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Petrology of gem peridot from Sapat mafic-ultramafic complex, Kohistan, NW Himalaya

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ABSTRACT: *A large quantity of peridot has recently been marketed from the Parla Sapat area to the NE of Naran. The peridot occurs in pockets and veins located in shear zones in partially serpentinized dunitic host rocks. The latter constitute basal cumulates of the Kohistan magmatic arc thrust onto the Indian plate during the Early Paleocene. The peridot is associated with serpentine (essentially chrysotile), minor magnetite, and local magnesite and talc. It is mostly yellowish green, takes a good polish, and suitable specimens are faceted into brilliant stones of highest quality. It occurs in euhedral to subhedral crystals, but most stones are broken due to crude methods of recovery. The stones are mostly <3 cm in length, but up to 15 cm long crystals weighing 2 kg have been recovered. The largest faceted stone is reported to measure about 310 ct.*

The peridot is pleochroic from pale green ($\alpha = \gamma$) *to yellowish green or olive in greenish yellow variety* ($\beta = Z$). *Refractive indices* ($\alpha = 1.644$ *to* 1.653, $\gamma = 1.682$ *to* 1.684 ± 0.003), *density (3.26 to 3.44) and EPMA data suggest that most specimens range in composition from* Fo_{89} *to* Fo_{92}, *but some are more magnesian (up to* Fo_{97}*). The depth of colour increases from light green to yellowish green with increase in the Fe content, but the greenish yellow colour may partly be related to a higher Ti content. Some peridot contains tiny inclusions of magnetite and hairy to acicular, brownish black ludwigite* $[(Ti_{0.011}\,Cr_{0.041}\,Fe^{3+}_{0.947})\,(Mg_{1.085}\,Fe^{2+}_{0.897}\,Mn_{0.004}\,Ni_{0.013})\,BO_5]$. *The paragenesis may be related to hydrothermal activity which also introduced* CO_2 *and B. The undeformed nature of the peridot suggests that the solutions may be related to the late phases of Himalayan metamorphism or leucogranites of the underlying Indian plate, both of which are of Eocene age.*

INTRODUCTION

Pakistan has gained a prominent position in the international market for supplying a wide variety of gemstones and mineral specimens. Some of this material comes from the neighbouring countries, especially Afghanistan, but most of it is of local origin and recovered essentially from the Hindu Kush-Karakoram-Himalayan region of the country. The Pakistani gemstones are associated with pegmatites (e.g., aquamarine, tourmaline, topaz, garnet), hydrothermal veins (pink topaz, rutile, azurite, zircon, green sphene), metasedimentary rocks (ruby, red spinel, green amphibole), and metasomatic rocks (calc-silicates). Butler (1963) has reported nephrite jade pebbles presumably derived from the Siwalik molasse of the Himalayan foot-hills near Teri, Kohat. Other occurrences have been given in Kazmi and O'Donoghue (1994).

Several gem minerals of simple to complex origin have also been reported from the Indus suture zone, which is the trace of the collisional boundary between the Indian plate to the south and the Cretaceous Kohistan magmatic arc to the north. These include emerald, beryl, epidote, actinolite, garnet (green, honey, and red-coloured varieties), rodingite, vesuvianite (Kazmi & O'Donoghue, 1990), and tiny grains of a chromium-rich, green tourmaline (Jan et al., 1971). These minerals are associated with metamorphosed/metasomatized ultramafic and mafic rocks of the suture zone. A detailed account of the Pakistani emeralds has been given in Kazmi and Snee (1989).

To the list of the suture-related gemstones can be added the recently discovered peridot, occurring to the northeast of Naran along the watershed between the Kaghan valley and Kohistan (35° 5'N, 73° 50'E). This is supposedly one of the most important discoveries of peridot which may have supplied tens of kilograms of rough stones worth many tens of millions of rupees. The area has reportedly provided some large stones of brilliant quality. Over the past three years, it has been a source of income to many people in a poor and mountainous area with scarce means of livelihood. The price of the rough peridot supply has ranged from Rs. 1000-1500 to Rs. 1.0-1.5 million per kilogram, depending on the quality and size of the material. Locally cut and polished stones sell from Rs. 10 or 15 per carat (low quality) to about Rs. 3000 per carat (excellent quality and large size).

The peridot is associated with ultramafic rocks in the hanging wall of the Indus suture zone. The gemological features of the mineral based on a couple of cut stones were first presented by Koivula et al. (1994). In this paper we present a summarized account of the occurrence, and physical and chemical characteristics of the gemstone. In addition to geological mapping and petrological studies of the host rocks (Jan, et al., 1993; Khan et al., 1995), we examined several lots of hundreds of peridot specimens available in the local market for a better understanding. Of these, we had a closer look at fifty randomly picked stones ranging in size from 1 to 5 cm.

GEOLOGY OF THE HOST ROCKS

Whilst in the central Himalaya the rocks of the Asian (Tibetan) plate are juxtaposed against those of the Indian plate along the Indus-Zangbo suture, in the northwest Himalaya the two plates are separated by a sandwich of the Kohistan-Ladakh magmatic arc. In northern Pakistan, the Indus suture has three manifestations: 1) it is a razor sharp boundary, with Kohistan rocks thrust onto the Indian plate (e.g., Sapat, Jijal, Timargara), 2) it consists of a series of thrust slices belonging both to Kohistan and Indian plate (e.g., Babusar: Chamberlain et al., 1991), or 3) it is made up of a tectonic melange comprising not only these two terranes but also a substantial quantity of ophiolites (e.g., Mohmand-Malakand, Mingora-Shangla). The Sapat mafic-ultramafic complex, which hosts the peridot, occurs in the immediate hanging wall of the Indus suture and occupies the tectonic base of the Kohistan magmatic arc.

Much of the Sapat complex consists of gabroic rocks, but in its basal part there are ultramafic cumulates directly in contact with the metasediments and gneisses of the Indian plate. It is these basal ultramafic cumulates, notably dunites and peridotites, which host peridot mineralization near West Sapat Gali (4285 m). The complex has been described by Jan et al. (1993) and Khan et al. (1995) and only a brief account is given here. It consists of the following five zones, from stratigraphic base upwards:

1. A 350 m thick zone of homogeneous dunites containing disseminated grains of chromite. Generally devoid of layering, these rocks show

local serpentinization, especially in the lower 10 m close to the suture.

2. The overlying 100 m zone comprises dunite, with up to 3 cm thick chromite-rich layers which are commonly altered to green serpentine and (?) chlorite. Also common in this zone are <1 to 30 cm thick veins of serpentine post-dating faulting in the layers.
3. Thin, rhythmic layers of dunite, pyroxenites, and sparse wehrlite, together constituting a 30 m thick zone.
4. A 140 m thick zone of layered dunites, pyroxenites, gabbros, and sparse peridotites and anorthosites, with thin chromite layers (cm-scale) in the lower part.
5. Homogeneous to locally layered gabbros with a variety of other lithologies. Forming much of the complex, these contain local layers/horizons of peridotites, pyroxenites (? olivine), troctolites, and anorthosites. Some of these occur in mappable units and may be representing basal cumulates repeated by folding. These rocks are locally cut by pyroxene-rich, plagioclase-poor pegmatites containing up to 45 cm long pyroxene crystals. A large body of coarse-grained pyroxenites, measuring >10 x 4 km, has been described to the southwest (Ghazanfar et al., 1991).

Preliminary petrographic and mineralogic data were provided for the complex by Jan et al. (1993). Olivine in the ultramafic rocks ranges from $Fo_{92.5}$ to Fo_{78}; however, it is highly magnesian (Fo_{96}-Fo_{98}) in some chromitites, probably as a result of subsolidus exchange of Mg-Fe with the associated chromite (Irvine, 1967). The clinopyroxene is diopsidic with high contents of Mg and Ca, and orthopyroxene (not common) apparently enstatite-bronzite. Chromite, accessory as well as segregated, shows high Cr/(Cr + Al) ratios (0.75-0.67) and low Fe^{3+}/R^{3+} ratios (<0.1). Amphibole is not uncommon in the basic members and most of the gabbroic rocks have been metamorphosed to epidote amphibolites. Jan et al. (1993) proposed that the complex represents the basal part of the Kohistan magmatic arc.

PARAGENESIS OF THE PERIDOT

The dunites and peridotites of the Sapat mafic-ultramafic complex are variably altered to serpentine and magnetite, accompanied by Mg-rich chlorite (clinochlore) and ferritchromite around chromite grains. Some alteration product also contains talc and a carbonate (?magnesite). Alteration is particularly intense in chromite-rich bands, along shear zones, and in the vicinity of the suture (Jan et al., 1993). Peridot mineralization has taken place along shears, the most prominent of which is a few hundred meters long zone to the northeast of Parla Sapat. The gemstone occurs along fractures and in pockets in sheared dunite host which may also contain serpentine-filled fractures. The peridot is invariably associated with serpentine, minor magnetite, Mg-carbonate, local talc and possibly chlorite (Fig. 1). (The matrix is soft, has a soapy touch and initially was taken to be talcosic). At least in some cases these occur in vein-like bodies formed probably after the main phase serpentine. A few of these vein-like bodies carry euhedral crystals of white magnesite up to 8 cm long.

The matrix serpentine is white to greyish white. Very locally it also occurs along thin fractures and pits in the peridot, as does the carbonate. A semiquantitative microprobe analysis on pressed powder is given in Table 1. There is nothing unusual about the analysis except for rather high FeO and Si:Mg ratio. The latter feature points towards antigorite, however, XRD and petrographic data, including refractive indices, suggest that the mineral is chrysotile. The magnetite ranges from tiny, equant grains to

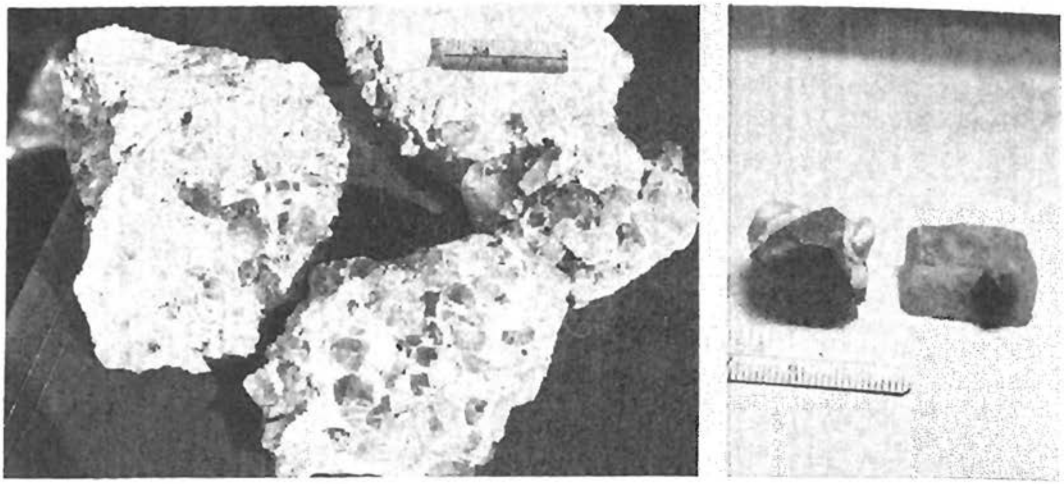

Fig. 1. Left: Crystals of peridot in white, soft serpentine matrix and traces of magnetite.
Right: Euhedral magnetite associated with peridot that is non-uniform in colour.

euhedral crystals up to 2 cm across and displaying perfect dodecahedral or octahedral forms, or a combination of the two. In one large crystal, the faces are striated parallel to the longer rhombic diagonal. Some appear to be aggregates of tiny grains forming patches (<0.5 x >2 cm) or lumps up to a centimeter or two across. The magnetite grains are typically embedded in serpentine matrix but in rare cases they are in contact with, or included in the marginal parts of, the peridot crystals. The grains are highly magnetic and one chemical analysis (Table 1) is not unusual in any way. It is poor in TiO_2, Al_2O_3, Cr_2O_3 and MnO, and contains small amounts of MgO and NiO. Magnetites of this composition are expected in such environments.

PHYSICS AND CHEMISTRY OF THE PERIDOT

General Statement

Our study and collected information suggest that the Sapat area has supplied a fairly large amount (possibly over 100 kg) of peridot to the market. The mineral specimens range in quality from mediocre to excellent. Most of them are less than 3 cm in length; many of these are over 1 cm. Specimens weighing 150-350 grams have been marketed, whereas two unusually large crystals are reported to have measured some 10 and 15 cm in length and weighed 1.2 and 2 kg. Of these, the larger stone was of poor quality but the 1.2 kg sample is said to be clear and of good quality. (We did not examine these two specimens). As can be seen from the physical properties given in the following, the best of the specimens are as good as those of any other area. Two features make them very special: 1) there are many stones which can be cut into large gems (over 10 ct). One cut stone is reportedly 310 ct, and 2) the stones are very suitable for faceting and take very good polish (Fig. 2).

Morphology

The peridot crystals from Sapat are subhedral to euhedral but most of the marketed specimens are broken due to crude methods of excavation, including blasting. Crystals are typically stubby orthorhombic, displaying prominent prisms (100) and (110), basal pinacoid (001), and pyramidal (021) and (111) faces. The faces lack overgrowths and are smooth, but in a few cases the prismatic

TABLE 1. MICROPROBE ANALYSES OF MATRIX SERPENTINE AND MAGNETITE

Oxide %	1	2	Cations	1	2
SiO_2	39.86	0.07	Si	2.002	0.002
TiO_2	0.09	0.02	Ti	0.003	0.000
Al_2O_3	0.05	0.03	Al	0.003	0.000
Cr_2O_3	0.12	0.04	Cr	0.005	0.001
FeO	1.98	94.69	Fe^{3+}	—	1.997
MnO	0.03	0.01	Fe^{2+}	0.084	0.952
MgO	37.70	0.62	Mn	0.001	0.000
NiO	0.19	0.39	Mg	2.847	0.034
			Ni	0.007	0.012
Total	80.02	95.87			

1. Matrix serpentine to peridot crystals. Number of cations based on 7 oxygens. (The mineral could not be polished. Broad beam analysis was performed on pressed powder and hence the poor total).
2. Magnetite associate with 1. Number of cations based on 4 oxygens.

faces have striations and pits elongated parallel to the c-axis. Some pyramidal faces are also pitted or rough. These pits are occupied by serpentine and a few show iron oxide stains.

A few grains are dark greenish grey in colour, subrounded in outline and have distinctly eched surfaces. These look like nuggets in serpentine matrix. We also saw rare pale green specimens with whitish-bands and looking sphenoid in appearance due to prominent growth of two pinacoidal surfaces. The largest of these measured 3 cm in length. Many of the peridot specimens display some fractures, but cleavages are not prominent, and they break along conchoidal fractures.

Optical characteristics

The peridot samples range in colour from light yellow green to deep yellow green, but in a few cases they are light green and in exceptional cases greenish yellow. They are transparent to translucent and mostly uniform in colour. There also are rare specimens of green sub-translucent (dull) appearance which contain whitish (more magnesian) bands. In thin section, the grains are colourless but thick mineral plates are green and pleochroic with the scheme: $\beta = Z$ = yellow green (or olive in greenish yellow variety), and $\alpha = \gamma$ = pale green.

The specimens locally contain tiny inclusions of (?magnetite) and a brown-black substance. These are mostly less than one fifteenth of a mm in size and make less than one tenth of a per cent by volume. In rare case, there are translucent to turbid halos around black granules visible only under the microscope. These may be alteration zones and are rounded, tubular, irregular or feathery in outline. In two samples we noted tiny green inclusions. Fractures may show iron stains, alteration or lined with inclusions. Some 5% of the rough stones are cabochon quality and contain brownish black needles or hair of ludwigite reaching up to 0.5 mm in thickness and over 1.0 cm in length. These acicular inclusions may grow in parallel bundles or networks (Fig. 3). Locally they may be sufficiently abundant to turn parts of the crystals dark or black. In several cases, these darkened parts constitute one end of the peridot crystals or form outer zones around clear cores. Such specimens are commonly associated in the field with a matrix turned dark probably due to a higher amount of magnetite (S.I. Hussain, personal communication).

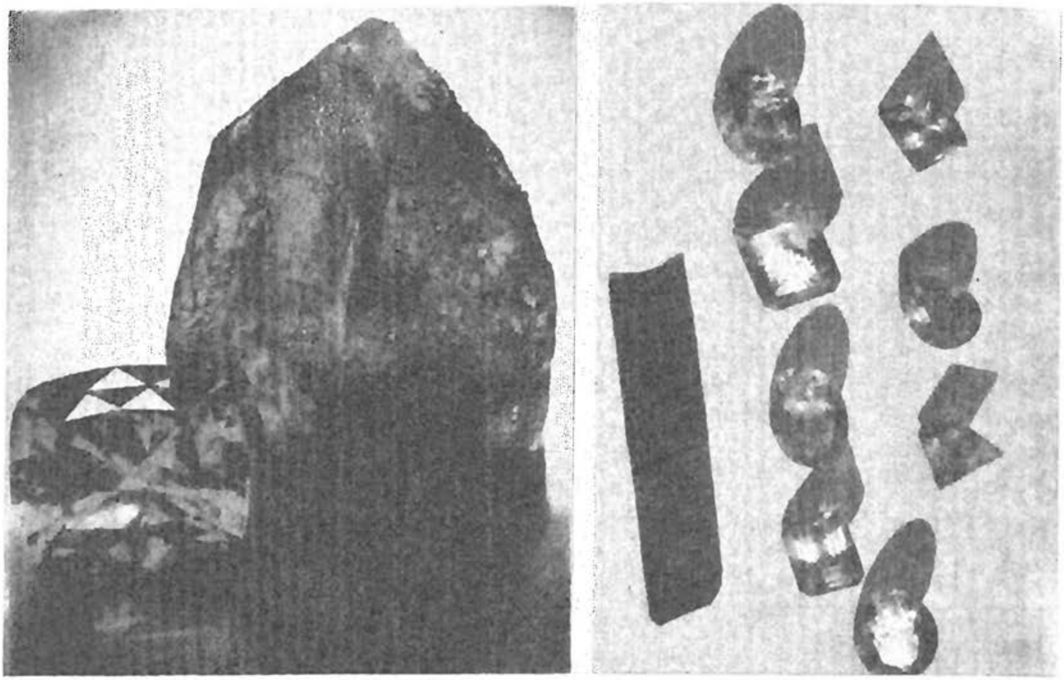

Fig. 2. Left: This beautiful picture decorated the cover of May-June, 1995, issue of Mineralogical Record.

Right: Differently faceted and polished peridot crystals.

Physical constants were determined for the peridot. Refractive indices in 25 samples show a range: α = 1.644 to 1.653, γ = 1.682 to 1.689, birefringence = 0.033 to 0.038, and specific gravity (hydrostatically determined in 10 crystals) ranges from 3.26 to 3.44. These values are similar to those of the two samples studied by Koivula et al. (1994) who also reported other optical determinations, such as, UV fluorescence: inert to both long and short wave; absorption spectrum: distinct but somewhat diffused absorption bands at about 453, 477, and 479 nm, as well as a weaker band at about 529 nm

Chemical characteristics

Common olivine is a solid solution of two end-members, forsterite (Mg_2SiO_4) and fayalite (Fe_2SiO_4). The refractive indices, specific gravity, cell dimension and other physical properties vary systematically with variation in chemical composition, which is commonly expressed in mole per cent forsterite ($Fo = 100\ Mg/(Mg + Fe^{2+})$). The name peridot is applied to gem quality olivine. It ranges in composition from about Fo_{88} to Fo_{93}, but most have a composition around Fo_{90}, irrespective of the individual paragenesis (Deer et al., 1982).

Our refractive indices data suggest that the Sapat peridot is mostly of a fairly constant composition of Fo_{89} to Fo_{92}. Only four have slightly higher forsterite content (Fo_{93} to Fo_{97}) and these include the greyish white band in one of the specimens. The composition derived from the specific gravity ranges from Fo_{93} to Fo_{75}. The discrepantly higher iron content here may be a consequence of over-estimated Sp. G. due to magnetite and other heavy

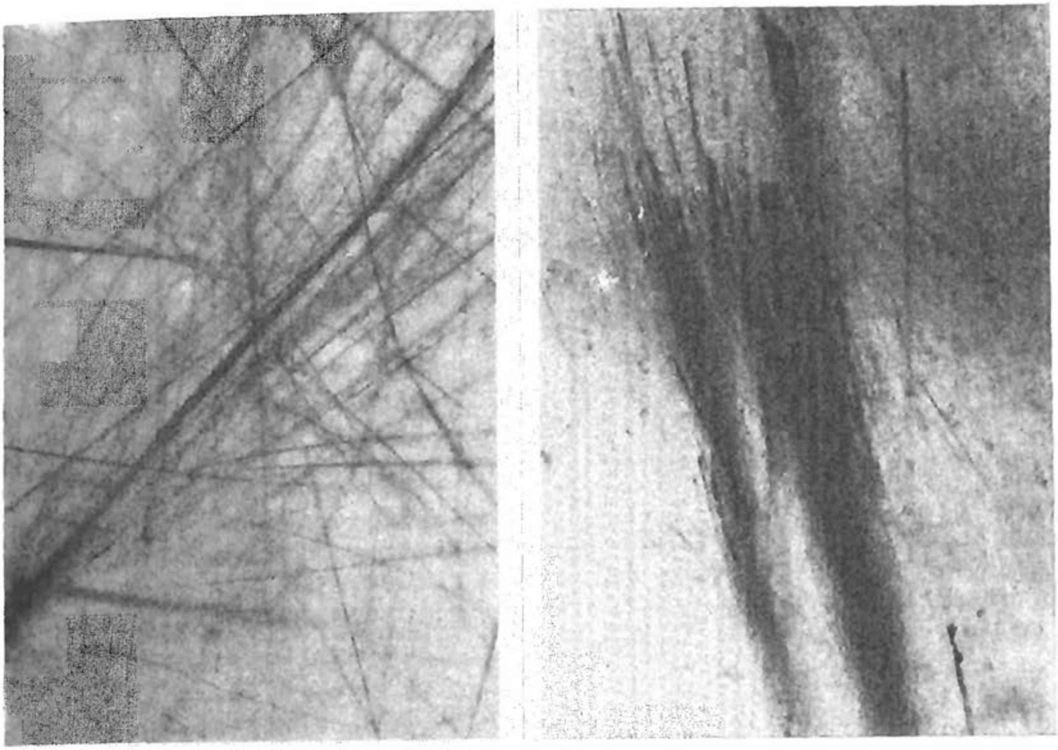

Fig. 3. Hairy ludwigite inclusions in peridot, forming networks (left) and brushes (right). Note also some bubly inclusions in the right photo. Plane polarized light. Length of picture is 4mm.

inclusions in the crystals or to undetected error.

Several specimens were analyzed by electron microprobe; selected analyses are listed in Table 2. All the analyses have negligibly low amounts of TiO_2, Al_2O_3, Cr_2O_3, and CaO. The MnO values range from 0.1 to 0.2 wt.% and NiO from 0.2 to 0.4 wt.%. The forsterite contents of the analyses range from Fo_{90} to Fo_{95} but one is abnormally rich in Mg ($Fo_{97.2}$). There is a close conformity between the forsterite contents determined optically and derived from the chemical data.

The depth of the colour of the peridot appears to depend on its iron content. Samples with high forsterite content (Fo_{95}) are greyish white to light yellowish green and those with low forsterite content (Fo_{90}) are deep yellowish green. The greenish yellow sample also has a low forsterite content ($Fo_{89.6}$ to $Fo_{90.2}$). The cause of departure of its colour from the rest is not clear to us. TiO_2 was determined in two of the four spot analyses on this sample. It is worth noting that in both of these, the TiO_2 content (0.08 and 0.15 wt.%) is higher than in the rest, and this may be a reason for its different colour.

Table 2 shows that the peridot analyses with low Fo content (anal. 4, 6, 7) have some deficiency in Si^{iv}, necessitating minor Fe^{3+} substitution for balancing the formula. Therefore, the possibility that the deeper colour of these samples is at least partly related to ferric iron cannot be discounted. Further data and more precise analyses, however, are needed to verify this idea. One

TABLE 2. SELECTED MICROPROBE ANALYSES OF PERIDOT AND LUDWIGITE

	1	2	3	4	5	6	7	8
SiO_2	41.57	41.38	41.45	40.11	40.10	39.94	38.75	0.02
TiO_2	nd	nd	0.01	0.01	0.00	nd	0.15	0.38
Al_2O_3	nd	nd	0.01	0.00	0.00	nd	nd	0.00
Cr_2O_3	nd	nd	0.00	0.00	0.01	nd	nd	1.40
Fe_2O_3	—	—	—	—	—	—	—	33.90
FeO	2.74	5.34	3.49	5.60	9.66	9.29	9.69	28.90
MnO	nd	nd	0.08	0.15	0.15	0.06	nd	0.11
MgO	53.03	50.40	53.49	51.74	48.52	49.84	48.59	19.62
CaO	0.03	0.00	—	0.02	0.00	0.00	0.00	nd
NiO	0.17	0.31	0.15	0.21	0.33	0.25	0.38	0.44
Total	97.84	97.54	97.43	97.84	98.68	98.77	99.38	100.37
α	1.644	—	1.646	1.646	1.652	—	—	—
γ	1.682	—	1.679	1.683	1.688	—	—	—
D	—	—	—	3.444	3.435	3.400	—	—
CAUTIONS BASED ON 4 (O) IN 1-7 AND 5 (O) IN 8								
Si	1.010	1.018	1.000	0.989	0.996	0.985	0.978	—
Ti	—	—	0.000	0.000	0.000	—	0.003	0.011
Al	—	—	0.000	0.000	0.000	—	—	0.000
Cr	—	—	0.000	—	0.000	—	—	0.041
Fe^{3+}	—	—	—	—	—	—	—	0.947
Fe^{2+}	0.056	0.110	0.070	0.115	0.201	0.192	0.205	0.897
Mn	—	—	0.002	0.003	0.003	0.001	—	0.004
Mg	1.920	1.848	1.924	1.900	1.797	1.834	1.827	1.085
Ni	0.003	0.006	0.003	0.004	0.006	0.005	0.008	0.013
mg*	97.0	94.1	96.2	94.0	89.5	90.2	89.6	54.7

mg* 100 Mg + Fe^{2+} + Mn + Ni) nd = not determined

1, 2: Different spots in a light green peridot containing black acicules.
3: Light yellowy green peridot.
4: Light yellowy green peridot.
5: Deep Yellowy green peridot (average of two similar analyses on different spots).
6, 7: Different spots in a greenish yellow peridot.
8: Chromian ludwigite inclusion in peridot. Total includes an assumed B_2O_3 content of 15.60%, making 1.00 Ba in formula.

of the samples containing well-formed black ludwigite needles is light green in colour. The analyses of this sample are highly magnesian but show some variation ($Fo_{94.4}$ to $Fo_{97.2}$) in three spots within a distance of 0.5 mm (Table 2, anal. 1 and 2). There are three possibilities for this variation: 1) the variation reflects minor analytical error, 2) an uneven exchange of Fe-Mg between the peridot and ludwigite, or 3) ludwigite grew after the peridot and there was a lack of Fe-Mg diffusion over the domain of the sample during its growth.

From XRD data, Koivula et al. (1994) concluded that the acicular inclusions in the peridot may be the magnesian-iron borate mineral ludwigite. The crystal chemistry of the ludwigite-vonsenite series has been presented by Bonazzi and Menchetti (1989). We performed electron microprobe analysis on two of the inclusions (Table 2, anal. 8). Boron was not determined, but an assumed B_2O_3 content of 15.60 wt.% leads to a perfect formula:

$(Ti_{0.011}Cr_{0.041}Fe^{3+}{}_{0.947})_{1.0}(Mg_{1.085}Fe^{2+}{}_{0.897}Mn_{0.004}Ni_{0.013})_{2.00}B_{1.00}O_5$. The needles, thus, are indeed ludwigite with substantial (45.3 mole%) substitution of vonsenite.

DISCUSSION

This study suggests that the peridot mineralization in the Sapat area may be related to a post-tectonic hydrothermal activity. In the absence of detailed geochemical (especially isotope) data, however, it is difficult to present a plausible mechanism for the origin of the mineralization. Our conclusion stems from the following observations:

1. The mineralization is hosted by ultramafic basal cumulates (dunite with some peridotite) of the Kohistan magmatic arc, thrust onto the Indian plate along the Indus suture during the Early Paleocene (Beck et al., 1995).
2. Hydration has resulted in variable degree of serpentinization of the host rocks, especially along frequent shear zones.
3. Serpentine fabric in the peridotites suggests syntectonic as well as post-tectonic growth.
4. The peridot mineralization is restricted to shears, veins, and pockets in dunitic rocks. The peridot and associated minerals are undeformed and locally appear to have grown in open spaces. It is likely that this localized mineralization post-dates the main phase serpentinization.
5. The peridot is invariably associated with light greyish to whitish serpentine (abundant), minor magnetite, and local magnesite, talc, and (?) chlorite. This mineralogy, coarse grain-size and the presence of ludwigite inclusions in the peridot suggest that the mineralization occurred in the presence of a fluid phase consisting of water with some carbon dioxide and boron.
6. The peridot ranges from Fo_{89} to Fo_{97}. Compositions more magnesian than Fo_{93} are unusual in igneous parageneses, but are found in some meteorites, metamorphic rocks, and adjacent to chromite grains due to Fe-Mg exchange (for references, see Arif & Jan, 1993). The consistent association of magnetite with the peridot and local inclusions of ludwigite suggest that some peridot may have been enriched in Mg during secondary processes.

From these observations we conclude that the Sapat ultramafic rocks were sheared during their emplacement onto the Indian plate. Consequent cooling and hydration resulted in local serpentinization. Subsequently, hydrothermal solutions affected parts of these sheared rocks, leading to the growth of the peridot and associated minerals. This, apparently, was not an isochemical process; it was accompanied by the likely introduction of CO_2, B, and possible removal of SiO_2, Cr_2O_3 and NiO. The data at our hand are inadequate to quantify these changes. Since the mineralization is apparently unaffected by deformation, the solutions may be related to the late phases of regional metamorphism of the underlying Indian plate or leucogranites both of which are of Eocene age (Treloar, 1995; Smith et al., 1994). The paragenesis of the Sapat peridot is similar to that of eastern Sayan, Russia (Glazunov et al., 1973). That gem chrysolite (Fo_{93}) occurs in asbestos-like, chrysotile-sepiolite shells and as crystalline inclusions in talc veins intersecting serpentinized carbonaceous peridotites.

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