MANTLE/CRUSTAL XENOLITHS IN HAWAIITE LAVAS: THE CIMA VOLCANIC FIELD, CALIFORNIA

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The Cima volcanic field in southeastern California is one of many isolated late Cenozoic basaltic volcanic fields in the Basin and Range province of the western U.S. Cima lavas are dominantly hawaiites like those in some other such fields (Best and Brimhall, 1974; Vaniman et al., 1982), but Cima differs from the other fields in having abundant mafic and ultramafic xenoliths in lavas of hawaiite composition. The xenoliths give direct information about complex events of melting and fractionation that occurred in the mantle before and during generation of hawaiite magmas, and about the nature of the mantle source of the hawaiites.

The Cima volcanic field comprises more than 50 vents and associated flows that were erupted over a period of at least 7 m.y. (Turrin and others, 1985). The tephra and flows are of small volume. Detailed studies (Breslin, 1982) of flows and tephra from two coalescing cones show substantial differences in the degree of silica saturation between the cones and show large ranges within a single flow in the ratios of molecular Mg/Mg+Fe (mg-ratio), 40-51, and normative an/an+ab (an-ratio), 22-45. The volcanic field as a whole has the chemical features of alkaline basaltic suites described by Thompson (1974) and Miyashiro (1978) as "straddle-types"; that is, the lavas vary from ne- to hy-normative (Fig. 1). There is no systematic relation between ages of lavas and either mg- or an-ratio. Similarly, there is no correlation between the presence of xenoliths and age, an- or mg-ratio (Fig.2), or normative ne. A small number of analyzed lavas (Semken, 1984; Breslin, 1982) have MORB-like isotopic compositions (ε_{Nd} +9 to +10; ε_{Sr} -21 to -22), and LREE-enriched compositions.

We separated the xenoliths into four groups based on their mineralogy: (1) Cr-diopside group of spinel lherzolite and websterite; (2) Cr-diopside group rocks with introduced plagioclase; (3) green-pyroxene (not Cr-diopside) group of websterite, gabbro, and microgabbro; and (4) Al-augite group of clinopyroxenite, gabbro, and microgabbro. Common mineral assemblages and average mineral compositions are given in Table 1.

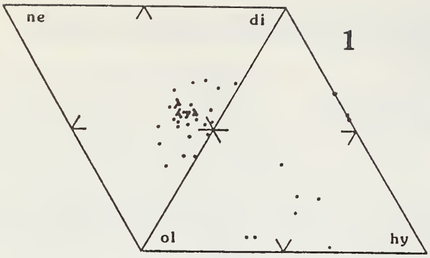
Rocks of the Cr-diopside group are refractory upper mantle lherzolites and websterites typical of basalt xenolith assemblages the world over. The rocks usually are medium grained with allotriomorphic-granular textures and common strain lamellae in olivine. Porphyroclastic or tabular textures are less common.

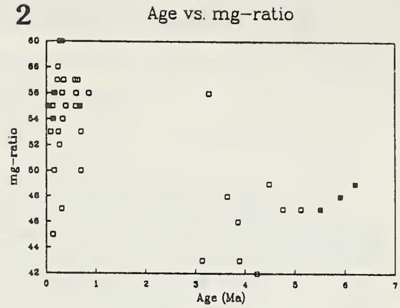
Many rocks of the Cr-diopside group were invaded by mafic melts from which plagioclase crystallized. These rocks form the second group, in which plagioclase commonly forms thin, irregular stringers in peridotite or pyroxenite. The rocks generally have a hybrid texture of metamorphic peridotite with igneous felsic minerals. In some samples deformation and recrystallization to a mosaic or tabular texture followed crystallization of plagioclase.

Rocks of the green-pyroxene group include websterite, which commonly has high orthopyroxene/clinopyroxene ratios, and two-pyroxene gabbro and microgabbro. All of these rocks have igneous textures. Large orthopyroxene and clinopyroxene grains generally show well-developed lamellar or complex blebby exsolution. Clinopyroxenes of both websterite and gabbro have Al_2O_3 and Cr_2O_3 values intermediate between, but distinct from, those in rocks of the Cr-diopside and Al-augite group (Table 1).

Rocks of the Al-augite group comprise clinopyroxenite and one-pyroxene gabbro and microgabbro. Rare Al-augite gabbro has been deformed and recrystallized to granulite texture.

Composite xenoliths are common at Cima. All the mafic lithologies are found in contact with Cr-diopside peridotite and are clearly dike-like intrusions in the host peridotite. In addition, composite Al-augite pyroxenite-gabbro xenoliths occur. Reactions between dikes and wallrocks in composite xenoliths from this locality have been described (Wilshire and others, 1985). A feature not previously described is the abundant evidence of fractionation within many dikes. In one composite xenolith of peridotite and hornblende microgabbro, hornblendite veins derived from gabbro penetrate the peridotite. Composite Al-augite pyroxenite/gabbro xenoliths contain plagioclase veins that extend from pyroxenite into gabbro. We interpret these veins as residual liquids that froze during a process of extraction from an early-crystallized pyroxene aggregate. Such a process would yield complementary pyroxenite and gabbro, as also shown by composite dikes with pyroxenite margins and gabbro cores that apparently resulted from initial crystallization of pyroxene at the dike margins.





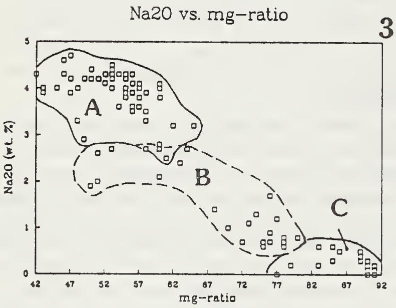


Fig. 1. Normative ne, ol, di, hy components of basalts

Fig. 2. Age vs. mg-ratio, basalts. Filled symbols, xenolith-bearing basalts.

Fig. 3. Mg-ratio vs. Na_2O, basalts and xenoliths. Field A = basalt; field B = gabbro, microgabbro, pyroxenite; field C = Cr-diopside group, feldspathic peridotite.

Crosscutting relations between dikes indicate that Al-augite pyroxenite and gabbro are younger than Cr-diopside websterite. No direct evidence of the age relation between rocks of the green-pyroxene group and either the Cr-diopside websterite or Al-augite group has been found. However, the presence of gabbro and microgabbro in both green-pyroxene and Al-augite groups and the occurrence of representatives of both groups as composites with peridotite suggest that all these xenoliths were in close proximity in their source area. Thus, the xenolith assemblage probably represents a complex terrane of metamorphic peridotite and mafic intrusions rather than samples of stratified mantle and crust.

Striking faceted xenoliths having angular, polygonal shapes are common at Cima. The facets are interpreted (Nicolas and Jackson, 1982; Wilshire and others, 1985) as hydraulic fractures produced by high fluid pressures in the mantle. Some of the fracture systems were intruded by various mafic magmas and healed by crystallization before entrainment in lava. Unhealed fractures were planes of weakness along which the rocks fractured during excavation. Planar facets are found on representatives of all mafic and ultramafic xenoliths at Cima, including the microgabbros. Thus, even those lithologies that were emplaced as dikes in hydraulic fracture systems were themselves subjected to hydraulic fracturing after consolidation. This indicates a mantle history of periodic buildup of fluid pressures, followed by the injection and crystallization of melts. Repetition of the sequence causes hydraulic fracturing of earlier injections and produces crosscutting relations that are consistent with the eruption history at Cima, which is characterized by the episodic generation of small volumes of melt over long periods of time. The fact that old and young lavas in the field contain the same xenolith populations indicates that the magmatic episodes occurred in the same source area and that earlier products of intrusion were affected by later episodes of melt production.

Some bulk chemical parameters (Fig. 3) indicate an overall compositional coherence in the xenolith-host rock assemblage, which we believe indicates a genetic relationship between the host rock and the igneous xenoliths. We interpret the xenolith assemblage to represent batches of basaltic melts emplaced in the mantle near the crust boundary (as envisaged by Thompson, 1974 and Ewart et al., 1980). The parent melts are not represented in erupted magma. Differentiation of the parent led to formation of evolved hawaiite liquids. Separation of Ca-poor pyroxene formed the green-pyroxene group and produced liquids that trend toward more undersaturated compositions (Thompson, 1974). Separation of kaersutite and aluminous high-calcium pyroxene that formed the Al-augite group, produced liquids of hy-normative compositions (Vaniman et al., 1982).

Characteristic features of the Cima volcanic field are a long eruptive history of small volumes of lava and a wide variability of normative composition. These features may arise from production of small volumes of melt that differentiate in the mantle. Numerous melt batches emplaced in a restricted mantle area may have been isolated from each other and may have evolved in different directions. A long history of these events makes mixing of derivative magmas likely. Incomplete mixing may explain the observed wide chemical variations within a single flow (Breslin, 1982).

TABLE 1. XENOLITH MINERAL ASSEMBLAGES AND AVERAGE MINERAL COMPOSITIONAL DATA

	Clinopyroxene and Orthopyroxene						Plagioclase			Olivine	Oxides			
Xenoliths	Ca	Mg	Fe	TiO_2	Al_2O_3	Cr_2O_3	An	Ab	Or	Fo	Oxide	Mg	Cr	Ti
Cr-diopside Group														
Lherzolite		(Cpx + Opx + Ol + Oxide)												
Cpx	45-49	46-50	4-5	0.17-0.40	3.2-5.4	0.76-1.2	--	--	--	--	Mg-Al chromite	0.69	0.39	0.0
Opx	1-2	87-90	8-11	.06-.09	2.5-3.9	.39-.52	--	--	--	--	Spinel	.68-.71	.12-.46	0.03-.07
Ol	--	--	--	--	--	--	--	--	--	90-91	--			
Websterite		(Cpx + Opx ± Ol ± Oxide)												
Cpx	46	44	10	.04	4.8	.88	--	--	--	--	--			
Opx	1-2	82-89	9-16	.08	3.4	.45	--	--	--	--	--			
Feldspathic Lherzolite (Cpx + Opx + Ol + Pc ± Oxide)														
Cpx	44-46	47-49	5-8	.40-.81	5.4-6.5	.56-.75	--	--	--	--	--			
Opx	1-2	81-89	9-18	.13-.27	2.7-4.0	.28-.43	--	--	--	--	Spinel	.60-.79	.14-.17	0.0
Pc	--	--	--	--	--	--	45-66	33-53	1-2	--	--			
Ol	--	--	--	--	--	--	--	--	--	88-90	--			
Green-pyroxene Group														
Websterite		(Cpx + Opx ± Pc ± Hbl ± Oxide)												
Cpx	39-43	45-48	12-13	.90-1.4	5.5-6.2	.17-.37	--	--	--	--	--			
Opx	3	72-79	18-25	.27-.30	2.7-3.0	.31-.36	--	--	--	--	Ilmenite	.26-.28	.40-.60	.96-.99
Pc	--	--	--	--	--	--	53-54	45-46	1	--	--			
Gabbro		(Cpx + Opx + Pc ± Ol ± Oxide)												
Cpx	40-43	40-43	17	.50-1.2	2.6-5.6	.04-.06	--	--	--	--	--			
Opx	2-4	70	26-28	.28-.32	2.4-3.0	.11-.17	--	--	--	--	Ilmenite	.28	.22	.99
Pc	--	--	--	--	--	--	48-55	44-51	1	--	Titanomagnesio-			
Ol	--	--	--	--	--	--	--	--	--	67	ferrite	.64	0.0	.71
Microgabbro		(Cpx + Opx + Pc ± Ol + Oxide)												
Cpx	40	44	16	1.6	5.6	.05	--	--	--	--	Titanomagnetite-			
Opx	2	70	28	.41	2.9	.01	--	--	--	--	Ulvospinel	.18	.09	.79
Pc	--	--	--	--	--	--	42	56	2	--	Titanomagnesio-			
Ol	--	--	--	--	--	--	--	--	--	70	ferrite	.14	.10	.79
Al-augite Group														
Pyroxenite		(Cpx ± Pc ± Hbl ± Ol ± Phlog. ± Oxide)												
Cpx	44-46	43-46	8-13	1.1-1.5	6.4-8.4	.01-.04	--	--	--	--	Titanian-			
Pc	--	--	--	--	--	--	59	40	1		hercynite	.31	.30	.63
Ol	--	--	--	--	--	--	--	--	--	70	Ilmenite	.25	.28	.99
											Pleonaste	.60-.61	.0-.01	.01-.07
Gabbro		(Cpx + Pc ± Ol ± Hbl + Oxide)												
Cpx	44-45	43-44	12	1.1-1.6	6.4-8.7	.0-.40	--	--	--	--	Pleonaste	.59-.67	.0	.01-.07
Pc	--	--	--	--	--	--	48-61	37-50	2	--	Titanian-			
											ferropleonaste	.18	.0	.53
Microgabbro		(Cpx + Pc ± Ol ± Hbl ± Oxide)												
Cpx	40	43	17	1.6	5.6	.05	--	--	--	--	Ilmenite	.19	.20	.98
Pc	--	--	--	--	--	--	45	53	2	--	Titanomagnetite-			
Ol	--	--	--	--	--	--	--	--	--	65	Ulvospinel	.22	.15	.84

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