



Queen Alexandra Range 93148: A new type of pyroxene pallasite?

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Abstract—Trace elements, including the rare earth elements, were measured in olivine and orthopyroxene from Queen Alexandra Range (QUE) 93148, and in olivine from two main group pallasites, Springwater and Mount Vernon. Although QUE 93148 was originally classified as a lodranite, a variety of data including oxygen isotopic compositions (Goodrich and Righter, 2000), preclude a genetic relationship with the acapulcoites/lodranites. Incompatible trace element (*e.g.*, Ti, Zr) distributions in orthopyroxene do indicate large amounts of melting and are consistent with the ultramafic assemblage observed in this meteorite. Trace element abundances in olivine are consistent with suggestions that QUE 93148 may be related to the main group pallasites (Goodrich and Righter, 2000), although there are some inconsistencies. Its trace element distributions are most like those of the pyroxene pallasites, suggesting that it may have formed in a similar manner. QUE 93148 may represent a new type of pyroxene pallasite with links to the main group pallasites.

INTRODUCTION

The achondrites are a diverse group of meteorites that have undergone igneous processing on mainly asteroidal-sized, but occasionally also larger, planetary bodies in the solar system. Primitive achondrites typically have experienced limited melting and retain at least some of the characteristics of their chondritic precursors. These meteorites can therefore provide important information about early differentiation processes on asteroidal bodies (*e.g.*, McCoy *et al.*, 1996, 1997a,b; Floss, 2000). Other achondrites, such as the howardite–eucrite–diogenite (HED) group are clearly the products of large-scale planetary differentiation (for a detailed review of achondritic meteorite groups, see Mittlefehldt *et al.*, 1998) and do not preserve information about the earliest stages of their formation.

Classification of newly discovered achondritic meteorites can require both petrologic and chemical studies, particularly when samples are small. Queen Alexandra Range (QUE) 93148 is an olivine-rich achondrite with lesser amounts of orthopyroxene, metal, troilite and chromite, that was originally classified as a lodranite (Mason, 1995). However, Goodrich and Righter (2000) noted that its oxygen isotopic composition (measured by Mayeda and Clayton) precludes a genetic relationship to the acapulcoites and lodranites. They furthermore observed that it has a lower Mn/Mg ratio than any major group of primitive or evolved achondrites and suggested that QUE 93148 may be a piece of the deep mantle of the HED parent body. They noted that it shows a number of affinities to main group pallasites, which together with the group IIIAB

iron meteorites, may comprise the core–mantle boundary and core, respectively, of this parent body (Mittlefehldt *et al.*, 1998).

In this study I have examined the trace element distributions of the individual minerals in QUE 93148 with the goal of evaluating its relationship to primitive achondrites such as the acapulcoites/lodranites, as well as to evolved achondrite groups. Trace element data are also reported for olivine from two main group pallasites, Springwater and Mount Vernon, in order to investigate the possibility of a link between QUE 93148 and these meteorites.

EXPERIMENTAL

Selected trace elements (including the rare earth elements (REE)) were measured in olivine and orthopyroxene from two polished thin sections of QUE 93148 (3 and 8) provided by the Meteorite Working Group. Trace elements were also measured in olivine from the pallasites Springwater (section Me 2220, provided by the Field Museum of Natural History) and Mount Vernon (USNM 300d, provided by the Smithsonian Institution). All samples were initially documented and characterized (mineral identification and major element compositions) using a JEOL 840a scanning electron microscope. The trace element measurements were made using a modified Cameca IMS-3f ion microprobe, according to methods described by Zinner and Crozaz (1986a). Secondary ions were sputtered from the sample surfaces using an O⁻ primary beam of 1–5 nA and collected at low mass resolution using energy filtering to remove complex molecular

interferences. Simple molecular interferences (*e.g.*, SiO^+) are not removed by this method and are corrected for using an analysis program developed to deconvolve major molecular interferences for the elements K-Ca-Sc-Ti, Rb-Sr-Y-Zr and Ba-REEs (Alexander, 1994; Hsu, 1995).

Sensitivity factors for the REE are given by Zinner and Crozaz (1986b). Sensitivity factors for other elements are from Hsu (1995). For QUE 93148, concentrations of the reference element SiO_2 were determined from quantitative energy dispersive analyses of the specific grains measured in the ion microprobe. For pallasite olivines, SiO_2 concentrations were taken from representative analyses given by Mittlefehldt *et al.* (1998). Detection limits are variable, depending on the specific element and phase being analyzed, but can be as low as several parts per billion in favorable cases. Errors (1σ) are generally $<10\%$, but can be higher (up to 50%) for some REE in olivine and orthopyroxene. Analysis spots were carefully chosen prior to the measurements in order to avoid cracks and inclusions and were examined afterwards to check for contamination in the third dimension. In addition, masses diagnostic of potential contaminating phases (*e.g.*, mass 31 for P) were continuously monitored during all analyses. REE abundances in Fig. 1 are normalized to the CI chondrite abundances of Anders and Grevesse (1989).

RESULTS

Queen Alexandra Range 93148

QUE 93148,8 consists of two large olivine grains partially surrounded by fusion crust. Several small metal-troilite-chromite blebs are enclosed within the olivine, as is a symplectic intergrowth similar to the ones described by Goodrich and Righter (2000). QUE 93148,3 contains a large rounded olivine grain adjacent to a large grain of Fe,Ni metal, as well as several smaller olivine and orthopyroxene grains. The REE and other trace elements were measured in both of the large olivine grains from section ,8 and in several olivines from section ,3. REE abundances in olivine are below detection limits, except for the heaviest REE (Table 1), which are present at levels of $\sim 0.007 \times \text{CI}$ for Er to $\sim 0.1 \times \text{CI}$ for Lu (Fig. 1). REE concentrations are also low in four orthopyroxene grains measured from section ,3 (Table 1; Fig. 1). Average heavy (H)REE abundances range from $\sim 0.04 \times \text{CI}$ for Gd to $\sim 0.5 \times \text{CI}$ for Lu. The light (L)REE do not exhibit the depleted slope typical of low-Ca pyroxenes but, rather, are present at approximately constant levels of $0.01\text{--}0.02 \times \text{CI}$ for La to Sm. The average REE pattern exhibits only a small negative Eu anomaly (Fig. 1); however, Eu concentrations in individual analyses are variable, ranging from below detection to $0.04 \times \text{CI}$.

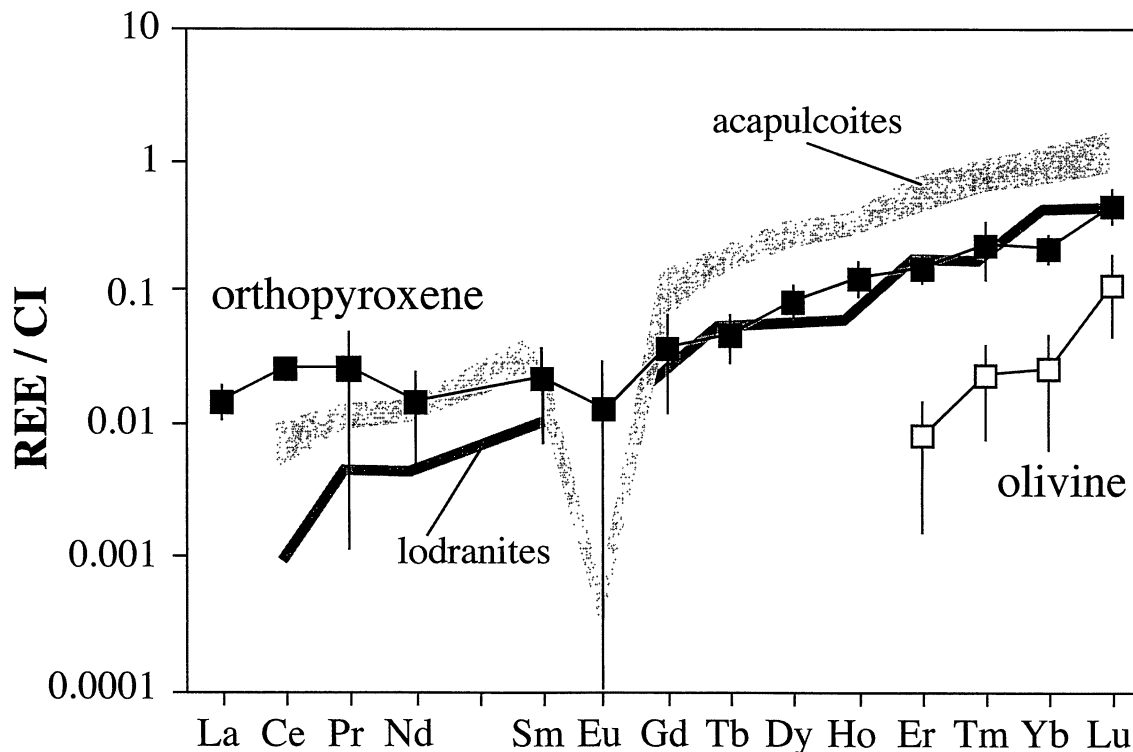


FIG. 1. Average CI chondrite-normalized REE patterns for orthopyroxene (filled squares) and olivine (open squares) in QUE 93148. Also shown are the ranges of patterns seen in orthopyroxene from acapulcoites (light shaded area) and lodranites (dark shaded area). Data for acapulcoites/lodranites are from Floss (2000).

TABLE 1. Element concentrations in QUE 93148 orthopyroxene and olivine.

	Orthopyroxene		Olivine	
	Average	Range	Average	Range
Na (ppm)	28 ± 35	8–90	6 ± 4	2–15
P (ppm)	10 ± 3	6–13	30 ± 24	10–83
K (ppm)	1.4 ± 0.9	0.8–2.8	2.3 ± 1.5	0.9–2.8
Ca (ppm)	5470 ± 730	4730–6280	670 ± 135	420–875
Sc (ppm)	12 ± 3	7–15	4.5 ± 0.9	2.3–5.4
Ti (ppm)	240 ± 80	115–300	28 ± 8	11–37
Cr (ppm)	6590 ± 2040	3670–8180	1070 ± 180	770–1400
Mn (ppm)	2280 ± 60	2170–2310	2445 ± 90	2340–2610
Sr (ppb)	180 ± 88	100–280	80 ± 40	30–170
Y (ppb)	210 ± 50	140–250	12 ± 5	7–27
Zr (ppb)	100 ± 60	50–200	38 ± 35	3–117
La (ppb)	3.7 ± 1.2	2.5–4.9	b.d.	b.d.
Ce (ppb)	16 ± 1	15–18	b.d.	b.d.
Pr (ppb)	2.4 ± 2.3	b.d.–5.7	b.d.	b.d.
Nd (ppb)	6.9 ± 4.7	2.7–13.2	b.d.	b.d.
Sm (ppb)	3.4 ± 2.4	1.1–6.0	b.d.	b.d.
Eu (ppb)	1.0 ± 1.0	b.d.–2.0	b.d.	b.d.
Gd (ppb)	7.8 ± 5.4	2.5–14.2	b.d.	b.d.
Tb (ppb)	1.8 ± 0.7	1.3–2.8	b.d.	b.d.
Dy (ppb)	22 ± 6	17–30	b.d.	b.d.
Ho (ppb)	7.3 ± 2.1	4.9–9.9	b.d.	b.d.
Er (ppb)	25 ± 6	17–30	1.4 ± 1.1	b.d.–2.6
Tm (ppb)	5.8 ± 2.8	3.0–8.3	0.6 ± 0.4	b.d.–1
Yb (ppb)	36 ± 20	23–45	4.6 ± 3.5	b.d.–7.9
Lu (ppb)	11.5 ± 3.6	8.5–16	2.9 ± 1.7	b.d.–4.5
# analyses*		5 (1)		14 (5)

*Numbers in parentheses refer to the number of analyses in which the REE (except La and Ce) were not measured.

Abbreviation: b.d. = below detection.

Also shown in Fig. 1 are the ranges in REE abundances for orthopyroxene from typical acapulcoites and lodranites (Floss, 2000). HREE abundances of QUE 93148 orthopyroxene are lower than those of orthopyroxene in acapulcoites and are similar to those of orthopyroxene from Lewis Cliff (LEW) 88280, the lodranite most depleted in REE (Floss, 2000); however, as noted above, the slope of the LREE pattern is distinctly different.

Abundances of other trace and minor elements in QUE 93148 orthopyroxene also show systematic differences from those in acapulcoites and lodranites (Fig. 2). Manganese, Ti and Zr concentrations are lower than those observed in both the acapulcoites and lodranites, whereas Cr concentrations are higher. Abundances of Y are similar to those seen in orthopyroxene from the lodranite LEW 88280 (Floss, 2000), consistent with the HREE data.

Trace element systematics in olivine (Fig. 3) are broadly similar to those observed in orthopyroxene. Manganese

abundances are lower than those observed in acapulcoite/lodranite olivines, consistent with the low Mn/Mg ratios determined by Goodrich and Righter (2000), and Cr concentrations are higher. Zirconium concentrations in QUE 93148 olivine are also lower than those seen in olivine from the acapulcoite/lodranite meteorites, but Ti abundances fall between the ranges observed in the two groups; Y abundances are similar to those of acapulcoite/lodranite olivine. Finally, abundances of Na and K in both olivine and orthopyroxene (Table 1) are lower than those observed in these phases in the acapulcoites and lodranites (Floss, 2000).

The minor element concentrations determined by ion microprobe for QUE 93148 olivine and orthopyroxene generally agree well with the electron microprobe data reported by Goodrich and Righter (2000). Manganese, Cr and Ca abundances in olivine show similar ranges in both data sets. Abundances of Cr in orthopyroxene are also in good agreement, but Mn and Ca concentrations determined by ion microprobe

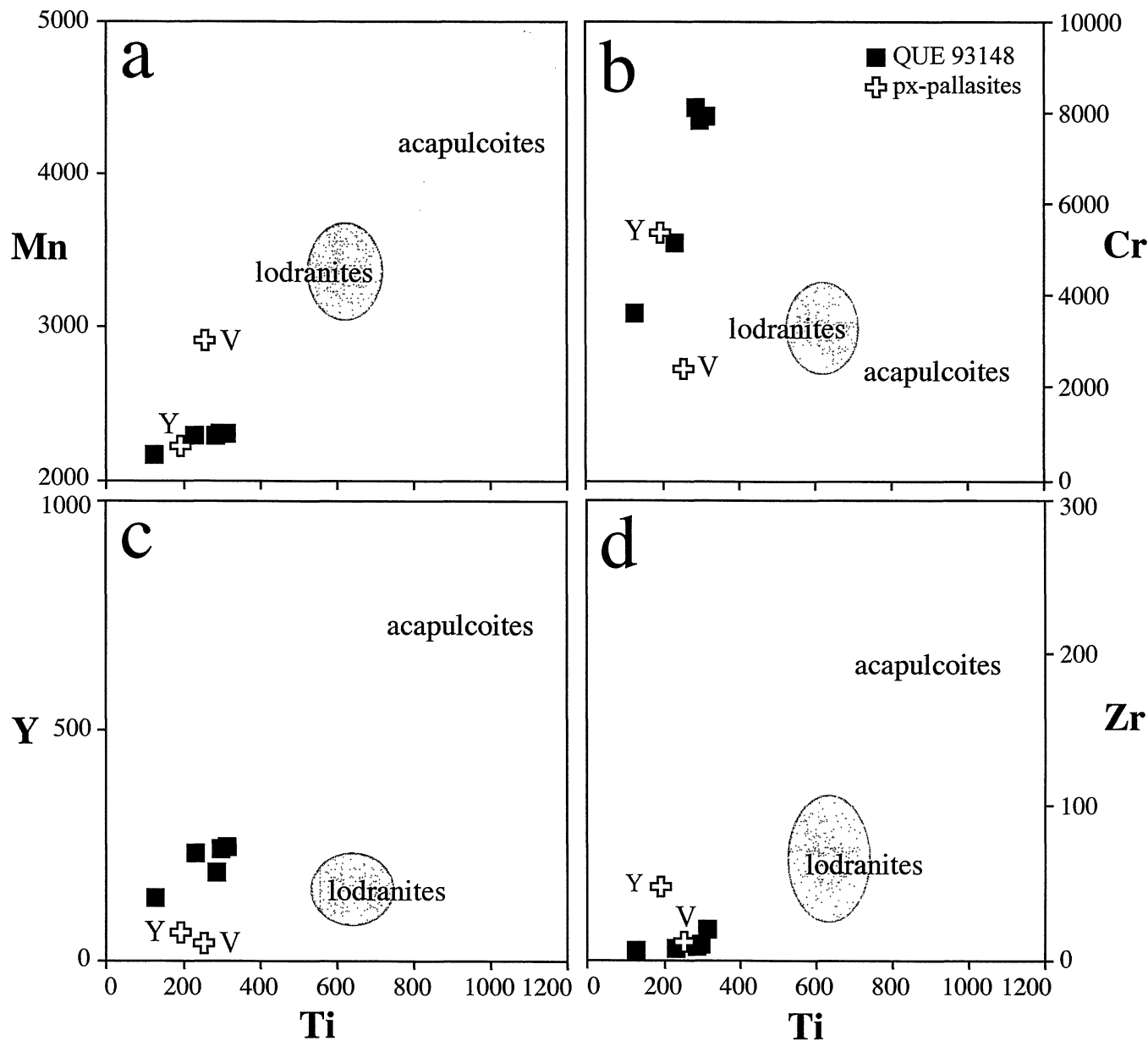


FIG. 2. Abundances of Ti vs. (a) Mn, (b) Cr, (c) Y, and (d) Zr in orthopyroxene from QUE 93148 (solid squares) and the pyroxene pallasites Vermillion (V) and Yamato-8451 (Y). Also shown are the fields for acapulcoites (light shaded areas) and lodranites (dark shaded areas). Concentrations are in parts per million, except Y and Zr, which are in parts per billion. Data for the pyroxene pallasites are from Boesenberg *et al.* (2000) and data for the acapulcoites/lodranites are from Floss (2000).

appear to be slightly lower than those reported by Goodrich and Righter (2000) for orthopyroxene.

Pallasites

Both Springwater and Mount Vernon are main group pallasites. The sections studied here are dominated by large rounded olivine grains set in a matrix of Fe,Ni metal and troilite, consistent with previous descriptions (Mittlefehldt *et al.*, 1998).

Springwater, furthermore, contains large amounts of farringtonite, that occurs primarily between olivine grains and appears to be replacing metal in these areas, as well as minor amounts of Ca-phosphate. No phosphates were observed in Mount Vernon. Although pyroxene is a trace component in some main group pallasites (Mittlefehldt *et al.*, 1998), none was found in the two sections studied here.

A suite of trace elements, including the REE, were measured in olivine grains from these two meteorites for comparison with

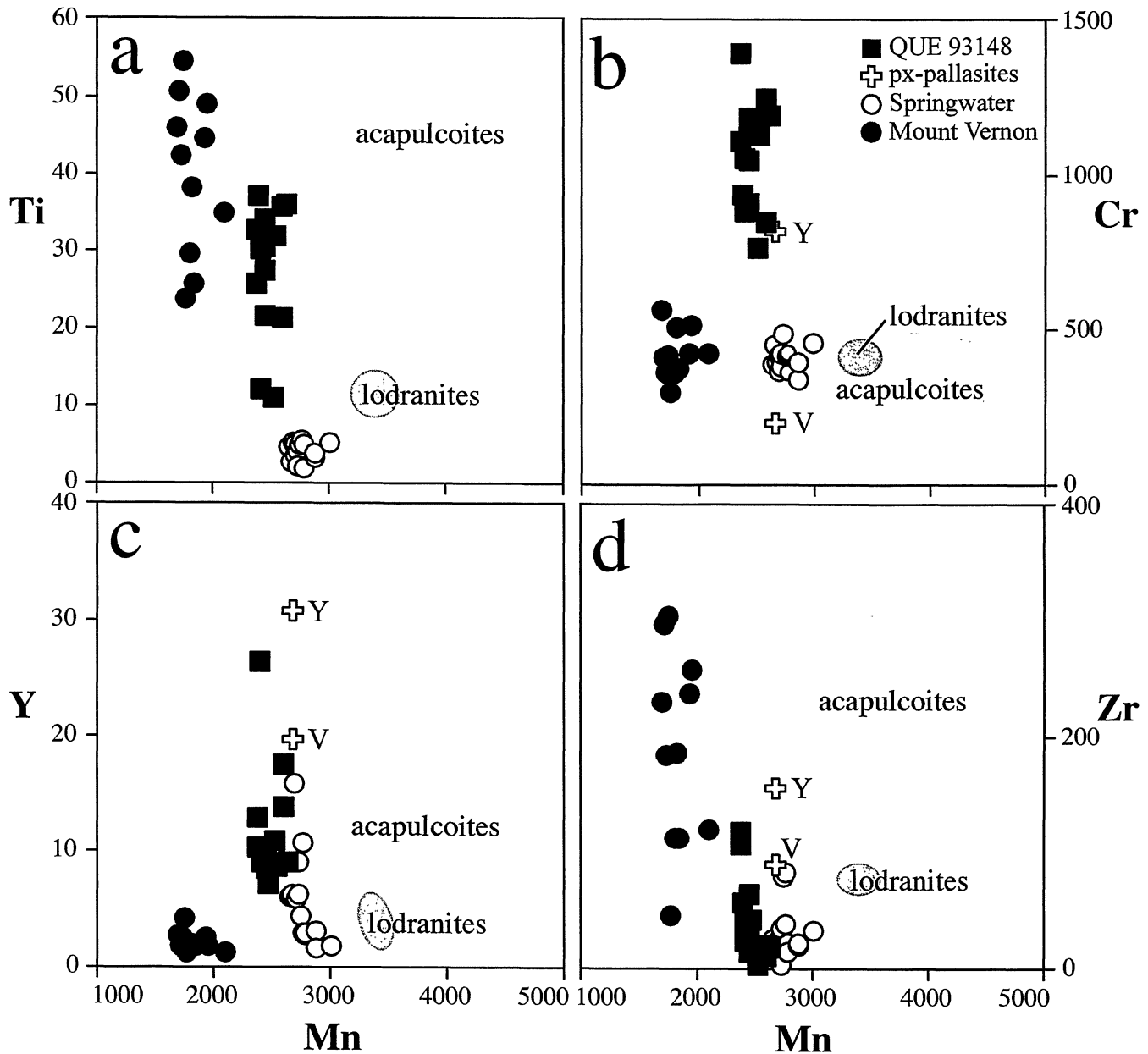


FIG. 3. Abundances of Mn vs. (a) Ti, (b) Cr, (c) Y, and (d) Zr in olivine from QUE 93148 (solid squares), the main group pallasites Springwater and Mount Vernon (open and filled circles, respectively), and the pyroxene pallasites Vermillion (V) and Yamato-8451 (Y). Also shown are the fields for acapulcoites (light shaded areas) and lodranites (dark shaded areas). Concentrations are in parts per million, except Y and Zr, which are in parts per billion. Data for the pyroxene pallasites are from Boesenberg *et al.* (2000) and data for the acapulcoites/lodranites are from Floss (2000).

QUE 93148 olivine. In Mount Vernon, all REE concentrations, including those of the HREE, are below detection limits. Springwater olivine also has HREE concentrations below detection limits, but exhibits elevated abundances of the LREE, La–Nd. The patterns are moderately LREE-enriched with abundances typically decreasing from La = $\sim 0.5 \times \text{CI}$ to Nd = $\sim 0.2 \times \text{CI}$. The elevated concentrations are most probably due to terrestrial contamination (*e.g.*, Crozaz and Wadhwa, 2000)

and are not discussed further here (but see below for a more detailed discussion of possible terrestrial weathering in QUE 93148). Average concentrations and the ranges observed for other trace elements are shown in Table 2. Measurements were made in both cores and rims of large olivine grains. Although occasional differences were seen between the cores and rims of grains for some elements (*e.g.*, K, Ca, Sr, Y), no consistent zoning profiles were observed in either Springwater or Mount Vernon.

TABLE 2. Element concentrations in pallasite olivine.

	Springwater		Mount Vernon	
	Average	Range	Average	Range
Na (ppm)	12 ± 25	3–100	2.2 ± 1.7	0.4–5.1
P (ppm)	66 ± 46	27–180	540 ± 210	260–940
K (ppm)	4.8 ± 9.1	1–37	0.79 ± 0.68	0.23–2.4
Ca (ppm)	89 ± 54	22–195	440 ± 410	b.d.–1150
Sc (ppm)	0.84 ± 0.38	0.42–1.91	4.9 ± 1.8	2.8–8.3
Ti (ppm)	4.4 ± 1.2	2.2–5.8	40 ± 10	24–55
Cr (ppm)	410 ± 40	340–490	430 ± 80	300–560
Mn (ppm)	2730 ± 90	2630–2970	1790 ± 120	1660–2060
Sr (ppb)	17 ± 8	8–32	37 ± 18	16–73
Y (ppb)	6 ± 4	2–16	2 ± 1	1–4
Zr (ppb)	29 ± 23	3–82	190 ± 80	46–310
# analyses	15		11	

Abbreviation: b.d. = below detection.

Trace element variations in the pallasite olivines are compared to each other and to those in QUE 93148 olivine in Fig. 3. The minor elements Cr and Mn show little variation within either pallasite, but Mn concentrations are distinctly lower in Mount Vernon than in Springwater (Table 2). Manganese abundances in QUE 93148 olivine fall between the two pallasites, but show some overlap with Springwater (Fig. 3). Chromium abundances are similar in the two pallasites and are significantly lower than those in QUE 93148. Abundances of Y are also similar in the pallasites and are generally lower than those in QUE 93148, although there is some overlap with Springwater olivines. Titanium and Zr abundances in Mount Vernon are elevated compared to the ranges observed for these elements in Springwater. Olivine in QUE 93148 has higher Ti abundances than Springwater olivine, and overlaps with that from Mount Vernon. In contrast, Zr abundances in QUE 93148 are more similar to those of Springwater, but also show some overlap with the range observed in Mount Vernon. Finally, concentrations of Na and K in Mount Vernon are similar to those seen in QUE 93148 (Table 2). Springwater has higher abundances of these elements, but it is likely that this is due to surface contamination: examination of the individual measurement cycles shows high initial count rates that drop off rapidly as the ion beam sputters into the grains.

DISCUSSION

Light Rare Earth Element Enrichment of Orthopyroxene in Queen Alexandra Range 93148

Although HREE abundances in orthopyroxene from QUE 93148 are similar to those seen in lodranite orthopyroxenes (Fig. 1), LREE abundances are higher and have a pattern

distinctly different from that of typical pyroxenes. Contamination with LREE-enriched phases such as plagioclase or Ca-phosphate can be ruled out because elevated abundances of Ca, Na, K or P are not present in the analyses. Indeed, plagioclase has not been observed in this meteorite, and Ca-phosphate has only been reported as a minor component in three multi-phase inclusions (Goodrich and Righter, 2000). Orthopyroxenes from lodranite MacAlpine Hills (MAC) 88177 are also LREE-enriched compared to those from other lodranites (Floss, 2000); these enrichments are accompanied by elevated and variable abundances of P, K, and Sr. In addition, olivine and some clinopyroxene grains from this meteorite also exhibit high and variable concentrations of these elements. Floss (2000) suggested that MAC 88177 experienced cryptic metasomatism at some point after partial melting and silicate melt removal. A similar origin for the LREE enrichment of QUE 93148 orthopyroxene appears to be unlikely, however, because the elevated LREE abundances are not accompanied by enrichments of any other elements.

Another possible source of the LREE enrichment in QUE 93148 orthopyroxene may be redistribution of the REE during this meteorite's residence in the Antarctic ice. Antarctic meteorites exhibit evidence for widespread REE mobilization, resulting in Ce and Eu anomalies and lower whole-rock REE abundances (*e.g.*, Mittlefehldt and Lindstrom, 1991). Floss and Crozaz (1991) showed, furthermore, that the trivalent REE may be dissolved from Ca-phosphates and redeposited onto other mineral grains. Cerium is preferentially retained during this process because it is partially oxidized to the less soluble tetravalent state. Thus, REE dissolution and redistribution due to Antarctic weathering commonly results in mineral REE patterns with either positive or negative Ce anomalies. However, orthopyroxene from QUE 93148 does not exhibit any

Ce anomalies, suggesting either that weathering conditions were different from other Antarctic meteorites, such that the formation of tetravalent Ce was not a significant process, or that the LREE enrichment is not due to Antarctic weathering.

Finally, the possibility remains that the REE pattern observed in QUE 93148 orthopyroxene may be a primary feature. The fact that olivine from this meteorite does not exhibit any LREE enrichment provides some support for this suggestion. However, it should be noted that terrestrial weathering can be quite variable, affecting some grains but not others within a given thin section (Floss and Crozaz, 1991; Crozaz and Wadhwa, 2000). Although the ultimate source of the LREE enrichment is unclear, the fact that elements such as Na, K, P, Ba, and Sr do not exhibit elevated abundances suggests that, if secondary processes are indeed responsible, they are unlikely to have affected the distributions of other elements.

Could Queen Alexandra Range 93148 Have Originated on an Acapulcoite/Lodranite-Like Body?

It is clear from the data presented above that there are systematic differences between the trace element chemistry of QUE 93148 and that of the acapulcoites and lodranites which have been studied to date (Floss, 2000). Although HREE and Y abundances in orthopyroxene are similar to those seen in the lodranites (Figs. 1 and 2), other incompatible elements such as Ti, and Zr are distinctly depleted compared to lodranite values. Furthermore, the oxygen isotopic composition of QUE 93148 precludes a genetic relationship to the acapulcoites and lodranites (Goodrich and Righter, 2000). Nevertheless, it is useful to compare this meteorite to primitive achondrites such as these, because the very small size of this meteorite (only 1.091 g) makes interpretations based on petrology extremely difficult. Comparison of the trace element compositions in individual minerals, however, can provide insights into the types of processes experienced by QUE 93148.

Acapulcoites and lodranites probably formed on a common parent body that experienced variable degrees of local partial melting and melt migration (McCoy *et al.*, 1996, 1997a,b). In simplified terms, acapulcoites, although they have been extensively heated, generally have maintained chondritic mineralogies and compositions, whereas lodranites have experienced the formation and removal of both Fe,Ni-FeS and silicate partial melts. Trace element studies of individual minerals from acapulcoites and lodranites (Floss, 2000) have shown that lodranite pyroxenes exhibit depletions of the REE and incompatible trace elements, such as Ti and Zr, relative to acapulcoite pyroxenes (*e.g.*, Fig. 3). These depletions can be attributed to the loss of a silicate partial melt from the lodranites. Lodranites are generally depleted in plagioclase, but contain significant amounts of orthopyroxene and minor clinopyroxene. In contrast, the mineralogy of QUE 93148 appears to be distinctly more ultramafic, consisting largely of olivine with lesser amounts of metal and orthopyroxene (Goodrich and

Righter, 2000). This suggests that, if QUE 93148 experienced processing on an acapulcoite/lodranite-like parent body, it must have experienced a larger degree of partial melting and melt removal than typical lodranites.

The systematic trace element differences between acapulcoite and lodranite orthopyroxene may be used to determine if Ti and Zr abundances in QUE 93148 orthopyroxene are compatible with an origin through partial melting of an acapulcoite-like precursor. Unfortunately, distribution coefficients for these elements are only poorly known, and have not been investigated under the conditions of acapulcoite/lodranite formation. However, McCoy *et al.* (1997b) estimate, on the basis of mineralogy, that the degree of silicate partial melt removal from lodranites such as MAC 88177 and LEW 88280 is 15 vol% or more. Simple batch melting calculations using the REE abundances in lodranite and acapulcoite pyroxenes similarly suggest that lodranite orthopyroxene compositions may be the result of 10 to 15% partial melting of an acapulcoite precursor (Floss, 2000). Using the basic equations governing equilibrium melting,

$$C_{\text{melt}} = C_{\text{initial}}/[D \times (1 - f) + f] \quad (1)$$

$$C_{\text{residue}} = D \times C_{\text{melt}} \quad (2)$$

where C represents the concentration of a given element, D is the solid-melt partition coefficient of that element, and f is the fraction of partial melt generated, one can estimate the amount of partial melt that would need to be removed in order to account for the Ti and Zr abundances observed in orthopyroxene from QUE 93148 if this meteorite, in fact, originated on a parent body like that of the acapulcoites/lodranites. The average concentrations of Ti (1000 ppm) and Zr (2 ppm) in acapulcoite orthopyroxene are assumed to be representative of the initial concentrations of this phase on the parent body before partial melting, and the average Ti (625 ppm) and Zr (650 ppb) concentrations in lodranite orthopyroxene represent those after removal of 15 vol% silicate partial melt. Equations (1) and (2) can then be used to solve for the D values of Ti and Zr.

The inferred partition coefficients obtained from this calculation are $D_{\text{Ti}} = 0.2$ and $D_{\text{Zr}} = 0.067$. There are few literature data available for partition coefficients for these elements in orthopyroxene. Two studies that determined D values for Ti and Zr in chondrule orthopyroxene report values lower than the inferred values obtained here. Kennedy *et al.* (1993) find that D_{Ti} ranges from 0.061 to 0.11 and D_{Zr} ranges from 0.0033 to 0.014 for experimental runs that appear to have achieved equilibrium. Jones and Layne (1997) report similar values, inferred from natural concentrations in chondrule orthopyroxene and glass. However, in addition to obvious differences in the formational histories between chondrules and the acapulcoites/lodranites, in both studies the Ca contents of the orthopyroxenes are lower ($W_{0.2-1.0}$) than those of orthopyroxenes from acapulcoites and lodranites ($W_{1.6-3.4}$;

McCoy *et al.*, 1996, 1997a; Mittlefehldt *et al.*, 1996). Forsythe *et al.* (1994) have noted that D values for high-field-strength elements increase with increasing Ca content of the pyroxenes. In their experiments (which modeled the formation of basaltic to dacitic magmas) D values also varied with composition and temperature. For low-Ca pyroxenes (Wo_{4-18}), D_{Ti} varied from 0.08 to 0.25 and D_{Zr} varied from 0.004 to 0.122. Other estimates for clinopyroxene partitioning (*e.g.*, Ray *et al.*, 1983; Blundy and Dalton, 2000) fall within these ranges. Thus, given the limitations associated with these ranges and the fact that partitioning experiments directly relevant to acapulcoite/lodranite melting have not been carried out, the inferred D values for Ti and Zr appear to be reasonable and may be used to test whether QUE 93148 could be the residue of a large degree of partial melting from an acapulcoite-like precursor.

The results suggest that QUE 93148 probably could not have formed on such a parent body (Fig. 4). If lodranite orthopyroxene trace element abundances do, in fact, represent those after removal of 15% silicate melt, then 80% silicate melt needs to be removed in order to duplicate the observed Ti abundances in QUE 93148 orthopyroxene (Fig. 4a). A similar calculation for Zr fails to duplicate the Zr abundances observed in QUE 93148 even at 100% melt removal (Fig. 4b). This discrepancy in the results between Ti and Zr reflects some of the uncertainties inherent in this type of calculation. Nevertheless, the exercise clearly demonstrates the extreme fractionation that would be required to relate the Ti and Zr abundances of QUE 93148 to those of the acapulcoites, and indicates that this meteorite probably did experience the high

degree of melting suggested by its ultramafic assemblage. It is highly unlikely, however, that such a process could have taken place on a primitive achondrite parent body which has retained significant primitive (*i.e.*, chondritic) chemical and mineralogical characteristics, like the acapulcoite/lodranite one.

Is Queen Alexandra Range 93148 Related to Brachinites?

Goodrich and Righter (2000) reported that the oxygen isotopic composition of QUE 93148 (determined by Mayeda and Clayton) was similar to that of Brachina, raising the possibility that this meteorite might be an unusual brachinite. However, Fe-Mn-Mg relations showed that QUE 93148 has a lower Mn/Mg ratio than any major group of primitive or evolved achondrites, including the brachinites. There are few trace element data available for individual minerals in brachinites, and none for orthopyroxene. However, some trace elements (Na, Ti, Cr, and Zr) have been measured in olivines from Allan Hills (ALH) 84025, Hughes 026 and Brachina (M. Wadhwa, pers. comm.) and are compared with the data for QUE 93148 olivine in Fig. 5. Although there is some overlap, particularly for Ti, the abundances for brachinite olivines generally fall outside of the ranges observed for QUE 93148 olivine. Clearly more data are needed for brachinites, but combined with the fact that Mn/Mg ratios of olivine are lower in QUE 93148 than in brachinites (Goodrich and Righter, 2000), these trace element data suggest that this meteorite is probably not a member of the brachinite group either, a conclusion also reached by these authors.

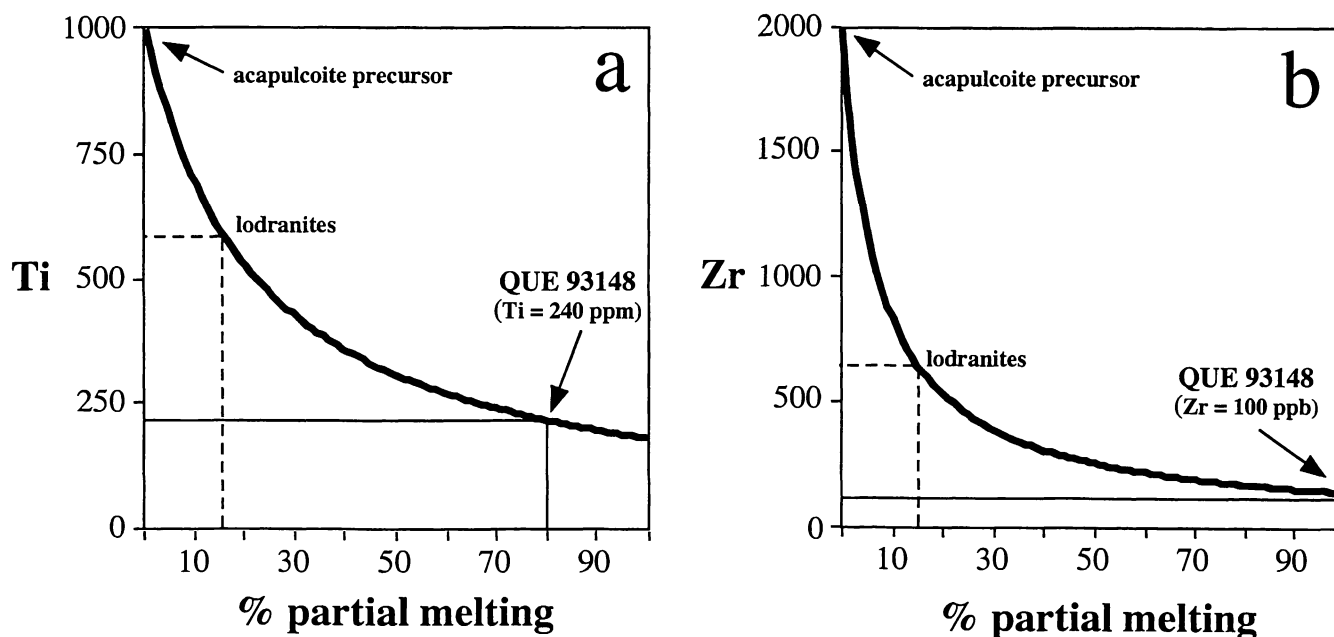


FIG. 4. Illustration of the change in concentration of (a) Ti (ppm) and (b) Zr (ppb) in residual orthopyroxene as a function of the degree of partial melt removed from an acapulcoite-like precursor. See text for details.

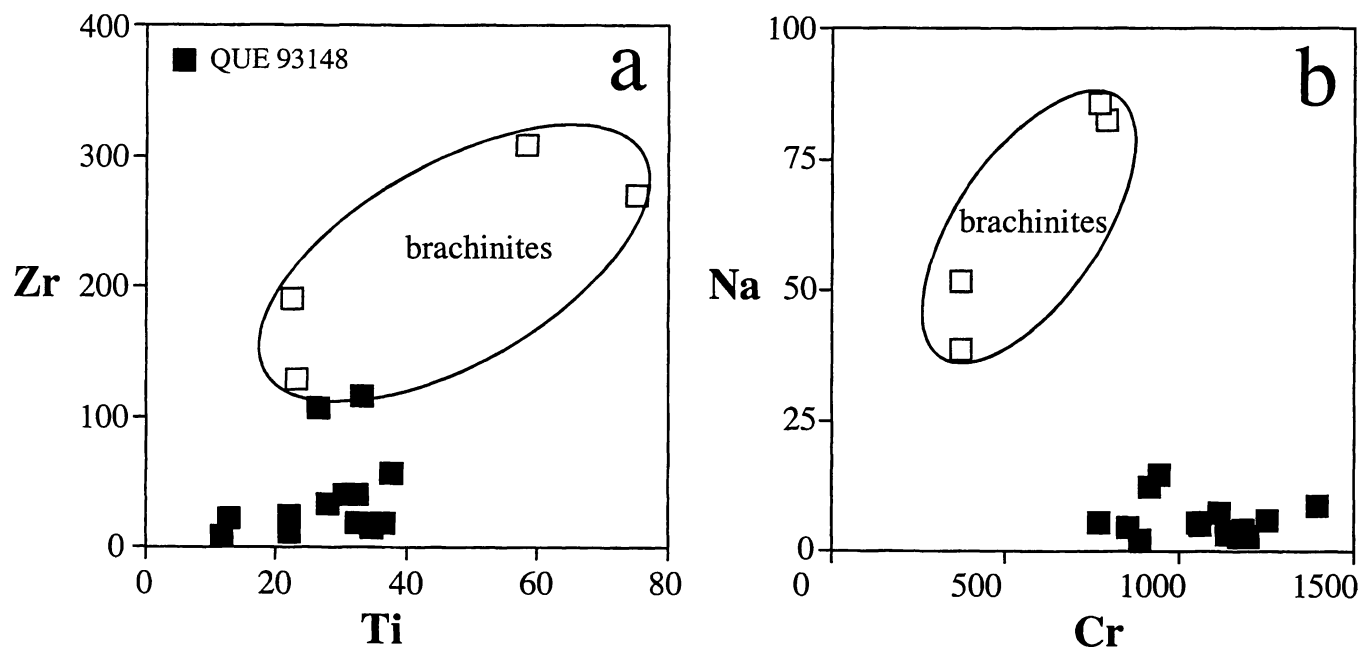


FIG. 5. Abundances of (a) Ti vs. Zr and (b) Cr vs. Na in olivine from QUE 93148 and the brachinites ALH 84025, Hughes 026 and Brachina. Concentrations are in parts per million (ppm), except for Zr, which is in parts per billion (ppb). Data for the brachinites are from M. Wadhwa (pers. comm.).

Is Queen Alexandra Range 93148 Part of the Howardite–Eucrite–Diogenite Parent Body?

As noted earlier, the low trace element abundances reported here, as well as its ultramafic assemblage, indicate high degrees of melting on the parent body of QUE 93148. Goodrich and Righter (2000) suggested that QUE 93148, which has an oxygen isotopic composition similar to the HED meteorites and shows some affinities to main group pallasites, may be a piece of the deep mantle of the HED parent body. They noted, furthermore, that if the HED parent body differentiated in an early magma ocean scenario such as that envisioned by Righter and Drake (1997), olivine from the HED deep mantle should have a major element composition similar to that observed in QUE 93148 olivine. Ruzicka *et al.* (1997) modeled the trace element evolution of the HED parent body through fractional crystallization from a magma ocean with $\sim 3 \times \text{CI}$ initial REE abundances. In their model, olivine crystallizes alone for the first 60% of the sequence. The REE patterns of these olivine cumulates are predicted to be HREE-enriched, with abundances ranging from $\text{Er} = 0.07 \times \text{CI}$ to $\text{Lu} = 0.2 \times \text{CI}$. Olivine from QUE 93148 has similar Lu concentrations, but a much steeper pattern (Fig. 2). Erbium concentrations are an order of magnitude lower than those predicted by the model of Ruzicka *et al.* (1997). A number of factors could contribute to this discrepancy, including (1) choice of partition coefficients used for the modeling, (2) the fact that the cumulate composition of Ruzicka *et al.* (1997) represents the composition for olivine after 61% fractional crystallization whereas actual REE

compositions would be lower at the onset of crystallization and would evolve during the extended period of olivine crystallization, and (3) that QUE 93148 may in fact be a residue of extensive partial melting rather than a cumulate from a fractionally crystallizing magma ocean. Indeed, as discussed below, Goodrich and Righter (2000) conclude that QUE 93148 has Mn/Mg ratios consistent with an origin as a residue rather than as the product of a melt.

Goodrich and Righter (2000) suggested that QUE 93148 may be related to main group pallasites, based on the fact that pallasites have oxygen isotopic compositions similar to that of QUE 93148, and that they, like QUE 93148, have low, slightly subchondritic Mn/Mg ratios. Goodrich and Delaney (2000) showed that Fe–Mn–Mg relations may be used to distinguish between melts and residues of starting material with chondritic Mn/Mg. They argue that meteorites with subchondritic Mn/Mg ratios, such as QUE 93148 and main group pallasites, must be residues of relatively high degrees of melting ($>30\%$). In contrast, mesosiderites, which also have similar oxygen isotopic compositions, exhibit a trend of constant FeO/MnO ratios that indicate formation as crustal cumulates, rather than melt residues (Goodrich and Righter, 2000). Thus, comparison of QUE 93148 with data from pallasites may provide useful constraints.

Figures 2 and 3 compare the trace element distributions of orthopyroxene and olivine from QUE 93148 with those of the main group pallasites studied here, and with data for the two pyroxene pallasites, Vermillion and Yamato-8451, from Boesenberg *et al.* (2000). QUE 93148 cannot be genetically related to the pyroxene pallasites (which themselves appear to

Righter, 2000), but their mineralogy, consisting of olivine and trace pyroxene in a metal matrix, is similar to that of QUE 93148. Although the data for the pyroxene pallasites are limited, there are similarities. Titanium, Y and Zr abundances in orthopyroxene from the pyroxene pallasites fall within or near the ranges observed for QUE 93148 orthopyroxene (Fig. 2). Manganese and Cr abundances in Yamato-8451 are also similar to those for QUE 93148, but Vermillion orthopyroxene has higher and lower concentrations, respectively. Figure 3 shows that both pyroxene pallasites have Mn concentrations in olivine similar to those of QUE 93148 olivine, and Yamato-8451 also has Cr abundances similar to those of QUE 93148, but Cr contents in Vermillion olivine are significantly lower. Yttrium and Zr abundances in olivine from the pyroxene pallasites are similar to those of QUE 93148 olivine, although their concentrations in Yamato-8451 olivine are slightly higher than the range seen in QUE 93148. Although it would clearly be desirable to have more data, these initial comparisons do suggest that QUE 93148 and the pyroxene pallasites, although not directly related, may have originated in a similar manner. Low Mn/Mg ratios for Vermillion and Yamato-8451 are also consistent with a similar origin for these meteorites and QUE 93148 (Goodrich and Righter, 2000).

Figure 3 also shows data for olivine from the main group pallasites, Springwater and Mount Vernon. As discussed earlier (see "Results"), the trace element distributions between the two pallasites are somewhat complex. Although they have similar Cr, Y and Zr concentration ranges, they differ in their Ti and Mn abundances. Springwater is an unusual pallasite in that its olivine is more ferroan than most (Mittlefehldt *et al.*, 1998) and it contains more phosphates than other pallasites (Buseck, 1977). The trace element distributions reported here appear to reflect its unusual nature. Calcium and P abundances are also lower in Springwater than in Mount Vernon (Table 2). Literature data suggest that other main group pallasites have Mn and Ca abundances in olivine similar to those seen in Mount Vernon (Mittlefehldt *et al.*, 1998).

The trace element abundances in olivine from QUE 93148 generally fall within the ranges observed for the two main group pallasites (Fig. 3), consistent with its major element composition (F_{085.5}; Goodrich and Righter, 2000) which is intermediate between those of Springwater and Mount Vernon (F₀₈₂ and F₀₈₇, respectively; Mittlefehldt *et al.*, 1998). The only exception is Cr, which is present at significantly higher levels in QUE 93148 than in the main group pallasites. QUE 93148 appears to be more similar to Springwater than Mount Vernon, based on its abundances of Mn, Y and Zr; however, its Ti concentrations are closer to those of Mount Vernon. Other elements such as Na, K, Ca and Sc have concentration ranges in QUE 93148 olivine that fall within those of Mount Vernon olivine (Tables 1 and 2). Springwater olivine also has similar Sc concentrations, but lower Ca contents; its Na and K abundances appear to be affected by contamination, as discussed earlier (see "Results"), and cannot be compared with the other results.

The results presented here thus provide a mixed picture. Much of the main group pallasite data, as well as oxygen isotopic compositions, do not preclude grouping QUE 93148 with these meteorites. However, there are significant differences as well. The higher Cr contents of QUE 93148 olivine are particularly problematic. In this regard, the high Cr content measured in olivine from the pyroxene pallasite Yamato-8451 (Fig. 3b) by Boesenberg *et al.* (2000) is intriguing. QUE 93148 does differ from main group pallasites in that it contains primary pyroxene, and is, in this respect, similar to the pyroxene pallasites. QUE 93148 seems to contain more pyroxene than the 1 vol% found in the pyroxene pallasites. However, as noted earlier, this is a very small sample and the 13% pyroxene reported by Goodrich and Righter (2000) may not be representative of the larger domain from which this meteorite originated.

QUE 93148 may, in fact, be genetically related to the main group pallasites, but represent a less ultramafic sample from the deep mantle of their parent body (the HED parent body?). This might account for some of the differences in trace element contents from the main group pallasites and the many similarities to the pyroxene pallasites.

CONCLUSIONS

Trace element distributions in QUE 93148 show that this meteorite is not the residue of a partial melting event on a primitive achondrite parent body, like the acapulcoite/lodranite one. It also does not appear to be related to the brachinites. However, its low trace element abundances, as well as its ultramafic assemblage, do indicate high degrees of melting on its parent body. Comparison of its trace element distributions to those of main group and pyroxene pallasites reveal a complex picture. Although a genetic relationship to the pyroxene pallasites is precluded by oxygen isotopic compositions, QUE 93148 appears to have a similar origin. It may represent a new type of pyroxene pallasite with genetic links to the main group pallasites, as suggested by Goodrich and Righter (2000).

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