

Relict pyroxenes from the Preston Peak ophiolite, Klamath Mountains, California

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Abstract

Relict clinopyroxenes in greenschist facies mafic rocks from the Preston Peak ophiolite are calcic with low Al_2O_3 and TiO_2 contents. Despite significant textural variation between the mafic rocks of the ophiolite, compositional variation, specifically iron enrichment, is minimal. The clinopyroxenes in the metadiabasic and metabasaltic rocks are distinctly hypersthene normative, while clinopyroxenes from coarse-grained xenoliths (disrupted cumulates) contain negligible normative nepheline. Furthermore, the pyroxene compositions indicate that the coarse-grained xenoliths crystallized from the least fractionated magmas, and clinopyroxene compositions from the younger metadiabase sill-dike complex and the overlying lavas indicate moderate but increasing differentiation. The pyroxene data, coupled with field relations and whole-rock geochemical data, are compatible with the suggestion that a substantial part of the mafic constructional pile of the ophiolite was produced during primitive island-arc magmatism. Near the base of the ophiolite both amphibolite and composite amphibolite-spinel lherzolite tectonic inclusions occur in serpentinite-matrix mélange. The spinel lherzolite is characterized by a mylonitic texture and contains porphyroclasts of aluminous pyroxenes. These tectonite inclusions appear to reflect a high-temperature ductile deformation which occurred early in the history of the ophiolite, for mafic dikes related to the overlying constructional pile intrude these tectonitic rocks.

Introduction

Ophiolite assemblages have commonly undergone complex metamorphic alterations, often including a pervasive greenschist facies event, which reflect the multi-stage history of these rocks (Coleman, 1977). Ion migration and redistribution, apparently widespread during low-grade greenschist facies metamorphism (e.g., Smith, 1968), limit the use of major-element chemical data for interpreting the origin of ophiolite lithologies. Although rare-earth elements do appear immobile during low-grade metamorphism (i.e., Pearce and Cann, 1971; Bickle and Nisbet, 1972; Kay and Senechal, 1976), these data rarely provide a unique "fingerprint" of magmatic history in the absence of good major-element control.

Many recent studies (e.g., Hashimoto, 1972; Valance, 1974; Garcia, 1975, 1979; Hynes, 1975; Barron,

1976; Nisbet and Pearce, 1977) indicate that relict pyroxenes appear to retain valuable information about both the original magmatic character and the differentiation history of metamorphosed mafic igneous rocks. Therefore, in light of these data, relict pyroxenes from five greenschist facies rocks, representative of the textural variation within the mafic segment of the Preston Peak ophiolite, have been analyzed in order to "see through" the metamorphism and better delineate the history of this ophiolite.

The Preston Peak ophiolite forms the base of an allochthonous sheet of the so-called western Paleozoic and Triassic rocks of the west-central Klamath Mountains (Fig. 1). Dismembered ophiolitic elements occur throughout the Klamath Mountains, but extensive, pseudostratigraphic terranes are best developed as complexly faulted thrust plates above major eastward-dipping regional faults (Irwin, 1977).

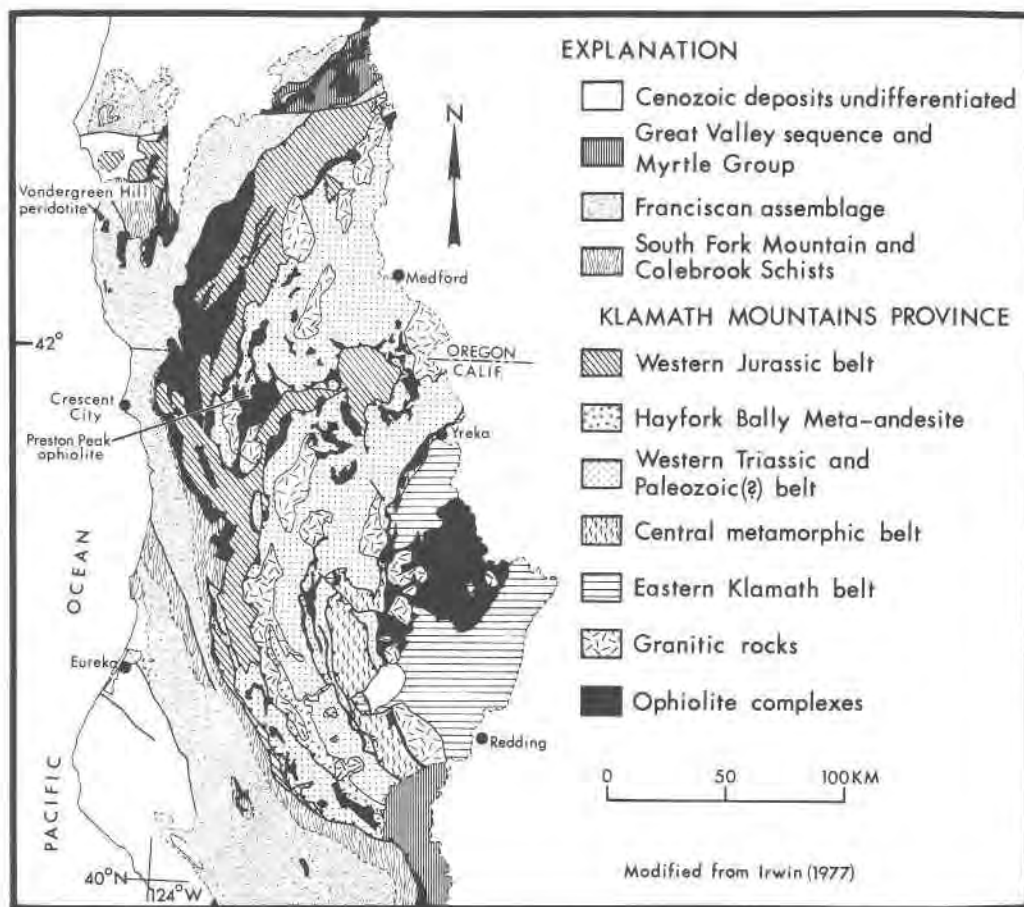


Fig. 1. Generalized geologic map of the Klamath Mountains, California and Oregon.

The ultramafic-mafic rocks which constitute these ophiolite allochthons are locally positionally overlain by fossiliferous metasedimentary rocks which fix a minimum age on the underlying metagneous rocks (Irwin, 1973). Although stratigraphic details remain conjectural, the overall tectonic pattern of the Klamath Mountains province appears to record gradual accretionary growth by the addition of fragments of volcanic arcs and associated epiclastic deposits, oceanic crust and upper mantle rocks, and mélangé terranes during Paleozoic to Late Mesozoic subduction (Hamilton, 1969, 1978).

The Preston Peak ophiolite consists of a basal ultramafic sheet overlain and intruded by a mafic complex locally overlain by metasedimentary rocks (*i.e.*, siliceous argillite, chert, and volcanic grit). A fault-bounded sequence of metabasaltic and metasedimentary rocks represents the fragmented upper part of

the ophiolite (Fig. 2). The ultramafic sheet which lies directly above a regional thrust fault is serpentinized peridotite (typically harzburgite) and minor dunite, locally with a tectonite fabric. The overlying mafic complex consists chiefly of statically metamorphosed diabase, diabase breccia, gabbro, and fine-grained basaltic rocks with a characteristic mineral assemblage: altered plagioclase, tremolite-actinolite, epidote, chlorite, opaque oxides/leucoxene (see Appendix for petrographic details). Complex field relations indicate that the mafic complex evolved through the continued episodic intrusion of basaltic magma (Snoké, 1977). Mafic rocks occur in the ultramafic rocks both as discrete dikes with chilled margins and as tectonic inclusions. The fault-bounded upper part of the ophiolite consists dominantly of spilite, including massive flows, pillow lavas and breccias, and flow and pyroclastic breccias. Detailed lithologic and

Mafic rocks with relict pyroxene grains are not widespread within the Preston Peak ophiolite. Relict pyroxenes in the medium- to coarse-grained rocks are invariably partially altered to various hydrous phases, and in fine-grained rocks the pyroxenes are commonly completely pseudomorphosed by actinolite and chlorite. The five mafic rocks chosen for study are the least altered examples of the major textural variations in the mafic segment of the ophiolite. More complete rock descriptions are presented in the Appendix and in Snoke (1977).

Pyroxene chemistry

The pyroxenes were analyzed on a MAC 400S microprobe using 3 wavelength-dispersive crystal spectrometers, accelerating voltage of 15 kV, and a sample current of 0.05 to 0.07 μ A. Analyzed natural and synthetic minerals were used as standards to minimize matrix effects. The data were corrected using the procedure of Bence and Albee (1968) with the appropriate alpha factors of Albee and Ray (1970). Each analysis is the average of at least five grains per sample. Each grain analysis was the average of at least five 20-second counts, in order to reduce the statistical counting errors to less than ± 2 percent of the amount present.

Pyroxene compositions from the five mafic rocks and spinel lherzolite are summarized in Table 1. In Figure 3 pyroxene compositions are plotted on the pyroxene quadrilateral and compared with several well-documented pyroxene crystallization trends.

These pyroxenes are characterized by low contents of Al_2O_3 and TiO_2 , characteristics typical of clinopyroxenes from nonalkalic rocks (Le Bas, 1962), including both ocean-floor tholeiite and volcanic arc basalt (Nisbet and Pearce, 1977). The pyroxenes from the coarse-grained xenoliths contain negligible normative nepheline, while the pyroxenes from the metadiabase and metabasalt are strongly hypersthene normative. Furthermore, all of the clinopyroxenes from the mafic rocks plot within the tholeiite field (Fig. 4) on Coombs' basalt plot (Coombs, 1963). Therefore, pyroxene compositions as well as the available rare-earth element distribution patterns of the metadiabases (Snoke *et al.*, 1977) imply a tholeiitic parentage.

The coexisting pyroxenes from the spinel lherzolite are aluminous and appear similar to pyroxenes described from ultramafic masses such as the Lizard peridotite (Green, 1964), the Tinaquillo peridotite (Green, 1963), and the peridotites from southwestern

Oregon (Medaris, 1972). The 100 Mg/(Mg+Fe+Mn) ratio (90.5) and the low CaO content of the orthopyroxene are similar to the orthopyroxenes from Cordilleran alpine peridotites (for example, Himmelberg and Coleman, 1968; Himmelberg and Loney, 1973). However, the high alumina content (6.0 weight percent) is unlike most Cordilleran alpine peridotites, with the only similar occurrence being the peridotites of southwestern Oregon (Medaris, 1972). The aluminous clinopyroxene likewise has a high 100 Mg/(Mg+Fe+Mn) ratio (92.9), but is also characterized by a high content of Na_2O . This Na_2O content is equivalent to 9.8 percent jadeite. The mineral chemistry of the clinopyroxene from the spinel lherzolite is also unlike analyzed clinopyroxenes from typical Cordilleran alpine peridotites but remarkably similar to the aluminous diopside described by Medaris (1972). In addition to Na_2O , the aluminous clinopyroxene has higher TiO_2 and Al_2O_3 contents than the coexisting aluminous orthopyroxene. The characteristics are identical to the relationships detailed by Medaris (1972) for coexisting pyroxenes from the southwestern Oregon peridotites.

Discussion

Compositional variation in pyroxenes from the Preston Peak ophiolite confirm the multi-stage history of the complex previously suggested by geologic mapping (Snoke, 1977) and whole-rock geochemistry (Snoke *et al.*, 1977). The new data indicate that spinel lherzolite containing aluminous pyroxenes occurs in the basal ultramafic sheet. This occurrence, along with some of the peridotites of southwestern Oregon (Medaris, 1972), is similar to the "high-temperature" peridotites described by Green (1967). Such lherzolitic rocks apparently represent somewhat less depleted mantle rock (Menzies, 1976a,b), in contrast to harzburgite-dunite tectonite, which is the characteristic ultramafic lithology of the Preston Peak ophiolite as well as all other Cordilleran ophiolites.

Some authors (for example, MacGregor, 1974) have argued that the alumina content of orthopyroxene is a useful geobarometer for the spinel lherzolite mineral assemblage. However, the Al_2O_3 isopleths in Obata's (1976) calculated phase diagram from the system MgO- Al_2O_3 - SiO_2 have a shallow slope in the spinel peridotite field and are almost horizontal below 1000°C. As Obata points out, these shallow slopes make it impossible to use Al_2O_3 solubility in orthopyroxene of a spinel lherzolite to esti-

Table 1. Compositions and structural formulae of relict pyroxenes from the Preston Peak ophiolite, Klamath Mountains, California

	Spinel lherzolite		Metapyroxenite	Metagabbro	Metadiabase		Metabasalt
	PP-408A (opx)	PP-408A (cpx)	298-6A	PP-374	298-6B	PP-376	32-14-7A
SiO ₂	53.6	52.8	52.8	53.6	53.1	52.3	52.8
TiO ₂	.16	.56	.22	.43	.5	.51	.44
Al ₂ O ₃	6.0	6.7	2.6	2.7	2.7	3.3	2.4
FeO*	6.1	2.0	3.7	4.9	5.5	5.7	6.6
MgO	32.9	15.4	16.7	16.4	17.4	15.3	16.9
MnO	.08	.09	.12	.14	n.d.	.10	.15
CaO	.9	21.0	23.3	22.7	21.4	21.6	21.3
Na ₂ O	.01	1.40	.13	.53	n.d.	.08	.10
Total	99.75	99.95	99.57	101.40	100.6	98.89	100.69
Structural formulae based on 6 oxygens							
Si	1.856	1.899	1.935	1.936	1.929	1.936	1.929
Al ^{IV}	0.144	0.101	0.065	0.064	0.071	0.064	0.071
Al ^{VI}	0.101	0.183	0.047	0.051	0.045	0.080	0.032
Ti	0.004	0.015	0.006	0.012	0.014	0.014	0.012
Fe	0.177	0.060	0.113	0.148	0.167	0.176	0.202
Mn	0.002	0.003	0.004	0.004	—	0.003	0.005
Mg	1.698	0.825	0.912	0.883	0.942	0.844	0.920
Ca	0.033	0.809	0.915	0.878	0.833	0.857	0.834
Na	0.001	0.098	0.009	0.019	—	0.003	0.007
X+Y	2.016	1.993	2.006	1.995	2.001	1.977	2.012
Atomic %							
Ca	1.7	47.7	47.1	45.9	42.9	45.6	42.5
Mg	88.9	48.6	46.9	46.2	48.5	44.9	46.9
Fe+Mn	9.4	3.7	6.0	7.9	8.6	9.5	10.6
$\frac{100 \text{ Mg}}{\text{Mg+Fe+Mn}}$	90.5	92.9	88.6	85.3	84.9	82.5	81.6

* Total iron as FeO.
n.d. = not determined.

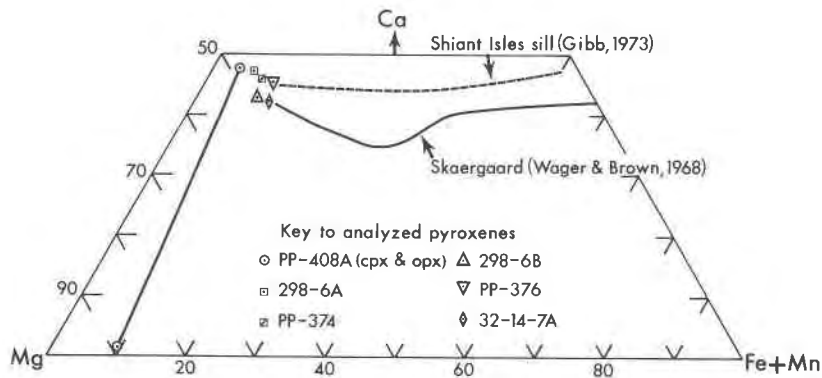


Fig. 3. The pyroxene quadrilateral with compositions of analyzed relict pyroxenes plotted with respect to Ca, Mg, and (Fe + Mn) atoms.

mate pressure. Therefore, although the co-existing mineral assemblage clearly indicates high-temperature recrystallization (probably 1000–1300°C, according to data of Herzberg and Chapman, 1976), correspondingly high pressures as suggested by Medaris (1972) cannot be evaluated.

The pyroxene compositions from the mafic rocks which intruded and overlie the basal ultramafic tectonite suggest additional implications concerning the evolution of the ophiolite. The analyzed clinopyroxenes display a remarkably small range in iron enrichment ($\text{Ca}_{47.1}\text{Mg}_{46.9}\text{Fe}_{6.0}$ – $\text{Ca}_{42.5}\text{Mg}_{46.9}\text{Fe}_{10.6}$), a characteristic also substantiated by whole-rock chemical data (Snok *et al.*, 1977). The limited iron enrichment is

similar to the limited iron enrichment pattern of Ca-rich pyroxenes from Eua, Tongan Islands (Ewart and Bryan, 1972). However, the coarse-grained ultramafic and mafic xenoliths, which appear to be disrupted cumulates or, in a few cases, fragmented plutonic screens, imply that conditions appropriate for magmatic differentiation prevailed during the evolution of the mafic complex. We favor a model involving the emplacement of multiple batches of magma which undergo limited differentiation *via* crystal settling to explain the chemical and petrological data. These small magma chambers appear to have been frequently intruded and disrupted by fresh pulses of younger magma.

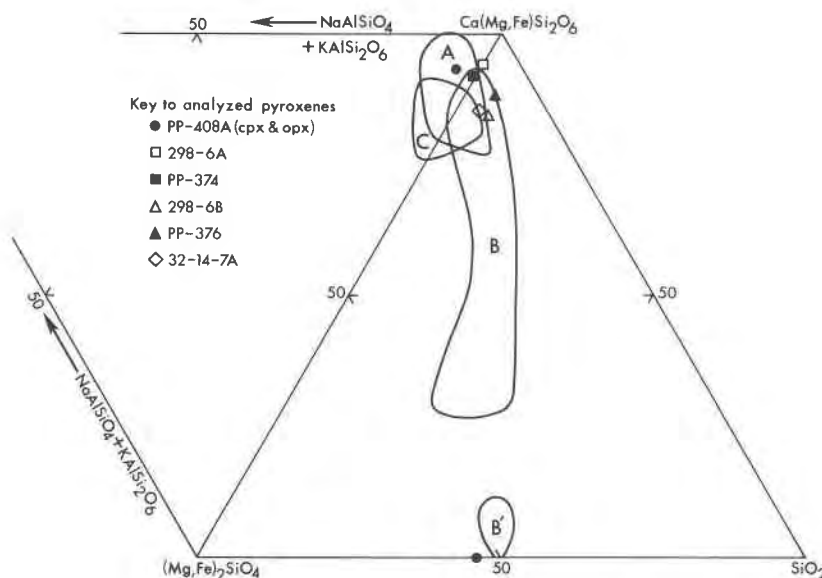


Fig. 4. Normative compositions of relict clinopyroxenes from the Preston Peak ophiolite plotted on a diagram after Coombs (1963). Pyroxenes from alkaline basaltic rocks plot in field A, tholeiitic rocks in field B, and peridotitic inclusions in field C.

Furthermore, the minor iron enrichment of the clinopyroxenes and their calcic character could also be related to P_{H_2O} during crystallization. Several authors (for example, Deer and Abbott, 1965; Murray, 1972) have argued that limited iron enrichment and high calcium content in clinopyroxenes are characteristic of tholeiitic magmas that have crystallized under high P_{H_2O} conditions. The following field observations are also suggestive of at least moderate P_{H_2O} conditions during the magmatic evolution of the mafic complex:

- (1) pyroclastic breccias consisting of texturally diverse basitic clasts are an essential element of the mafic complex,
- (2) hornblende-bearing gabbroic rocks are a relatively common constituent of the mafic complex,
- (3) hornblende-plagioclase pegmatoid and hornblende-rich dikes are locally present in the mafic segment of the ophiolite.

Finally, Mg/Fe ratios in the analyzed clinopyroxenes suggest that the upper lavas (for example, 32-14-7A) crystallized from magmas slightly more differentiated than the magmas which produced the coarse-grained rocks. This observation is further substantiated by the variation in clinopyroxene composition between the clinopyroxenite xenolith (298-6A) and its diabasic host (298-6B), as shown in Figure 3. In other words, the fine-grained lavas appear more differentiated than diabases from the dike-sill complex, which in turn are more differentiated than the coarse-grained xenoliths. Norman and Strong (1975) have documented a similar relationship in ophiolitic rocks from Newfoundland, and Strong and Malpas (1975) suggest that this increase in magmatic differentiation from coarse- to fine-grained rocks is a general feature of ophiolites.

In summary, one of us (AWS) has argued that a considerable portion of the Preston Peak ophiolite developed during primitive island-arc magmatism (Snoké, 1977; Snoké *et al.*, 1977). Our data indicate that a composite, polygenetic history seems to be necessary to account for the lithologic variation in the ophiolite. Furthermore, field, petrologic, and geochemical data from the mafic constructional pile of the ophiolite are consistent with available data from terranes considered to represent the early stage of island-arc evolution such as Eua, Tongan Islands (Ewart and Bryan, 1972). The relict pyroxenes in the mafic rocks (and the spinel lherzolite) which we have analyzed appear to have retained their original

chemical composition and are consistent with the primitive island-arc origin for this ophiolite complex.

Appendix

298-6A—Serpentinized clinopyroxenite. The original primary igneous minerals were olivine and clinopyroxene. The presence of primary olivine is inferred from serpentine-chlorite-talc pseudomorphs webbed with magnetite. The pyroxene grains are partially pseudomorphosed by colorless clinoamphibole and chlorite but are locally well preserved. Thin exsolution lamellae parallel to (100) are common in the clinopyroxenes.

PP-374—Saussuritized gabbro. Despite ubiquitous greenschist facies alteration, calcic plagioclase and relicts of clinopyroxene are still present. The original hypidiomorphic-granular texture with a weak grain shape orientation is well preserved. Plagioclase is heavily saussuritized, but original features such as twin lamellae and compositional zoning are still evident. Pyroxene grains are totally to partially pseudomorphosed by fibrous pale green tremolite-actinolite and irregular chlorite aggregates.

298-6B—Metadiabase. An intergranular texture is well preserved with clinopyroxene grains locally forming slightly larger subhedral grains. The mineral assemblage is altered plagioclase, clinopyroxene, tremolite-actinolite, chlorite, epidote, and opaque oxides/leucogene. The pyroxene grains are exceptionally fresh with hydrous alteration minerals (chiefly tremolite-actinolite and chlorite) concentrated along cracks within the grains and around the margins of the grains.

PP-376—Metadiabase. This sample has a well-developed intergranular texture with the identical mineral assemblage as 298-6B. Pyroxene grains are noticeably more altered to tremolite-actinolite and chlorite than in 298-6B, but many relict grains are present. A modal analysis of this rock yielded the following data (in volume percent): altered plagioclase = 41½, tremolite-actinolite = 20½, epidote = 14½, clinopyroxene = 13, chlorite = 8, and opaque oxides/leucogene = 2½.

32-14-7A—Microporphyratic metabasalt. The sample is aphanitic with microphenocrysts of altered plagioclase and clinopyroxene. The complete mineral assemblage is typical of low-grade greenschist metamorphism and includes: plagioclase (altered calcic plagioclase and metamorphic albite), clinopyroxene

(relict), tremolite-actinolite, clinozoisite, chlorite, carbonate, and opaque oxides/leucosene. The rock is incipiently brecciated with the fractures filled by clinozoisite, albite, carbonate, and chlorite. The pyroxene microphenocrysts are altered along cracks within the grains, but kernels of fresh clinopyroxene are common.

PP-408A—Serpentinized spinel lherzolite. The original anhydrous mineral assemblage was forsterite, enstatite, diopside, and chromian spinel. Despite some hydrous alteration, the original porphyroclastic texture as well as many of the primary minerals are well preserved. Multi-grain augen occur in a serpentinized matrix of forsterite, enstatite, diopside, and spinel. The augen are dominantly enstatite and diopside but also include forsterite grains. The mineral grains in the augen show ubiquitous evidence of solid-state deformation including undulatory extinction, kink bands, and deformed exsolution lamellae. Grain boundaries within the multi-grain augen are irregular and interlocking. The boundary between the augen and the matrix is sharp to intergrown. These characteristics are identical to the petrographic description given by Medaris (1972) for the so-called "high-pressure" Vondergreen Hill peridotite of southwestern Oregon.

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