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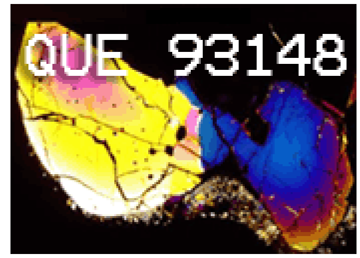
QUE 93148: A Part of the Mantle of Asteroid 4 Vesta?



--- A tiny meteorite tells a story of melting in the deep mantle of a big asteroid.

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Meteorites recovered from Antarctica and other places on Earth are generally first classified based on their mineralogies and textures. While this approach works fairly well for large meteorites, it is quite a bit more difficult to determine what group a meteorite belongs to when only a small fragment is found. This is especially true when that fragment consists of only one or two different coarse-grained minerals. Such was the case for QUE 93148 found in the Queen Alexandra Range, Antarctica in 1993. Although it was originally classified as a lodranite, geochemical data soon showed that it did not belong to this group. It currently appears that QUE 93148 is related in some way to main group pallasites and may be a chip of the mantle of the asteroid in which pallasites formed.

Reference:

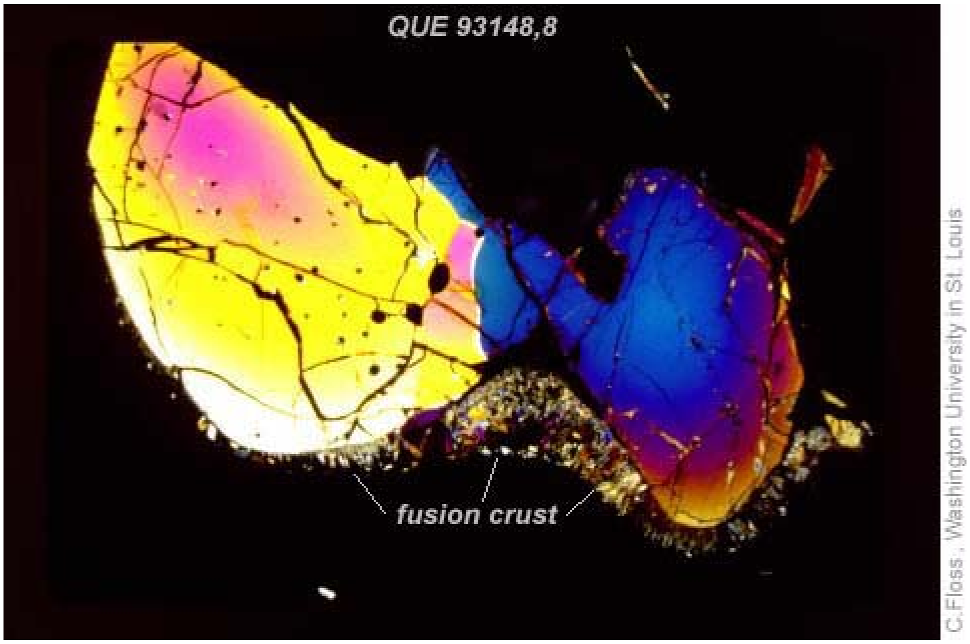
Floss, Christine, (2002) Queen Alexandra Range 93148: a new type of pyroxene pallasite? *Meteoritics and Planetary Science,* v. 37, p. 1129-1139.

Melted Meteorites and Asteroid Insides

Several types of meteorites formed by igneous (melting) activity in asteroids. Some, such as eucrites, are pieces of lava flows. They formed when the interior of an asteroid partially melted and the magma oozed to the surface in dikes and erupted. (Rocks, like all complex substances, do not melt at a single melting temperature. They partially melt over a range of temperature and the initial melt is quite different in composition from the rock that is melting. This leads to planetary differentiation--the formation of a crust and underlying rocky mantle.) Some meteorites resemble the rocks left behind inside an asteroid that melted. The magma migrated away, traveling up to erupt, leaving behind a residue depleted in some minerals. The lodranites, for example, are partial melting residues. In other cases melting was very substantial and metallic iron fell to a core. At the boundary between the core and the overlying rocky mantle, the mineral olivine may have accumulated, producing olivine-metal mixtures called pallasites. So, study of igneous meteorites (collectively called achondrites) gives us a wealth of information about melting in asteroids. One trick to all this, however, is to link the right meteorites to each other. In the case of QUE 93148, the first step is to classify it correctly.

Classification of QUE 93148

QUE 93148 is a small meteorite--only 1.1 g. It is a coarse-grained olivine-rich achondrite. In addition to olivine, it contains small amounts of orthopyroxene and metal, with trace amounts of troilite, chromite and phosphate. The photograph shows a thin section of QUE 93148, with two large olivine grains partly surrounded by fusion crust, the thin layer of melted rock formed when the meteorite blazed through Earth's atmosphere.



Cross-polarized transmitted light photograph of thin section QUE93148,8. The section contains two large olivine grains that are partly surrounded by fusion crust. The field of view is about 6 mm across.

Based on this mineralogy and the major element compositions of the olivine and orthopyroxene, this meteorite was initially classified as a lodranite. However, studies done by myself and by colleagues Cyrena Goodrich from the University of Hawaii and Kevin Righter at JSC soon showed that many of the geochemical characteristics of QUE 93148 didn't fit with those of other known lodranites. There are three key characteristics that indicate that this meteorite is not a lodranite.

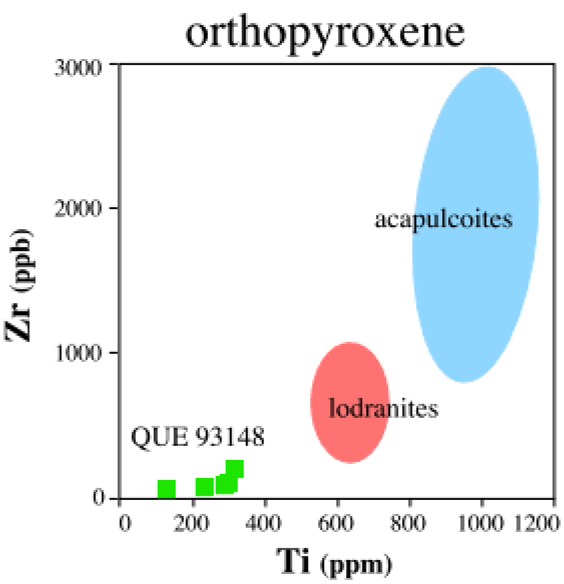
Trace Elements in QUE 93148

Trace elements (those which are only present in very small amounts in a mineral) are useful for identifying what kinds of processes were involved in forming a rock. They tend to be incompatible in most rock-forming minerals, which means that as minerals crystallize from a magma, these elements will accumulate in the left over magma until near the end of crystallization when they are essentially forced into the last minerals crystallizing. Conversely, when a rock starts to melt, incompatible elements will preferentially go into the magma and the remaining residual rock will be depleted in those elements. These behaviors lead to large differences in incompatible trace element abundances in rocks and minerals that can provide clues to the kind of processes that affected a given rock or meteorite.

I measured the concentrations of trace elements using an ion microprobe at Washington University in St. Louis. This instrument works by focusing a high-energy beam of oxygen ions onto a polished sample of QUE 93148. The beam digs a hole while sputtering all the elements in the sample into a cloud of neutral atoms and ions. The ions are accelerated into a mass spectrometer, where they are magnetically separated by mass and then counted. We determine the concentrations of elements in the sample by comparison with minerals of known composition. There are some corrections to be made, such as for interferences by assorted molecules, but analysts have figured out how to make them accurately and routinely.

Ion microprobe at Washington University in St. Louis.

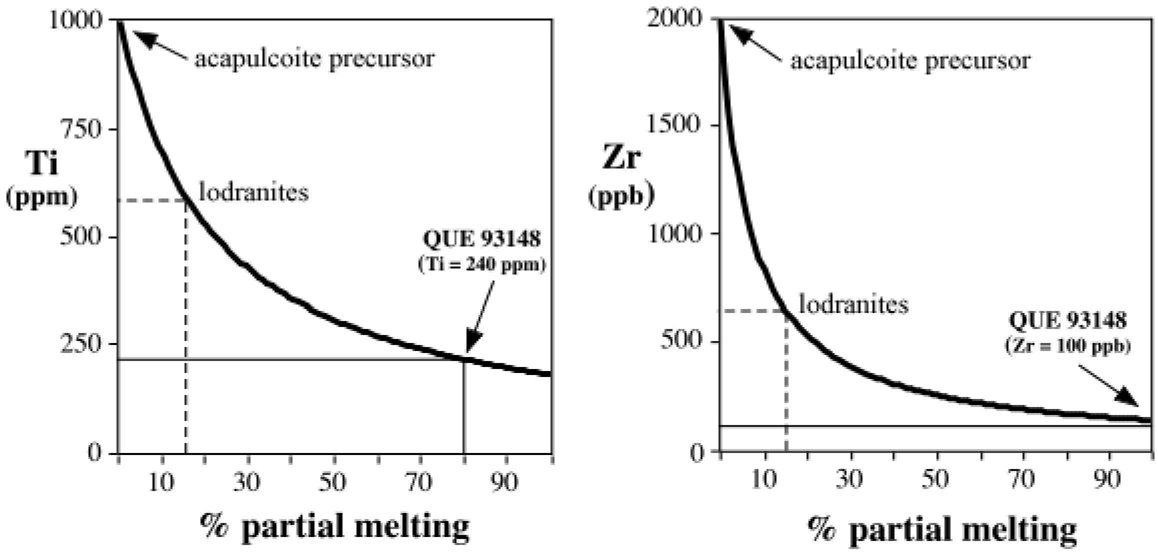
I was initially interested in QUE 93148 because of its classification as a lodranite. The lodranites and the related acapulcoites come from a common parent body which experienced only a limited amount of heating. I have been studying these meteorites to try to better understand how they are related to each other and the types of melting processes they have undergone. The silicate minerals in acapulcoites do not seem to have experienced any melting, whereas some silicate melting and removal of those melts has occurred in the lodranites. This is reflected in depleted abundances of incompatible trace elements such as titanium (Ti) and zirconium (Zr) in the pyroxenes of the lodranites compared to those of the acapulcoites, as shown in the figure. When the lodranite precursor rocks (similar to acapulcoites) melted, Ti and Zr were carried off with the magma, leaving behind rocks (the lodranites) depleted in these elements compared to the original rock.



(Adapted from Floss (2002) *Meteorit. Planet. Sci.* v. 37, p.1132.)

Plot of Ti vs. Zr abundances in QUE 93148 compared with the range of abundances observed in acapulcoites and lodranites.

The pyroxenes from QUE 93148, however, have much lower abundances of these elements than any of the lodranites. A simple calculation can be done to show whether QUE 93148 is, like the lodranites, the residue of a melting event on the acapulcoite-lodranite parent body. Tim McCoy of the Smithsonian Institution and his colleagues have estimated that the lodranites are residues of about 15% partial melting. As the figure below shows, much higher degrees of melting (from about 80% to more than 100%) would be needed to account for the Ti and Zr abundances in QUE 93148 orthopyroxene. The mafic mineralogy (e.g., high abundance of olivine) of QUE 93148 does imply a high degree of melting on the its parent body, but so much melting could not have taken place on the acapulcoite-lodranite parent body, because these meteorites still have a lot of primitive (i.e., chondritic) chemical and mineralogical characteristics. QUE 93148 does not seem to be related to the acapulcoites-lodranites.

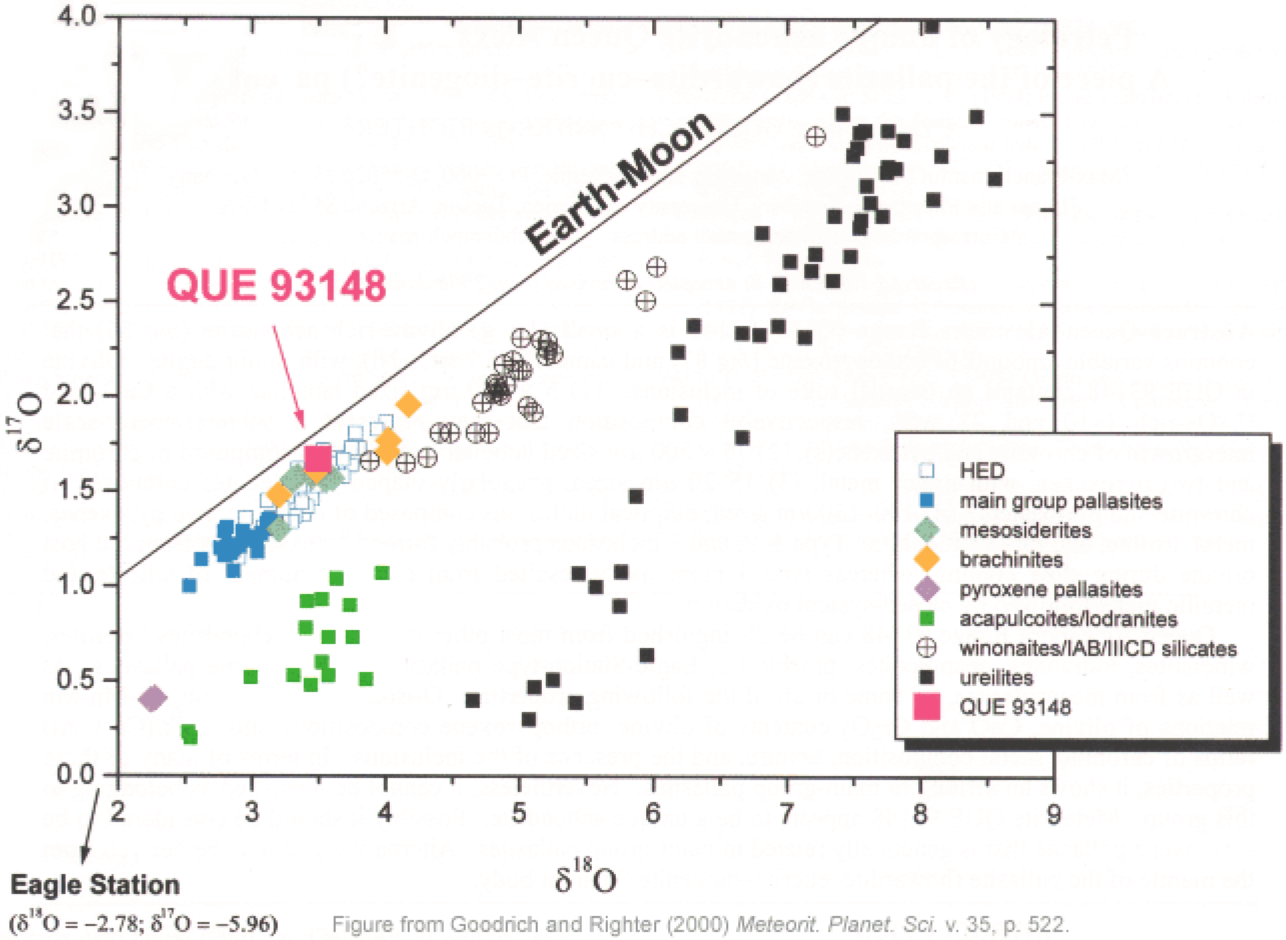


Adapted from Floss (2002) *Meteorit. Planet. Sci.* v. 37, p. 1132.

The curves show the change in abundances of Ti and Zr in residual pyroxene as a function of the amount of partial silicate melt removed from the source. Lodranites are the residues of about 15% melting whereas the Ti and Zr abundances of QUE 93148 pyroxene, indicated by the arrows, require from about 80% to more than 100% melting.

Oxygen Isotopes

The oxygen isotopic composition of QUE 93148 also indicates that this meteorite is not a lodranite. One of the most significant observations in meteorite research was the discovery 30 years ago, by Bob Clayton from the University of Chicago and his colleagues, that the solar nebula has a heterogeneous distribution of the three stable isotopes of oxygen. Since that time, it has been established that most meteorite groups can be distinguished on the basis of their oxygen isotopic compositions. Mass dependent fractionation processes (such as melting and differentiation) result in variations along a slope 1/2 line for a given planet or parent body, whereas other deviations are inherited from inhomogeneities in the solar nebula and are constant for a given differentiated parent body. Thus oxygen isotopes are a powerful tool for recognizing relationships among meteorites. Two meteorites with similar oxygen isotopic compositions share a common oxygen reservoir, but may or may not come from the same parent body. However, different oxygen isotopic compositions generally preclude an origin on the same parent body. The figure below shows the oxygen isotopic composition of QUE 93148, determined by Bob Clayton, compared to those of several known meteorite groups.



Oxygen isotopic compositions of QUE 93148 and other achondrites.

QUE 93148 is clearly different from the lodranites (and related acapulcoites), shown as small green squares. It's also different from other meteorite groups such as the ureilites, the winonaites and the pyroxene pallasites. However, notice that the oxygen isotopic composition of QUE 93148 does fall along the same mass fractionation line as several groups of meteorites, such as the HED meteorites, main group pallasites, mesosiderites and the brachinites.

Fe-Mn-Mg Relations

Finally, Cyrena Goodrich and her colleague Jeremy Delaney from Rutgers University showed that the concentrations of iron (Fe), manganese (Mn), and magnesium (Mg) can be used to determine relationships among groups of meteorites. She and Kevin Righter compared the Fe/Mn/Mg data of olivine from QUE 93148 with that of other achondrites (see figure below) and concluded that QUE 93148 could not be related to the brachinites. The Fe-Mn-Mg compositions of QUE 93148 olivine are similar to mesosiderite olivine, but Goodrich and Righter noted that other data argue against QUE 93148 belonging to this group. For example, QUE 93148 olivine has higher abundances of Ca and Cr than does mesosiderite olivine. In addition, mesosiderites are metal-silicate impact mixtures, while QUE 93148 shows clear igneous textures in some thin sections.

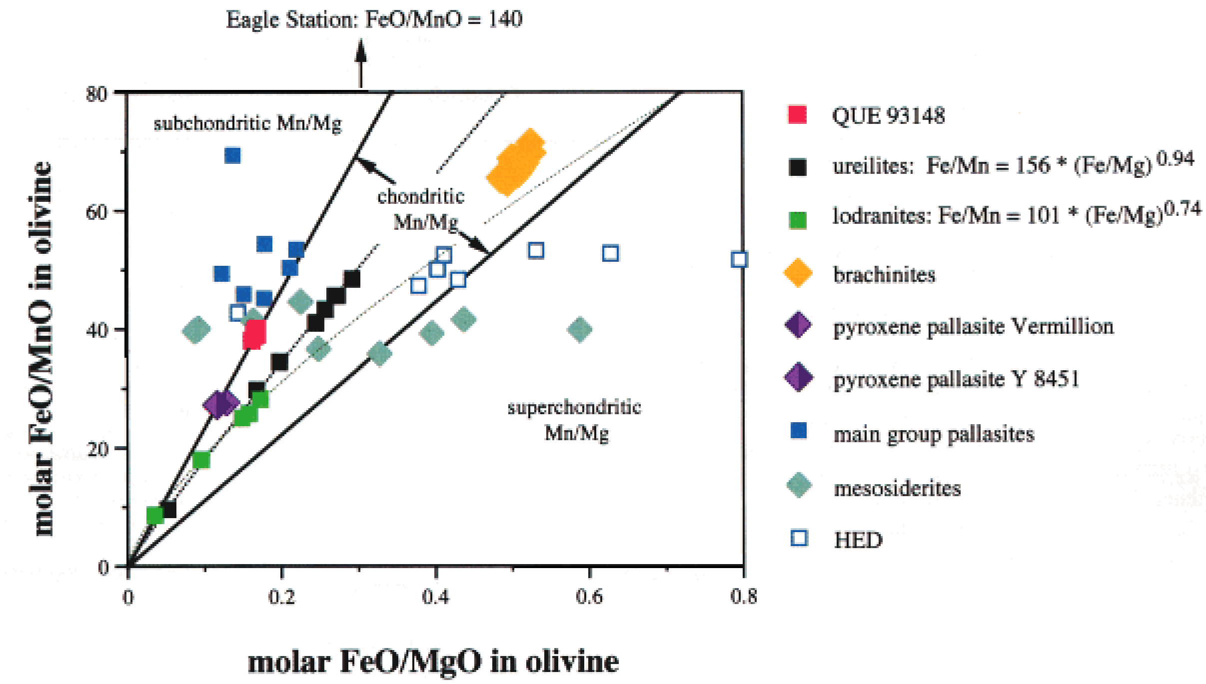


Figure from Goodrich and Righter (2000) *Meteorit. Planet. Sci.* v. 35, p. 532.

Plot of the molar ratios of FeO/MgO vs. FeO/MnO in olivine from QUE 93148 and other achondrite meteorites.

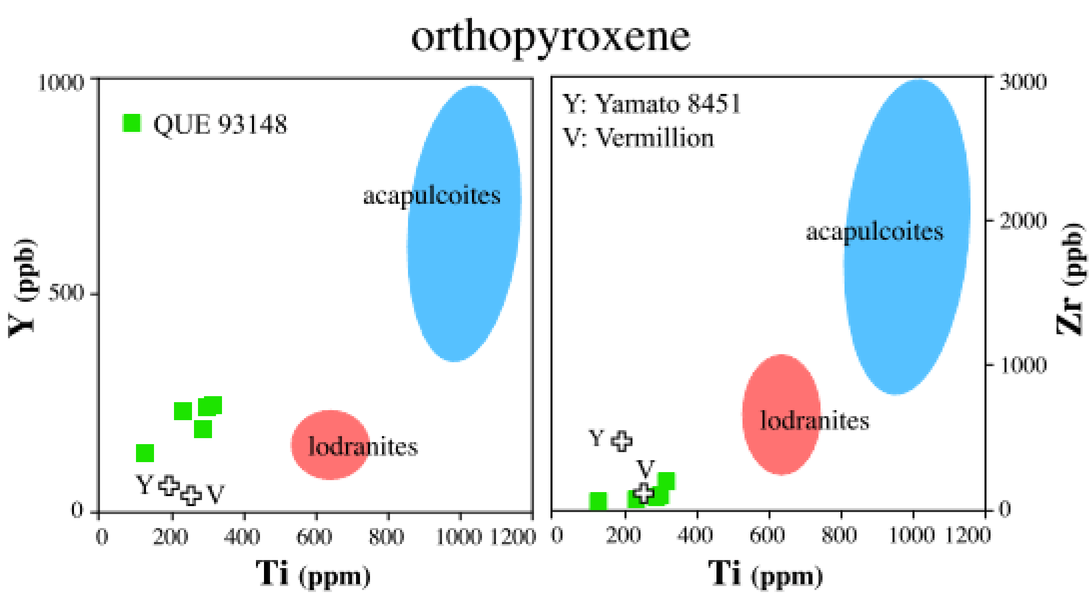
The HED-Pallasite-QUE 93148 Connection

The geochemical data I discussed above show that not only is QUE 93148 not a lodranite, but it also doesn't belong to several other groups of igneous meteorites--the ureilites, winonaites, pyroxene pallasites, brachinites or mesosiderites. So what is QUE 93148? In the oxygen isotope diagram shown above, QUE 93148 plots in the same region as the HED (howardite-eucrite-diogenite) meteorites and the main group pallasites. The HED meteorites are a large group of crustal igneous rocks consisting of basalts, gabbros and orthopyroxenites. This is the only group of meteorites for which a potential parent body has been identified. Tom McCord and colleagues first showed in 1970 that the reflectance spectrum of asteroid 4 Vesta matched the spectrum of a basaltic eucrite. Since that time, there have been countless debates over whether or not 4 Vesta is indeed the HED parent body, but the issue remains unresolved. Nevertheless, this group of meteorites did originate on an asteroid-sized body. The main group pallasites have oxygen isotopic compositions similar to the HED meteorites and Dave Mittlefehldt and his colleagues have suggested that they may have originated on the same parent body. Pallasites are stony iron meteorites that consist predominantly of large olivine crystals in a metal matrix (see the photo below.) They are generally thought to represent material from the core-mantle boundary of an asteroid. One of the hypotheses for the origin of the HED meteorites, suggested by Kevin Righter and Michael Drake from the University of Arizona, argues that this parent body differentiated in an early magma ocean. Cyrena Goodrich and Kevin Righter noted that the major element composition of olivine from QUE 93148 is similar to what would be expected in olivine from the deep mantle of such a parent body. In addition, the trace element data for QUE 93148 that I discussed earlier show that it experienced high degrees of melting, as would be expected of a sample originating on an asteroid that had melted substantially.

Pallasite sample showing rounded olivine crystals (brown) in a metal matrix (silver). The sample is about 8 centimeters across.

Is QUE 93148 a Pallasite?

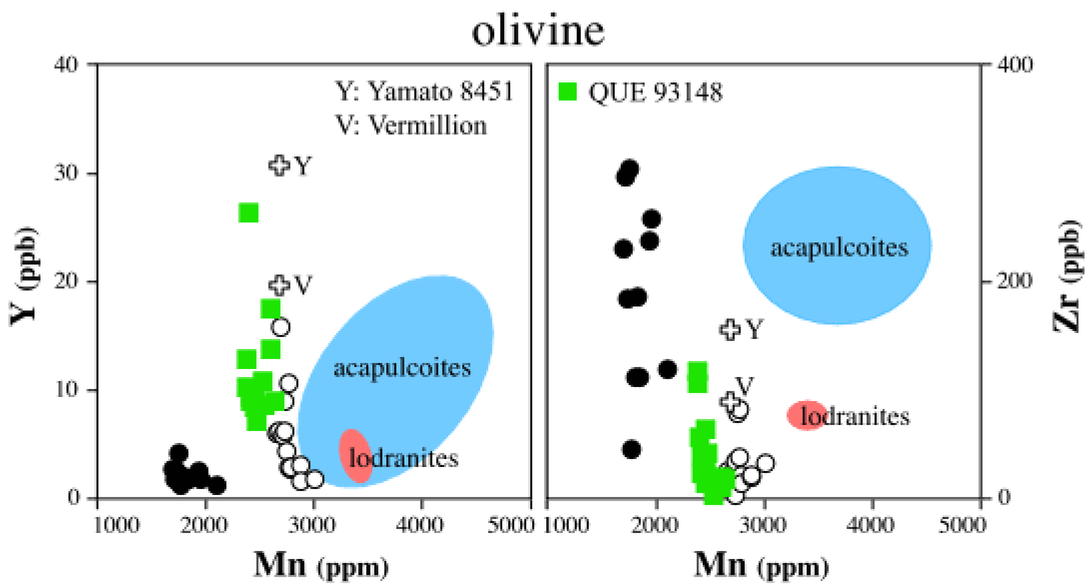
In order to see if QUE 93148 might be related to the pallasites, I compared its trace element data to that from two main group pallasites, Springwater and Mount Vernon. I also compared my data to data obtained by Joseph Boesenberg and his colleagues at the American Museum of Natural History for two pyroxene pallasites (i.e., pallasites that contain small amounts of pyroxene in addition to olivine and metal), Vermillion and Yamato 8451. The oxygen isotope data show that QUE 93148 isn't related to the pyroxene pallasites, but if their trace element distributions are similar this could indicate that they formed by similar processes as the pyroxene pallasites.



Adapted from Floss (2002) *Meteorit. Planet. Sci.* 37, p. 1132.

Plots of Ti vs. Y and Zr in QUE 93148 pyroxene compared with those in the pyroxene pallasites, Vermillion, and Yamato 8451.

The first set of figures here shows the Ti, Y (yttrium),and Zr abundances in pyroxene from QUE 93148, with the acapulcoite and lodranite ranges shown for reference, and also shows the abundances of these elements in pyroxene from the two pyroxene pallasites. The second set of figures shows Mn, Y and Zr abundances in olivine from QUE 93148, again with the acapulcoite and lodranite ranges, and shows the abundances of these elements in olivine from the pyroxene pallasites and also in olivine from two the main group pallasites, Springwater and Mount Vernon.



Adapted from Floss (2002) *Meteorit. Planet. Sci.* 37, p. 1132.

Plots of Mn vs. Y and Zr in QUE 93148 olivine compared with those in the pyroxene pallasites, Vermillion and Yamato 8451 and in the main group pallasites Springwater (open circles) and Mount Vernon (filled circles).

There are some differences, but both pyroxene and olivine in QUE 93148 have elemental abundances similar to those in the pyroxene pallasites. The two main group pallasites have elemental abundances that are quite different from each other, and QUE 93148 olivine abundances fall between the two for all three elements. Although it would be nice to have more data, the available information seems to indicate that QUE 93148 is most like the pyroxene pallasites.

A Piece of an Asteroid's Mantle?

QUE 93148 cannot be directly related to the pyroxene pallasites because of their different oxygen isotopic compositions, but its oxygen isotopes are similar to the main group pallasites (and the crustal HED meteorites). The trace element data also show that it must have experienced a high degree of melting, such as would occur in the deep mantle of a differentiated parent body. Putting all the evidence together, it seems likely that QUE 93148 may represent a new kind of pyroxene pallasite that is genetically linked to the main group pallasites. If the main group pallasites and the HED meteorites are indeed from the same parent body and if this parent body is in fact the asteroid 4 Vesta (two big unresolved 'ifs') then QUE 93148 might be our first sample from the mantle of this asteroid.

Additional Resources

Boesenberg J. S., Davis A. M., Prinz M., Weisberg M. K., Clayton R. N., and Mayeda T. K. (2000) The pyroxene pallasites, Vermillion and Yamato 8451: not quite a couple. *Meteorit. Planet. Sci.,* v. 35, p. 757-769.

Floss C. (2002) Queen Alexandra Range 93148: a new type of pyroxene pallasite? *Meteorit. Planet. Sci.,* v. 37, p. 1129-1139.

Goodrich C. A. and Righter K. (2000) Petrology of unique achondrite Queen Alexandra Range 93148. A piece of the pallasite (howardite-eucrite-diogenite?) parent body? *Meteorit. Planet. Sci.,* v. 35, p. 521-535.

Mittlefehldt D. W., McCoy T. J., Goodrich C. A., and Kracher A. (1998) Non-chondritic meteorites from asteroidal bodies. In *Planetary Materials,* Vol. 36 (ed. J. J. Papike), 195 pp. Mineralogical Society of America.