

# IDENTIFICATION OF EXTRATERRESTRIAL PERIDOT BY TRACE ELEMENTS

Andy H. Shen, John I. Koivula, and James E. Shigley

Twenty-six peridot samples from the Esquel pallasite meteorite and 27 samples from 10 terrestrial sources were studied by laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS). Among the 32 elements analyzed, six of them—Li, V, Mn, Co, Ni, and Zn—provided an excellent separation between pallasitic and terrestrial peridot.

**P**eridot, known by the ancient Egyptians as “the gem of the sun,” has long been valued as a gemstone. It was mined on Zabargad (now St. John’s Island) in the Red Sea some 3,500 years ago, making it one of the earliest known gemstones (Gübelin, 1981; Ogden, 1992). Peridot is the gem-quality green variety of olivine, an important mineral found in ultramafic igneous rocks such as dunite and in mafic rocks such as basalt. Among the major modern productive localities, the main sources of peridot are peridotite xenoliths in alkali basalts (U.S., Myanmar, China) and serpentized dunites (Pakistan).

Olivine is believed to be one of the major minerals in the earth’s mantle and in many rocky planets and smaller bodies in the solar system. Pallasite is a

rare type of stony iron meteorite that contains gem-quality crystalline olivine in an iron-nickel matrix (figure 1). It is believed to have formed in asteroids composed of an iron-nickel core and a silicate mantle (Dodd, 1981). The olivine crystals can be extracted from some of these meteorites to make beautiful—although typically small—faceted gems (Koivula et al., 1993a,b, 1994). Pallasitic peridot gemstones were first characterized in 1991, and the subsequent report by Sinkankas et al. (1992) found that their optical and physical properties, such as refractive index and specific gravity, were very similar to and overlapped those of their terrestrial counterparts, negating any useful separation through standard gemological testing.

Nevertheless, the inclusion suites of pallasitic peridot can be quite telling, allowing relatively easy separation from terrestrial material (e.g., Koivula, 1981; Koivula and Fryer, 1986; Milisenda et al., 1996; figures 2 and 3) by means of magnification. In addition, due to pallasite’s fiery descent through earth’s atmosphere, inclusion-free extraterrestrial olivine of significant size (>1 ct) is virtually unheard of. Olivine is generally heat- and impact-sensitive and is prone to cracking, so any peridot pieces extracted from such meteorites are typically fractured, and any gems fashioned from them usually weigh less than half a carat.

Because pallasitic peridot is a commercially available extraterrestrial gem, there is sufficient interest to make its identification worthwhile. A peridot without diagnostic inclusion features requires chemical analysis to make the determination. We used LA-ICP-MS to study the trace-element chemistry because of the wide range of elements this technique can analyze, as well as its superior sensitivity.

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See end of article for About the Authors and Acknowledgments.

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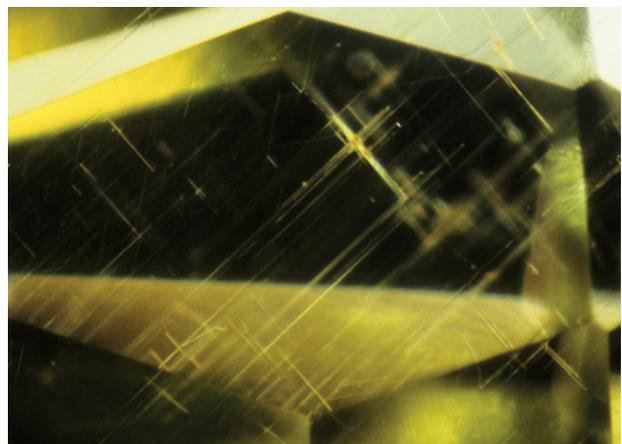


Figure 1. These polished pallasitic peridot specimens (50.00 and 25.66 ct) are from the Esquel meteorite, which was found in Argentina in 1951. Photo by Maha Smith.

In terms of chemical composition, olivine is among the most extensively studied minerals, with scores of published studies on major and trace-element chemistry of samples from many natural occurrences. In the GEOROC database maintained by the Max Planck Institute for Chemistry in Mainz, Germany (<http://georoc.mpch-mainz.gwdg.de/georoc>), more than 40,000 records are dedicated to olivine. Yet geochemical studies focusing on gem-quality peridot are very limited, and not all trace elements are included in GEOROC's data. The gemological literature contains very few papers on pallasitic peridot (see Sinkankas et al., 1992; Pearson, 2009), let alone detailed studies of its trace-element composition. To our knowledge, though much research has been published on the trace-element composition of olivine in pallasite (see Hsu, 2003 and the references therein), most of the literature is focused on deducing the parent body or the thermal history of the pallasites, and very few articles have mentioned terrestrial olivine at all. One recent study (Leelawatanasuk et al., 2011) specifically focused on comparing gem peridots from terrestrial and extra-

terrestrial sources, though using EDXRF rather than LA-ICP-MS. In this article, we present our chemical analysis results comparing pallasitic peridots to

Figure 2. Cruciform acicular dislocations have been observed in pallasitic peridot. Such features have not been seen in terrestrial material. Photomicrograph by J. I. Koivula; magnified 15 $\times$ .



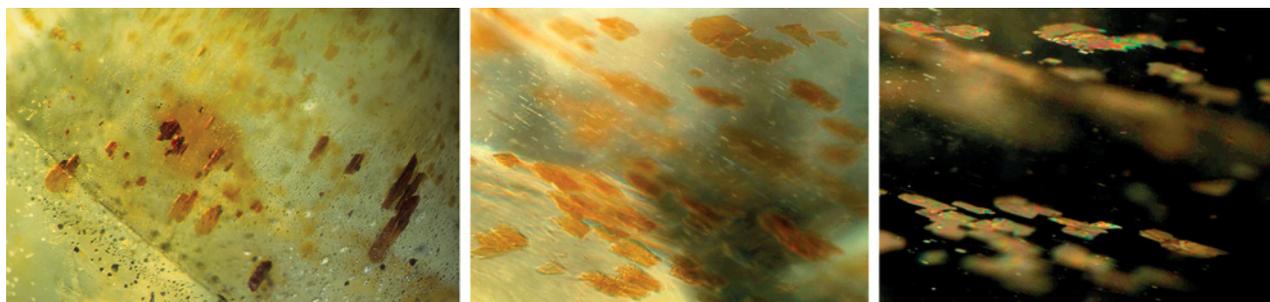


Figure 3. Other internal features distinctive of pallasitic peridot are striated brownish red plates (left) and thin transparent reddish brown platy inclusions (center); the platy inclusions also showed iridescence (right). Neither type of inclusion could be identified with Raman analysis. Photomicrographs by J. I. Koivula; magnified 80× (left) and field of view 1.2 mm (center and right).

natural samples from several known terrestrial localities.

### MATERIALS AND METHODS

Twenty-six samples of pallasitic peridot and 27 terrestrial samples were examined as part of this study. The latter consisted of 22 pieces of rough, four faceted stones, and one cabochon (table 1). Three of the pallasitic peridot samples were faceted stones, but the remainder were still in matrix as part of three polished slabs from the Esquel meteorite (e.g., figure 1).

We performed chemical analyses with a Thermo X Series II ICP-MS. A New Wave Research UP-213 laser ablation unit with a frequency-quintupled Nd:YAG laser (213 nm wavelength) running at 4 ns

pulse width was chosen to ablate the samples. We used 55  $\mu\text{m}$  diameter laser spots, a fluence of around  $10 \text{ J/cm}^2$ , and a 7 Hz repetition rate. For most of the terrestrial samples, we selected three spots for analysis, though some of the rough was tested on up to six spots. The faceted pallasitic samples received three analysis spots and the pieces in the slabs only two. For the ICP operations, the forward power was set at 1300 W and the typical nebulizer gas flow was  $\sim 0.90 \text{ l/min}$ . The carrier gas used in the laser ablation unit was He, set at  $0.78 \text{ l/min}$ . The actual nebulizer flow rate varied somewhat from run to run. The criteria for the alignment and tuning sequence were to maximize Be counts and keep the ThO/Th ratio below 2%. We used National Institute of Standards and Technology SRM (standard reference

TABLE 1. Terrestrial peridot samples used in this study.

Locality	No. samples	Weight (ct)	Description	Source <sup>a</sup>	References
China	2	2.98–4.51	Emerald and triangular cut	GIA	Huang and Xu (2010)
Hawaii, USA	1	0.48	Rough	JIK	Baker et al. (1996)
Kilbourne Hole, Texas, USA	2	2.06–2.88	Rough	GIA	Bussod and Williams (1991), Fuhrbach (1992)
San Carlos, Arizona, USA	3	1.17–10.85	Rough and oval cut	GIA, JIK	Frey and Prinz (1978)
Mogok, Myanmar	2	0.93–1.90	Rough	GIA	Webb (1993)
Norway	2	9.53–17.11	Oval cut	GIA	Kostenko et al. (2002)
Pakistan	3	0.64–15.11	Rough and cabochon	GIA	Kane (2004), Bouilhol et al. (2009)
Saudi Arabia	4	1.60–2.88	Rough	JR	McGuire (1988), Camp et al. (1992)
Tanzania	2	2.49–2.79	Rough	GIA	Furman (2007)
Zabargad (St. John's Island), Egypt	6	2.33–5.17	Rough	LT, JH	Kurat et al. (1993), Brooker et al. (2004)

<sup>a</sup> Initials other than GIA refer to authors or those listed in the Acknowledgments.

material) 610 and 612 glasses for calibration. We analyzed three spots apiece on the standards at the beginning of the experiment; after every four to five sample runs, three additional spots were measured. This process allowed us to correct the drift of the instrument.

To obtain accurate and precise trace-element chemistry, we selected  $^{29}\text{Si}$  as our internal standard. To determine the accurate concentration of Si, we used the method developed by Breeding and Shen (2008), renormalizing each experimental run into a model molecular formula of  $(\text{Mg,Fe,Mn,Ni})_2\text{SiO}_4$  and then calculating the Si concentration from that formula. The calculated Si concentrations were used as internal standard values for experimental runs, and the concentrations of the other 27 trace elements were then calculated.

## RESULTS AND DISCUSSION

Table 2 shows the chemical elements that can be used to separate pallasitic and terrestrial peridot. Most olivines belong to a complete solid-solution series between forsterite ( $\text{Mg}_2\text{SiO}_4$ ) and fayalite ( $\text{Fe}_2\text{SiO}_4$ ). Tephroite ( $\text{Mn}_2\text{SiO}_4$ ) and Ni-olivine ( $\text{Ni}_2\text{SiO}_4$ ) have the same olivine structure and can form a solid solution—typically in small amounts—with forsterite and fayalite. Most peridot falls toward the forsterite end of the solid solution. The major-element composition of our samples is given in table 2 as molar percent forsterite. This limited range of compositional variation accounts for the restricted variability of the gemological properties (Phillips and Griffen, 1981; Deer, et al., 1982).

**TABLE 2.** Concentration ranges of diagnostic trace elements, and gemological properties, of tested peridot samples.

Element (ppm)	Terrestrial	Extraterrestrial
Li	1.10–14.5	0.21–0.96
V	0.11–4.46	9.18–23.4
Mn	772–1410	1920–2490
Co	84.8–147	4.37–19.6
Ni	1770–4070	8.53–112
Zn	9.04–67.4	5.20–9.98
Molar fraction (forsterite%)	$\text{Fo}_{96.0}\text{--}\text{Fo}_{88.6}$	$\text{Fo}_{90.0}\text{--}\text{Fo}_{85.5}$
SG <sup>a</sup>	3.27–3.36	3.35–3.40
RI ( $n_\alpha$ ) <sup>a</sup>	1.640–1.655	1.652–1.662
RI ( $n_\beta$ ) <sup>a</sup>	1.657–1.675	1.670–1.683
RI ( $n_\gamma$ ) <sup>a</sup>	1.680–1.693	1.690–1.703

<sup>a</sup> Values estimated (RI) or calculated (SG) from Deer et al. (1982).

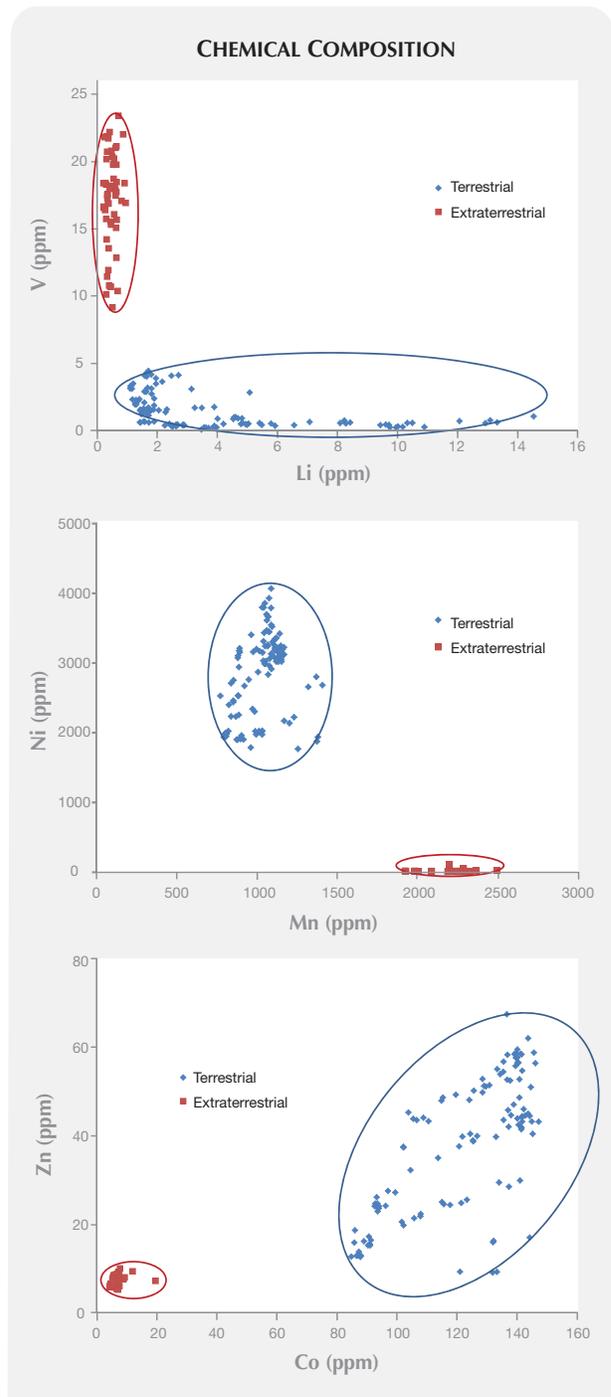


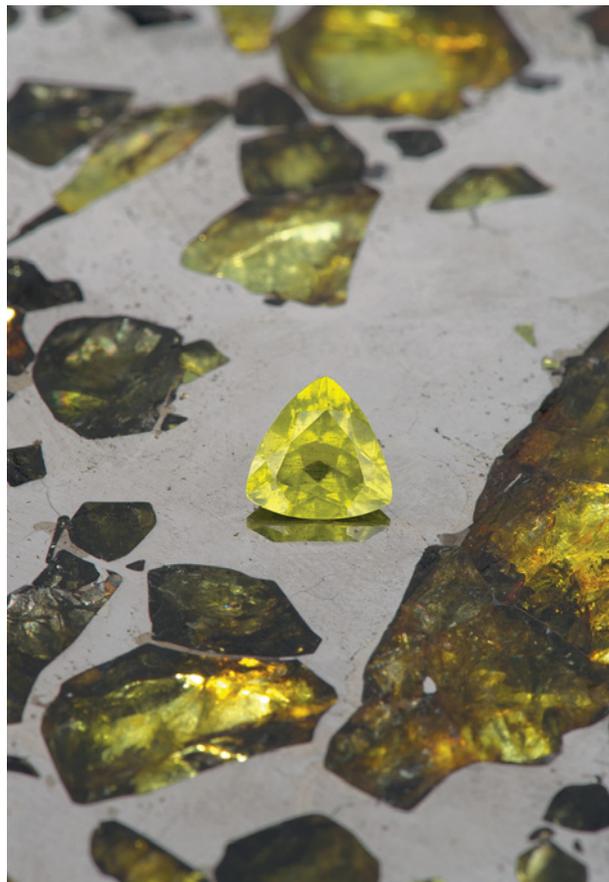
Figure 4. Chemical plots of vanadium vs. lithium (top), nickel vs. manganese (middle), and zinc vs. cobalt (bottom) all show an obvious separation between the extraterrestrial and terrestrial peridot groups. The concentration ranges of these elements are listed in table 2.

Of the 32 elements studied, six—Li, V, Mn, Co, Ni, and Zn—were diagnostic. Figure 4 (top) is a plot of V vs. Li, which displays an obvious separation between pallasitic and terrestrial peridot. The same observations are seen in the plots of Ni vs. Mn (figure 4, middle) and Zn vs. Co (figure 4, bottom). In all three of these plots, the data points for the samples of pallasitic and terrestrial origin are clearly segregated. When we compared our extraterrestrial data set with published pallasitic olivine chemical data, our Ni, Co, and Mn concentrations agreed with the results in Hsu (2003) almost perfectly. All but one of these six elements, Li, can also be determined using EDXRF, but the concentrations of V in terrestrial peridot and those of Co and Zn in pallasitic peridot may be difficult to detect or determine accurately with EDXRF because they are so low. However, if an EDXRF instrument can accurately determine Mn and Ni, then it is possible to perform the separation based on these two elements alone (Leelawathanasuk et al., 2011).

Although we analyzed a limited number of peridot samples from a single pallasite and various terrestrial sources, each group showed remarkable consistency. Leelawathanasuk et al. (2011) studied four different pallasite meteorites, and their results also showed good consistency among those samples. In addition, our major-element compositional data agreed well with the chemistry of most pallasitic olivines (from over 40 fall locations) listed in Wasson and Choi (2003). This consistency in major-element chemistry has been noted in the literature.

## CONCLUSION

Twenty-six samples of pallasitic peridot and 27 representative samples from 10 world localities were analyzed by LA-ICP-MS. The results showed that six



*Figure 5. Though its rarity limits its commercial significance, pallasite can make an attractive gemstone. This faceted stone (1.12 ct) from the Esquel pallasite is resting on a polished slab that was cut from the same meteorite. Courtesy of Robert A. Haag; photo by Robert Weldon.*

elements—Li, V, Mn, Co, Ni, and Zn—provided excellent separation between pallasitic (figure 5) and terrestrial origin. The collection of additional data on pallasitic and terrestrial peridot is ongoing.

### ABOUT THE AUTHOR

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