

Chapter 3

ULTRAMAFIC XENOLITHS FROM SALT LAKE CRATER - AN OVERVIEW

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INTRODUCTION

Perhaps the most tangible evidence for mantle composition comes from studies of ultramafic xenoliths carried to the surface by ascending basaltic magmas. Ultramafic xenoliths in Hawaiian lavas represent a variety of mantle and crustal materials derived from a range of depths. These rocks include cumulate varieties, some of which are clearly related to Hawaiian volcanism, as well as tectonite varieties that may or may not be related. Xenolith suites in the Honolulu Volcanic Series (nephelinitic lavas) are of particular interest as they include garnet-bearing pyroxenites and lherzolites. It is noteworthy that these xenolith varieties have not been observed in lavas of tholeiitic composition. Hawaiian xenoliths have been investigated by numerous workers (Green, 1966; Jackson, 1966, 1968; White, 1966; Kuno, 1969; Jackson and Wright, 1970; Beeson and Jackson, 1970; Reid and Frey, 1971; Wilkinson, 1976; Frey, 1979; among others), but those at the Salt Lake Crater locality have received greatest attention.

The Salt Lake Crater xenolith suite is dominated by two main assemblages: garnet-free Cr-diopside spinel lherzolites (averaging 75% olivine, 15% opx, 10% cpx) and garnet pyroxenites (averaging 75% cpx, 15% gar, 10% olivine). Most of the xenoliths contain small amounts of spinel and some contain traces of kaersutitic amphibole and phlogopite. In addition, there are rarer tectonite dunites, garnet lherzolites, and clinopyroxenites as well as xenocrysts of clinopyroxene and amphibole. Similar lithologies occur in different proportions in some other Honolulu Series vents, although garnet-bearing varieties are absent in most localities (Jackson and Wright, 1970). Primary textures in many (garnet) pyroxenites in Honolulu Series vents are somewhat obscured by varying degrees of subsolidus recrystallization; cumulate textures have not been identified (Jackson, 1966, 1968). Four textural variants of garnet pyroxenite at Salt Lake Crater were recognized by Beeson and Jackson (1970) and each has been found in sharp contact with spinel lherzolites within rare individual xenoliths

(Jackson, 1966; Reid and Frey, 1971). Garnet pyroxenites are relatively Fe-rich compared with spinel lherzolites (Kuno, 1969; Jackson and Wright, 1970). Relatively few of the xenoliths have been analyzed for minor and trace elements (Nagasawa et al., 1969; Griffin and Murth, 1969; Reid and Frey, 1971; Philpotts et al., 1972; Shimizu, 1975; Glassley and Piper, 1978; Leeman et al., 1979; Frey, 1979) or isotopic ratios (O'Neil et al., 1970; Shimizu, 1975).

The genesis of the garnet pyroxenites and their relation to the spinel lherzolites has been discussed by Wilkinson (1976) and Frey (1979) who summarized earlier interpretations. The garnet pyroxenites have been interpreted as (1) high-pressure cumulates from alkalic or nephelinitic basaltic magmas, (2) residue remaining after fractional fusion of more primitive mantle rocks, (3) trapped basaltic magmas that crystallized and re-equilibrated at high pressure, (4) parents to more refractory lherzolite residue from which a basaltic component was removed, and (5) anatectic melts of upper mantle aluminous peridotite akin to mafic segregations in high-temperature alpine peridotites. The garnet lherzolites have not been integrated in these models and it appears that they are tacitly included by most authors with the pyroxenite suite. Of all the xenolith variants, the garnet lherzolites are perhaps closest to a source lithology that upon partial melting could yield Hawaiian tholeiitic magmas (Jackson and Wright, 1970; Leeman et al., 1977).

Mineralogy of Garnet-Bearing Xenoliths

Initial studies (Leeman et al., 1979) of bulk rock major and trace element compositions and mineral compositions for a suite of Salt Lake Crater xenoliths are summarized below. For this work, a variety of lithologies and textural variants were chosen (largely from collections of E. D. Jackson) to represent the garnetiferous rocks, dunites and spinel lherzolites. Most of these samples are free of all but minor exsolution textures, but some of the garnetiferous rocks display reaction textures (e.g., cpx + sp + gar + olivine) indicating subsolidus re-equilibration. Microprobe analyses (Table 1) of selected samples show that olivines, garnets, and pyroxenes essentially are uniform in composition, but the spinels display discrete ranges in composition that correlate with textural relations. Those spinels that occur as discrete primary grains are low-Cr hercynites whereas those with garnet reaction rims are high-Cr hercynites. Mg/(Mg + Fe) ratios of all minerals and the bulk-rock are correlated and decrease in the order lherzolite garnet lherzolite - olivine garnet pyroxenite - garnet pyroxenite - pyroxenite (also see Beeson and Jackson, 1970; Shaw and Jackson, 1973).

Estimates of Depth of Origin of the Xenoliths

Temperatures and pressures of equilibration for pyroxenes in the garnetiferous xenoliths were calculated using a variety of thermometers and the clinopyroxene geobarometer of Mercier and Carter (1975). Temperatures calculated by the methods of Wood and Banno (1973), Wood

(1974), Wells (1977), Mercier (1976), and Mysen (1976) are similar and average about $1100 \pm 100^\circ\text{C}$ both for our data and those of Kuno (1969), Beeson and Jackson (1970), and Glassley and Piper (1978). Pressures calculated from clinopyroxene compositions average 18 ± 3 kb using average temperature estimates for each sample. Temperatures and pressures based on the orthopyroxene (not present in all samples) geothermometer and geobarometer (Mercier and Carter, 1975; Mercier, 1976) are somewhat higher, averaging about 1200°C and 25 kb, respectively. According to these calculations, the xenoliths fall near the high-temperature oceanic geotherm (based on P-T equilibration conditions for xenoliths) of Mercier and Carter (1975) at depths of at least 60 km and perhaps as great as 75 km. The method of Herzberg (1978a, b) indicates initial equilibration temperatures about $150\text{--}200^\circ\text{C}$ higher and equilibrium pressures in the above range. If the latter results are appropriate, the xenoliths record P-T conditions near the dry peridotite solidus of Green and Ringwood (1967). The main conclusion from these calculations is that all of the xenoliths apparently were derived from depths near the immediate source of tholeiite magmas (about 60 km), as deduced from studies of seismic tremor preceding summit eruptions at Kilauea and Mauna Loa (cf. Eaton and Murata, 1960). Thus, they may represent mantle lithologies within or near the partial melt zone (see Wright, 1971; Jackson and Wright, 1970).

Geochemistry of the Xenoliths

Twenty samples were analyzed for major and trace elements using instrumental neutron activation methods. Variations in composition (Figure 1) are correlated with lithology, and several groupings are apparent. The garnet lherzolites are notably distinct from the garnet pyroxenite group with regard to composition and it is likely that these two lithologies represent different parageneses.

The garnet pyroxenites display systematic variations as a function of MgO content for all analyzed major elements and the transition metals. These trends are suggestive of fractional crystallization processes and the rocks may be interpreted as (1) a series of residual liquids derived from an initial liquid (having at least 20% MgO) that subsequently crystallized at high pressure, or (2) a series of high pressure cumulates (or crystal-liquid mushes) related to some mafic magma. The low contents of TiO_2 , Na_2O , K_2O (from Beeson and Jackson, 1970) and high contents of CaO in these rocks suggest that, if the first interpretation is correct, these liquids are not related to Hawaiian magmas erupted at the surface. They more closely resemble mafic segregations in alpine peridotites as stressed by Wilkinson (1976). If the second interpretation is correct, the bulk-rock and mineral compositions do not seem compatible with a cumulate origin from Hawaiian tholeiitic magmas, although the xenoliths may be cumulates from Honolulu Series magmas (Frey, 1979). Finally, the analyzed pyroxenites do not appear to be residues of fractional melting of more primitive pyroxenite to yield Hawaiian magmas (Mg nos. ≥ 60) as

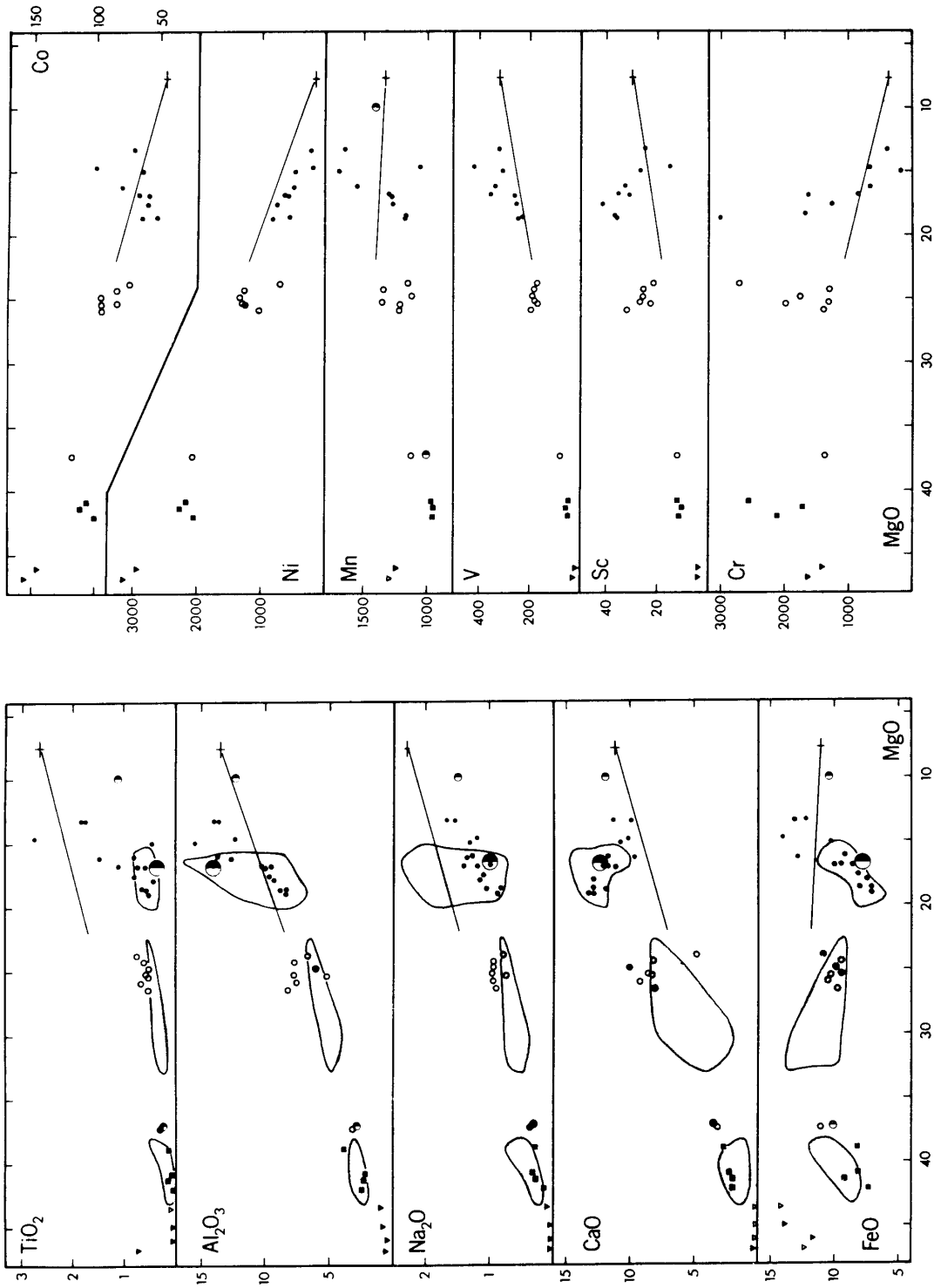


Figure 1. MgO-variation diagrams for Salt Lake Crater xenoliths. Plotted points are from our work and Jackson and Wright (1970). Shaded fields represent data from Kuno (1969) for lherzolites, "olivine eclogites" and pyroxenites, respectively, with decreasing MgO. Small half-filled circles represent partial melt (1474°C, 20 kb) and garnet lherzolite starting material (col. 5, Table 2) from Kushiro (1973). Large half-filled circle represents "average" magmatic segregation from alpine peridotites (Dickey, 1970). Also shown are olivine-control lines and average summit tholeiite (+) from Kilauea (this paper). Key: garnet pyroxenites and clinopyroxenites (●), garnet lherzolites (○), lherzolites (■), and

their Mg numbers are too low (Table 1). Such an hypothesis would require that the primitive pyroxenites have an even lower Mg number (e.g., 65).

Compared with the pyroxenites, the analyzed garnet lherzolites are more uniform in composition, with the exception of an olivine-rich sample (Table 2, cols. 1-3) and have Mg numbers ranging between 86 and 81. For most elements, these rocks lie near tie-lines between Hawaiian tholeiites and more refractory Cr-diopside spinel lherzolites and dunites (Mg nos. = 89-91 and 87-88, respectively). If the garnet lherzolites are related to tholeiitic volcanism, two classes of interpretation seem likely. First, they may approximate picritic partial melts (25% MgO) of a more primitive source, such as those proposed by O'Hara et al. (1975) or Green (1973), that were trapped and crystallized at depth. Arguments based on Ni partitioning (Leeman et al., 1979) suggest that it is unlikely that Hawaiian tholeiites could be derived from such a picritic magma. A second possibility is that some of the garnet lherzolites may approximate source materials for the tholeiitic magmas.

Although high pressure melting studies of such rocks are not extensive, experimentally derived partial melt (20 kb, 1475°C, anhydrous) from an olivine-rich garnet lherzolite (Table 2, Col. 5) has a certain likeness (Mg no. = 61; see also Figure 1) to Hawaiian tholeiites. However, P₂O₅, K₂O, Na₂O and TiO₂ are higher in tholeiites (Kushiro, 1973). These discrepancies are probably related to low contents of these elements in the starting composition. Wright (1971) circumvented this problem in modeling the source material for Mauna Loa tholeiites by postulating small amount of apatite, rutile and amphibole (Table 2, Col. 4). Available evidence (Jackson and Wright, 1970; Wright, 1971; Shaw and Jackson, 1973) seems to indicate that source material for Hawaiian tholeiites may be more iron-rich than pyrolite (Green, 1973) or average garnet lherzolite in kimberlites (O'Hara et al., 1975). Garnet lherzolites from Salt Lake Crater may provide the closest approach to the required source material of all recognized Hawaiian xenolith variants. Extraction of tholeiitic melt from such rocks could yield a dunite residue akin to those at Salt Lake Crater (Jackson and Wright, 1970).

CONCLUSION

Circumstantial evidence favors a garnet lherzolite source for Hawaiian magmas; spinel peridotites are sufficiently depleted in magmaphile elements that they could produce only small amounts of basaltic magma, at best. Consequently, it is proposed that spinel peridotites and dunites are the residuum remaining after different degrees of partial melting of more fertile source materials (cf. Jackson and Wright, 1970).

Additional work is required to test this hypothesis and to define more clearly the relation between Hawaiian xenoliths and Hawaiian magma series (cf. Frey, 1979; Leeman et al., 1979). Measurements of the isotopic compositions of Sr, Nd, and Pb appear most likely to help resolve these questions.

Table 1. 100 Mg/(Mg + Fe) in Coexisting Phases

	Rock	Oliv	Gar	Cpx	Opx	Sp
<u>Garnet lherzolites</u>						
1	85.7	86.8	76.1	86.1	86.5	72.6-64.6
2	82.3	83.7	75.1	83.7	85.3	68.9-67.6
3	81.7	82.2	72.7	82.6	83.1	61.0-53.5
4	81.5	83.5	70.7	83.6	n.p.	66.7-64.7
5	--	81.7	69.8	81.6	83.2	n.a.
<u>Garnet pyroxenites</u>						
6	82.6	n.p.	74.2 ^b	82.6 ^a	n.p.	n.a.
7	81.1	n.a.	73.1 ^b	81.6 ^a	83.8 ^a	n.a.
8	80.9	n.p.	--	79.2	82.3	--
9	80.0	--	73.2	81.8	83.4	--
10	70.2	n.p.	72.3	n.a.	n.a.	61.3-56.7
11	75.9	79.9	69.0	80.8	81.5	45.8
12	74.8	n.a.	70.6 ^b	77.8 ^a	81.8 ^a	n.a.
13	75.7	n.a.	74.8	89.6 ^a	81.0 ^a	n.a.
14	73.0	--	64.3	77.6	78.6	--
15	72.2	n.p.	69.8	77.4	n.p.	56.7-56.1
16	66.0	n.a.	63.3	70.9	n.p.	n.a.
17	65.0	n.p.	64.0	74.5	n.p.	41.8

^areconstructed from host and exsolution lamellae

^bexsolved garnets in pyroxene host

Analyses 1-4, 10, 11, 15, 17 (Leeman et al., 1979); 5, 8, 8, 14 (Kuno, 1969); 6, 7, 12, 13, 16 (Beeson and Jackson, 1970).

n.p. = not present; n.a. = present but not analyzed; -- = no data

Table 2. Compositions of Hawaiian Xenoliths and Some Other Mantle Materials

	1	2	3	4	5	6	7
SiO ₂	44.82	(43.0) ^a	(44.6) ^a	43.03	43.70	45.20	45.16
TiO ₂	0.52	0.60	0.29	0.60	0.25	0.05	0.71
Al ₂ O ₃	8.21	6.60	3.04	4.34	2.75	1.50	3.54
FeO	9.77	10.20	11.10	12.67	10.05	5.60	8.45
MgO	26.53	24.90	37.30	35.00	37.22	41.80	37.47
CaO	8.12	8.20	3.25	3.06	3.26	1.04	3.08
Na ₂ O	0.89	0.87	0.35	0.65	0.33	0.18	0.57
K ₂ O	0.03	--	--	0.10	0.14	0.16	0.13
Mg#	82.90	81.30	85.70	83.10	86.90	93.00	88.80

- 1 Garnet lherzolite, 66 SAL-1, Salt Lake Crater (Jackson and Wright, 1970)
 - 2 Garnet lherzolite, avg. of 5, Salt Lake Crater (Leeman et al., 1979)
 - 3 Olivine-rich garnet lherzolite, Salt Lake Crater (Leeman et al., 1979)
 - 4 Calculated parental material for Mauna Loa magmas (Wright, 1971)
 - 5 Sheared garnet lherzolite, 1611, Lesotho (Boyd and Nixon, 1973)
 - 6 Average garnet lherzolite in kimberlite (O'Hara et al., 1975)
 - 7 Phrolite (Green, 1973)
- a SiO₂ calculated by difference

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