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Textural and chemical characteristics of olivine and pyroxenes in the ultramafic rocks from the Indus suture zone in Swat, NW Pakistan: implications for petrogenesis and alteration

by *Mohammad Arif*¹ and *Charlie J. Moon*²

Abstract

Bodies of ultramafic rocks occur at a number of localities along the Indus suture in the Swat valley. The present mineralogical characteristics of these dominantly harzburgitic rocks seem to be a result of a number of phenomena including partial melting, serpentinization, metamorphism and talc-carbonate alteration. The low modal abundance and compositional characteristics of pyroxenes [high values (88–99) of Mg # = $100 \text{ Mg}/(\text{Mg} + \text{Fe}^{2+})$ and low amounts of Al_2O_3 (mostly < 2.5 wt%)] suggest that the host rocks underwent an intermediate degree of partial melting prior to emplacement. A variable amount of hydration has resulted in the formation of abundant serpentine and bastitization of the original orthopyroxene grains in most of the investigated samples. The mode of occurrence, texture and the composition of olivine [high to very high Mg # (~ 80 to > 98); low NiO relative to the forsterite and MnO contents in several of the samples] all indicate its development during a prograde regional metamorphism under greenschist to lower amphibolite facies conditions. The very fine grained prismatic habit of pyroxene grains, distributed within the serpentine matrix in some of the samples, also suggests a metamorphic origin. The very high Mg # of olivine in the presence of magnetite, especially where the latter occurs as submicroscopic lamellae within the grains of highly magnesian olivine, in the majority of the rocks signifies that the metamorphism probably took place mostly under high f_{O_2} . However, as olivine in some of the samples (which also contain awaruite) has distinctly low Mg # (< 90), the conditions of f_{O_2} may have been variable during the metamorphism. A further process of alteration by a CO_2 -rich fluid has led to the formation of magnesite veins in the serpentinites, transformation of metamorphic olivine to magnesite and, locally, to the development of assemblages rich in magnesite associated with talc and/or quartz.

Keywords: ultramafic rock, harzburgite, metamorphism, alteration, Indus suture zone, NW Pakistan.

Introduction

The area between the Mingora town and Lilaunai village of Swat, NW Pakistan, contains good exposures of mafic-ultramafic rocks. These rocks lie along the Indus-Tsangbo Suture (ITS) which marks collision of the Indo-Pakistan plate with the Kohistan island arc (TAHIRKHELI et al., 1979; TRELOAR et al., 1989). They occur as sheets and lenses incorporated in the metasedimentary rocks of the Indo-Pakistan plate (see ARIF, 1994). Despite their important tectonic setting and great petrologic significance, details regarding the formation and evolution of these rocks are virtually

lacking. A few mineralogical accounts (ASHRAF et al., 1989; ARIF and JAN, 1993) are the only published information about these rocks. The present study focuses on textural and mineral-chemical features of the serpentinized ultramafic rocks with the object to investigate their genesis and post-formational changes.

General geology

The ITS assumes a broad wedge-shaped complex zone in the Swat valley and contains diverse rock assemblages separated by faults of different ages.

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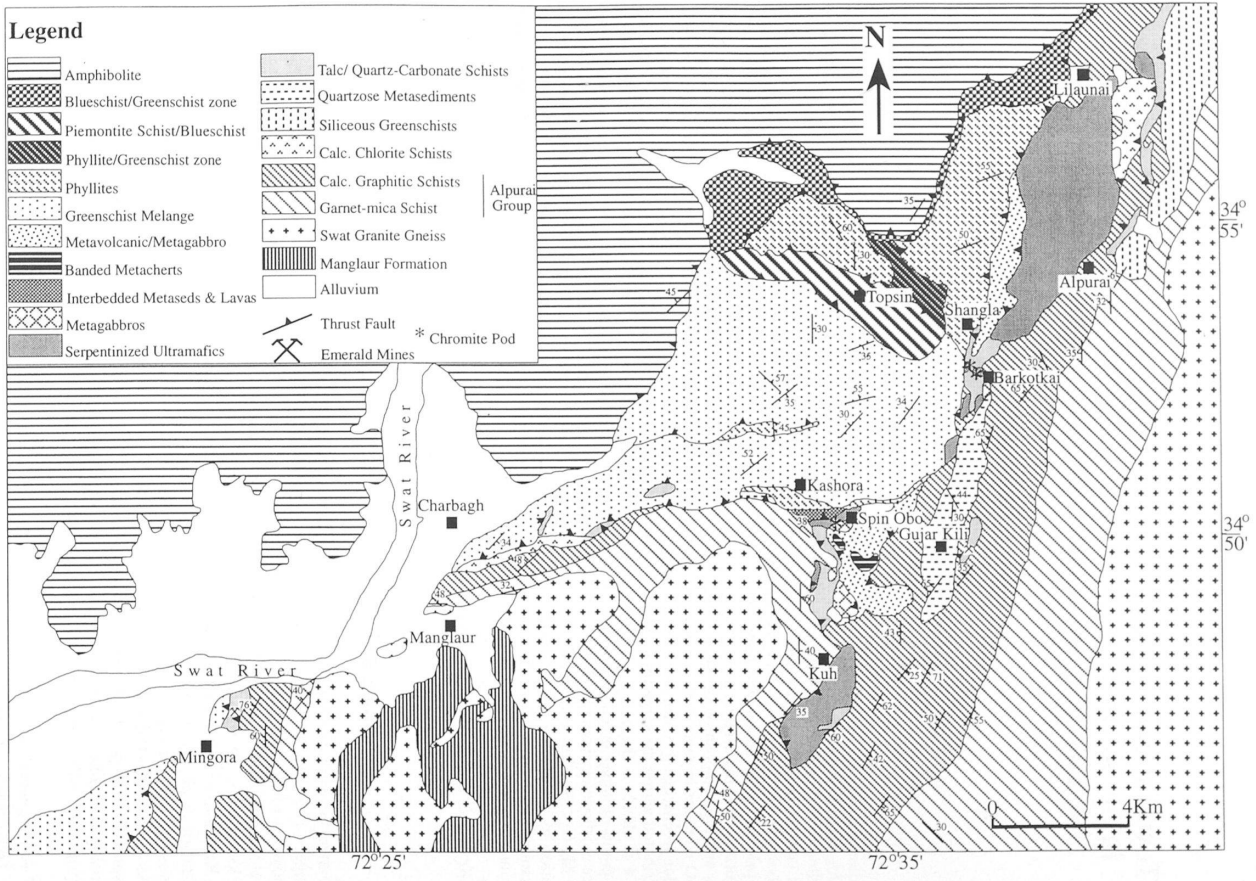


Fig. 1 Geological map of the Lilaunai-Mingora area, Swat (modified after KAZMI et al., 1984).

This assortment of rocks, collectively known as the Indus suture mélange group, has been distinguished into three principal types of mélanges: the blueschist mélange, the greenschist mélange, and the ophiolitic mélange (KAZMI et al., 1984, Fig. 2).

Ophiolitic rocks (e.g., ultramafics, gabbros, lavas and metasediments), constituting the ophiolitic mélange, occur as small to large lensoidal bodies distributed within and along the northern edge of the Indo-Pakistan plate. The main localities where such rocks are exposed include the Barkotkai-Lilaunai area, the Gujar Kili village, the Spin Obo-Kuh area and the Mingora town (Fig. 1). The ophiolitic rocks are metamorphosed under upper greenschist to lower amphibolite facies conditions. However, the original igneous features (i.e., porphyritic, vesicular, glassy and pillow structures) of the volcanic rocks are largely preserved.

Ultramafic rocks are the most abundant type among all the lithologies of the different ophiolitic occurrences in the area (Fig. 1). They mostly consist of serpentized harzburgites with minor amounts of other varieties such as dunite, lherzolite, websterite and pyroxenite. As multiple episodes of alteration and metamorphism have obscured their primary fabric, a distinction of the ultramafic rocks into types such as cumulate and/or tectonite is not possible on the basis of their texture alone. Besides hydration leading to serpentization, carbonation also has played its role in obscuring the original mineralogy of the ultramafic rocks. The process of carbonation, which has produced different types of magnesite-rich rocks, probably took place after serpentization because veins of magnesite cutting across serpentine occur in several of the samples studied.

At places (e.g., near the Barkotkai village), the serpentized ultramafic rocks contain small bodies of chromitites and accessory to trace amounts of Ni-rich phases. Locally, the carbonate-rich assemblages in the study area contain emerald deposits which produce one of the world's finest gemstone quality emeralds (Fig. 1).

Samples and methods

A total of 74 samples were collected from the bodies of serpentized ultramafic rocks in the Lilaunai-Barkotkai and Spin Obo-Kuh areas (Fig. 1). All the samples were studied petrographically and 49 were selected for chemical analyses of their olivine and pyroxene grains. The analyses were carried out through Jeol

Superprobe model JXA-8600 with an on-line computer for ZAF corrections. Quantitative analyses were conducted using wavelength dispersive system and natural and synthetic standards under the following operating conditions: 15 kV accelerating voltage; 30×10^{-9} A probe current; 20 (2×10) seconds peak, 10 (2×5) seconds negative background and 10 (2×5) seconds positive background counting times. The accuracy of the ZAF correction is generally better than 2%.

Results and comparison

PETROGRAPHY

Virtually all the ultramafic rocks are serpentized to varying degrees. Some of these rocks are so thoroughly altered that, except for some relic cores of chrome spinel, none of the original mafic phases (i.e., olivine or pyroxene) has survived. Such pervasively serpentized rocks have a green to yellowish green surface colour, are locally sheared and jointed, and almost totally composed of fine grained serpentine. The serpentine displays non-pseudomorphic textures and appears to be in textural equilibrium with olivine and pyroxene, where present. It suggests that either the serpentization took place under relatively high-temperature conditions or the rocks underwent prograde metamorphism (WICKS and O'HANLEY, 1988). At places, the completely serpentized rocks are foliated.

Most of the serpentized ultramafic rocks contain bastites (grains having a bronze-like metallic lustre and formed by the complete transformation of orthopyroxene, DEER et al., 1992) suggesting that their dominant precursors were harzburgites. An outstanding feature of the studied ultramafic rocks is that some of them contain thin to fairly thick (> 2 mm across) veins of olivine (FO_{98}) (ARIF and JAN, 1993, Fig. 2b) which cut across the main serpentine matrix without affecting the latter. Therefore, the generation of these veins cannot be attributed to a later high-temperature magmatic activity. Rather, they formed due to a fluid activity along shear zones during the main regional metamorphism in the area (see also TROMMSDORFF and EVANS, 1972, 1980; PERETTI et al., 1992). In addition, thin microscopic veins of olivine also traverse some of the bastite grains (Fig. 2a). Strictly speaking, these can best be described as the product of high-temperature transformation of bastites along intragranular fractures. Furthermore, well-formed grains and patches of fresh olivine occur within as well as adjacent to those of bastites. Develop-

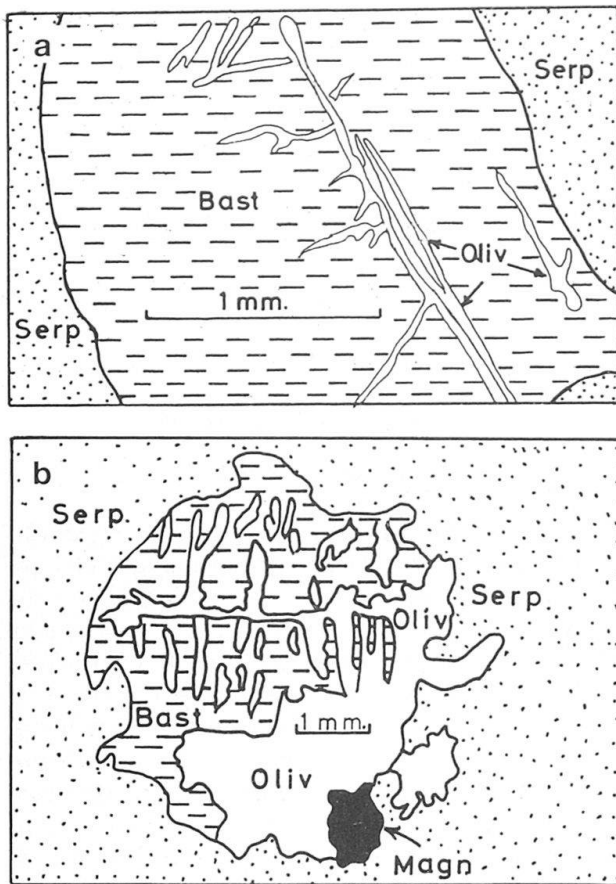


Fig. 2 Reproduced from coloured photomicrographs. (a) Thin veins of olivine traversing a grain of bastite. (b) Development of olivine at the expense of bastite.

ment of olivine within, and at the expense of, bastites is clearly demonstrated microscopically (Fig. 2b).

Locally, the grains of olivine are elongated and exhibit bladed and lenticular shapes with long, drawn out tails (Fig. 3a). Such highly elongated olivine grains occur in numerous examples of talc-olivine assemblages described from the regionally and contact metamorphosed ultramafic terranes in the central Alps of Switzerland and Italy, and in the state of Washington (cf. EVANS and TROMMSDORFF, 1974). The elongated olivine grains in some of the samples show interfingering relationship with each other and/or those of clinopyroxene. Olivine in some of the rocks is rather coarse grained. SEM studies revealed that the olivine grains in some of the rocks contain abundant, preferentially oriented, submicroscopic lamellae of magnetite (ARIF and JAN, 1993, Fig. 9). Olivine grains in some of the samples are rimmed with magnetite (Fig. 3b). There appears to be two generations of olivine in some of the rocks: one occurring as large grains and the other in the form of very fine grained aggregates. In some

samples, the fine grained variety of olivine occurs along fracture in the serpentine-dominated rock. Some of the large grains of olivine are porphyroclastic and surrounded by the fine grained variety thereby exhibiting grain boundary recrystallization. Rarely, the coarse-grained olivine is strained and exhibits kink bands.

Although being rarer and less abundant than orthopyroxene as bastites, the clinopyroxene is mostly unaltered. Fresh blebs and lamellae of clinopyroxene also occur within bastites in some of the samples (Fig. 4a). Rarely, clinopyroxene, like olivine, exhibits undulose extinction, bending and features of recrystallization. Also, in some of the samples, it occurs as very fine grained prismatic or needle-like crystals distributed within the matrix of serpentine (Fig. 4b). The clinopyroxenes of the latter textural type resemble that reported from the Malenco peridotites in northern Italy (PERETTI et al., 1992), and apparently

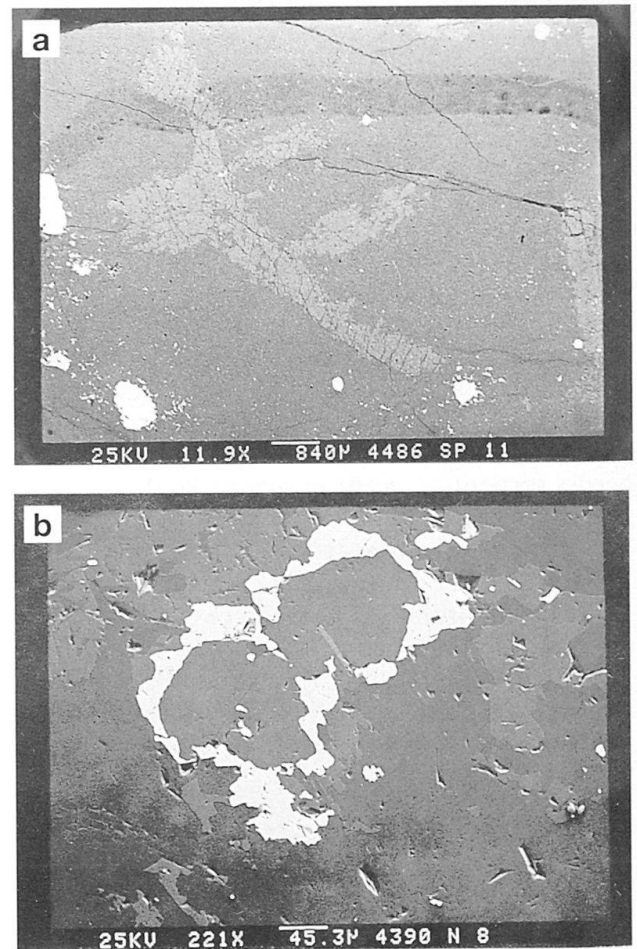


Fig. 3 SEM images (scaled in μm). a) Elongated grains of olivine (light grey) in a serpentine matrix (darker background). b) A rim of magnetite (bright white) around olivine (middle of the picture) in a serpentine matrix (black background).

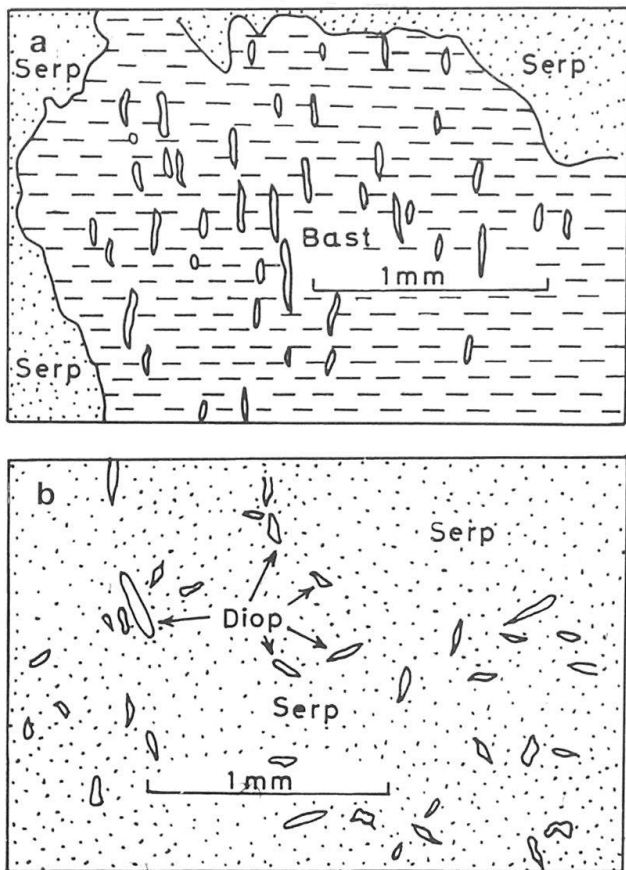


Fig. 4 Reproduced from coloured photomicrographs. (a) Crystallographically oriented lamellae of diopside in a grain of bastite. (b) Serpentine matrix containing very fine grained, prismatic crystals of diopside.

formed due to metamorphism. Grains of fresh (unbastitized) orthopyroxene were observed in one of the samples studied. But even these grains show conversion to talc along margin and intra-granular cracks.

Chrome spinel, the only trace of the original mineralogy in most of the serpentinized ultramafic rocks, occurs as relic cores invariably zoned and/or rimmed with ferritchromite and/or magnetite. Besides bordering grains of olivine and chrome spinel, the major occurrence of magnetite is as trails and veins along those of serpentine and olivine. In addition, it occurs as lamellae within the bastites probably exsolved from the original orthopyroxene during its bastitization.

Trace amounts of Ni-rich phases including sulphides and awaruite (an alloy of nickel and iron) also occur in some of these serpentinized rocks. The mode of occurrence, textural features, chemistry and genesis of these minerals are discussed by ARIF and MOON (1994).

Phase chemistry

OLIVINE

The composition of olivine was determined in a total of 48 samples. In order to check for within sample variation in composition, an average of two to three grains of olivine were analysed in most of the samples. In addition, within-grain variation (e.g., zoning) was looked for by analysing different positions in most of the studied

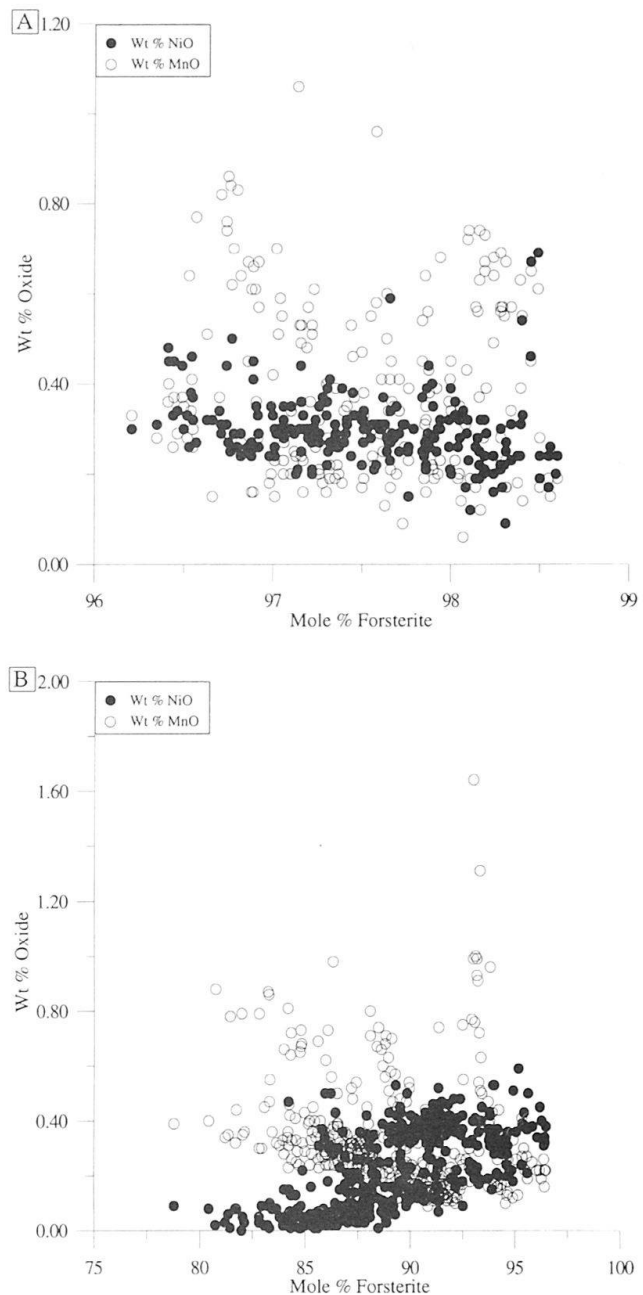


Fig. 5 Chemical variation in olivine in terms of MnO, NiO and forsterite contents. (A) and (B) contain analyses with mol% Fo > 96 and Fo ≤ 96%, respectively.

Tab. 1 Representative analyses of olivine and pyroxenes.

Samp.*	B21 (9)	B29 (8)	B30 (21)	B30 (7)**	L26 (6)	L25(25)	L21(15)	B30 (7)	B30***	L10 (3)	L10 (5)***	B34 (3) ****	L24 (7)
Phase	Olivine	Olivine	Olivine	Olivine	Olivine	Olivine	Olivine	Diopside	Diopside	Diopside	Diopside	Diopside	Enstatite
SiO ₂	42.48±0.28	42.27±0.19	41.97±0.19	41.90±0.23	41.19±0.12	40.92±0.42	40.54±0.35	53.70±0.39	55.42	53.35±1.19	55.37±0.11	55.14±0.50	56.80±0.63
TiO ₂	0.02±0.02	0.02±0.01	0.01±0.00	0.01±0.00	0.01±0.00	0.02±0.01	0.01±0.01	0.03±0.02	0.01	0.02±0.01	0.01±0.01	0.00±0.00	0.02±0.01
Al ₂ O ₃	0.00±0.00	0.00±0.01	0.01±0.03	0.00±0.00	0.00±0.01	0.05±0.13	0.01±0.02	1.52±0.47	0.01	0.98±0.281	0.01±0.01	0.01±0.01	1.66±0.24
Cr ₂ O ₃	0.04±0.02	0.03±0.02	0.03±0.01	0.03±0.01	0.05±0.03	0.08±0.12	0.04±0.03	0.53±0.21	0.05	0.43±0.18	0.03±0.01	0.05±0.01	0.51±0.06
FeO	1.73±0.16	2.58±0.41	2.99±0.21	3.09±0.17	8.98±0.89	10.47±1.78	13.77±1.83	1.88±0.23	0.44	2.75±1.36	0.90±0.10	0.73±0.02	6.00±0.26
MnO	0.25±0.14	0.21±0.19	0.41±0.23	0.47±0.23	0.16±0.04	0.18±0.06	0.25±0.05	0.07±0.03	0.06	0.07±0.01	0.06±0.02	0.02±0.01	0.15±0.03
MgO	55.30±1.07	56.42±0.78	55.51±0.37	55.45±0.40	50.22±0.97	49.31±1.88	47.44±1.40	18.42±0.64	18.87	17.79±0.21	18.05±0.04	17.99±0.09	34.37±0.26
CaO	0.00±0.00	0.01±0.01	0.03±0.02	0.02±0.01	0.01±0.01	0.04±0.12	0.05±0.12	24.18±0.61	26.20	24.48±0.80	26.16±0.12	26.03±0.20	0.66±0.23
Na ₂ O	0.01±0.01	0.01±0.01	0.01±0.01	0.00±0.00	0.00±0.01	0.01±0.02	0.01±0.01	0.08±0.04	0.00	0.05±0.01	0.01±0.01	0.01±0.00	0.01±0.00
K ₂ O	0.01±0.01	0.01±0.00	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	0.01±0.01	0.01±0.00	0.01±0.01	0.01±0.01
NiO	0.26±0.07	0.33±0.06	0.30±0.07	0.30±0.10	0.37±0.03	0.34±0.08	0.10±0.14	0.04±0.01	0.07	0.03±0.01	0.05±0.03	0.03±0.01	0.09±0.02
Total	100.10±1.00	101.89±0.63	101.28±0.48	101.29±0.59	101.00±0.20	101.44±0.68	102.23±0.36	100.46±0.45	101.14	99.96±0.56	100.64±0.21	100.02±0.66	100.27±0.72
Number of ions based on four and six oxygens for olivine and pyroxene, respectively.													
Si	1.003±0.012	0.987±0.004	0.988±0.002	0.987±0.003	0.997±0.003	0.993±0.005	0.990±0.002	1.942±0.010	1.984	1.950±0.023	1.994±0.002	1.996±0.004	1.955±0.009
Ti	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.001±0.001	0.000	0.001±0.001	0.000±0.001	0.000±0.000	0.001±0.000
Al	0.000±0.000	0.000±0.000	0.000±0.001	0.000±0.000	0.000±0.000	0.002±0.004	0.000±0.001	0.065±0.020	0.000	0.043±0.012	0.000±0.000	0.000±0.000	0.067±0.010
Cr	0.001±0.000	0.001±0.001	0.000±0.001	0.000±0.000	0.001±0.000	0.001±0.002	0.001±0.001	0.015±0.006	0.001	0.013±0.005	0.001±0.001	0.001±0.001	0.014±0.002
Fe ²⁺	0.034±0.003	0.050±0.008	0.059±0.004	0.061±0.003	0.182±0.019	0.213±0.038	0.282±0.039	0.057±0.007	0.013	0.085±0.042	0.028±0.003	0.022±0.001	0.173±0.006
Mn	0.005±0.003	0.004±0.004	0.008±0.005	0.009±0.005	0.003±0.001	0.004±0.001	0.005±0.001	0.002±0.001	0.002	0.002±0.001	0.002±0.000	0.001±0.000	0.004±0.001
Mg	1.947±0.024	1.964±0.015	1.949±0.009	1.948±0.005	1.812±0.026	1.784±0.049	1.727±0.037	0.993±0.032	1.007	0.970±0.004	0.970±0.002	0.971±0.006	1.763±0.010
Ca	0.000±0.000	0.000±0.000	0.001±0.001	0.001±0.000	0.000±0.000	0.001±0.003	0.001±0.003	0.937±0.024	1.005	0.958±0.022	1.010±0.003	1.010±0.006	0.024±0.009
Na	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.006±0.002	0.000	0.003±0.001	0.000±0.000	0.001±0.000	0.001±0.000
K	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000	0.000±0.000	0.000±0.000	0.000±0.000	0.000±0.000
Ni	0.005±0.001	0.006±0.001	0.006±0.001	0.006±0.002	0.007±0.001	0.007±0.001	0.002±0.003	0.001±0.000	0.002	0.002±0.001	0.001±0.001	0.001±0.000	0.002±0.000
Total	2.995±0.013	3.012±0.004	3.011±0.003	3.012±0.002	3.002±0.003	3.005±0.006	3.009±0.003	4.020±0.006	4.014	4.024±0.016	4.005±0.002	4.004±0.003	4.004±0.005
Mg #	98.3±0.14	97.5±0.41	97.1±0.21	97.0±0.20	90.9±0.99	89.3±1.98	84.8±2.13	94.57±0.65	98.73	92.07±3.56	97.23±0.30	97.79±0.09	91.09±0.31
Wo	-----	-----	-----	-----	-----	-----	-----	47.15±1.25	49.63	47.63±1.58	50.32±0.11	50.41±0.25	1.23±0.44
En	-----	-----	-----	-----	-----	-----	-----	49.98±1.25	49.73	48.18±0.50	48.31±0.17	48.49±0.21	89.96±0.41
Fs	-----	-----	-----	-----	-----	-----	-----	2.87±0.34	0.64	4.19±2.02	1.37±0.15	1.10±0.04	8.81±0.32

* Abbreviations used for sample designation: B = samples from the Barkotkai area, L = samples representing the Lilaunai village (see Fig. 1). Number in parentheses denotes the total number of analyses performed in a given sample whose average composition is presented.

** Composition of vein olivine

*** Occurring as exsolution lamellae in bastites

**** Distributed as fine prismatic crystals in serpentine matrix

Total iron as FeO

Mg # = $100 \times \text{Mg}/(\text{Mg} + \text{Fe}^{2+})$

grains. As mentioned above, olivine also occurs as veins cutting across the main serpentine matrix and traversing grains of bastites in some of the samples. However, the compositions of the matrix and vein olivine do not differ greatly from each other (Tab. 1).

The maximum variation in the composition of olivine within a given sample does not exceed 3 mol% Fo [i.e., $Mg \# = 100 \times Mg/(Mg + Fe^{2+})$]. Only three of the olivine-containing samples show variation of more than 2.5 mol% Fo (i.e., $\sigma = 2.6-2.8$). In contrast, most of the samples have olivine with a rather uniform composition ($\sigma \leq 0.5$ mol% Fo). The concentrations of all the minor elements (TiO_2 , Al_2O_3 , Cr_2O_3 , and CaO) are low (mostly less than 0.05 wt% each).

An outstanding feature of the analysed olivine is its high Fo (forsterite) content (96–98 mol%) in several of the samples studied. These values exceed the maximum limit of the range observed in the Fo content of olivines in both cumulate and residual peridotites from most other ophiolite complexes (see COLEMAN, 1977). A survey of the relevant literature reveals that metamorphosed ultramafic rocks are the only terrestrial silicate rocks whose olivine ($Mg \#$ 96.0–98.9 with significant Ni and Cr) (cf. DEER et al., 1982) is similar in composition to the one studied. Typical examples are those described from East Dover, south-central Vermont (HOFFMAN and WALKER, 1978) and Toulumne River, Sonora, California (MORGAN, 1978). Formation of olivine in rocks of these areas is supposed to be

due to upper greenschist to lower amphibolite facies regional metamorphism.

Analytical data on olivines from layered intrusions show that their NiO content increases with Fo and those containing more than ~ 80 mol% Fo carry $NiO \geq 0.2$ wt% (see SIMKIN and SMITH, 1970). In contrast, the NiO values of some of the studied olivines are rather low (< 0.1 wt%) with respect to their Fo contents (~ 90) (Tab. 1). The range of MnO content (0.2–0.7 wt%) is high and mostly exceeds that of NiO (0.2–0.4 wt%). Excess of MnO over NiO seems to be a characteristic feature of metamorphic olivines of ultramafic igneous parentage (EVANS, 1977). Based on the composition of olivine, the studied samples can be divided into two groups: 1) rocks with olivine having $Fo \geq 96\%$ and MnO mostly more than NiO; and 2) rocks containing olivine with $Fo \sim 96\%$ and $MnO \leq NiO$. These two groups of olivine have been plotted separately in figure 5.

PYROXENES

Virtually all of the clinopyroxene analyses closely approximate the end-member diopside composition (Tab. 1). The TiO_2 and Na_2O contents fall mostly below 0.1 wt%. As is the case with magnesian olivine (described above), the MnO content (0.01–0.13 wt%) is higher than that of NiO (0.01–0.07 wt%) in most of the clinopyroxene analyses. In a given sample, there are significant differences between the composition of the commonly occurring diopside (i.e., distributed as discrete grains) and that having other modes of occurrence and textures (namely, lamellae and blebs in bastites and very fine grained prismatic crystals within the main serpentine matrix). For example, the lamellae of diopside in bastites are very low in FeO^* relative to the main diopside occurring as discrete grains (e.g., the two types of analyses from samples B30 and L10 in Tab. 1). This is probably because the process of exsolution, producing the lamellae, was accomplished under high pressure of oxygen so that the Fe was mainly extracted as magnetite which forms a dust over the bastite grains.

Except for only a few, most of the clinopyroxene analyses contain significant amounts of Al_2O_3 (reaching up to 3 wt%) and Cr_2O_3 (0.03–1.0 wt%). The Cr content of many of the analyses is high enough to make them qualify as chromium diopsides (i.e., with average $Cr_2O_3 \approx 0.67$ wt%; COLEMAN, 1977).

As mentioned above, orthopyroxene has been invariably transformed fully to bastites in almost all of the studied samples. However, grains of

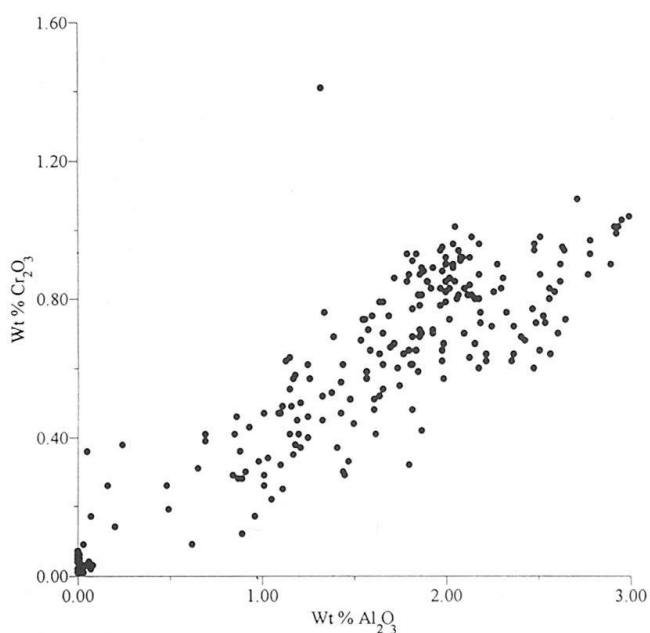


Fig. 6 The Al_2O_3 and Cr_2O_3 variation in clinopyroxene.

orthopyroxene having unaltered portions were observed in one of the samples. The chemical composition of these relics falls in the range of enstatite (Tab. 1). Small amounts of Al_2O_3 (1.4–2.0 wt%), Cr_2O_3 (0.4–0.6 wt%), CaO (0.5–1.1 wt%), and traces of MnO (0.1–0.2 wt%) and NiO (~ 0.1 wt%) also occur in the analyses.

Like olivine, pyroxenes in the studied rocks are characterized by high to very high concentrations of MgO (clinopyroxene: Mg # $\approx 94.3 \pm 1.9$, range = 87.7–99.4; orthopyroxene: average Mg # ≈ 91). The overall chemical variation and relative proportions of enstatite, ferrosilite and wollastonite in most of the clinopyroxenes and the range in Mg # of orthopyroxene from the studied rocks are similar to the pyroxenes from metamorphic peridotites.

The Al and Cr contents of the clinopyroxene analyses show a positive correlation and distinguish them into two types (Fig. 6). The analyses with low Al and Cr are mostly those representing the second generation of diopside, i.e., either distributed as fine grained prismatic crystals or occurring as lamellae in bastites (see Fig. 4 and Tab. 1).

Discussion

GENESIS AND EMPLACEMENT

On the basis of their field distribution and lithological association, it can be suggested that the studied ultramafic rocks are a part of an Alpine type peridotite or ophiolite complex which was emplaced as a result of the Himalayan collision between the Indo-Pakistan and Eurasian plates along the Indus suture zone. The original mineralogy of these rocks has largely been obscured by extensive alteration (mainly serpentinization and carbonation) under a variety of physicochemical conditions. But as most of the rocks contain well-preserved orthopyroxene bastites, harzburgite was probably the predominant lithology and they, therefore, belong to the harzburgite subtype of ophiolites (COLEMAN, 1977). The restricted chemical variation and compositional characteristics of pyroxenes in the studied rocks duplicate those from residual (metamorphic) peridotites.

The residual peridotites of ophiolite complexes are distinguished, on the basis of their modal and mineralogical compositions, into three principal classes (ISHIWATARI, 1985): (1) mainly consisting of lherzolites containing an average of 12 modal % Al-rich clinopyroxene (with up to 6 wt% Al_2O_3) (e.g., the Ligurian peridotites); (2)

dominantly composed of harzburgites which are almost clinopyroxene-free (containing only 0.8% of virtually Al-free clinopyroxene) (e.g., the Papuan harzburgites); and (3) containing both lherzolite and harzburgite (the Yakuno peridotites). The harzburgites of the Yakuno ophiolite invariably contains a small amount of Al-poor clinopyroxene (~ 2.5 modal % with $\text{Al}_2\text{O}_3 < 1$ wt%). These features are attributed to variable amounts of depletion by different degrees of partial melting which the peridotites suffered before emplacement. Thus, it has been suggested that the Ligurian peridotites represent upper mantle residue left after low degrees (< 15%) of partial melting, the Yakuno type are residual rocks which had undergone an intermediate degree (> 15% to < 30%) of partial melting and the Papuan harzburgites could be a residue left after a high degree (> 30%) of partial melting (see also MYSEN and KUSHIRO, 1977; JACQUES and GREEN, 1980).

The peridotites of the study area consist mainly of harzburgite but include also a minor amount of lherzolite. Most of the harzburgites contain a small amount of Al-bearing clinopyroxene (Al_2O_3 mostly < 2.5 wt%) (Fig. 6). Thus, in terms of the modal abundance and chemical composition of their clinopyroxene, the studied peridotites are more or less similar to those of the Yakuno ophiolite and, therefore, had suffered an intermediate degree of partial melting before emplacement.

ALTERATION

The presence of variable amounts of serpentine and the common bastitization of orthopyroxene suggest that serpentinization affected the studied rocks. This apparently seafloor serpentinization was followed by another higher temperature event as indicated by (1) the non-pseudomorphic texture of the serpentine, (2) the chemical characteristics (SiO_2/MgO ratios > 1) and XRD traces of the serpentine which are like those of antigorite (see ARIF, 1994) – the high-temperature member of the serpentine family, and (3) the coexistence of serpentine in textural equilibrium with olivine of metamorphic origin (as discussed below).

After serpentinization, the studied ultramafic rocks were most probably subjected to further modifications by a low grade metamorphism. This is shown by the invariably zoned character of chrome spinel grains in the serpentinized ultramafic and chromite-rich rocks (see also ARIF and JAN, 1993). Rarely, there also seem to be two

generations (magmatic and metamorphic) of diopside in the studied rocks. However, metamorphism of the investigated rocks is more clearly evident from the following textural and chemical characteristics of their olivine: (i) distribution as veins in serpentine matrix; (ii) occurrence as fresh grains adjacent to, unaltered inclusions and/or patches (apparently developing from the host bastite) as well as veins (as if healing the intragranular fractures) in, the completely bastitized orthopyroxene (Fig. 2); (iii) displaying inter-fingering relationships; (iv) rather coarse grain size (> 2 mm across) and/or elongated shapes in some of the samples (Fig. 3a); (v) containing preferentially oriented lamellae of magnetite; (vi) bordering as rims by Cr-magnetite/ferritchromite (Fig. 3b); (vii) variable but mostly very highly forsteritic composition (reaching up to 98.5 mol% Fo); and (viii) relative to Fo contents, low NiO but high MnO concentrations (Fig. 5).

The occurrence of such a highly magnesian olivine is rare but its formation is possible and could be due to one of the following two processes:

a) Serpentinization of the original olivine of "normal" composition (Fo ~ 90) usually involves the release of abundant Fe because serpentine, unlike its precursor, can accommodate only a small amount of this component. This leads to the formation of magnetite which, therefore, occurs as a common and ubiquitous accessory phase in the serpentinized ultramafic rocks from almost every occurrence in the world. In other words, the resulting serpentine is expected to be always much more magnesian than its precursor olivine. A simple dehydration of the serpentine during metamorphism may lead to the development of highly magnesian olivine.

b) Serpentinization of the original ultramafic rock may lead to the formation of serpentine plus brucite [Mg(OH)₂]. A reaction between these two phases during prograde metamorphism may give rise to olivine which would be much more magnesian than the one present in the original, un-serpentinized (or, as is more usually the case, partly serpentinized but not metamorphosed) ultramafic rock.

Highly magnesian olivine can form by both the processes provided that the fugacity of oxygen is high enough to prevent the magnetite from being involved in the dehydration reaction and/or facilitate further oxidation and exsolution of iron as magnetite. However, the presence of awaruite in some of the studied rocks indicates the operation of highly reducing conditions (see PERETTI et al., 1992). Assuming that awaruite was originally formed due to a former incipient ser-

pentinization, its persistence can be explained as follows:

(i) The scarce occurrence and very fine grained nature of awaruite indicate that the role of small-scale or "micro-environmental" chemical conditions has come into play to help it (awaruite) survive the otherwise high f_{O_2} -metamorphism.

(ii) A large-scale variation in f_{O_2} during metamorphism: that is, some of the rocks (which contain awaruite) were metamorphosed under lower f_{O_2} conditions than most others (i.e., those lacking awaruite).

The second explanation is favoured because the Fo content of olivine in the awaruite-bearing rocks is distinctly low compared to most of those lacking this highly reduced phase. In fact, the Fo content of the studied olivine is much more variable and falls down to ~ 80 in some of the analyses. Most other studies of secondary olivine in metamorphosed Alpine ultramafic bodies also show a considerable range in forsterite contents (e.g., TROMMSDORFF and EVANS, 1972; COATS and BUCHAN, 1979). Besides f_{O_2} , the Fe/Mg ratio of the rock and the nature and amounts of co-existing phases (especially talc), also affect the amount of iron incorporated into olivine during metamorphism (TROMMSDORFF and EVANS, 1974; EVANS, 1977). As the Mg #s of serpentine in the two groups of rocks are not greatly different (see ARIF, 1994) and talc is absent from the olivine-containing assemblages in both the cases, the low Fo content of olivine in the awaruite-bearing rocks is most probably due to their metamorphism under relatively low f_{O_2} conditions, thereby partly reducing and, thus, allowing magnetite to take part in the olivine-forming dehydration reaction and/or preventing further oxidation and exsolution of iron as magnetite.

Conclusions

The following broad conclusions, arranged in chronological order, can be drawn from the foregoing discussion:

1. The major bulk of the investigated harzburgite-dominated ultramafic rocks most probably originated as a residue of partial melting of the oceanic upper mantle.

2. The rocks underwent a more or less pervasive serpentinization and bastite development, accompanied by macro-, micro- as well as intragranular fracturing.

3. A low regional metamorphism under relatively static conditions affected the rocks producing olivine (and, locally, diopside) in the serpenti-

ne matrix and along major, minor and intra-granular fractures.

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