremolite, actinolite, and serpentine (Fig. 6b, c, and 7b). Moreover, the crack and fracture were refilled with secondary calcite minerals (Fig. 7c). While olivine relics as small anhedral grains within serpentine and talc altered (Fig. 5d).

4.2. Whole-Rock Chemistry

The major and trace element compositions of the dunite and pyroxenites veins of MOC are shown in (Table 1). The Mg# in dunite ranges from 91.8 to 92.4, whereas in pyroxenite it is 89.9 to 92.9. The Al₂O₃ and CaO values in the dunite samples range from 0.1-0.23 wt% and 0.18–0.68 wt%, respectively, which are lower than the associated pyroxenites vein. While The values of Fe₂O₃ and MgO in the identified dunite samples range from 9.28 to 9.75 wt.% and 48.8 to 50.8 wt.% respectively, which are higher than the concentrations in the pyroxenite samples.
Fig. 6. Microphotograph of pyroxenite veins of the MOC a) Cataclastic texture of websterite b) Alteration of orthopyroxene to tremolite. c) Clinopyroxene showed alteration to serpentine and talc around boundaries. d) Dissolution and replacement of pyroxene around their grain boundary.

Fig. 7. Microphotograph of pyroxenite veins of the MOC a) interstitial plagioclase grain with dissolution and replacement of pyroxene around their grain boundaries. b) Pyroxenite has been extensively altered to tremolite, actinolite, and serpentine. c) Secondary calcite-filled cracks and secondary veins. D) Serpentine and talc as alteration products of olivine and pyroxene.

The websterite has Al₂O₃ and CaO concentrations of 1.04–1.38 wt% and 15.3–19.35 wt%, respectively. The Fe₂O₃ and MgO concentrations of samples range from 4.08–5.53 wt% and 21.7–23.6 wt%, respectively. Pyroxenite has lower Al₂O₃ and CaO concentrations (0.65–1.29 wt% and 1.49–12.3 wt%, respectively) than the websterite and dunite associations. Their Fe₂O₃ and MgO concentrations...
(4.15-7.43 wt% and 24.4-39.7 wt%, respectively) are higher than those associated with websterite and dunite.

The major element binary diagrams with MgO wt% were utilized as a fractionation index. The differences between dunite and pyroxenites rocks (Fig. 8) show that MgO has a reverse correlation with SiO2, Al2O3, CaO, and TiO2 (Fig. 8a, b, c, and g), which is related to the proportions of olivine, orthopyroxene, clinopyroxene, and spinel. This negative association is attributed to a partial melt extraction-induced depletion process, as discussed by Coleman (1977), Katzir et al. (1999), and Mirza (2008). Dunite rocks are mainly characterized by moderate amounts of MgO and exceptionally small amounts of Al2O3, CaO, and TiO2, as well as the presence of incompatible elements.

The dunite rock and pyroxenites veins in the MOC exhibit a high amount of chromium (1895–4030 ppm), a low amount of Cr (1895–4030 ppm), a low concentration of Sr (< 10.6 ppm), and an extremely limited presence of incompatible high field strength (HFSE) elements such as Zr (< 4 ppm), Y (< 1.8 ppm), Th (< 0.05 ppm), Nb (< 1.16 ppm), Ta (< 0.1 ppm), and Ce (< 0.1 ppm) (Table 1). The concentrations of Co and Ni exhibit an ordered increase from the pyroxenite associated with dunite and increasing amounts of MgO (Fig. 9a and f). These findings indicate that the concentration of Ni is mostly associated with olivine and, to a limited extent, orthopyroxene. While V exhibits an inverse correlation with MgO (Fig. 9e), which is consistent with the process of melt extraction (Mirza, 2008; Palme and O'Neill, 2004), the observed correlation between the increase in Ni and the decrease in V content with increasing MgO concentration in ultramafic rocks (Fig. 9e) can be attributed to varying degrees of melt extraction that occur after the least-depleted peridotite. In other words, the peridotite that is most similar to the composition to the primitive mantle should have the lowest Ni content.

| \hline
| \textbf{Dunite} & \textbf{websterite} & \textbf{pyroxenite} |
|-------------|-----------------|--------------------|
| DS-8        | DS-13           | DS-9a              |
| SiO2        | 38.9            | 37.3               |
| Al2O3       | 0.1             | 0.23               |
| Fe2O3       | 9.28            | 9.75               |
| CaO         | 0.18            | 0.68               |
| MgO         | 50.8            | 48.8               |
| Na2O        | 0.02            | 0.01               |
| K2O         | 0.01            | 0.01               |
| Cr2O3       | 0.437           | 0.546              |
| TiO2        | <0.01           | 0.01               |
| MnO         | 0.13            | 0.14               |
| P2O5        | <0.01           | 0.01               |
| SrO         | <0.01           | <0.01              |
| BaO         | <0.01           | <0.01              |
| LOI         | 1.31            | 2.38               |
| Total       | 101.18          | 99.86              |

Trace

| Ba         | 0.9 <0.5        | <0.5 <0.5 <0.5 1   |
| Ce         | 0.1 <0.1        | <0.1 <0.1 <0.1 <0.1 <0.1 |
| Cr         | 2580 3240       | 2540 2720 2810 2860 2830 2670 2830 2670 |
| Cs         | <0.01 <0.01     | <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 <0.01 |
| Dy         | <0.05 <0.05     | 0.15 0.3 0.15 0.15 0.16 0.13 0.16 0.13 0.16 0.05 0.28 |
| Er         | <0.03 <0.03     | 0.12 0.17 0.12 0.16 0.2 0.13 0.12 0.03 0.18 |
| Eu         | <0.02 <0.02     | <0.02 <0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 0.02 |
| Ga         | 0.3 0.5         | 1.3 1.4 1.3 1.5 1.3 1.5 1.3 1.5 0.9 0.8 1.7 |
| Gd         | <0.05 <0.05     | 0.06 0.11 0.07 0.1 0.07 0.05 0.05 <0.05 0.15 |
| Hf         | 0.06 0.12       | <0.05 0.09 <0.05 <0.05 <0.05 <0.05 <0.05 0.06 0.06 0.06 |
| Ho         | <0.01 <0.01     | 0.03 0.06 0.04 0.05 0.05 0.04 0.04 <0.01 0.07 |

Table 1. Major oxide (in wt.%), trace, and rare earth elements (in ppm) chemical content for the dunite, websterite, and pyroxenite of MOC
La 0.1 0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 
Lu <0.01 <0.01 0.02 0.02 0.02 0.01 0.01 0.02 0.02 0.01 
Nb 0.08 <0.05 <0.05 <0.05 <0.05 <0.05 <0.05 0.07 0.05 0.16 
Nd 0.1 <0.1 <0.1 0.1 0.1 0.1 0.1 <0.1 0.1 <0.1 
Pr <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 <0.02 
Rb <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 <0.2 0.2 <0.2 0.4 
Sm <0.03 <0.03 0.3 0.05 0.05 0.04 0.03 0.06 <0.03 <0.03 
Sr 0.7 1.7 10.2 5.3 5.3 7.2 6 9.7 6.1 10.6 
Ta <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 <0.1 
Tb <0.01 <0.01 0.02 0.04 0.02 0.03 0.02 0.02 0.01 <0.01 
Tm <0.01 <0.01 0.02 0.02 0.02 0.02 0.02 0.01 0.01 <0.01 
V 12 29 138 166 135 147 135 141 125 44 
W <0.5 <0.5 <0.5 <0.5 <0.5 <0.5 <0.5 <0.5 <0.5 <0.9 
Y 0.1 <0.1 1.1 1.8 1.3 1.2 1.1 1.2 1 0.6 
Yb <0.03 <0.03 0.16 0.2 0.14 0.15 0.14 0.17 0.12 <0.03 
Zr 1 4 <1 2 <1 <1 <1 <1 <1 <1 
Zh 130 132 43 37 47 44 46 40 80 104 
Cu 4 3 280 62 36 182 119 20 172 3 
Ni 2700 2610 685 557 527 515 500 530 1830 2190 1340 
Pb 6 4 7 6 5 3 5 3 4 3 2 
Sc 3 5 39 48 40 41 39 40 29 8 50 
Zn 40 47 15 14 22 15 22 15 24 45 22 
Mg# 92.4 91.8 92.6 92.2 90.6 90.9 89.9 92.3 92.7 92.2 92.9 

As a result of serpentinization and sea floor weathering, the Sc, V, and Ga elements are mostly immobile or unaffected (Niu, 2004). The magnesium covariation diagrams show an obvious negative correlation between the elements Sc, V, and Ga in the rock samples (Figs. 9c, e, and j). This correlation is attributed to the fact due to their incompatibility; these elements are more likely to accumulate in the melt than in minerals (Engler et al., 2002). There is a noticeable dispersion of highly incompatible elements such as Ba, Nb, Rb, and Th among the lithophile trace elements. But the random patterns of Ga, Zr, Ba, Nb, and Th (Fig. 8d, i, g, and c) are because they don't mix well when the mantle melts (Mirza, 2008).

The chondrite-normalized diagram of rare earth elements (REEs) in dunite and pyroxenite veins from the MOC (Fig. 10 and 11) show that the distribution of REEs in the samples is slightly variable and fluctuates. The dunite samples are characterised by slightly flattened patterns, which are typical of ophiolitic ultrabasic rocks (Coleman, 1977; Tankut, 1990). The little variable observed in the trend of the patterns defines a pronounced depletion in the middle REEs (Eu-Dy), except for a minor positive anomaly in Eu. This depletion is compatible with a supra-subduction zone origin (Hamasalh, 2004). This is emphasised by the sample trend clearly reflected in one of the dunite samples, the LaN/YbN ratio, which is (2.3), and the other is below the detection limit. Dunite have low amounts of TiO₂. This is a characteristic of Alpine-type ophiolites, which formed in the upper part of the mantle during
Fig. 8. Major oxides variation diagram plotted versus the MgO content of dunite and pyroxenites

The main process before ultramafic rocks were emplaced by plate tectonics and some of the asthenospheric mantle partially melted (Al-Jubury et al., 2023).

The pyroxenite variety samples exhibit similar chondrite normalised REE patterns (Fig. 12). Variable REE distributions are seen in pyroxenite (Table 1) when compared to chondrite normalized REE patterns. They display a significant depletion of light rare earth elements (LREEs) in comparison to middle rare earth elements (MREEs) and heavy rare earth elements (HREEs). The (La/Yb)N values range from 0.3 to 0.9, except for D-28, where (La/Yb)N is (3.5). Nevertheless, pyroxenite dykes have a positive Eu anomaly in almost all samples, with the exception of samples DS-14a and 25. The total rare earth element (REE) concentrations observed in dunite are notably deficient, ranging from 0.1 to 0.4 ppm. In contrast, both kinds of pyroxenites display higher ΣREE values relative to dunite, with concentrations varying from 1.9–3 ppm, except for sample D-28, which is only 0.3 ppm.

In the spider diagram normalized to NMORB (Fig. 12), dunite and pyroxenite veins display a harmonious pattern. The analyzed REE element patterns show that they are relatively enriched in LILE and HFSE. However, both rock types exhibit non-smooth NORB patterns and have shown strong
Fig. 9. Trace element variation diagram plotted versus the MgO content of dunite and pyroxenites. Legend has described in (Fig. 8)

positive Cs, Rb, Th, U, and K anomalies, except negative anomalies have been observed in Ba, Nb, and Ce. While in HREE, that split into two types of patterns in Ti, Y, and Yb elements. The isolated pyroxenite veins slightly show positive anomalies in HREE patterns, except for sample D-28, which showed negative anomalies with HREE patterns in dunite rock. Additionally, Zr has a similar trend and exhibits a negative anomaly in the websterite; however, it displays a positive anomaly in dunite and pyroxenite.

The spider diagram, which is based on the NMORB and PM in all samples, shows that LIL has a similar trend to HFS, which is slightly variable. This suggests that both types of samples came from different magmatic sources (Fig. 12 and 13). It depicts the relative enrichment of LILEs compared to HFSE. These diagrams show positive anomalies of Cs, Rb, K, and Pb in relation to Nb, La, and Zr, except for Ba, which is shown to be depleted on all samples. These patterns refer to fluid infiltration during serpentinization (Deschamps et al., 2013; Godard et al., 2008).
Fig. 10. The REE patterns of dunite in MOC have been normalized to chondrite (Boynton, 1984)

Fig. 11. The REE patterns of pyroxenite in MOC have been normalized to chondrite (Boynton, 1984)
Fig. 12. Spider diagram of trace elements dunite and pyroxenite veins have been normalized to N-MORB (Sun and McDonough, 1989)

Fig. 13. Spider diagram of trace elements dunite and pyroxenite veins have been normalized to Primitive mantle (PM) (Sun and McDonough, 1989). The legend has been described in (Fig. 8)
5. Discussion

5.1. Partial Melting of Mantle Rocks

Ophiolitic peridotites are important geological archives that provide conclusive evidence of metasomatism and partial melting. The major element multiple plots with MgO of all samples (websterites, and pyroxenite) (Fig. 8) shows the presence of simple trend lines that extend from the dunite to the orthopyroxenites and ultimately to the websterite. This suggests that these samples may have originated from similar sources but underwent different degrees of partial melting (Maaløe 2005). The geochemical properties of these rocks, mostly influenced by partial melting and interactions between fluids, melts, and rocks, can be used to assess the extent of partial melting. However, given the intricate and varied characteristics of mantle melting, it is essential to use a modelling method to provide an accurate evaluation.

Rock geochemistry can be used to infer the extent of partial melting (Niu et al., 2004). A significant degree of partial melting of the mantle source is indicated by primitive mantle PM normalized incompatible element patterns for selected pyroxenite vein rock samples. In comparison to the DMM melting curves in the spinel stability field, the study samples contained relatively low HREE abundances (Hoog et al., 2009), while DMM melting patterns indicate 15% in websterite and 25% in pyroxenite, except for one sample shown at 30% (Fig. 14a).

The MgO concentration and Mg# in the mantle that formed peridotites are important signs of depletion because they show how much the rocks have melted (Frey et al., 1985; Hirose et al., 1998). Low concentration of TiO$_2$, Al$_2$O$_3$, and CaO in peridotitic rocks compared to the primitive mantle show a large amount of partial melting (Khedr et al., 2014; Takazawa et al., 2003). Additionally, ultramafic rocks with relatively low TiO$_2$ and Al$_2$O$_3$ indicate a supra-subduction tectonic setting for the MOC (Fig. 14b), followed by late-stage intrusions of boninitic fore arc magma (Mohammad, 2020). Samples that were studied show that they partially melted more than primitive mantle sources, as they have higher MgO concentrations and lower TiO$_2$, Al$_2$O$_3$, and CaO concentrations. In the Sc versus Yb diagram, the studied rocks lie near the termination of the polybaric melting curves (Niu et al. 1997).

To further figure out the partial melting pyroxenites, we employed the non-modal dynamic melting model (Kapsiotis, 2016) to simulate the overall Ni and Yb concentration in the rocks. It is widely accepted that both Ni and Yb are fluid-immobile elements (Parkinson et al., 1998). Ni is relatively compatible with olivine and pyroxene during melting while Yb is relatively incompatible (Green et al., 2000; Suhr, 1999), the degree and type of partial melting can be determined by comparing the Ni/(Yb*1000) vs. Yb (Uysal et al., 2012). The Ni/Yb versus Yb non-modal shows that there is about 10% to 15% partial melting in websterite, as shown in the primitive mantle diagram (Fig. 15a) (Palme, 2003). In contrast, for pyroxenite rocks, the data concentrated around 10% - 18%, except one sample indicating 28% (Fig. 15a).

Comparatively, in the Yb vs. Sc diagram for websterite, the data are concentrated in <5% to 8% partial melting of the fertile MORB mantle (FMM) (Pearce et al., 1993). However, pyroxenite rocks displayed ranges between <5% - 10% partial melting, except for one sample that showed 24% (Fig. 15b), resembling forearc serpentinized peridotites (Khedr et al., 2022). The high percentage of partial melting, typically 20-25% (up to 30%) in residual dunite and 10-18% (up to 28%) in pyroxenite (Fig. 15b), supports an SSZ environment. This suggests that fluids derived from the subducting slab are more dominating than in a back-arc setting such as a forearc setting, resulting in a significant amount of partial melting.
Fig. 14. a) PM normalized incompatible element patterns for selected pyroxenite rocks (McDonough and Sun, 1995) compared to the partial melting curves, supporting a DMM source (Workman et al., 2005). b) chondrite-normalised Sm/Yb versus Yb Diagram of websterite and pyroxenite whole rock data and refertilisation hydrous melting trends (Barth et al., 2008).

Fig. 15 a) non-modal dynamic melting of a PM source (Palme et al., 2003) (after Kapsiotis, 2016) for the studied dunite and pyroxenites; b) Yb vs. Sc binary plot for dunite and kinds of pyroxenites (Pearce, 1993). The PM compositions are (after McDonough and Sun, 1995).

A Yb_N vs. (Sm/Yb)_N diagram (Fig. 14b) shows the impact of fluid additions during hydrous partially melted in the mantle wedge above a subducted slab. Since fluid-mobile trace elements are provided at each melting increase, hydrous melting produces virtually flat REE patterns rather than significantly LREE-depleted residua like anhydrous melting. As shown in Figure 14, dunite, websterite, and pyroxenite originate from SSZs. The refertilisation-hydrous melting concepts reproduce the depleted MREE in comparison with LREE or HREE relatively (Nayak et al., 2023), and the almost positive Eu anomaly (Fig. 11) of the pyroxenite venis MOC within the shear zone, but they predicted lower LREE and HREE contents than observed. The high and considerably fractionated HREE amounts indicate partial melting (Barth et al., 2008).
5.2. Petrogenesis and Tectonic Setting

Pyroxenites vines are characterized in the MOC within the mantel and crustal sections. The mode of the vein is parallel to the foliation (Fig. 4a). They are generally classified as pyroxenite without determining their types. Different genesis is postulated for pyroxenite (for detail see the Al Hamudi et al. 2022; Mirza, 2008).

The most often debated theory of pyroxenites creation in the recent past was related to the melt-rock reaction. When olivine from harzburgite wall rock first dissolves by interacting with Si-enriched melt and also pyroxene then precipitates in situ (Bodinier et al., 2008; Marchesi et al., 2013; Rogkala et al., 2017; Roux and Liang, 2019;). The pyroxenites under investigation are thought to be indicative of early accumulations of boninite melts, which have been identified in supra-subduction settings (Batanova et al., 2011; Varfalvy, 1997). The presence of a rock association consisting of harzburgites, dunes, chromitites, webstrite, and pyroxenite veins inside supra-subduction ophiolites might be seen as evidence of magmatic alteration of the mantle by tholeiite and boninite melts, as suggested by Marchesi et al. (2013) and Pagé et al. (2008).

The analysis of geochemical data distribution has led to the identification of webisterite and pyroxenite, which suggests that their sources are slightly different. The webisterite has higher concentrations of rare earth elements (REE) than other rocks. The REE concentrations and patterns of the two pyroxenite types are similar to the patterns of the whole rock, which is depleted in light rare earth elements (LREE) and enriched in heavy rare earth elements (HREE). This LREE depletion implies that the mantle source was depleted (Coleman, 1977; Tankut, 1990), which is consistent with a supra-subduction zone origin (Hamasalh, 2004). The average total REE contents in webisterite are 2.2 ppm, which is higher than those in pyroxenite (1.6 ppm), which suggests that the two types of pyroxenites may have formed from different melts or undergone different magmatic processes. The average (Mg#) in webisterite is 91.6%, and the lower and higher (Al₂O₃) contents range from 1–1.3 wt%. The average (Mg#) content is 92.6% in pyroxenite with lower (Al₂O₃) content ranging from 0.65 to 1.29 wt%, which may reflect a more depleted source region. The relative depletion of Al₂O₃ from dunite to pyroxenites indicates that the Al₂O₃ extraction occurred during partial melting, and it is consistent with the melting trend (Page et al., 2008).

The bulk chemical trends shown by the samples are entirely consistent with the process of refertilization. The enrichment in Ba, Th, and U compared to LREE (Fig. 13) provides further constraints on refertilization mechanisms. Entrapment and in situ crystallization of interstitial melt and melt impregnation processes (Obata and Nagahara, 1987; Rampone et al., 1997). There is a need for localized volume expansion in this model. The two sides of the webistrite vein fit together, which means there was a fracture before the webisterite and pyroxynite crystallised (Fig. 4a). Also, the existence of plagioclase as interstitial between mantle pyroxene (Fig. 6d and 7a) refers to the percolating melt impregnation (Coltorti et al., 2010).

On an ACM diagram (Fig. 17a), the samples correspond to ultramafic cumulatic rocks with ophiolitic affinity (Coleman, 1977). The REE elements normalized to the primitive mantle showed enrichment in LILE and depletion in HFSE, which are also distinctive characteristics of dunite and pyroxenite rocks found in ophiolite complexes and dykes ranging from tholeiite to boninite affinities (Fig. 17b and 18a) within the supra-subduction zone (Fig. 17b and 18b) (Aditi et al., 2012). Their low
The dunite, webstrite, and pyroxenite in the MOC show relatively low \( \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} \) ratios are (0.01), (0.02-0.03), and (0.015–0.025), respectively, which shows that they are depleted. The amount of \( \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} \) is slightly higher in webstrite than in pyroxenite and dunite. This is because of melt trend extraction and metasomatism, which make webstrite more concentrated than pyroxenite and dunite. The \( \frac{\text{MgO}}{\text{SiO}_2} \) ratios shown by the selected samples range from (1.3), (0.4–0.5), and (0.7–0.9), respectively. Those values at the higher end are more typical of refractory mantle rocks (dunite) than both pyroxenite vein rock types (Fig. 16). Unlike residual dunite, webstrite, and pyroxenite do not go in the direction that parallels the terrestrial configuration. Instead, they followed a trend vertically towards the lower (\( \frac{\text{MgO}}{\text{SiO}_2} \)) ratio at a fixed \( \frac{\text{Al}_2\text{O}_3}{\text{SiO}_2} \) (0.02) (Fig. 16), indicating the presence of secondary \( \text{SiO}_2 \) addition (\( \text{SiO}_2 \) metasomatism from melting or fluid). Despite secondary compositional changes, The webstrite and pyroxenite originate from a refractory peridotite parent (Whattam et al., 2011), as evidenced by their low HFSE/LREE ratios and low concentration of HFS and HREE which are below the primitive mantle values (Fig. 13).

REE abundance indicates that their mantle source is extremely depleted. This depleted magma can form from the melting of highly depleted mantle sources as a result of secondary or even third-stage melting at shallow depths with or without water-rich fluids, as proposed by Duncan and Green (1987). Furthermore, pyroxenite veins from MOC ultramafic rocks reveal low \( \text{Cr}_2\text{O}_3 \) content range from (0.3 to 0.6%), as well as low abundances of \( \text{Na}_2\text{O} \) (0.1 to 0.25%) and \( \text{TiO}_2 \) (<0.01 to 0.05%) (Fig. 17(a,b)). These geochemical compositions suggest that pyroxenite veins show for arc-like character, consistent with a depleted mantle source. Moreover, these REE and trace element patterns are also akin to those of SSZ fore-arc ultramafic rocks from Zagros ophiolites.

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**Fig. 16.** Plot of dunite, websterite, and pyroxenite rocks in \( \text{Al}_2\text{O}_3/\text{SiO}_2 \) vs. \( \text{MgO}/\text{SiO}_2 \) space (legend for samples are described in Fig. 8)
Fig. 17. a) AFM diagram of ultramafic rocks of MOC and fields of ultramafic cumulate, metamorphic peridotites (after Coleman, 1977). b) discrimination TiO2–SiO2/100–Na2O (wt.%) diagram of ultramafic dunite and pyroxenite veins rocks showing different oceanic environments (Beccaluva et al., 1989).

Fig. 18. a) The V/Ti subduction-melting proxy can be used to differentiate between island arc tholeiite (IAT), MORB, and boninite magmas (after Shervais, 1982). b) Ultramafic rocks from the MOC are plotted above the EMORB-NMORB array on the Nb/Yb vs. Th/Yb diagram (after Pearce, 2008). The Th/Yb vs. Nb/Yb proxy is used for identifying suprasubduction zone (SSZ) ophiolites from those from mid-ocean ridges. And legend has been described in Fig. 8.
6. Conclusions

Based on the discussion of the presented data, the pyroxenite veins in the Sarshew Valley are crosscutting the mantle units and they classified as websterite and pyroxenite. The multielement and REE diagrams, as well as the relation between trace element content (i.e., V, Ti), clearly indicate the pyroxenite veins are characterized by low Ti boninitic, which is determined to be progressive source depleted in the SSZ region. Geochemical data (major elements, trace elements, and REE) indicates that the two types of pyroxenite veins (websterite and pyroxenite) formed due to different degree of partial melting from the same mantle. There is a strong loss of LREE due to partial melting of the refractory mantle, followed by partial melting of the fertile mantle. Based on the geochemical concentrations of major and trace elements, models of partial melting suggest that in websterite rock, partial melting ranges between 10 and 15%, and the ratio for pyroxenite was revealed to be between 10 and 28%. The enrichment in Ba, Th, and U compared to LREE provides further constraints on refertilization mechanisms. Field observation and the presence of plagioclase as interstitial between mantle pyroxene suggest that the websterite and pyroxenite veins formed by entrapment and in situ crystallization of interstitial melt and melt impregnation processes.

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