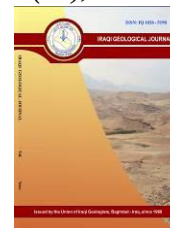




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Petrogenesis and Tectonic Setting of Amphibolite Pods from the Walash Group, Rayat Area, NW Zagros Fold-Thrust Belt, Kurdistan Region, NE Iraq

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Abstract

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Amphibolite pods hosted in serpentized ultramafic rocks from the Rayat area (Walash Group) of NE Iraq provide a critical record of pre-collisional magmatism and syn-collisional metamorphism within the Neo-Tethyan NW Zagros Fold-Thrust Belt, Kurdistan Region of Iraq. This study investigates their petrogenesis and tectonic setting through integrated petrography, mineral chemistry, and whole-rock geochemistry. Two principal amphibolite types are identified: garnet-bearing amphibolite (hornblende, garnet, pyroxene and plagioclase) and garnet-barren amphibolite (dominantly hornblende and plagioclase). Mineral chemistry classifies amphiboles as tschermakite to magnesio-hornblende, plagioclase as Na-rich (albite), pyroxenes as diopside, and garnet as almandine-spessartine. Geochemical data indicate a basaltic (tholeiitic) protolith of ortho-amphibolite origin. The rocks exhibit moderate enrichment in large-ion lithophile elements (LILE; e.g., Ba, U), negative Nb and Eu anomalies, and depletion in light rare earth elements. Chondrite-normalized rare earth element patterns with $(La/Yb)_N$ typically <1 , alongside trace element ratios (e.g., Nb/Y, Zr/Y) and Ti-V, collectively point to a depleted mantle source and back-arc basin basalt affinity, with some samples showing normal mid-oceanic ridge basalt (N-MORB) characteristics. This study uses amphibole thermo-barometry to identify an upper-amphibolite facies evolution, with peak conditions (674-796 °C at 6.4-6.9 kbar) indicating magmatic underplating in a back-arc setting. Subsequent retrograde equilibration (549-596 °C at 3.6 kbar) and mylonitic textures—marked by chloritization, sericitization, and epidote-record a protracted exhumation and tectonic juxtaposition within a serpentinite-hosted mélange. These amphibolites represent back-arc basin crust derived from a spinel lherzolite source, preserved as tectonic pods emplaced during Walash Group obduction and Neo-Tethys closure along the Arabia-Eurasia suture.

Keywords: Walash Group; Amphibolite; Back-Arc Basin Basalt; Petrogenesis; Neo-Tethyan Ophiolite; NW Zagros Fold-Thrust belt; Iraq

1. Introduction

The investigation of amphibolite is crucial for understanding of metamorphic and magmatic processes. This provides important information on tectonic settings, temperature and pressure conditions and the processes that shape the Earth's crust. The variety of mineral chemistry and textural relationships within these amphibolite pods provide critical constraints on the thermobaric evolution and subduction-related processes of the Neo-Tethyan lithosphere (Gill and Fitton, 2022). Amphibolite bodies of the NW Zagros Fold-Thrust Belt of northeast Iraq have received much scholarly attention. Amphibolites are

commonly found as discontinuous pods, lenses and dikes in different geological settings. Amphibolites and hornblendite occur as pods and lenses in sharp contact with peridotite and serpentinite rocks in the Penjween ophiolite (Hadi et al., 2013) and later were studied for their mineralogy, geochemistry and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology (Kettanah et al., 2022).

The NW Zagros Fold-Thrust Belt, as composite tectonic boundary, resulted from the Neo-Tethys Ocean's closure and the subsequent collision of the Arabian and Eurasian plates (Alavi, 1994; Jassim and Goff, 2006; Moghadam and Stern, 2015; Moghadam et al., 2020; Chaharlang et al., 2020). This zone, extending from southeastern Turkey to southern Iran, is a component of the larger Alpine-Himalayan orogenic system (Al Humadi et al., 2019; Ghanbarian et al., 2021). Throughout the Kurdistan Region of Iraq, this suture is defined by a dense stack of allochthonous units, most notably the Walash-Naopurdan volcano-sedimentary sequence. Present study investigation centers on the Rayat area within the Choman District, focusing specifically on Walash Group exposures situated near the Iran-Iraq border. It represent an Eocene-aged part of the suture, recording the complex history of ancient oceanic and arc-related crustal fragments (Ahmed et al., 2020; Ismail et al., 2009). The amphibolite pods within the Walash Group are critical markers of the thermobaric evolution of the Arabian margin during the final stages of Neo-Tethyan subduction and the onset of continental convergence (Agard et al., 2005; Jafari et al., 2023).

Previous research within Rayat area have mainly concentrated on the podiform chromitites, which have shown the presence of platinum-group minerals such as laurite and the production of low-temperature high-Cr spinel (Arai et al., 2006; Ismail et al., 2009; Ahmed et al., 2020). The tectonic development and mantle-source properties of this suture section have been further clarified by isotopic studies (Rb-Sr and Sm-Nd) of the accompanying serpentinites (Aziz et al., 2011). Amphibolites within these complexes are especially significant, as they generally signify metamorphosed mafic protoliths originating in suprasubduction settings and later modified during tectonic burial and exhumation (Shakerardakani et al., 2019). Therefore, this study aims for integrating the detailed petrography, mineral chemistry, and the whole-rock geochemistry to clarify the petrogenesis and tectonic setting of amphibolite pods within the Walash Group. The results document the protolith origin, metamorphic phase equilibria, and fluid-mediated processes, to clarify our knowledge about lithospheric evolution within the NW Zagros Fold-Thrust belt.

2. Location, Geology and Tectonic Setting of the Study Area

The tectonic framework of Iraq is primarily defined by its position on the northeastern margin of the Arabian Plate (Jassim and Goff, 2006). The present study area is situated within the NW Zagros Fold-Thrust Belt as shown in Fig. 1, represents a complex region marking the boundary where the Arabian Plate continues to collide with the Eurasian Plate (Jassim and Goff, 2006; Fouad, 2015). This suture represents the final closure of the Neo-Tethys Ocean, characterized by the structural juxtaposition of various allochthonous units against the Arabian continental margin during the Cenozoic (Alavi, 1994; Numan, 1997).

Tectonically, the study area is situated within the Penjween-Walash subzone of the NW Zagros Fold-Thrust Belt (NE Iraq). This subzone is characterized by a complex sequence of lower and upper allochthonous thrust sheets (Aswad, 1999; Aziz et al., 2011; Ali et al., 2013; Qaradaghi and Merza, 2023). The upper allochthon is also known as the "Ophiolite-bearing terrane" (Ismail et al., 2017). In contrast, the lower allochthon consists of volcanic and sedimentary rocks associated with the Walash-Naopurdan nappe (Aswad, 1999).

The study area is located within the Choman region, part of the Walash Group which belong to the Arabia-Eurasia suture zone. It is located at coordinates: latitude $36^{\circ} 42' 10.66''$ N and longitude $44^{\circ} 58' 33.90''$ E, near Alana village, within the Choman region and close to Rayat Town, approximately 115

km from the Erbil Governorate (Figs. 1 and 2). Rayat is one of the remnant fragments of oceanic lithosphere that has been exposed near Rayat Town in the Zagros region, NE Iraq (Fig. 2). It comprises the Walash Group, this tectonic *mélange* was predominantly composed of serpentinites (60-65%), calcareous shales (30-35%), and subordinate volcanic-sedimentary units including conglomerates, greywackes, and red calcareous argillites (Al Jawadi, 1980). Structurally, the ultramafic rocks at Rayat are divided into three thrust-bounded units. A lower thrust emplaced serpentinitized peridotite and recrystallized limestone over folded calcareous sediments, while an upper thrust placed ferruginous conglomerates of the Walash Group over the serpentinite and its envelope (Al-Mehaidi, 1975; Ahmed et al., 2020; Ismail et al., 2009). This imbricate structure records the tectonic stacking and accretion of oceanic and arc-related materials during the final closure of the Neo-Tethys and the development of a Paleogene volcanic arc (Aswad et al., 2014).

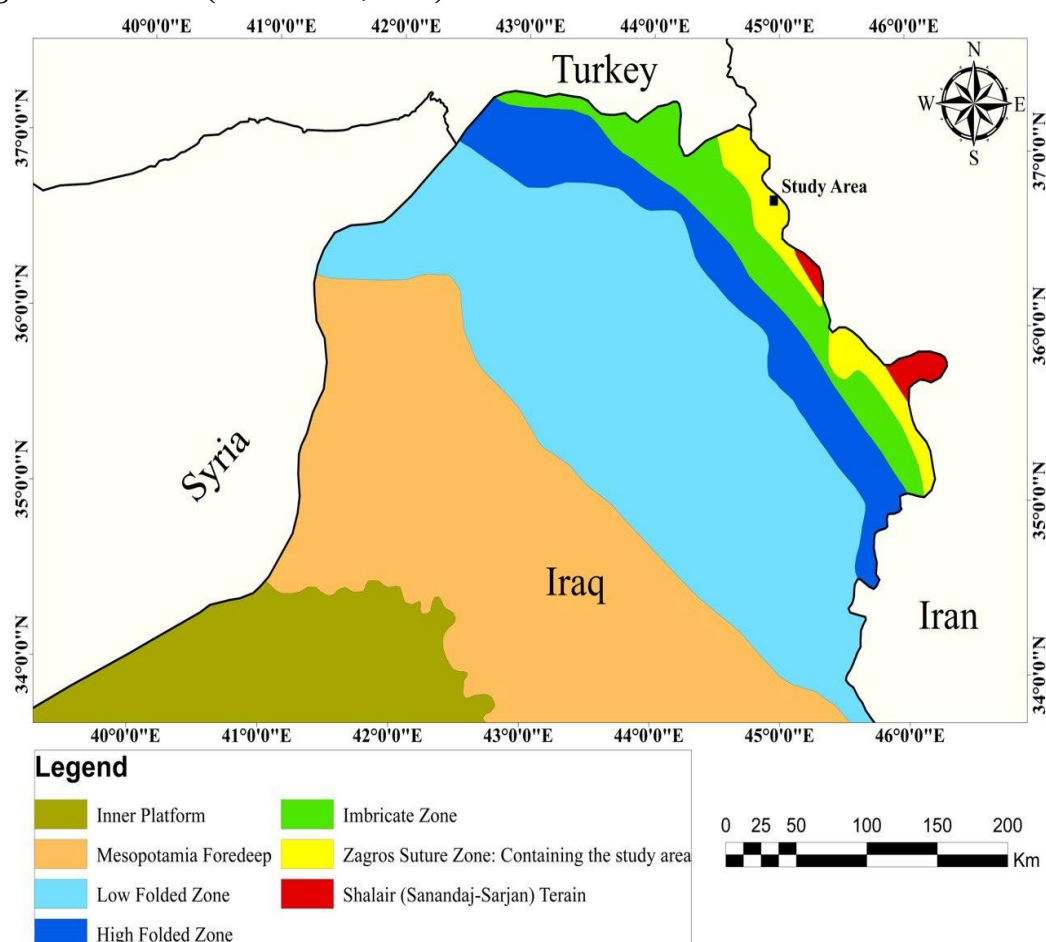


Fig. 1. Simplified tectonic map of Northern part of Iraq, modified from Fouad (2015), exhibiting locations of study areas

In the Rayat area, serpentinite bodies typically occur as elongated slices along the structural boundaries of the Walash and Naopurdan nappes (Aziz et al., 2011). These serpentinites represent fragments of the Neo-Tethyan oceanic lithosphere, forming a narrow NW-SE trending belt along the Iraq-Iran border within the Penjween-Walash subzone. While these ultramafic bodies frequently host pods of chromite (Arai et al., 2006), they also serve as the primary host for metamorphic blocks of higher-grade crustal material. Specifically, the amphibolite and garnet amphibolite which analyzed in this study occurs as discrete pods sequestered within the strongly sheared serpentinites of the Rayat area, marking a distinct petrological contrast to the surrounding lithosphere.

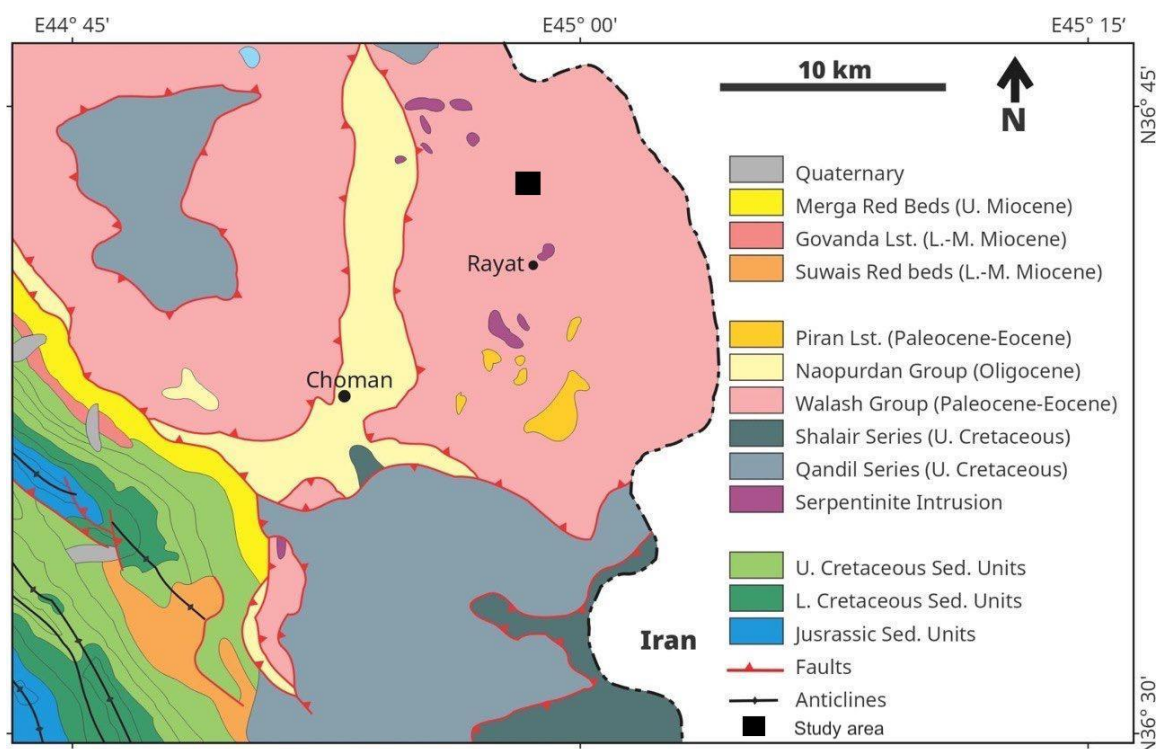


Fig. 2. Geological map of the study area (Sissakian and Fouad, 2015)

3. Methodology and Field Work

The studied amphibolites occur as discrete pods ranging from 0.8 to 2 m in diameter scattered on top of the eroded serpentinite host rocks. These rocks are characterized by a compositional layering, defined by dark amphibole-rich and small light-colored mineral lines of heterogeneous grain size (Fig. 3). Thin sections were examined in detail using polarizing microscopy to identify constituent minerals and textural relationships, and to document the effects of deformation, alteration and metamorphism. Modal mineral abundances were determined by point-counting method.

This study is based on ten amphibolite and one host serpentinite rock samples. Petrographic analysis, including thin section preparation and optical microscopy, was conducted in the Department of Earth Sciences and Petroleum at Salahaddin University, Erbil, Iraq. The chemical composition of constituent minerals was determined by electron probe micro-analyzer (EPMA) at Charles University in Prague, Czech Republic. Whole-rock geochemistry, including major and trace elements, was performed at ACTLABS in Seville, Spain.

A full description of the whole-rock geochemical analytical protocols and quality control measures is available via the ACTLABS website (<http://www.actlabs.com>). Major elements were determined by ICP-AES, while trace and rare earth elements were analyzed via ICP-MS. To ensure the complete dissolution of resistant mineral phases, samples were prepared using the lithium borate fusion method (Packages ME-ICP06 and ME-MS 81D). Loss on ignition (OA-GRA05) was also performed to further characterize the samples. The precision of all measurements, defined as the relative standard deviation of replicate analyses, was better than 10%. Accuracy, determined through the analysis of international rock standards, was within $\pm 2\%$ for major oxides and $\pm 5\%$ (relative) for trace and rare earth element concentrations.

Mineral chemistry was determined for two representative samples: R4 (Amphibolite) and R6 (Garnet amphibolite). These samples were selected as the most suitable candidates for thermodynamic modeling as they preserve the full equilibrium assemblage of garnet, hornblende, pyroxene, and plagioclase. A total of 68 individual spot analyses were conducted using a FEG-EPMA JXA-8530F

(Jeol) electron microprobe, focusing on grain cores and rims to evaluate chemical homogeneity and metamorphic evolution. Analyses were performed under operating conditions of 15 kV accelerating potential and a 20 nA beam current. Quantitative data were acquired for the elements Na, Al, P, K, Ca, Cl, Ti, Cr, Ba, V, Fe, Mn, Ni, Zn, Mg, F, and Si, using the following reference standards: Na (albite), Al (pyrope), P (apatite), Mg (MgO), Si (quartz), K (sanidine), Ca (diopside), Cl (tugtupite), Ti (rutile), Cr (chromium oxide), Ba (barite), and V (vanadium), Fe (magnetite), Mn (rhodonite), Ni (pentlandite), and Zn (willemite). Fluorine was analyzed using F-topaz as the standard. A peak counting time of 10 seconds and a background counting time of 5 seconds were used for all elements. The acquired X-ray intensities were corrected using the ZAF online program.

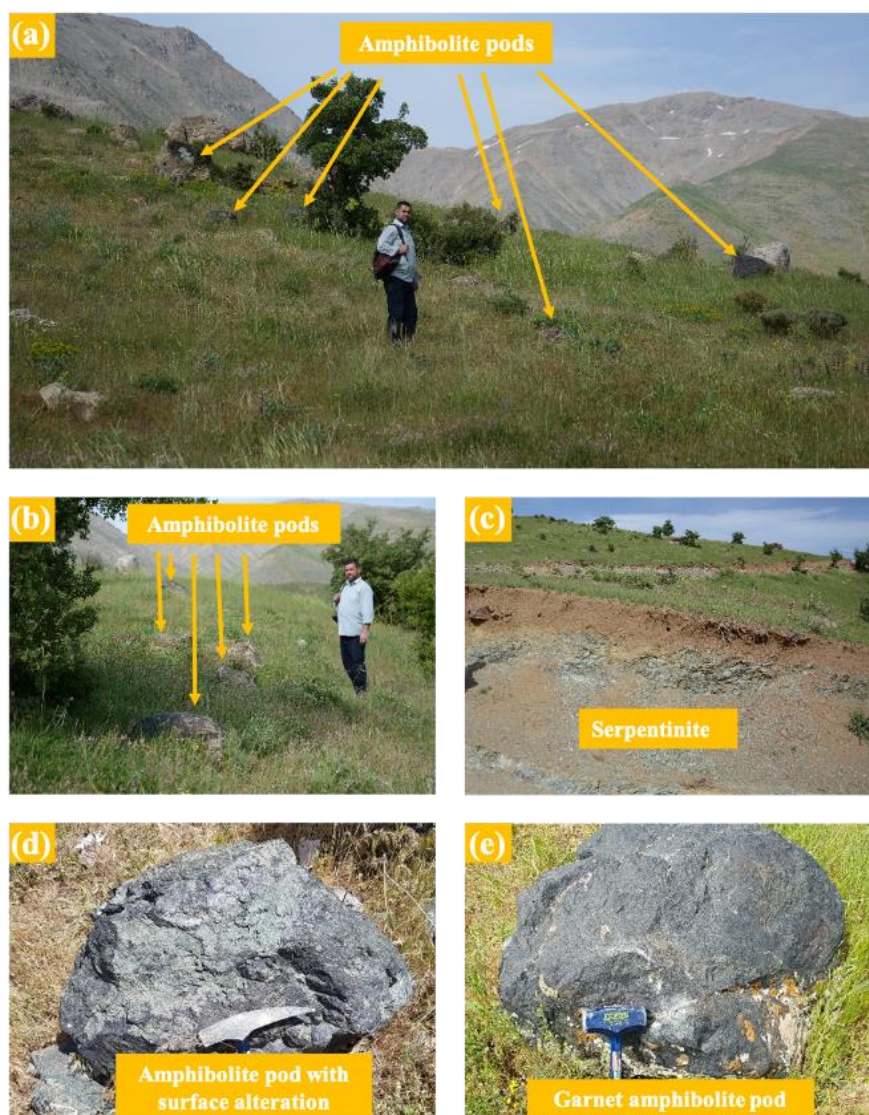


Fig. 3. Field photographs of amphibolite pods: a) General view of the area showing multiple amphibolite pods; b) Close view of five distinct amphibolite pods; c) Host serpentinite rock; d) Amphibolite pod exhibiting surface alteration; e) Fresh, unaltered garnet amphibolite pod

4. Results

4.1. Petrography

Under plane-polarized light, the host rock serpentinite is dominated by fine-grained serpentine (Fig. 4a, b) forming a dense and fibrous aggregates that extensively replace the primary ultramafic minerals,

including olivine and pyroxene. Relict pyroxene crystals are preserved as pale brown, prismatic shapes with moderate relief, commonly fractured and partially altered along grain margins and cleavage to serpentine. Opaque minerals occur as fine, disseminated crystals and along micro-fractures. The overall texture reveals incomplete serpentinization, with partial preservation of the parental pyroxenitic texture of the parent rock.

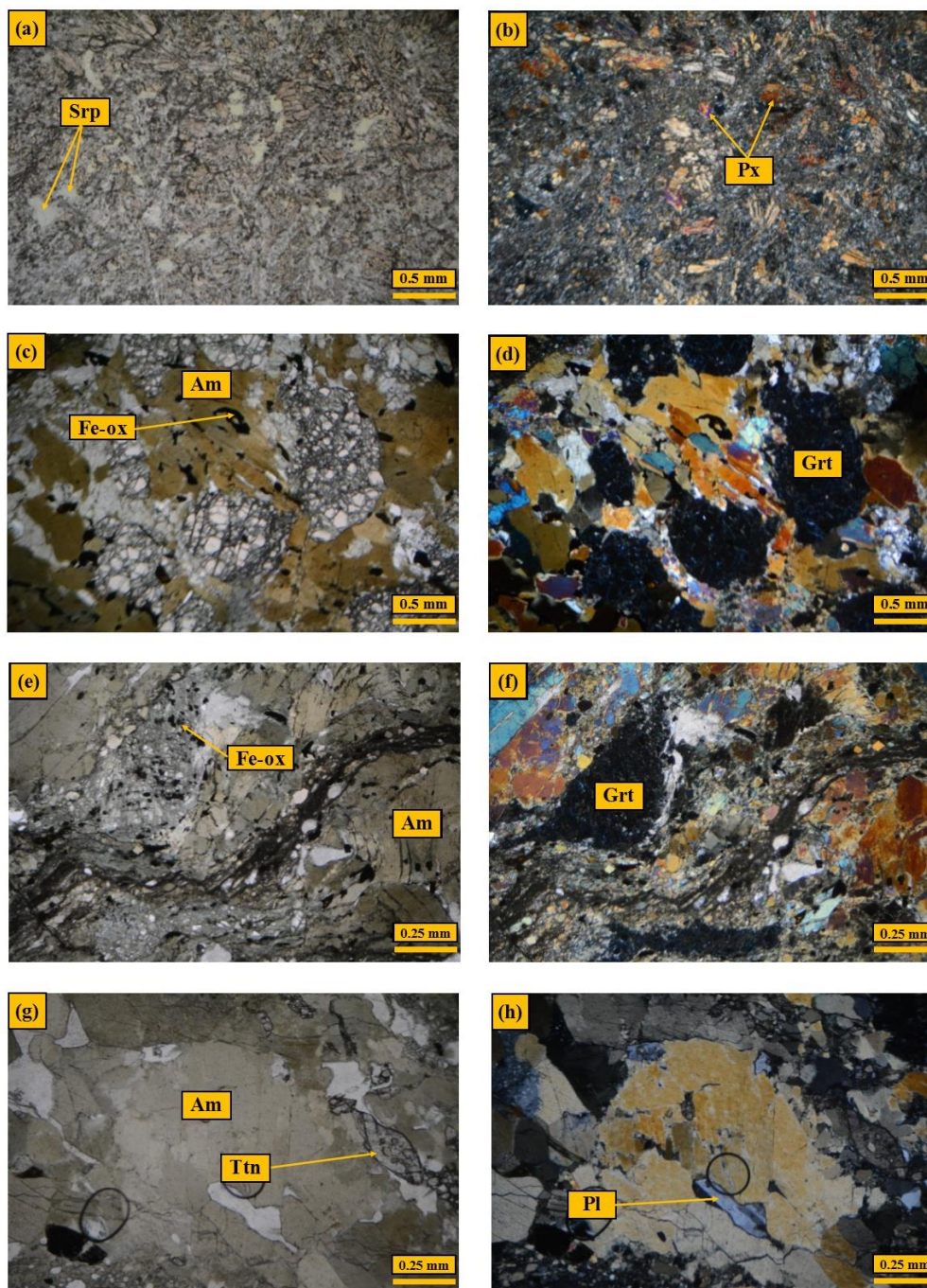


Fig. 4. Photomicrographs of the studied rocks, (A and B) are host serpentinite rock and (C) to (H) are illustrate amphibolite and garnet amphibolite rocks: a) Serpentine host rock (Plain polarized light: PPL); b) Garnet amphibolite containing amphibole and garnet crystals (Crossed polarized light: XPL); c) Cataclastic and griding texture in garnet bearing amphibolite sample (XPL); d) Apatite occurring as inclusions within amphibole crystal (XPL); e) Plagioclase crystal partially enclosed by amphibole (XPL); f) Small grains of opaque minerals within amphibole crystals (PPL). Abbreviations: Am-Amphibole; Pl-Plagioclase; Grt-Garnet; Px-Pyroxene; Ttn-Titanite; Srp-Serpentine

Petrographic investigation reveals that the amphibolites can be categorized into two distinct groups: garnet amphibolite and amphibolite. The garnet amphibolite comprises hornblende (70-85%), garnet (5-10%), and plagioclase (5-10%), with accessory pyroxene (<4%), titanite (<3%), opaque minerals (<5%), and rutile (<1%). Secondary sericite (<2%), epidote (<1%) and chlorite (<3%) are present. The amphibolite is dominated by hornblende (80-90%) with plagioclase (5-15%) and accessory titanite (<3%), apatite (<1%), opaque minerals (<5%), and rutile (<1%), alongside with minor secondary sericite and chlorite.

The dominant texture is granoblastic, characterized by mixed amphibole, plagioclase, and garnet (Fig. 4c, d). Deformation evidence is prevalent, with porphyroclastic and mylonitic textures reflecting diverse grain sizes (Fig. 4e, f) resulting from cataclastic processes. Poikiloblastic texture is prevalent, characterized by massive hornblende crystals that contain inclusions of plagioclase, opaque minerals (most likely ilmenite), apatite and titanite. Furthermore, relict igneous textures, specifically blasto-ophitic and blasto-subophitic textures, are preserved where hornblende encloses plagioclase (Fig. 4g, h).

Garnet appears as fractured, anhedral crystals, often with inclusions of opaque minerals and rutile. Extensive alteration of garnet to chlorite along fractures is pervasive (Fig. 5a, b). Amphibole is the principal mineral (60-80%), exhibiting strong pleochroism from yellow to greenish-brown. It occurs as fine- to medium-grained subhedral to anhedral crystals, displaying characteristic two-set cleavage at $\sim 124^\circ/56^\circ$ in cross-section. Many crystals show undulose extinction, fracturing, and deformation features. The strong blue-green pleochroism and interference colors observed in the tschermakite crystals (Fig. 4e, f) result from intervalence charge transfer (Fe^{2+} to Fe^{3+}) within the crystal lattice. This is characteristic of Al-rich calcic amphiboles in high-grade metamorphic environments (Deer et al., 1997). Plagioclase (10-15%) is fine-grained and commonly exhibits partial to complete sericitization (Fig. 5c, d). It frequently occurs in the relict blasto-ophitic textures.

Accessory minerals comprise titanite as wedge-shaped inclusions (Fig. 5e, f), rutile as elongated, high-relief grains (Fig. 5g, h), apatite as rare euhedral inclusions (Fig. 5c, d), and opaque minerals (Fig. 5a-d). Also, secondary epidote presents as alteration product from plagioclase and hornblende (Fig. 5c, d).

4.2. Mineral Chemistry

The composition of the major and the minor oxides of the primary rock-forming phases, including amphibole, pyroxene, plagioclase, and garnet, were analyzed on polished thin sections for one amphibolite sample (R4) and one garnet amphibolite sample (R6) by using electron probe micro-analyses (EPMA).

4.2.1. Amphibole

Amphibole is the most abundant phase in the studied amphibolite samples. Selected (EMPA) analyses of amphibole and its chemical formula normalized to 23 oxygens, are presented in Table. 1. The (Ti versus Si) diagram by (Leake, 1965) shows that all amphiboles from the studied samples are classified as the metamorphic amphibole (Fig. 6a), have low (Ti) content ranging from 0.04 to 0.21 atoms per formula unit (apfu). The classification diagram of amphibole reveals that most amphiboles are plotted within the tschermakite and magnesio-hornblende fields (Fig. 6b), reflecting high-grade metamorphism. However, the occurrence of ferro-actinolite in sample (R6) is interpreted as a localized retrograde product. These amphiboles exhibit intermediate (Si) contents, ranging from 6.41 to 6.94 apfu and intermediate Mg#: $\text{Mg}/(\text{Mg} + \text{Fe}^{2+})$ value, ranging between 0.61 and 0.68. Tschermakite amphiboles are marked by their high (Al) contents and are commonly found in high-grade metamorphic rocks, reflecting conditions of high temperature and pressure (Kabir et al., 2016). The magnesium hornblende

typically coexists with garnet and other amphiboles, with its composition can vary with metamorphic conditions (Zenk and Schulz, 2004).

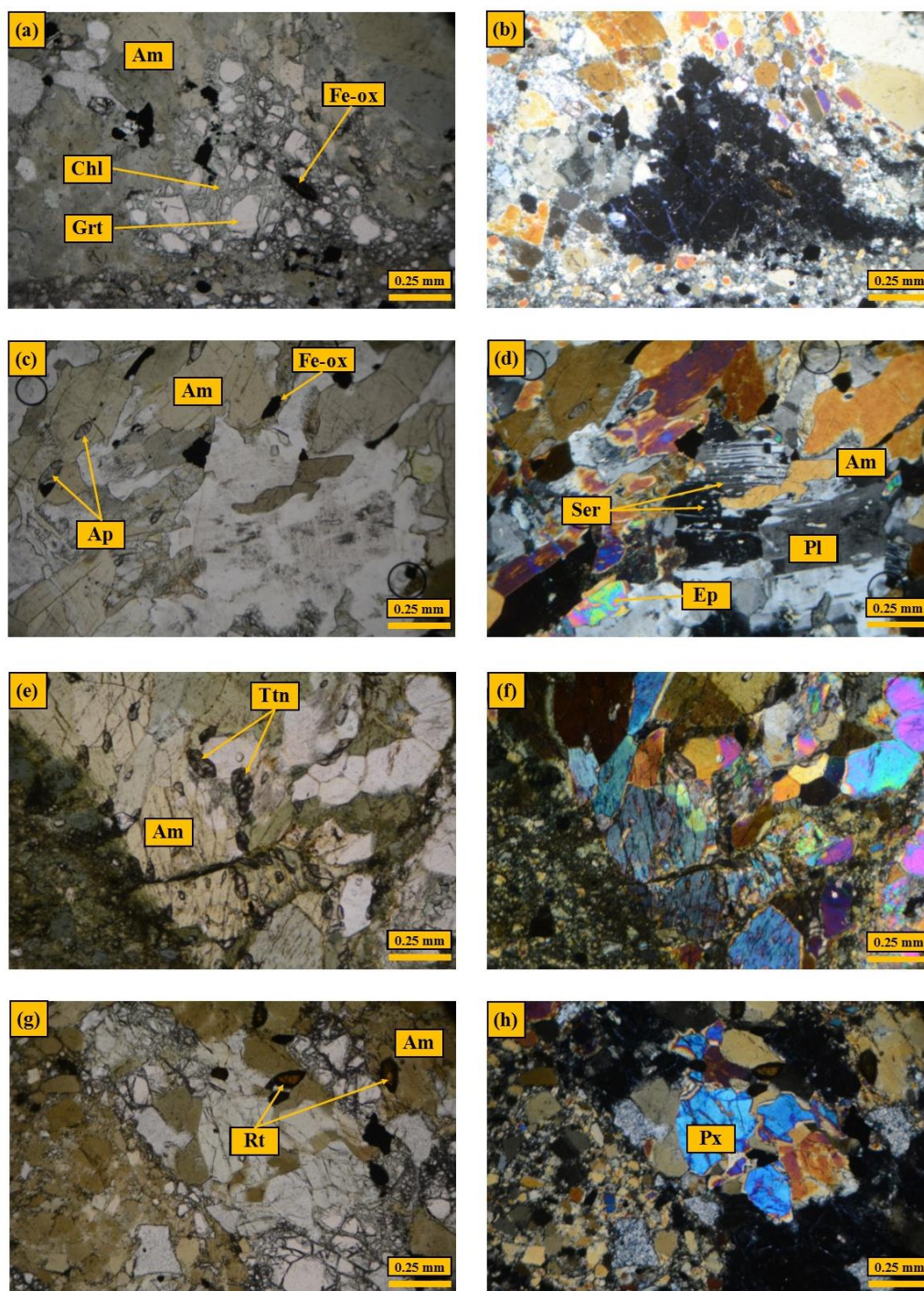


Fig. 5. Photomicrographs illustrating alteration and accessory mineralogy in the studied amphibolites: a, b) Highly fragmented garnet crystal showing alteration to chlorite along fractures (PPL and XPL); c, d) Plagioclase crystal exhibiting partial alteration to sericite, and hornblende partially altered to epidote (PPL and XPL); e, f) Small titanite crystals characterized by high relief and characteristic diamond-shaped morphology (PPL and XPL); g, h) Fine-grained rutile and iron oxide inclusions enclosed within amphibole crystals (PPL and XPL). Abbreviations: Grt: Garnet; Pl: Plagioclase; Rt: Rutile; Chl: Chlorite; Ser: Sericite; Ep: Epidote; Fe-ox: Iron oxide; Amp: Amphibole; Ttn: Titanite; Ap: Apatite; PPL: Plane-polarized light; XPL: Cross-polarized light

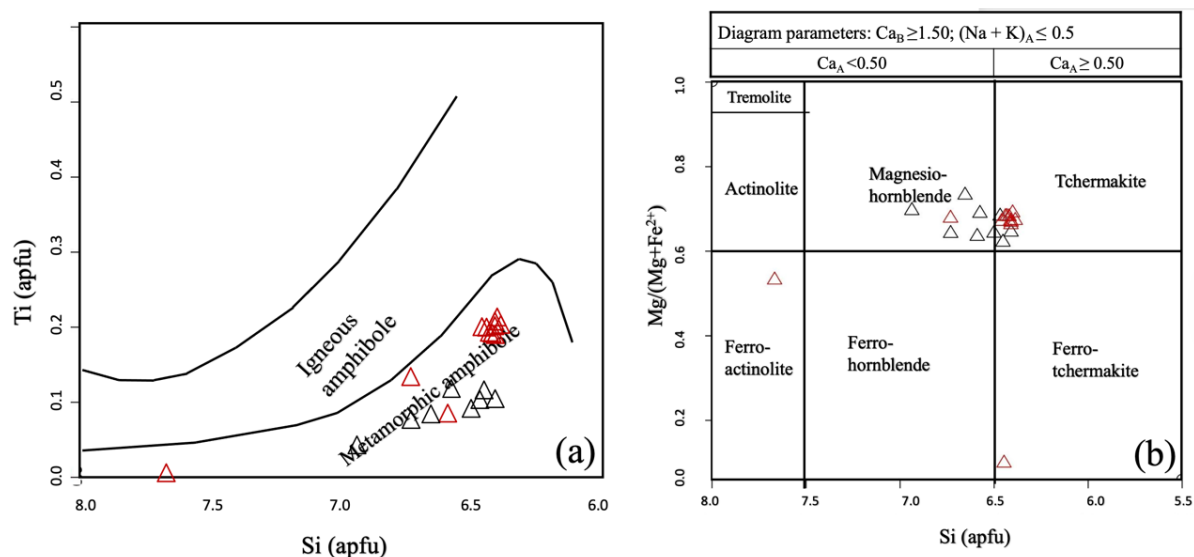


Fig. 6. a) The Ti versus Si diagram of Leake (1965) Si vs Mg/ (Mg+Fe²⁺); b) Classification of amphiboles of the studied rocks (Leake et al. 1997). Black trigonal= amphibole, red triangular= garnet amphibolite

Table 1. Amphibole composition from studied amphibolite rocks and its formula calculated to 23 oxygen

Oxides(wt%)	R4-104	R4-105	R4-117	R4-118	R4-123	R6-04	R6-05	R6-23	R6-26	R6-62	R6-63
SiO ₂	43.01	44.07	47.25	45.38	44.44	43.38	43.30	43.41	43.88	45.87	43.30
TiO ₂	0.93	0.76	0.38	0.68	1.05	1.73	1.91	1.83	1.80	1.21	1.86
Al ₂ O ₃	12.29	11.03	7.97	10.36	11.32	12.15	12.27	12.34	12.00	10.57	12.59
FeO _i	16.39	16.43	17.01	15.80	14.98	14.24	14.43	14.96	14.91	14.47	14.22
MnO	0.23	0.31	0.30	0.31	0.27	0.05	0.06	0.06	0.09	0.11	0.06
MgO	10.13	10.24	11.49	10.76	11.06	11.23	11.12	11.01	11.18	11.48	10.93
CaO	11.21	11.18	10.99	11.38	10.96	11.16	10.88	11.07	11.04	11.07	11.22
Na ₂ O	1.79	1.69	1.03	1.49	1.72	2.01	2.06	2.18	2.07	1.66	2.04
K ₂ O	0.22	0.17	0.15	0.20	0.11	0.08	0.09	0.10	0.08	0.13	0.07
Cr ₂ O ₃	0.04	0.05	0.02	0.04	0.05	0.02	0.06	0.05	0.00	0.05	0.05
Total	96.24	95.93	96.59	96.38	95.97	96.03	96.18	97.02	97.03	96.61	96.34
Atoms per formula unit (apfu)											
T: Si	6.41	6.59	6.94	6.73	6.57	6.43	6.40	6.39	6.44	6.73	6.41
Al ^{iv}	1.59	1.41	1.06	1.27	1.42	1.57	1.60	1.61	1.56	1.27	1.59
C: Al ^{vi}	0.57	0.53	0.32	0.54	0.55	0.55	0.54	0.53	0.52	0.56	0.61
Ti	0.10	0.09	0.04	0.08	0.12	0.19	0.21	0.20	0.20	0.13	0.21
Fe ³⁺	0.67	0.60	0.88	0.49	0.64	0.49	0.57	0.54	0.57	0.46	0.40
Cr	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.01	0.01
Mg	2.25	2.28	2.51	2.38	2.44	2.48	2.45	2.42	2.45	2.51	2.41
Fe ²⁺	1.37	1.46	1.21	1.47	1.21	1.27	1.21	1.30	1.26	1.32	1.36
Mn	0.03	0.04	0.04	0.04	0.03	0.01	0.01	0.01	0.01	0.01	0.01
B: Ca	1.79	1.79	1.73	1.81	1.74	1.77	1.72	1.74	1.74	1.74	1.78
Na	0.21	0.21	0.27	0.19	0.26	0.23	0.28	0.26	0.26	0.26	0.22
A: Ca	0.00	0.00	0.00	0.00	0	0.00	0.00	0.00	0.00	0.00	0.00
Na	0.31	0.28	0.02	0.24	0.23	0.35	0.31	0.37	0.33	0.21	0.37
K	0.04	0.03	0.03	0.04	0.02	0.02	0.02	0.02	0.01	0.02	0.01
(Na+K) _A	0.35	0.31	0.05	0.27	0.25	0.37	0.33	0.39	0.34	0.24	0.38
Mg/(Mg+Fe ²⁺)	0.62	0.61	0.68	0.62	0.66	0.66	0.67	0.65	0.66	0.66	0.64
(Na+Ca) _B	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00

Site assignments follow the IMA classification (Leake et al., 1997): T = Tetrahedral sites; C = Octahedral sites; B = M4 site (linking chains); A = Large central cavity.

4.2.2. Feldspar

The ternary (Ab-An-Or) classification plot of (Deer et al., 1992) shows that most feldspar crystals in the studied samples are Na-rich, have mainly albite composition, with minor points classified as orthoclase (Fig. 7a). The composition of albite as average in the studied rocks is $An_{1.77} Ab_{97.77} Or_{0.46}$ in garnet amphibolite and $An_{2.4} Ab_{96.92} Or_{0.67}$ in amphibolite, which is related to retrograde alteration, are further detailed in the discussion. The composition of plagioclase in amphibolite can range from oligoclase to nearly pure albite; it often coexists with magnesio-hornblende and tschermakite, reflecting a complex interplay of mineral stability under metamorphic conditions (Salimi et al., 2020). Representative (EPMA) of feldspar and their formula are given in Table. 2.

4.2.3. Pyroxene

The ternary pyroxene classification diagram as defined by (Morimoto, 1988); (Fig. 7b) reveals that the studied pyroxenes are classified as diopside, suggesting that they are highly magnesian and calcium-rich and low iron content, with an average formula $Wo_{47.84} En_{36.05} Fs_{16.1}$, which is calculated following the method of (Sakakibara, 1991). Representative (EPMA) of pyroxene from the studied amphibolite samples and their formula are calculated to (6) oxygen and are given in Table 3.

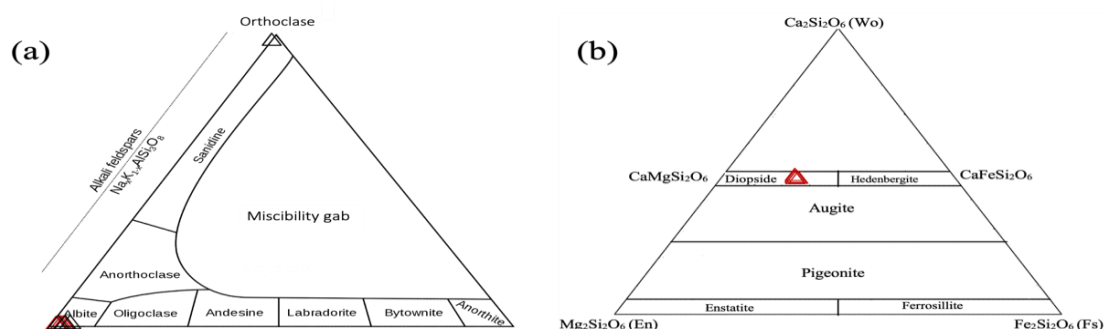


Fig. 7. a) Classification diagram of feldspar for studied samples (Ab-An-Or; Deer et al., 1992); b) Classification plot for pyroxene of the studied amphibolite rocks (Morimoto, 1988)

Table 2. EPMA analysis of feldspar from the studied amphibolite and its formula calculated to 32 oxygen

Oxides (wt%)	R6-01	R6-02	R6-03	R6-27	R6-28	R4-114	R4-115	R4-116	R4-119	R4-120
SiO ₂	68.68	69.68	68.89	70.21	68.91	68.37	68.11	68.02	65.05	64.96
TiO ₂	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00
Al ₂ O ₃	19.79	19.62	19.88	19.51	19.92	19.42	19.84	19.61	18.18	18.04
FeO	0.38	0.21	0.12	0.19	0.11	0.00	0.02	0.02	0.14	0.25
MnO	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.03
MgO	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.02	0.01	0.02
CaO	0.51	0.21	0.38	0.24	0.46	0.26	0.69	0.51	0.01	0.03
Na ₂ O	10.88	11.30	11.21	11.07	10.92	11.13	10.69	10.86	0.22	0.22
K ₂ O	0.09	0.06	0.09	0.07	0.08	0.12	0.12	0.11	16.01	15.96
Total	100.38	101.11	100.59	101.32	100.43	99.35	99.52	99.17	99.79	99.70
Atoms per formula unit (apfu)										
Si	11.95	12.02	11.96	12.07	11.97	12.01	11.94	11.97	12.04	12.04
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al	4.06	3.99	4.07	3.95	4.08	4.02	4.10	4.06	3.97	3.94
Fe ²⁺	0.06	0.03	0.02	0.03	0.02	0.00	0.00	0.00	0.02	0.04
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.01
Ca	0.09	0.04	0.07	0.04	0.09	0.05	0.13	0.10	0.00	0.01
Na	3.67	3.78	3.77	3.69	3.68	3.79	3.63	3.71	0.08	0.08
K	0.02	0.01	0.02	0.02	0.02	0.03	0.03	0.02	3.78	3.78
An	2.50	1.03	1.82	1.20	2.28	1.25	3.43	2.53	0.07	0.16
Ab	96.94	98.65	97.66	98.40	97.22	98.05	95.89	96.84	2.04	2.02
Or	0.57	0.32	0.52	0.40	0.50	0.71	0.68	0.63	97.88	97.82

Table 3. EPMA of pyroxene from studied amphibolite and its formula calculated to 6 oxygen

Oxides (wt%)	R6-55	R6-56	R6-57	R6-58	R6-59
SiO ₂	50.60	50.68	50.47	51.57	51.28
TiO ₂	0.54	0.46	0.47	0.45	0.50
Al ₂ O ₃	5.04	4.77	4.85	4.18	4.46
FeO	9.93	9.58	9.64	9.25	9.16
MnO	0.03	0.06	0.07	0.06	0.11
MgO	11.34	11.47	11.39	11.65	11.71
CaO	21.01	21.49	21.14	21.13	21.46
Na ₂ O	0.93	0.88	0.89	0.83	0.91
K ₂ O	0.01	0.02	0.00	0.01	0.00
Cr ₂ O ₃	0.07	0.00	0.00	0.03	0.01
NiO	0.03	0.01	0.02	0.00	0.00
Total	99.52	99.40	98.94	99.16	99.60
Atoms per formula unit (apfu)					
Si	1.90	1.90	1.90	1.94	1.92
Aliv	0.10	0.10	0.10	0.06	0.08
Alvi	0.12	0.11	0.12	0.13	0.12
Ti	0.02	0.01	0.01	0.01	0.01
Cr	0.00	0.00	0.00	0.00	0.00
Fe ³⁺	0.01	0.02	0.02	0.00	0.00
Fe ²⁺	0.30	0.28	0.29	0.29	0.28
Mg	0.63	0.64	0.64	0.65	0.65
Ni	0.00	0.00	0.00	0.00	0.00
Mn	0.00	0.00	0.00	0.00	0.00
Ca	0.84	0.86	0.85	0.85	0.86
Na	0.07	0.06	0.07	0.06	0.07
Σcats	4.00	4.00	4.00	4.00	4.00
XDi	0.63	0.65	0.64	0.65	0.65
XHd	0.30	0.28	0.29	0.29	0.28

XDi = Mole fraction of diopside; XHd= Mole fraction of hedenbergite

4.2.4. Garnet

The chemical composition of the garnets is classified using ternary diagrams based on the established nomenclature systems. On the ternary (Almandine + Spessartine)-Grossular-Pyrope diagram (Fig. 8), the analyzed garnets plot within the almandine + spessartine compositional field. Furthermore, the Almandine-(Grossular + Andradite)-Spessartine classification diagram confirms that the samples fall into the almandine field (e.g., Deer et al., 1992; Locock, 2008). The garnets exhibit heterogeneous compositions characterized by low andradite (<1.5 mol. %) and spessartine (1 -5.8 mol. %) contents, moderate pyrope (10-24 mol. %) and grossular (24-33 mol. %) components, and a dominant almandine content ranging from 45 to 50 mol. %. The general structural formula for the studied garnets is $(\text{Fe}^{2+}_{1.48}\text{Ca}_{0.91}\text{Mg}_{0.49}\text{Mn}_{0.08})_{2.96}(\text{Al}_{1.92}\text{Fe}^{3+}_{0.01}\text{Ti}_{0.01})_{1.94}\text{Si}_{3.06}\text{O}_{12}$. Representative (EPMA) data for garnet and corresponding structural formula are provided in Table. 4.

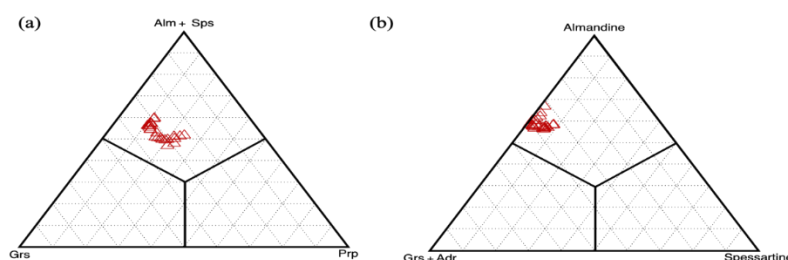


Fig. 8. Llassification diagrams of garnet (Deer et al., 1992): a) Ternary classification plot of (Almandine + Spessartine)- Grossular- Pyrope; b) Almandine- (Andradite+ Grossular)- Spessartine

Table 4. EPMA of garnet from the studied garnet amphibolite and structural formula calculated on the basis of 12 oxygen

Oxides (wt%)	R6-08	R6-09	R6-32	R6-34	R6-37	R6-39	R6-41	R6-43	R6-47
SiO ₂	39.32	39.57	39.18	38.71	38.76	40.89	38.62	38.35	38.24
TiO ₂	0.03	0.15	0.13	0.12	0.12	0.12	0.19	0.17	0.16
Al ₂ O ₃	20.92	20.77	20.95	21.04	20.96	20.45	21.06	20.80	20.66
FeO	23.49	21.57	22.60	21.92	22.26	22.86	22.89	23.27	22.80
Fe ₂ O ₃	0.01	0.24	0.47	0.39	0.15	0.32	0.00	0.18	0.04
MnO	0.50	0.36	0.59	0.92	1.07	1.23	1.77	2.57	2.53
MgO	6.01	5.30	5.48	4.60	3.93	4.07	3.11	2.87	2.65
CaO	8.34	11.07	10.12	11.49	11.69	11.38	11.49	10.96	11.33
Na ₂ O	0.02	0.02	0.04	0.01	0.04	0.01	0.03	0.00	0.03
K ₂ O	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.01	0.00
Total	98.64	99.05	99.58	99.22	98.97	101.32	99.16	99.17	98.43
Atoms per formula unit (apfu)									
Si	3.07	3.07	3.04	3.02	3.04	3.13	3.04	3.04	3.05
Al ^{iv}	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Al ^{vi}	1.93	1.90	1.92	1.94	1.94	1.85	1.95	1.94	1.94
Ti	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fe ³⁺	0.00	0.01	0.03	0.02	0.01	0.02	0.00	0.01	0.00
Fe ²⁺	1.53	1.40	1.47	1.43	1.46	1.46	1.51	1.54	1.52
Mn	0.03	0.02	0.04	0.06	0.07	0.08	0.12	0.17	0.17
Mg	0.70	0.61	0.63	0.54	0.46	0.46	0.37	0.34	0.31
Ca	0.70	0.92	0.84	0.96	0.98	0.93	0.97	0.93	0.97
Alm	50.53	45.75	48.05	47.07	48.19	47.14	50.46	50.81	50.23
And	0.04	0.72	1.42	1.18	0.45	0.99	0.00	0.55	0.13
Grs	24.04	31.34	27.44	31.35	33.20	32.40	33.05	31.19	32.94
Prp	24.18	21.35	21.75	18.20	15.72	16.61	12.47	11.56	10.77
Sps	1.14	0.82	1.34	2.07	2.43	2.86	4.02	5.88	5.85

End-member proportions are expressed as mole percentages (mol%). Alm: Almandine (Fe²⁺); Prp: Pyrope (Mg); Grs: Grossular (Ca); Sps: Spessartine (Mn); And: Andradite (Ca-Fe³⁺).

In addition to the chemical compositions of the major minerals, the mineral chemistry of the accessory and secondary phases—including apatite and titanite (Table. 5), epidote and chlorite (Table. 6)—was determined using electron microprobe analysis (EPMA). Structural formulas were calculated based on their respective stoichiometric oxygen bases: 25 oxygens for apatite, 5 oxygens for titanite, 25 oxygens for epidote, and 28 oxygens for chlorite. Cation site assignments and nomenclature follow the established criteria of (Pasero et al., 2010) for apatite, (Enami et al., 1993) and (Kowallis et al., 2022) for titanite, (Armbruster et al., 2006) for epidote, and (Foster, 1962) for chlorite.

The Apatite phase is classified as Fluorapatite (Pasero et al., 2010), characterized by a strong dominance of fluorine over chlorine (F ~0.74 apfu vs. Cl ~0.05 apfu). Titanite grains exhibit high stoichiometric purity, with silicon and titanium concentrations near 1.00 apfu and 0.93 apfu, respectively, and a distinct trace signature of Vanadium (V ~0.01 apfu). Epidote group minerals were identified based on their distinct Al (3.72-4.82 apfu) and Fe (1.05-2.10 apfu). The calculated Pistacite (Ps) content shows a wide range from 55.9% to over 115%. Additionally, Chlorite group minerals are identified as Brunsvigite, with an average Fe/(Fe+Mg) ratio of 0.56 and (Si) concentrations ranging from 5.77 to 5.93 apfu.

4.3. Geochemistry

The geochemical characteristics of the garnet amphibolite and amphibolite rocks have been studied through the analysis of (10) samples. The results of the analysis for major oxides (expressed as weight percent (wt%)) and the trace and rare earth elements (in ppm) and corresponding detection limit for each element are provided in (Table 7). The rocks are characterized by intermediate SiO₂ (41-45.1 wt%), high Fe₂O₃ (15.35-17.4 wt%), MgO (8.22-10.3 wt%), and Al₂O₃ (11.8-13.65 wt%) contents, and moderate TiO₂ concentrations (1.66-2.45 wt%). The studied samples exhibit high Na₂O/K₂O ratios (>2) and

elevated compatible element contents (e.g., Cr, Ni, V, and Co), consistent with the geochemical characteristics of primitive sodic volcanic suites (Rollinson, 1993; Wilson, 1989).

Chondrite-normalized (REE) patterns (Boynnton, 1984; Fig. 9a) show light rare earth elements (LREE) depletion, with $(La/Yb)_N$ ratios predominantly ≤ 1 . The (REE) patterns are flat in the heavy REE (HREE) segment and display weak to moderate negative (Eu) anomalies ($Eu/Eu^* = \sim 0.8-0.9$); furthermore, the La/Sm ratios are low (0.42-0.63). Trace element patterns normalized to the primitive mantle are characterized by positive anomalies in (Ba, U, and K) and distinct negative anomalies in (Nb, Zr, and Ti), (Fig. 9b). They exhibit enrichment in large-ion lithophile elements (LILEs; e.g., Rb, Sr, K, Ba) relative to high-field-strength elements (HFSEs).

Table 5. EPMA of apatite and titanite, with structural formulas calculated based on 25 and 5 oxygen, respectively

Oxides (wt%)	Apatite								Titanite					
	R4-1	R4-2	R4-3	R4-4	R4-6	R6-1	R6-2	R6-4	R4-102	R4-103	R4-108	R6-13	R6-16	R6-30
SiO ₂	0.06	0.14	0.06	0.08	0.06	0.20	0.12	0.04	30.67	30.75	30.35	30.48	30.43	30.3
TiO ₂	-	-	-	-	-	-	-	-	37.47	37.87	37.51	38.22	37.55	38.1
Al ₂ O ₃	-	-	-	-	-	-	-	-	1.36	1.11	1.28	1.21	1.18	1.20
FeO	0.30	0.32	0.31	0.36	0.23	0.38	0.23	0.35	0.90	0.74	0.76	0.85	0.94	0.93
MnO	0.01	0.03	0.04	0.05	0.10	0.02	0.01	0.03	0.07	0.05	0.09	0.00	0.02	0.01
MgO	-	-	-	-	-	-	-	-	0.15	0.00	0.00	0.02	0.02	0.02
CaO	55.62	55.30	55.87	55.46	55.39	55.78	55.75	55.32	27.53	27.58	27.62	27.63	27.46	27.6
Na ₂ O	0.02	0.02	0.00	0.02	0.01	0.00	0.02	0.01	0.00	0.01	0.01	0.01	0.00	0.03
K ₂ O	-	-	-	-	-	-	-	-	0.02	0.01	0.01	0.02	0.00	0.01
La ₂ O ₃	0.02	0.02	0.00	0.05	0.10	0.02	0.00	0.00	-	-	-	-	-	-
Ce ₂ O ₃	0.03	0.04	0.00	0.04	0.00	0.10	0.00	0.07	-	-	-	-	-	-
P ₂ O ₅	43.79	43.25	43.63	43.35	43.04	43.22	42.58	42.95	0.442	0.302	0.469	0.562	0.640	0.55
V ₂ O ₅	-	-	-	-	-	-	-	-	0.576	0.493	0.525	0.622	0.643	0.64
Cl	0.13	0.08	0.08	0.09	0.11	0.28	0.33	0.33	0.010	0.000	0.012	0.000	0.000	0.00
F	1.53	1.62	1.50	1.47	1.36	1.38	1.31	1.45	0.000	0.000	0.011	0.000	0.024	0.00
Total	101.5	100.8	101.5	100.9	100.4	101.3	100.3	100.5	99.20	98.92	98.64	99.61	98.91	99.5
O=F,Cl	0.67	0.70	0.65	0.64	0.60	0.64	0.63	0.68	0.00	0.00	0.01	0.00	0.02	0.00
Total	100.8	100.1	100.8	100.3	99.80	100.7	99.74	99.87	99.20	98.92	98.63	99.61	98.89	99.5
Atoms per formula units														
Si	0.009	0.023	0.010	0.013	0.010	0.033	0.020	0.007	1.005	1.010	1.001	0.995	1.000	0.99
Ti	-	-	-	-	-	-	-	-	0.924	0.936	0.931	0.938	0.928	0.93
Al	-	-	-	-	-	-	-	-	0.052	0.043	0.050	0.046	0.046	0.04
Fe	0.041	0.044	0.042	0.049	0.031	0.052	0.032	0.048	0.025	0.020	0.021	0.023	0.026	0.02
Mn	0.001	0.005	0.005	0.007	0.013	0.002	0.002	0.004	0.002	0.002	0.003	0.000	0.000	0.00
Mg	-	-	-	-	-	-	-	-	0.007	0.000	0.000	0.001	0.001	0.00
Ca	9.598	9.615	9.651	9.637	9.687	9.674	9.780	9.673	0.967	0.971	0.976	0.966	0.967	0.97
Na	0.007	0.007	0.000	0.007	0.003	0.000	0.005	0.003	0.000	0.001	0.001	0.001	0.000	0.00
K	-	-	-	-	-	-	-	-	0.001	0.000	0.000	0.001	0.000	0.00
La	0.001	0.001	0.000	0.003	0.006	0.001	0.000	0.000	-	-	-	-	-	-
Ce	0.002	0.003	0.000	0.002	0.000	0.006	0.000	0.004	-	-	-	-	-	-
P	5.971	5.941	5.955	5.952	5.948	5.922	5.903	5.934	0.012	0.008	0.013	0.016	0.018	0.01
V	-	-	-	-	-	-	-	-	0.012	0.011	0.011	0.013	0.014	0.01
Cl	0.035	0.022	0.022	0.025	0.030	0.077	0.092	0.090	-	-	-	-	-	-
F	0.779	0.833	0.766	0.753	0.703	0.704	0.679	0.746	0.000	0.000	0.001	0.000	0.002	0.00
OH	0.186	0.145	0.212	0.222	0.266	0.219	0.229	0.163	-	-	-	-	-	-
Total	16.62	16.63	16.66	16.67	16.69	16.69	16.74	16.67	3.008	3.003	3.008	3.000	3.003	3.00

Table 6. EPMA of epidote and chlorite, with structural formulas on the basis of 25 and 28 oxygens, respectively

Oxides (wt%)	Epidote												Chlorite	
	R4-99	R4-100	R4-101	R4-110	R4-111	R4-113	R6-11	R6-12	R6-19	R6-21	R6-22	R6-54	R6-1	R6-2
SiO ₂	38.06	38.38	38.38	37.48	38.03	37.89	38.23	38.20	38.65	38.60	37.97	37.97	25.79	26.31
TiO ₂	0.30	0.21	0.28	0.17	0.25	0.20	0.25	0.10	0.05	0.10	0.05	0.08	0.02	0.00
Al ₂ O ₃	25.71	25.05	25.83	21.99	24.62	24.70	23.70	21.99	25.21	24.74	21.07	20.45	17.78	16.34
FeO	8.35	8.66	7.92	12.55	8.72	8.80	11.45	12.27	9.78	9.83	14.04	14.35	26.54	26.69
Fe ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-	0.84	0.73
Cr ₂ O ₃	-	-	-	-	-	-	-	-	-	-	-	-	0.04	0.07
MnO	0.16	0.14	0.16	0.32	0.12	0.16	0.40	0.18	0.13	0.10	0.42	0.17	0.45	0.68
MgO	0.18	0.11	0.21	0.02	0.17	0.15	0.08	0.01	0.00	0.00	0.00	0.00	12.18	12.51
NiO	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.02
CaO	22.91	22.78	22.79	22.11	22.31	22.39	21.60	22.71	22.98	22.95	22.22	22.59	0.11	0.09
Na ₂ O	0.02	0.00	0.01	0.00	0.01	0.02	0.00	0.03	0.00	0.02	0.00	0.01	0.01	0.04
K ₂ O	0.01	0.01	0.00	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.02	0.01	0.08	0.00
H ₂ O*	-	-	-	-	-	-	-	-	-	-	-	-	10.68	10.61
Total	95.71	95.33	95.58	94.65	94.23	94.30	95.70	95.50	96.81	96.34	95.76	95.61	94.51	94.09
O=F,Cl	-	-	-	-	-	-	-	-	-	-	-	-	0.00	0.00
Total	95.72	95.33	95.58	94.66	94.23	94.30	95.71	95.50	96.81	96.34	95.78	95.61	94.51	94.09
Atoms per formula units														
Si	6.042	6.114	6.086	6.091	6.127	6.105	6.099	6.147	6.079	6.103	6.123	6.142	5.776	5.934
Ti	0.036	0.025	0.033	0.021	0.030	0.024	0.029	0.013	0.006	0.012	0.005	0.009	0.004	0.001
Al ^{iv}	-	-	-	-	-	-	-	-	-	-	-	-	2.224	2.066
Al ^{vi}	-	-	-	-	-	-	-	-	-	-	-	-	2.484	2.288
Al	4.810	4.704	4.828	4.212	4.676	4.691	4.457	4.170	4.673	4.610	4.004	3.898	-	-
Fe ³⁺	1.109	1.154	1.051	1.705	1.175	1.186	1.528	1.651	1.287	1.300	1.893	1.941	0.141	0.124
Fe ²⁺	-	-	-	-	-	-	-	-	-	-	-	-	4.971	5.034
Mn	0.022	0.019	0.022	0.045	0.016	0.021	0.053	0.024	0.017	0.014	0.058	0.024	0.085	0.130
Mg	0.044	0.025	0.049	0.004	0.042	0.035	0.020	0.003	0.000	0.001	0.000	0.000	4.068	4.206
Ca	3.896	3.888	3.872	3.849	3.852	3.866	3.692	3.916	3.873	3.889	3.838	3.915	0.027	0.022
Na	0.007	0.000	0.003	0.000	0.002	0.005	0.000	0.010	0.000	0.005	0.000	0.002	0.008	0.034
K	0.002	0.002	0.000	0.002	0.000	0.000	0.002	0.001	0.000	0.000	0.004	0.001	0.044	0.000
Cr	-	-	-	-	-	-	-	-	-	-	-	-	0.007	0.013
Ni	-	-	-	-	-	-	-	-	-	-	-	-	0.000	0.004
OH*	-	-	-	-	-	-	-	-	-	-	-	-	16.00	16.00
Total	15.97	15.93	15.94	15.93	15.92	15.93	15.88	15.94	15.94	15.93	15.93	15.93	35.84	35.85
Fe/Fe+Mg	0.962	0.979	0.955	0.997	0.966	0.971	0.987	0.998	1.000	0.999	1.000	1.000	0.560	0.550
Variety name	-	-	-	-	-	-	-	-	-	-	-	-	Brun	Brun
Pistacite (Ps)%	57.77	62.12	55.94	88.93	63.48	63.18	76.97	90.65	65.64	68.05	99.80	105.57	-	-

Pistacite (Ps)%= (Fe³⁺/(Fe³⁺+Al-2))*100, Brun: Brunsvigite
Chlorite oxides represents reformatted oxide percentages based on 28 oxygens (with Fe²⁺/Fe³⁺ and OH calculated assuming full site occupancy)

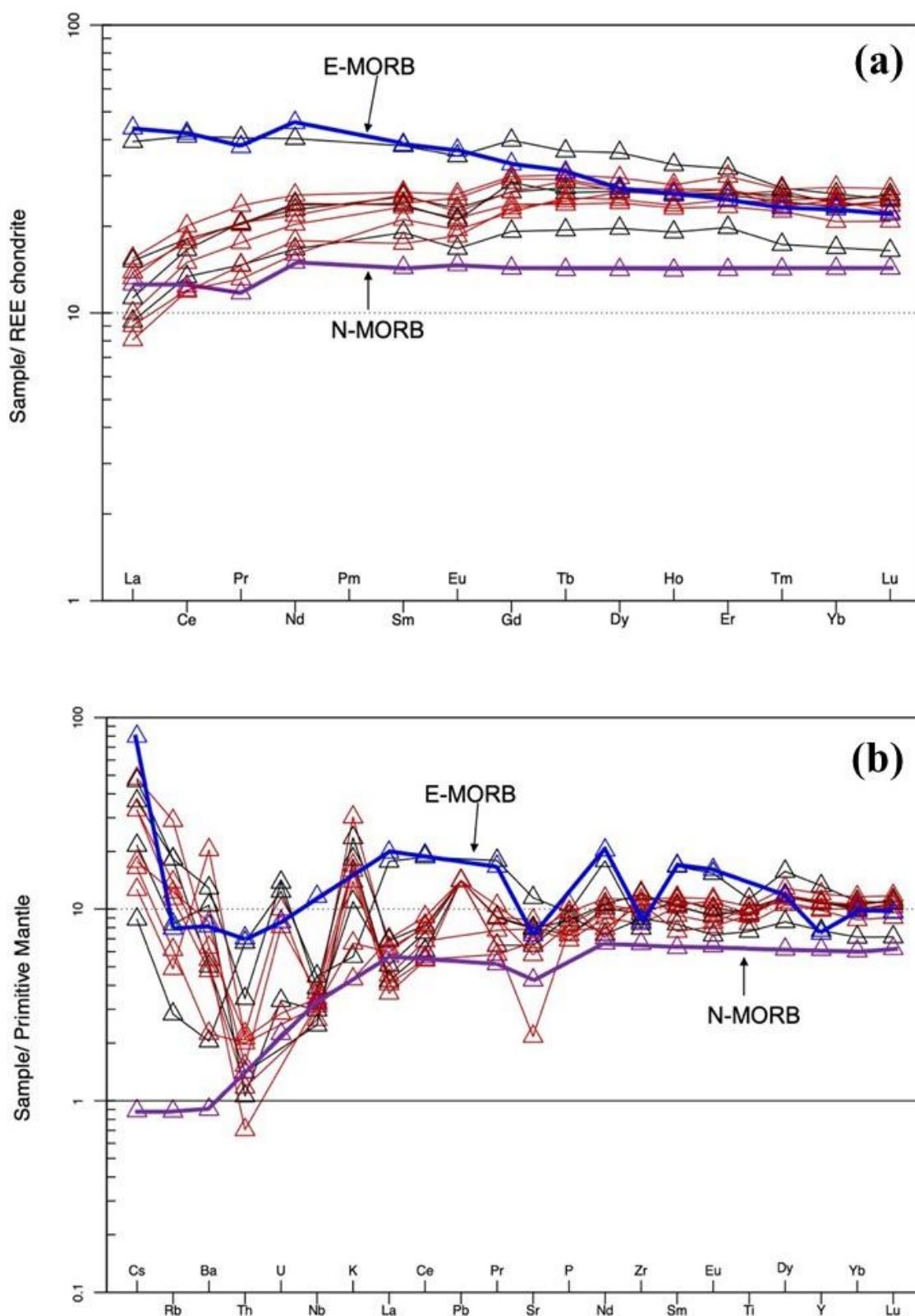


Fig. 9. a) Chondrite-normalized rare earth elements patterns (Boynton, 1984); b) Mantle-normalized trace element spider diagrams for studied samples (Sun and McDonough, 1989). E-MORB and N-MORB data from (Sun and McDonough, 1989)

Table 7. Representative whole-rock geochemistry for the studied samples

Rock name		Amphibolite						Garnet Bearing amphibolite				
Samples number	LOD	R1	R4	R5	R9	R2	R3	R6	R10	R11	R12	Mean
<i>Major and minor oxides (wt%)</i>												
SiO ₂	0.01	42.90	41.00	42.80	42.20	45.10	43.50	42.50	44.90	43.30	42.90	43.11
TiO ₂	0.01	2.07	2.45	1.66	2.19	1.82	2.00	2.24	2.04	2.03	2.21	2.07
Al ₂ O ₃	0.01	13.65	11.80	12.85	13.05	13.20	13.20	13.20	13.40	13.65	13.00	13.10
Fe ₂ O ₃	0.01	16.50	17.30	16.15	17.40	15.35	15.55	17.05	16.20	16.55	16.35	16.44
MnO	0.01	0.25	0.26	0.25	0.23	0.25	0.24	0.28	0.26	0.27	0.23	0.25
MgO	0.01	9.43	9.58	10.05	9.11	9.00	9.06	8.31	8.22	10.30	9.16	9.22
CaO	0.01	11.60	13.40	10.40	9.55	11.45	10.25	11.15	10.80	8.36	11.05	10.80
Na ₂ O	0.01	1.96	1.24	2.10	2.00	2.39	2.13	2.41	2.52	2.18	2.15	2.11
K ₂ O	0.01	0.33	0.17	0.55	0.71	0.42	0.91	0.13	0.20	0.48	0.51	0.44
P ₂ O ₅	0.01	0.16	0.21	0.20	0.19	0.15	0.16	0.21	0.18	0.17	0.23	0.19
Cr ₂ O ₃	0.002	0.04	0.04	0.06	0.03	0.06	0.05	0.03	0.04	0.03	0.05	0.04
LOI	0.01	1.31	1.56	1.67	1.83	1.26	1.67	1.17	1.44	2.18	1.58	0.04
Total		100.27	99.11	99.14	98.58	100.67	99.09	98.74	100.24	99.53	99.47	99.48
<i>Trace elements (ppm)</i>												
Rb	0.20	5.30	1.80	11.60	11.60	7.20	18.40	3.10	0.57	8.80	7.80	7.95
Sr	0.10	169.00	242.00	136.50	167.00	166.50	184.50	160.50	122.00	45.70	142.00	153.57
Ba	0.50	73.20	14.30	35.20	90.10	33.30	44.20	142.50	15.70	38.10	59.70	54.63
Ni	1.00	84.00	101.00	89.00	80.00	91.00	85.00	78.00	76.00	67.00	85.00	83.60
Cr	5.00	336.00	324.00	427.00	228.00	429.00	397.00	221.00	284.00	196.00	349.00	319.10
Ga	0.10	21.80	23.00	20.20	19.50	20.80	21.30	23.10	22.10	21.00	20.00	21.28
Nb	0.05	2.12	3.19	1.77	2.77	1.89	2.35	2.43	2.22	2.28	2.62	2.36
V	5.00	526.00	588.00	474.00	541.00	470.00	482.00	537.00	496.00	497.00	507.00	511.80
Y	0.10	49.50	60.20	35.20	48.50	44.80	49.10	54.60	50.00	49.40	45.50	48.68
Zn	2.00	123.00	134.00	185.00	272.00	134.00	183.00	132.00	113.00	147.00	138.00	156.10
Zr	1.00	106.00	89.00	100.00	134.00	94.00	117.00	125.00	111.00	120.00	137.00	113.30
Cs	0.01	0.17	0.07	0.29	0.37	0.26	0.38	0.10	0.13	0.26	0.14	0.22
Co	1.00	54.00	60.00	54.00	54.00	52.00	52.00	55.00	53.00	52.00	55.00	54.10
Hf	0.05	3.05	2.81	2.73	3.69	2.83	3.31	3.42	3.05	3.57	3.69	3.22
Ta	0.10	0.20	0.20	0.10	0.10	0.10	0.20	0.20	0.10	0.20	0.20	0.16
Th	0.05	0.09	0.57	0.12	0.29	0.10	0.19	0.18	0.17	0.06	0.13	0.19
U	0.05	0.07	0.26	<0.05	0.29	<0.05	0.21	0.06	<0.05	<0.05	0.17	0.11
Co	1.00	54.00	60.00	54.00	54.00	52.00	52.00	55.00	53.00	52.00	55.00	54.10
Cu	1.00	85.00	86.00	228.00	124.00	91.00	123.00	105.00	87.00	88.00	163.00	118.00
Pb	2.00	<2	3.00	<2	<2	2.00	<2	<2	<2	<2	2.00	0.70
Tl	10.00	0.02	<0.02	0.04	0.03	0.03	0.04	<0.02	<0.02	0.02	0.02	0.02
<i>REE (ppm)</i>												
La	0.10	3.50	12.20	2.90	4.70	3.10	4.30	4.80	4.10	2.50	2.80	4.49
Ce	0.10	13.40	33.20	10.80	14.60	12.10	14.20	16.20	14.60	9.60	9.70	14.84
Pr	0.02	2.51	4.95	1.79	2.49	2.14	2.51	2.88	2.47	1.78	1.60	2.51
Nd	0.10	13.70	24.20	10.00	14.40	12.20	13.10	15.40	14.20	10.70	9.60	13.75
Sm	0.03	4.94	7.42	3.71	4.63	4.55	5.02	5.12	4.69	3.40	4.12	4.76
Eu	0.02	1.70	2.58	1.23	1.54	1.57	1.65	1.90	1.84	1.36	1.43	1.68
Gd	0.05	6.81	10.30	4.97	7.35	6.18	6.84	7.72	7.57	5.99	5.80	6.95
Tb	0.01	1.29	1.73	0.92	1.24	1.13	1.36	1.43	1.38	1.16	1.19	1.28
Dy	0.05	8.70	11.60	6.33	8.52	7.77	8.51	9.49	8.73	8.44	7.98	8.61
Ho	0.01	1.86	2.35	1.37	1.86	1.66	1.84	2.00	1.93	1.88	1.70	1.85
Er	0.03	5.39	6.67	4.16	5.47	4.91	5.41	6.26	5.63	5.63	5.19	5.47
Tm	0.01	0.79	0.88	0.56	0.83	0.73	0.86	0.87	0.76	0.80	0.78	0.79
Yb	0.03	4.88	5.41	3.52	5.13	4.34	5.01	5.71	5.15	5.23	4.94	4.93
Lu	0.01	0.79	0.80	0.53	0.83	0.67	0.76	0.87	0.72	0.81	0.79	0.76
ΣREE		70.3	124.3	52.8	73.6	63.1	71.4	80.7	73.8	59.3	57.6	72.67
FeO _t		14.85	15.57	14.53	15.66	13.81	13.99	15.34	14.58	14.89	14.71	14.79
Ti		12399	14676	9943	13118	10902	11980	13418	12220	12160	13238	12405.29
(La/Sm) _N		0.44	1.03	0.49	0.63	0.43	0.53	0.59	0.55	0.46	0.42	0.56
(La/Yb) _N		0.49	1.53	0.56	0.62	0.49	0.58	0.57	0.54	0.32	0.39	0.61
Eu/Eu*		0.89	0.90	0.87	0.80	1.01	0.86	0.92	0.94	0.92	0.89	0.90

DL: Detection limit, Eu/Eu*: Eu anomaly which was calculated according to $[Eu_N / \sqrt{(Sm_N)(Gd_N)}]$ (Taylor and McLennan, 1995).FeO_t: FeO Total, N: Chondrite normalized (Sun and McDonough, 1989).

5. Discussion

5.1. Geothermobarometry

To constrain the geothermobarometric conditions of the Rayat amphibolite pods within the Walash Group, a multi-method approach was employed using Excel-based spreadsheets. Cation proportions and site assignments for the amphiboles were determined using the IMA-97 classification scheme (Leake et al., 1997). All analyzed grains are calcic amphiboles ($Ca_B > 1.50$ apfu) falling specifically within the magnesio-hornblende and tschermakite fields, which ensures the validity of the chosen thermobarometric models. To address the uncertainty of Fe^{3+} content in these calcic amphiboles, the (Schumacher, 1997) averaging method was applied.

Given the high-grade mineral assemblages, several calibrations were utilized. The Ti-in-amphibole thermometer of (Liao et al., 2021) was applied as an independent, plagioclase-free check, with pressure constraints guided by the Al-in-hornblende barometry results, while additional temperatures were calculated using the amphibole-plagioclase geothermometers of (Otten, 1984) and (Colombi, 1989), based on the (Al^{iv}) content in hornblende and the (An) content of coexisting plagioclase. Pressure constraints were guided by the Al-in-hornblende barometer of (Schmidt, 1992), which was also used to derive lithostatic pressure and corresponding crustal depth. The results are summarized in Table. 8.

The geothermobarometric results indicate a consistent thermal and baric environment for the two studied rocks. The amphibolite (R4) yields an average peak temperatures that ranging from 660 °C (Otten, 1984) to 674 °C (Liao et al., 2021) at a calculated average pressure of 6.4 kbar (Schmidt, 1992). In contrast, the garnet- amphibolite (R6) records slightly higher conditions, with average temperatures ranging from 775 °C to 796 °C and an average pressure of 6.9 kbar. These calculated conditions signify that the Walash Group amphibolites reached the upper-amphibolite facies (Bucher and Grapes, 2011). The presence of diopside and almandine-rich garnet in (R6), coupled with temperatures reaching nearly 800 °C and pressures around (7 kbar), confirms a high-temperature/medium-pressure environment. The average pressures correspond to a burial depth of approximately 21-25 km. The absence of garnet in the (R4) pods suggests these sections may have been restricted by bulk rock composition or slightly lower peak conditions insufficient for almandine formation in these specific mafic protoliths (Barker, 1990; Spear, 1994).

The accessory mineral chemistry further constrains the (P-T-t) path of the Rayat amphibolites. The presence of rutile and (Fe-Ti) oxides supports the high-grade peak at 674-796 °C and confirms Ti-saturation for the thermometric calibrations. Furthermore, the stability of rutile in the (R6) pods is consistent with the calculated pressures of 6.9 kbar, marking the transition into upper-amphibolite facies conditions. The stability of F-rich apatite reflects a magmatic arc precursor (Piccoli and Candela, 2002), while subsequent overprinting by titanite and epidote indicates fluid-mediated retrograde metamorphism during the tectonic juxtaposition of these pods within the serpentinite-hosted mélangé (Agard et al., 2011; Polat et al., 2009).

The coexistence of these two distinct metamorphic grades is characteristic of a tectonically thickened crust within the NW Zagros Fold-Thrust Belt, where different structural levels experienced varying (P-T) conditions throughout a single orogenic event (England and Thompson, 1984). The extreme temperatures preserved in the hornblende cores suggest these pods were likely influenced by high heat flow within a volcanic arc setting prior to their incorporation into the suture zone. The juxtaposition of the higher-grade (R6) and lower-grade (R4) pods suggests that different structural levels of the subducting Neo-Tethyan lithosphere were tectonically interleaved during the Arabian-Eurasian collision. Later stages of the (P-T) path are indicated by the occurrence of albite, signifying a cooling and exhumation path from the lower crust to shallower levels (Yardley, 1989).

Table 8. The P-T estimates for the studied amphibolite rocks

Sample No.	Parameters from amphibole (apfu)					P (kbar)		T (C°)		
	Ti	Al ^{iv}	Al ^{vi}	Al _{Total}	Na _A	K _A	Schmidt (1992)	Otten (1984)	Colombi (1989)	Liao et al. (2021)
R4-104	0.10	1.59	0.57	2.16	0.31	0.04	7.3	670	702	679
R4-105	0.09	1.41	0.53	1.94	0.28	0.03	6.2	648	684	662
R4-117	0.04	1.06	0.32	1.38	0.02	0.03	3.6	596	564	549
R4-118	0.08	1.27	0.54	1.81	0.24	0.04	5.6	636	659	644
R4-123	0.12	1.42	0.55	1.97	0.23	0.02	6.4	686	715	710
			R4-Average*				6.4	660	690	674
R6-4	0.19	1.57	0.55	2.12	0.35	0.02	7.1	777	788	798
R6-6	0.21	1.60	0.54	2.14	0.31	0.02	7.2	800	808	819
R6-23	0.20	1.61	0.53	2.14	0.37	0.02	7.2	789	799	809
R6-29	0.20	1.56	0.52	2.08	0.33	0.01	6.9	787	797	809
R6-62	0.13	1.27	0.56	1.83	0.21	0.02	5.7	705	795	724
R6-63	0.21	1.59	0.61	2.20	0.37	0.01	7.5	794	731	819
			R6-Average				6.9	775	786	796

* Analysis R4-117 was excluded from peak P-T calculations as it represents equilibration during retrograde stage

5.2. Petrographic and Mineral Chemistry

Petrographic investigation and mineral chemistry of the Rayat amphibolites reveal a complex, multi-stage metamorphic and structural history within the NW Zagros Fold-Thrust Belt. They are characterized by a well-developed mylonitic texture, featuring significant grain-size reduction and the preservation of porphyroclasts within a foliated matrix (Song and Cao, 2021). While these relict domains suggest a mafic igneous precursor, the dominant texture reflects intense ductile deformation and high-grade recrystallization associated with its tectonic juxtaposition with altered ultramafic rocks.

The presence of garnet and rutile in the mineral assemblage coupled with the composition of key amphiboles, notably tschermakite and magnesio-hornblende, provide evidence of peak metamorphism under medium pressure amphibolite-facies conditions (Demange, 2012; Kabir et al., 2016; Leake et al., 1997). Also, the composition of the garnet, dominantly almandine-grossular with significant pyrope and minor spessartine, is typical of amphibolite-facies metabasites.

A subsequent retrograde overprint during exhumation is evidenced by fluid-mediated reactions, including the systematic chloritization of garnet and sericitization of plagioclase, the latter reflected in the near-pure albite compositions (An₂₋₃). This evolution reflects a complex magmatic-hydrothermal transition characterized by fluctuating oxidation states and high iron activity. The pistacite (Ps) content in epidote group minerals is characterized by an extremely wide range with values often greater than 100% saturation (e.g. Ps = 115.4% in sample R6). The extreme iron-to-aluminum ratio (Fe³⁺ up to 2.10 apfu) indicates that the hydrothermal fluids were significantly enriched in (Fe³⁺), probably under high oxygen fugacity (fO₂) conditions (Bird and Spieler, 2004) typical of the late stage alteration of basaltic protoliths in the NW Zagros Thrust-Fold Belt. The transition from titanite to epidote as a primary calcium-bearing phase indicates a shift in fluid chemistry toward lower (TiO₂) activity and higher silica saturation, further supported by the high stoichiometric purity of the titanite grains (Si~ 1.00 apfu) (Enami et al., 1993). The presence of iron-rich brunsvigite (Fe/(Fe+Mg) ~0.56) and fluorapatite points toward the circulation of halogen-bearing, moderately saline fluids. These fluids likely facilitated the transport and subsequent precipitation of transition metals like vanadium, which was consistently detected in the titanite structure (~0.01 apfu) (Kowallis et al., 2022; Piccoli and Candela, 2002). This suggests widespread infiltration of hydrous fluids during cooling and decompression (Demange, 2012; Li et al., 2018).

Furthermore, the extensive development of cataclastic and mylonitic textures, along with undulose extinction in amphibole, documents considerable post-peak, brittle-ductile deformation under retrograde conditions, which aligns with tectonic emplacement processes in significant suture zones (Mason and Mason, 1990; Passchier and Trouw, 2005).

5.3. Geochemistry

Alkalis and large ion lithophile elements (LILEs) are highly mobile during metamorphism and the use of standard classification diagrams can be misleading. Instead, the original igneous protolith can be more reliably determined by immobile elements such as rare earth elements (REEs) and high field strength elements (HFSEs). The high (MgO, Cr and Ni) contents imply a mafic igneous rock source such as basalt or gabbro (Polat et al., 2012). Moderate concentrations of (TiO₂) imply the existence of titanium-rich minerals, including ilmenite, rutile, and titanite (Koepeke and seidel, 2004), which aligns with a mid-ocean ridge basalt (MORB) affinity. The significant negative (Nb-Ta) anomaly, along with positive (Ba, U and K) anomalies, from the primitive mantle-normalized patterns, indicate subduction zone magmatism. Consequently, the observed characteristics suggest either an island arc or a back-arc basin setting, wherein the magma source underwent metasomatism due to fluids originating from the subducted slab (Hawkesworth et al., 1993). The negative (Zr and Ti) anomalies detected are further evidence for this interpretation, as these high-field strength elements (HFSEs) are retained in residual phases such as rutile within the subducted slab (Foley et al., 2000).

REE patterns provide key information about the mantle sources and the melting processes. The dominant LREE-depleted patterns with (La/Yb)_N < 1 and lower La/Sm ratios manifest that the magmas are derived from a depleted mantle source similar to N-MORB or back-arc basin basalt produced by high degree of partial melting (Wilson, 1989).

The single sample with (La/Yb)_N > 1 suggests that it could originated from a more enriched mantle source, possibly influenced by subduction (Foley et al., 2000). Flat (HREE) patterns indicate that garnet was not a major residual phase in the mantle source during melting, and is consistent with melting at relatively shallow depths (e.g., spinel peridotite stability field) (Cox et al., 1979). Nevertheless, the incorporation of (Y and HREE) into garnet and amphibole during subsequent metamorphism likely because of their present distribution (Grauch, 2019; Guo et al., 2021). The negative europium (Eu) anomalies indicate plagioclase fractionation in the magmatic precursor, a process frequently observed in basaltic differentiation cases (Rollinson, 1993).

5.4. Protolith Petrogenesis and Magmatic Affinity

The studied amphibolites are classified as ortho-amphibolites, pointing to an igneous protolith, specifically metabasalts. This classification is supported by high concentrations of chromium and nickel, which are indicative of a mafic precursor (Leake, 1965), (Fig. 10). Geochemical classification diagrams further confirm a basaltic bulk composition (Pearce, 1996) as shown in (Fig. 11a). A tholeiitic magmatic origin (Ross and Bédard, 2009), (Fig. 11b). Furthermore, the mineralogical composition, which includes calcic diopside pyroxene (Wo₄₈En₃₅Fs₁₇) and Na-rich plagioclase (oligoclase-albite), aligns with crystallization from a tholeiitic basaltic melt (Cox et al., 1979).

Enrichment in large-ion lithophile elements (LILE), such as Ba, Rb, and Sr, alongside negative Nb anomalies in primitive mantle-normalized diagrams, implies that the protolith magma either interacted with crustal materials or was affected by subduction-related fluids prior to or during its emplacement (Humphris and Thompson, 1978).

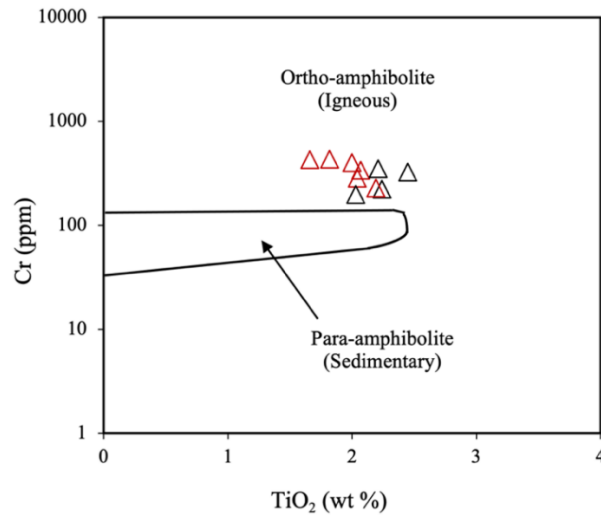


Fig. 10. Cr versus TiO_2 data from Leake (1965) for the studied rocks

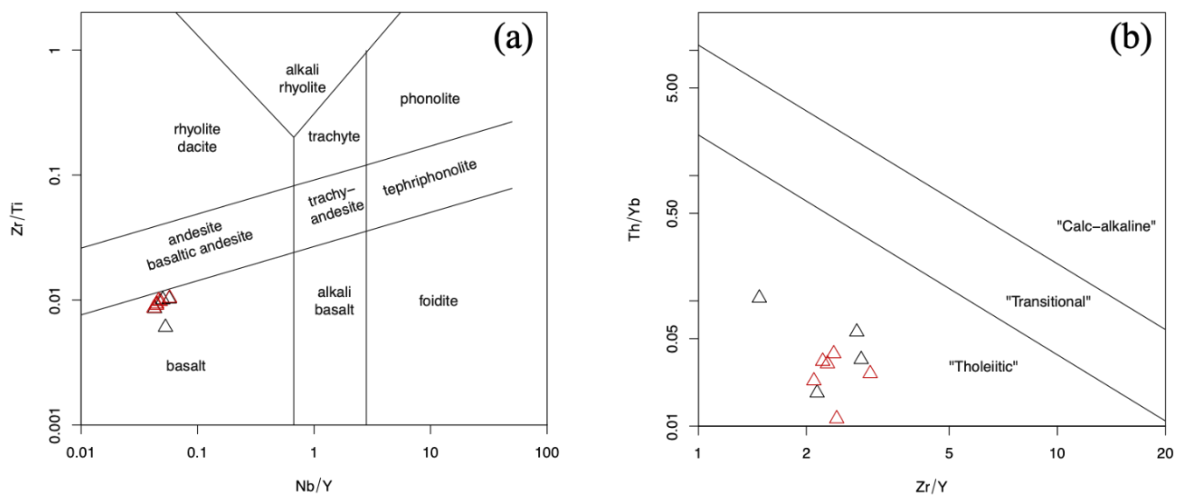


Fig. 11. Chemical classification diagram of studied amphibolite and garnet-bearing amphibolite rocks: a) Nb/ Y vs. Zr/ Ti plot (modified by Pearce 1996). b) Zr/ Y vs. Th/ Yb of Ross and Bedard (2009)

5.5. Tectonic Discrimination

Geochemical tectonic discrimination diagrams suggest a back-arc basin (BAB) setting for the protolith of these amphibolites. The (Ti-V) plot (Shervais, 1982) shows that the majority samples fall within the back-arc basin basalt (BABB) field (Fig. 12a). This is supported by the (TiO_2 - FeO_t / MgO) diagram (Fig. 12b), where garnet amphibolites mainly plot in the back-arc basin basalt field, while other amphibolites are found in both the back-arc basin basalt and mid-ocean ridge basalt (MORB) fields. Furthermore, triangular plots of immobile trace elements (e.g., Th-Hf-Ta), (Fig. 13) place most samples within or near the N-MORB field (Wood, 1980). This combined (N-MORB to BABB) signature is a classic fingerprint for basalts formed in extensional, supra-subduction zone environments like back-arc basins, where magmas from a depleted mantle source are variably influenced by subduction components (Pearce, 1984).

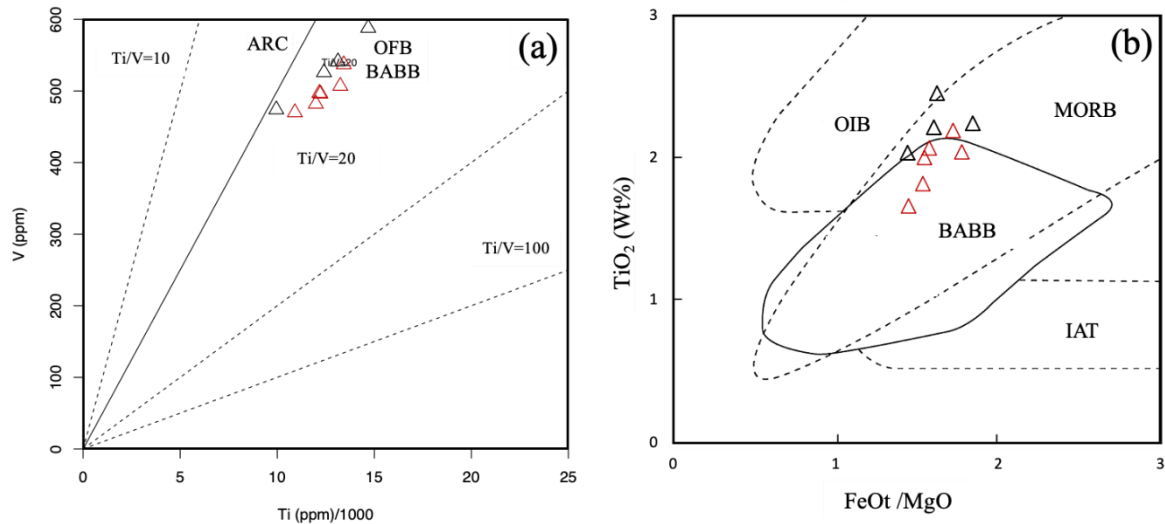


Fig. 12. Diagram of tectonic classification for the studied amphibolite samples: (a) V and Ti/1000 diagram (after Shervais, 1982); (b) TiO_2 vs. FeO_t/MgO diagram (after Shuto et al., 2006)

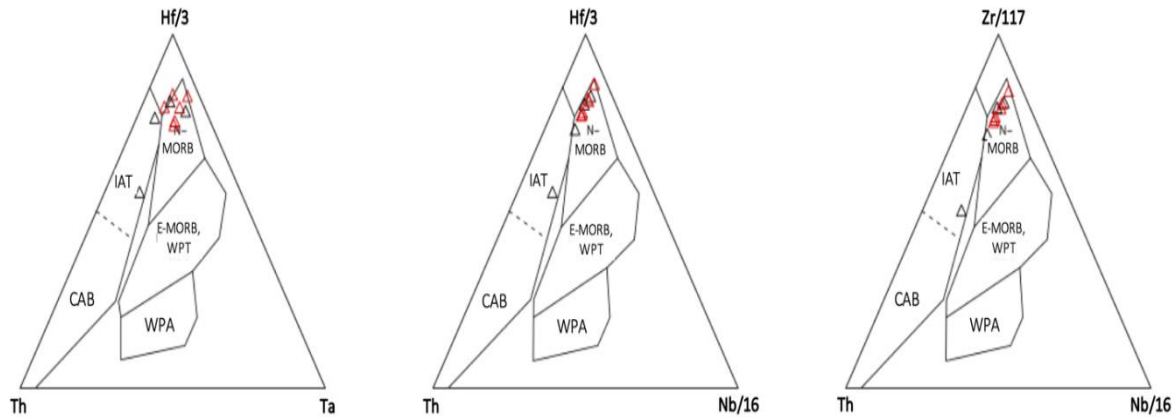


Fig. 13. Triangular plots of the Th-Hf-Ta-Zr-Nb of Wood (1980), as implemented in GCDkit (Janousek et al., 2006) for the studied rocks. IAT: island arc tholeiite, N-MORB: normal mid oceanic ridge basalt, E-MORB: enriched mid-ocean ridge basalt, WPA: within-plate alkaline, CAB: calc-alkaline basalt, WPT: within-plate tholeiite

5.6. Partial Melting Constraints and Mantle Source Characteristics

The mantle source region and melting conditions are constrained by rare earth element (REE) systematics. The samples generally exhibit light rare earth element (LREE) depletion with $(\text{La}/\text{Yb})_N$ ratios ≤ 1 , uniform heavy rare earth element (HREE) patterns, and negative europium anomalies. This pattern indicates partial melting inside the stability field of spinel lherzolite at relatively shallow depths, where garnet is absent as a residual phase (Cox et al., 1979). Diagrams such as $(\text{La}/\text{Sm})_N$ versus $(\text{Tb}/\text{Yb})_N$ (Wang et al., 2002), as shown in Fig. 14a and (Sm/Yb) versus (Sm) , (Li and Chen, 2014), (Fig. 14b), indicate that the basaltic protoliths were derived from a spinel lherzolite mantle source. Typical melting degrees, based on (Sm/Yb) ratios and (Sm) concentrations (~ 3.42 - 7.42 ppm), suggest the protolith basalts were generated by approximately 5-10% partial melting of a depleted mantle source, consistent with the high degrees of melting expected in back-arc spreading centers (Gill and Fitton, 2022).

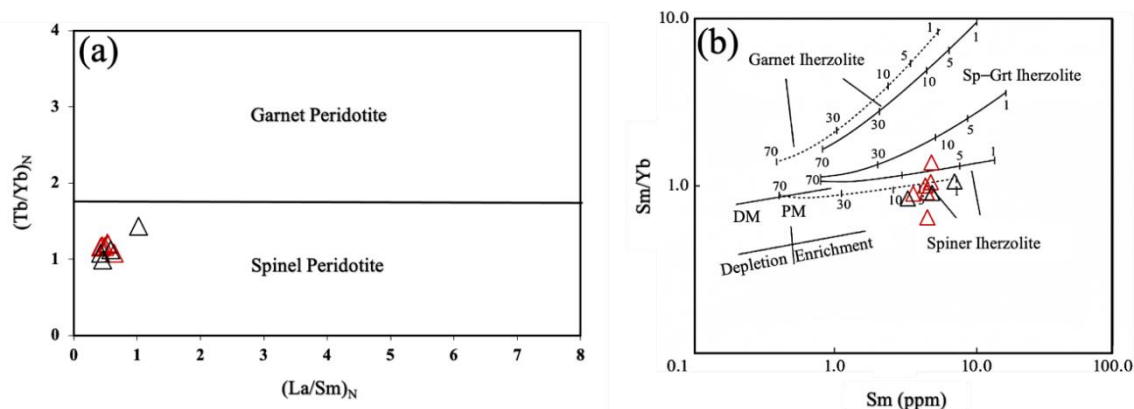


Fig. 14. a) $(La/Sm)_N$ vs. $(Tb/Yb)_N$ plot (modified after Wang et al., 2002 by Zheng et al., 2017); b) and Sm/Yb vs Sm plot (Li and Chen, 2014)

5.7. Tectonic Scenario

The Walash group represents volcano-sedimentary rocks formed as part of the lower allochthonous thrust sheet with a significant magmatic history of distinct subduction-related signatures dating from Eocene to Oligocene (43-24 Ma) (Ali et al., 2013) and (34.6 to 39.2 Ma) (Kettanah et al., 2023; Qaradaghi and Merza, 2023). In general, the studied amphibolite samples are related to earlier back-arc basin magmatism of the Walash group, including pyroclastic rocks in the Mawat area of 43.01 ± 0.15 Ma (Ali et al., 2013), Mawat diabase dykes (40.2-32.3 Ma) by (Aswad et al, 2014), clastic sequences derived from basalt and andesitic basalt in the Hasanbag area (Ali et al., 2017) and diabase rocks from Sidakan area (Kettanah et al., 2023). The ongoing convergence of the Arabian-Eurasian microplate led to the obduction of the Walash subduction-related Group, over the northeastern edge of the Arabian Plate reflecting intensified convergence along the Neotethyan margin.

Petrographic and mineral chemistry data limit peak metamorphic conditions to the upper-amphibolite facies (Spear, 1994), with temperatures reaching 674-796 °C and pressures of 6.4-6.9 kbar. These conditions pertain to lower crustal depths (about 21-25 km) and indicate the metamorphism of mafic protoliths (such as tholeiitic back-arc basalts) within a thermally elevated subduction setting. The presence of high-grade amphibolite pods within a low-temperature serpentinite matrix indicates a polymetamorphic history: deep-seated metamorphism of oceanic crustal fragments, followed by their tectonic disintegration and incorporation into a rising, hydrated mantle wedge, ultimately resulting in exhumation within an accretionary complex (Wakabayashi, 2012). These fragments in matrix, typical of subduction zone mélanges, highlight the dynamic role of serpentinite as a lubricant and transport medium in the ascent of high-grade rocks to shallow crustal levels (e.g., Guillot et al., 2015). The amphibolites subsequently underwent metamorphism under upper-amphibolite facies conditions,

The tectonic evolution of the Rayat amphibolites pods and associated chromitites pods (~5 km away) within the Walash Group records a multi-stage history within a Cretaceous-Paleogene suprasubduction zone (Ahmed et al., 2020). The chromitites crystallized from early boninitic melts in a nascent fore-arc mantle wedge (Arai, 1997; Zhou et al., 2014), while the protolith of the amphibolites formed later as mafic crust in an extending back-arc basin. The amphibolites subsequently underwent metamorphism under amphibolite-facies conditions during subduction to mid- to lower-crustal depths (Brown, 2007; Spear, 1994). The tectonic arrangement of these fore-arc mantle and metamorphosed back-arc crustal components is elucidated by a subduction channel mélange model (Angiboust et al., 2011; Guillot et al., 2001). In this context, serpentinite, generated by the hydration of the mantle wedge, functioned as a lubricant, promoting the mechanical mixing and incorporation of blocks from various lithospheric levels during subduction. The exhumation inside the ascending serpentinite matrix

facilitated retrograde greenschist-facies alteration of the amphibolites by fluid infiltration (Bebout and Barton, 2002; Scambelluri et al., 1995). Final obduction emplaced this polymetamorphic block-in-matrix assemblage onto the Arabian margin, recording the complete tectonic cycle from subduction initiation and fore-arc magmatism, through back-arc spreading, to the closure of the Neo-Tethyan Ocean and the tectonic construction of a composite suture zone (Wakabayashi, 2012).

6. Conclusions

Based on the integrated data, the study concludes that the studied amphibolites represent metamorphosed fragments of Neo-Tethyan back-arc basin crust. Their geochemical signature featuring LREE-depleted patterns, negative (Nb) anomalies, and key trace-element ratios indicates a tholeiitic basaltic protolith formed in an extensional back-arc basin setting, derived from a depleted spinel lherzolite mantle source. The mineral assemblages and thermobarometry reveal that these rocks subsequently experienced amphibolite-facies metamorphism.

Peak metamorphic conditions reached upper-amphibolite facies, with temperatures and pressures averaging 674-690 °C at 6.4 kbar for (R4) and 775-796 °C at 6.9 kbar for (R6). The structural evolution is marked by mylonitic textures and retrograde equilibration, characterized by chloritization, sericitization, and the presence of epidote, which—along with the lower (P-T) conditions (549-596 °C at 3.6 kbar)—record a protracted exhumation history and structural overprinting during tectonic transport.

The Rayat amphibolites and associated chromitites collectively record a complete suprasubduction zone cycle within the Neo-Tethyan realm. Their tectonic juxtaposition in a serpentinite-hosted *mélange* chronicles a progression from early fore-arc magmatism to back-arc crustal formation, followed by deep subduction metamorphism, and final exhumation and accretion within a subduction channel. This *mélange* confirms the Walash Group as a composite suture zone formed by tectonic mixing during oceanic closure.

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Declaration of Competing Interest

The author declares no competing financial interests or personal relationships that could have influenced the work reported in this paper.

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Data Availability

All data generated or analyzed during this study are included in this published article.

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