Assimilation of peridotite in zoned calc-alkaline plutonic complexes: evidence from the Big Jim complex, Washington Cascades

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Abstract. The Big Jim complex is a concentrically zoned ultramafic to felsic plutonic complex which intruded the pelitic Chiwaukum schist. Most of the major plutonic rock types (from websterite through hornblendite, gabbronorite, hornblende gabbro and diorite, to granodiorite) enclose harzburgite and metaperidotite xenoliths similar to foliated metaperidotite lenses included in the Chiwaukum schist. The larger xenoliths preserve tectonite fabrics. All have Mg #'s (mole fraction MgO/(MgO + FeO*)) from 0.90 to 0.89, the same as those of Chiwaukum metaperidotites, and distinctly different from undeformed Big Jim dunite (Mg # s 0.84 to 0.82) and websterite (0.82 to 0.78). Contact relations indicate widespread, stepwise replacement of harzburgite by pyroxenite, hornblendite, gabbro and diorite. Thermodynamic modelling using an expanded regular solution model for silicate liquids (Ghiorso 1985; Ghiorso and Carmichael 1985) predicts that reaction between olivine (Fo90) and a liquid with the composition of Big Jim diorite +1.5 wt% H₂O, at 1,100° C and 3 kb, would produce websterite (Mg #'s 0.75 to 0.81) and dunite (0.79 to 0.82). This process is exothermic and results in a negative change in volume, since it increases total solid mass. Under conditions of decreasing temperature, modelled crystal fractionation with assimilation of olivine reproduces important features of the chemical variation observed in the Big Jim complex where crystal fractionation alone fails. The Big Jim complex has affinities with other ultramafic to felsic plutonic complexes such as the Bear Mountain complex (Snoke et al. 1981, 1982) and the Emigrant Gap complex (James 1971). The latter have wehrlite and clinopyroxenite, rather than websterite, but both have concentric zoning, with olivinebearing rock types surrounded by successively more felsic pyroxenite, gabbro and diorite. In general, concentrically zoned complexes of this type may form where magma reacts with mantle-derived wall rock or ultramafic cumulates. Assimilation of peridotite in fractionating magma may be important in subduction-related magmatic arcs.

Introduction

This paper presents a theory for the origin of compositional variation in some zoned ultramafic-mafic and ultramaficfelsic plutonic complexes. These are found in the western North American Cordillera from Kluane Lake in the Yukon (Kelemen, unpublished data) to Baja California (Snoke et al. 1982; Walawender and Smith 1980); the northern Appalachian Mountains (Cawthorn 1978), Japan (Onuki 1963, 1965), the southern Caribbean Mountain system (Murray 1972; AW Snoke, personal communication 1983), and the Ladakh batholith of the NW Himalaya (Honegger et al. 1982; Kelemen and Sonnenfeld 1983). Potentially related zoned gabbro-diorite associations are common; interesting examples are exposed in the Aleutian arc (Drewes et al. 1961; Fraser and Snyder 1959; Perfit et al. 1980).

The complexes to be discussed are compositionally zoned, with ultramafic rock separated from intermediate plutonic rocks by zones with successively more Al, Na and K, and less Mg, Fe and Cr. The zoning is developed in a variety of configurations: ultramafic rock may lie in the focus of a series of concentric zones, or near the periphery of the complex with successively more "felsic" types in the center. Contacts between the various rock types are primarily gradational. Exceptions are discordant dunite and wehrlite at Union Bay, Duke Island, Giant Mascot, and Emigrant Gap (Ruckmick and Noble 1959; Irvine 1974; Aho 1956; James 1971), wehrlite and pyroxenite dikes at Emigrant Gap, and hornblende-rich dikes in virtually all the complexes.

Zoning has been ascribed to three processes: (1) multiple intrusion, with successively more mafic magma intruded into the hotter, weaker center of an earlier pluton (Ruckmick and Noble 1959; Irvine 1963; Taylor and Noble 1960; Taylor 1967); (2) antiformal folding during diapiric emplacement of formerly stratiform cumulates (Irvine 1967, 1974; Findlay 1969; James 1971); and (3) flow differentiation, with early formed crystals migrating to the center of a moving body of magma (Bhattacharji 1964; Bhattacharji and Smith 1964; James 1971; Murray 1972). These hypotheses are similar in that they describe zoning in which the ultramafic rocks lie in the center, not always the case in otherwise similar complexes. Furthermore, they all assume that ultramafic rocks are younger than, or coeval with, more felsic types. In many complexes, however, felsic rocks are younger than at least some of the ultramafic rocks. This situation is especially clear where dunite and/or peridotite xenoliths are deformed while host pyroxenite is not, as at Emigrant Gap (James 1971) and Bear Mountain (Snoke et al. 1981).



Fig. 1. Regional geologic map. Compiled from Tabor et al. (1982) and unpublished field maps by B.R. Frost (personal communication 1983) and Kelemen (1984)

It is our hypothesis that concentric zoning in some complexes was caused by stepwise reaction between pre-existing ultramafic wall rock (alpine peridotite, ultramafic cumulates) and later magmas, ranging in composition from basalt to andesite. Ramp (1975) and Evans (1985) have invoked similar explanations for the origin of pyroxenite reaction zones on an outcrop scale. To demonstrate this hypothesis we describe one ultramafic-felsic plutonic complex, the Big Jim complex, in the Chiwaukum Mountains, an arcuate range in the north-central Cascades of Washington. The Big Jim complex intrudes tectonite harzburgite as well as pelitic schist. Harzburgite xenoliths within the complex are derived from the wallrock, and predate the plutonic rocks. Not all zoned ultramafic-mafic and ultramafic-felsic plutonic complexes intrude alpine peridotite, and we do not mean to imply that this specific case is universally applicable. Nevertheless, field relations observed at Big Jim allow generalization about reaction between ultramafic rock and more felsic liquid.

Regional geology

The SE to NW trend of the Chiwaukum Mountains parallels the main contacts between the Chiwaukum schist to the NE and the Mt. Stuart batholith to the SW (Fig. 1). The Chiwaukum schist has been described by Plummer (1969, 1980), Getsinger (1978), Kaneda (1980), Berti (1983), and Evans and Berti (1986). The petrology of the Mt. Stuart batholith was discussed by Pongsapich (1974) and Erikson (1977).

The Chiwaukum schist consists primarily of pelitic rocks; it also includes lenses of ultramafic rock, amphibolite and marble. The ultramafic lenses have contacts and internal foliation parallel to foliation in pelitic schist. Some are relatively coarse, tectonite harzburgite; others are metaserpentinites, as indicated by their simple mineral assemblages and "jackstraw texture" (Evans and Trommsdorff 1974; Snoke and Calk 1978) in some specimens.

A metamorphic foliation, defined by parallel alignment of micas, compositional banding, and well developed kink-banding in olivine, formed in the Chiwaukum schist prior to intrusion of the Mt. Stuart batholith. Undeformed rocks of the batholith cross-cut foliation in the schist, and contact metamorphic andalusite and cordierite helicitically enclose the preexisting foliation (Plummer 1980; Erikson 1977; Evans and Berti 1986). A contact metamorphic gradient is associated with the Mt. Stuart batholith, reaching pyroxene hornfels facies along contacts with gabbro and diorite. Metabasites locally have the assemblage Opx - Cpx - Plag - Hb; pelitic rocks contain Sill - Gnt - Cord. Along contacts and in isolated screens, pelitic rocks have undergone partial melting. Restites contain Opx, aluminous spinel, Cord, Gnt, and corundum. A regional gradient extends from chlorite-bearing argillite and greenstone in the south (Southwick 1974) to kyanite-staurolite schists in the north. Hornfels throughout the area show partial reequilibration to regional metamorphic conditions. Contact metamorphism was dynamic, while subsequent recrystallization occurred under relatively static conditions (Kaneda 1980; Berti 1983; Evans and Berti 1986).

The Mt. Stuart batholith ranges in composition from gabbronorite to granite. Gabbronorite, hornblende gabbro, and pyroxene diorite are restricted to the margins of the batholith; more felsic rocks (quartz diorite to granite) comprise >70% of the outcrop area (Fig. 1). Tabor et al. (1982) report K-Ar ages between 83 and 95 Ma for the batholith, and a concordant U-Pb age of 97 MY on zircon from Big Jim gabbro. These data suggest that the complex is an early member of the batholith, continuous at depth with gabbroic rocks and mafic diorite of Icicle Ridge a few km to the south.

Mafic xenoliths are included in almost all rocks of the batholith, and increase in abundance in the more mafic rocks. Most inclusions are simply melanocratic clots of hornblende, biotite, opaque oxides and plagioclase; on Icicle Ridge, the xenolith suite includes olivine gabbronorite, websterite, orthopyroxenite, and hornblendite (Pongsapich 1974; Erikson 1977). Distinctive, elongate xenoliths, usually of hornblendite but locally with cores of relict peridotite, occur in gabbro and diorite near contacts with ultramafic rock. Members of the Mt. Stuart batholith rarely show evidence of penetrative deformation (Pongsapich 1974; Erikson 1977).

Contact relations

Metaperidotites in the Chiwaukum schist crop out in elongate lenses along or near contacts between the schist and the Mt. Stuart batholith. Pyroxenite, hornblendite, and gabbroic bodies of the Mt. Stuart batholith are also exposed along contacts between the schist and the batholith, often in direct contact with metaperidotite (Plummer 1969; Pongsapich 1974; Frost 1976; Getsinger 1978; Erickson 1977; Kaneda 1980; and Tabor et al. 1982).

Frost (1976) described contact metamorphosed metaperidotites from Icicle Ridge, about 5 km south of the Big Jim complex (Fig. 1). They have the assemblage Ol-Opx-Chl-Cr spinel, and



Fig. 2. Hornblende oikocrysts including spatially separated, optically continuous relicts of orthopyroxene, from contact zone between metaperidotite and biotite hornblende diorite of the Mt. Stuart batholith, Icicle Ridge, Washington. Field of view is approximately 2 mm wide



Fig. 3. Geologic map of the northern portion of the Big Jim complex

associated mafic rocks have Opx - Cpx - Hb - Plag, indicative of pyroxene hornfels facies. Along the contact between metaperidotite and gabbro are "amphibole-rich hybrid rocks": hornblendite, hornblende pyroxenite, hornblende peridotite, and diorite with ultramafic xenoliths and schlieren. Textures from samples collected by Frost (personal communication 1982) and Kelemen suggest that some of the hybrid rocks formed by reaction between magma and metaperidotite (Fig. 2). Optically continuous, spatially separate relicts of olivine and orthopyroxene within individual hornblende crystals show that reaction occurred at temperatures high enough to stabilize pargasitic hornblende in ultramafic and mafic bulk compositions. Brown hornblende in the xenoliths is optically identical to that in host diorite.

The Big Jim complex is a group of ultramafic to granitic rocks exposed over approximately 20 km^2 (Fig. 3). Dunite underlies

about 3% of the northern lobe, lherzolite <2%, websterite 10%, hornblendite 15%, melanocratic diorite and gabbro 25%, and leucocratic diorite to granodiorite 45% (Fig. 3). The complex shows roughly concentric zoning, with the most mafic rocks ringed by successively more felsic varieties (Tables 1–4 present chemical analyses of representative rock samples. Note that websterite, gabbronorite, and melanocratic diorite from the complex all have equivalent concentrations of silica; mafic in this context means high MgO, FeO, Cr_2O_3 and NiO, low alumina and alkalies; felsic is the inverse).

Sub-rounded to sub-angular xenoliths of harzburgite are extremely common in Big Jim websterite. Some preserve parallel orientation of long, planar surfaces. Many have a bimodal grain size distribution: a few large grains of olivine with strain lamellae in a matrix of micron to mm scale olivine neoblasts. Xenoliths typi-

	USGS PCC-1	BJ82-239	BJ82-219a	BJ82-229a	BJ82-129a	BJ82-247	BJ82-133a
SiO ₂	42.0	42.8	43.8	42.0	40.0	46.3	45.0
TiO ₂	0.0	0.1	< 0.1	0.1	0.1	0.2	0.4
$Al_2 \tilde{O}_3$	0.8	1.5	1.0	0.5	0.5	2.3	3.8
Fe ₂ O ₃ *	8.0	9.3	9.45	10.3	15.9	10.6	12.1
MnO	0.11	0.08	0.09	0.10	0.15	0.14	0.17
MgO	43.0	41.5	42.2	44.0	42.0	29.5	27.0
CaO	0.5	1.1	0.9	0.5	0.5	8.4	7.3
Na ₂ O	< 0.1	0.1	0.1	< 0.1	< 0.1	0.4	0.7
K ₂ Õ	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
LÕI	5.12	2.55	1.42	1.17	0.35	1.33	2.88
Cr_2O_3	0.300	0.240	0.310	0.350	0.300	0.290	0.250
Total	99.8	99.3	99.3	99.0	99.8	99.6	99.6

Table 1. Chemical analyses of olivine-bearing ultramafic rocks. All reported chemical analyses performed by Bondar-Klegg, Ltd. of Vancouver, BC. Values in wt%

USGS PCC-1: USGS standard; BJ82-239: metaperidotite from Chiwaukum schist; BJ82-219a,-229a: harzburgite xenoliths; BJ82-129a, 247, 133a: replacive veins cutting websterite; 129a: dunite, 247: wehrlite, 133a: olivine hornblendite

Table 2. Chemical analyses of Big Jim websterite and hornblendite. Values in wt%

	BJ82-113p	BJ82-113t	BJ82-129b	BJ82-134d	BJ82-219d	BJ83-133b	BJ82-235a
SiO ₂	54.0	53.3	54.3	51.3	54.4	51.8	45.8
TiO	0.4	0.3	0.3	0.5	0.3	0.4	1.2
Al ₂ Õ ₂	2.0	2.0	2.0	4.4	2.4	4.0	11.2
Fe ₂ O ₂ *	11.2	9.7	10.7	11.4	11.3	12.3	12.0
MnO	0.22	0.18	0.17	0.19	0.19	0.17	0.17
MgO	21.0	22.0	25.0	20.5	23.5	25.0	15.5
CaO	11.3	10.0	6.7	10.3	6.2	3.0	11.0
Na ₂ O	0.3	0.3	0.2	0.7	0.1	0.5	1.4
K ₀	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	0.1
LÕI	0.18	1.53	0.06	0.68	1.42	1.87	1.25
Cr ₂ O ₃	0.170	0.210	0.220	0.160	0.180	0.210	0.110
Total	100.77	99.52	99.6	100.1	100.0	99.2	99.8

BJ82-113p, 113t: websterite and replacive, tremolite-rich ultramafic amphibolite; BJ82-129b, 134d, 219d: hornblende websterite; BJ82-133b: massive hornblendite; BJ82-235a: hornblendite dike

Table 3. Chemical analyses of Big Jim gabbronorite. Values in wt%

	BJ82-11	BJ82-38	BJ82-51a	BJ82-110a
SiO ₂	50.6	51.0	51.1	52.4
TiO ₂	1.0	0.9	0.6	0.5
Al ₂ Õ ₃	15.3	9.0	9.0	5.8
Fe ₂ O ₃ *	11.0	10.9	12.5	12.6
MnO	0.17	0.17	0.23	0.22
MgO	10.4	14.2	15.0	18.2
CaO	9.8	11.8	10.3	9.7
Na ₂ O	1.6	1.0	0.9	0.6
K₂Õ	< 0.1	0.1	< 0.1	< 0.1
LÕI	0.83	1.0	0.17	0.18
Cr_2O_3	0.070	0.140	0.070	0.140
Total	100.8	100.2	99.9	100.3

Table 4.	Chemical	analyses	of	Big	Jim	diorite	to	granodiorite.
Values in	1 wt%							

	BJ82-6a	BJ82-33	BJ82-50	BJ82-55a	BJ82-96b	
SiO ₂	50.6	65.3	55.5	55.5	59.0	
TiO ₂	2.0	0.8	0.9	0.9	1.2	
Al ₂ Õ ₃	13.1	14.5	16.3	15.3	15.5	
Fe ₂ O ₃ *	12.2	5.0	7.9	9.2	6.7	
MnÕ	0.15	0.08	0.10	0.12	0.10	
MgO	9.2	2.9	7.0	7.8	4.1	
CaO	6.9	4.2	7.7	8.0	6.4	
Na₂O	2.1	3.1	3.1	2.8	3.4	
K₂Ō	2.6	3.1	1.1	0.5	1.7	
LŌI	0.86	0.83	0.54	0.18	0.77	
Cr_2O_3	0.050	0.020	0.040	0.030	0.025	
Total	99.8	99.8	100.2	100.3	98.9	

cally include cm scale aggregates of Opx + olivine + Cr - Al spinel, inferred to be the prograde breakdown products of chromian chlorite (+/- Fe-Cr oxides). Some large xenoliths preserve tectonite fabrics (Fig. 4a), unlike undeformed lherzolite, websterite and dunite of the complex (Fig. 4b), but identical to fabrics in alpine peridotite lenses of the Chiwaukum schist. A few also preserve jackstraw texture, characteristic of Chiwaukum metaserpentinites. Chemical compositions of two harzburgite xenoliths are similar to that of a Chiwaukum metaperidotite and different from all Big Jim ultramafic rocks (Table 1). On the basis of this evidence it is inferred that the xenoliths are derived from alpine peridotite wall rock.



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Fig. 4. a Tectonite fabric in large, foliated harzburgite xenolith included in websterite.
b Polygonal crystals of olivine, and disseminated magnetite, in undeformed dunite. Field of view is approximately 2 mm wide. These photographs, and all photographs and sketches following this figure, from the Big Jim complex

On a thin section scale, the xenoliths are cut by micron to cm width veins of Opx, Cpx, and/or Hb. In textures very similar to Big Jim websterite, Opx occurs in mosaic textured aggregates of microcrystals or in subhedral crystals elongate parallel to vein contacts. Cpx is always anhedral and riddled with Hb inclusions. Hb is subhedral, elongate parallel to vein contacts, or anhedral. It is always poikilitic to Opx and Cpx. Opx, Cpx and Hb locally include relict olivine, optically continuous with olivine in vein walls.

Elongate trains of such xenoliths cross lithologic contacts within the Big Jim complex. These pass from websterite with harzburgite xenoliths through hornblendite, gabbronorite, and diorite including concentrically zoned blocks. A typical, large xenolith in diorite has a core of harzburgite, surrounded by concentric zones rich in magnesio-cummingtonite, tremolite, and hornblende, with a rim of hornblende gabbro. Smaller xenoliths in gabbro and diorite have been converted to homogeneous, angular blocks of hornblendite, melanocratic gabbro, and diorite. The latter are mineralogically almost identical to the host, but slightly darker or with a different texture. All stages in the transformation process may be seen in various blocks in a single outcrop (Fig. 5).

Both Pongsapich (1974) and Erikson (1977) report the abundance of "cognate" mafic xenoliths in the Mt. Stuart batholith. These are texturally and mineralogically identical to mafic xenoliths in the Big Jim complex. At Big Jim, the xenoliths are the result of reaction between magma and ultramafic blocks. Reaction did not involve melting of the xenolith; although some of the blocks are sub-rounded, others are angular, and all have sharp contacts with the host. Instead, assimilation involved the transfer of components by infiltration or by diffusion down activity gradients between xenolith and host.

Canon

Fig. 5. Harzburgite, hornblendite, and gabbro xenoliths in diorite

Petrography

Websterite

Websterite varies from 75 to 20% Opx, 60 to 20% Cpx, 40 to 5% Hb, and 10 to 0% opaque oxides. Opx > Cpx is more common than Cpx>Opx. Websterite only contains plagioclase within 5 m of contacts with gabbronorite or melanocratic diorite. Where it occurs, plagioclase is calcic, with An>80 in some cases. Olivine occurs as optically continuous, spatially separated relicts included in both Opx and Cpx within a few cm of harzburgite xenoliths (Fig. 6).

Opx occurs either in aggregates with 120 degree triple junctions (Fig. 7), or as subhedral prisms defining a general flow foliation. Opx has micron scale Cpx exsolution lamellae and local inclusions of pale brown Hb. Cpx is usually anhedral, interstital to Opx; it is consistently riddled with micron to mm scale Hb inclusions. These comprise up to 50% of the volume of Cpx crystals, and are optically continuous with adjacent, interstitial Hb. In some specimens, Hb includes optically continuous, spatially separate relicts of Opx and/or Cpx suggesting a reaction relationship in which pyroxene+melt reacted to form amphibole. Hb in websterite also

Fig. 6. Spacially separate, optically continuous olivine relicts in orthopyroxene from websterite in vicinity of harzburgite xenoliths. Field of view 2 mm wide. Ruled areas: Opx; stippled: olivine; grey: hornblende

forms cm scale, poikilitic veins cutting the equant, fine-grained pyroxenite matrix.

Dunite veins

Anastomosing dunite veins cut websterite in three distinct bands. Each band is mineralogically different from the others. The upper (eastern) band is composed of wehrlite as well as dunite, with 20 to 30% Cpx interstitial to olivine in some specimens. The central band is virtually pure olivine, except for crystals of relict pyroxene near vein walls. The lower (western) band contains hornblende dunite and olivine hornblendite as well as dunite, with Hb interstitial to olivine.

Olivine in one dunite analyzed by electron microprobe is Fo83 to 84 throughout the probe section (except adjacent to a late tremolite - Mg cummingtonite vein, where it is as Fe rich as Fo74). In contrast, olivine in harzburgite xenoliths ranges from Fo80 in small neoblasts adjacent to orthopyroxene veins to Fo90 in the larger crystals. Furthermore, olivine in the dunite vein has 0.20 ± 0.03 wt% NiO, whereas olivine in xenoliths has 0.38 ± 0.05 wt% NiO. The dunite veins include equant grains of olivine and uniformly distributed, interstitial, 0.1 mm scale opaque





diorite Jim co caused a well and set Typ moaxia Cpx Plagion in plag rocks. come r clase p

Fig. 8. Dunite veins (no pattern) in websterite (ruled areas). Field of view 3 meters wide

oxides (magnetite?), distinctly different from the aggregates of red brown Cr-Al spinel with Opx in harzburgite xenoliths.

Veins vary in width from 1 cm to more than 10 meters. The undisturbed continuity of the contacts of spatially associated blocks across intervening dunite indicate that the veins formed by in situ replacement of websterite. Neither dilation nor contraction of the bulk rock could be established in the field. Contacts between dunite veins and websterite are very sharp in some outcrops, gradational in others. Within websterite adjacent to veins, there is an abrupt increase in the proportion of modal Hb, and in pyroxene grain size. Lenticular websterite septa remain within wide veins (Fig. 8). Lherzolite, with embayed, relict pyroxene, forms bands in dunite veins continuing from pyroxenite septa. Reaction rims of light green Hb surround the pyroxene relicts.

Hornblendite

Hornblendite, with >50% brown to green Hb and <10% plagioclase, forms a discontinuous zone peripheral to websterite of the Main Ultramafic Slabs and Divide Peak. Elsewhere, hornblendite crops out in narrow screens with steep contacts in melanocratic

Fig. 7. Polygonal texture in orthopyroxene in websterite. Field of view 2 mm wide

diorite and in narrow lenses along the contact between the Big Jim complex and the schist. Unlike Big Jim diorite, which often caused partial melting in the schist, hornblendite does not have a well developed thermal aureole. Contacts between hornblendite and schist are invariably concordant to foliation in the schist.

Typically, poikilitic Hb includes pyroxene pseudomorphs of homoaxial tremolite and magnesio-cummingtonite (Fig. 9), or relict Cpx or Opx. Locally, embayed, relict olivine is present as well. Plagioclase, where present, is usually strongly saussuritized, unlike in plagioclase-bearing websterite, gabbronorite and more felsic rocks. Between hornblendite and diorite, the rocks generally become more coarse grained; in places these are hornblende-plagioclase pegmatoids, similar in texture to hornblende-plagioclase pegmatoids in other zoned complexes (Irvine 1974; Walawender 1976; Snoke et al. 1981, 1982).

Gabbroic rocks

Gabbronorite and hornblende gabbro (containing plagioclase with an average An > 50) are not common at Big Jim. In the field, dark intrusive rocks with >10% Plag were mapped as "gabbro and mafic diorite" unless they had >10% biotite. Rocks with >50% feldspar+quartz, and rocks with >10% biotite, were mapped as "biotite-hornblende diorite to granodiorite". This distinction results in a map pattern of regular compositional zoning, and is born out by chemical analyses, which show the mafic diorite is indeed richer in Mg, Fe and Ca and poorer in silica, alumina and alkalies than the biotite-hornblende diorite.

Gabbroic rocks, sensu stricto, are restricted to narrow zones (</=5 m) adjacent to websterite and hornblendite. In gabbronorite from such zones, calcic plagioclase ranges from An65 to An > 80 in a single specimen, though compositional zoning of individual crystals is rarely observed. Microprobe analyses of Opx and Cpx from gabbronorite and adjacent websterite show no discontinuity in mineral compostion between the two rock types. Some contacts between websterite and gabbronorite are sharp; most are gradational over a distance of a few meters. Plagioclase is rarely in contact with pyroxenes, the minerals being separated by a mm scale rim of brown to green hornblende. Some Opx aggregates preserve the equant mosaic texture characteristic of Opx in websterite. Beyond 5 m from websterite, pyroxene is virtually absent and plagioclase is andesine.



Fig. 9. Pyroxene pseudomorphs in hornblende oikocryst, in hornblendite. Field of view 0.5 mm wide

Many mafic diorites have large, composite plagioclase crystals with embayed, unzoned cores. These vary in composition, but the most calcic have An > 70, possibly An > 80. Rims of these composite crystals are zoned and range from An55 to An35. The cores have numerous inclusions of more sodic plagioclase, which are in optical continuity with the second generation rims. Both inclusions and rims probably formed by reaction between calcic plagio-clase cores and a more sodic melt.

Biotite-hornblende quartz diorite to granodiorite

Biotite-hornblende diorite to granodiorite is the most abundant phase of the Big Jim complex, where it comprises almost 50% of the plutonic rocks. Zoned plagioclase crystals range from An 55 to 25. Mafic minerals show consistent relationships, with biotite rimming and possibly replacing hornblende. Hornblende is of two distinct types, a brown variety often rimming composite amphibole glomerocrysts, and a pleochroic, green to tan variety which forms the core of such composite assemblages.

Hornblendite dikes

Narrow, melanocratic dikes composed of 70 to 100% brown hornblende cut all rock types in the complex except diorite and granodiorite. Hornblende, usually in prismatic crystals and rarely exceeding 2 or 3 mm in maximum dimension, may be accompanied by biotite, orthopyroxene, and/or very subordinate plagioclase. These dikes are restricted to within a few meters of ultramafic rocks. Hornblendite dikes are generally much finer grained, have sharper contacts with gabbro and websterite hosts, and include fewer alteration minerals than massive hornblendite in the complex. Hornblendite dikes cross cut massive hornblendite bodies. Furthermore, much of the hornblendite in the complex seems to have formed by replacement of websterite and peridotite, whereas hornblendite dikes are clearly injected: they dilate lithologic contacts, including earlier hornblendite dikes.

Ultramafic amphibolite

The term ultramafic amphibolite was used by Evans and Leake (1970) to describe rocks with ultramafic bulk composition com-

posed primarily of metamorphic amphibole. In this study, ultramafic amphibolite is distinguished from hornblendite in that it includes less than 50% hornblende. It has formed locally, as an alteration product of hornblendite, websterite, dunite veins, and olivine-rich xenoliths. It is composed of fibrous intergrowths of calcic and magnesian clinoamphibole, and minor olivine neoblasts with sharp crystal faces against the amphiboles. Opaque minerals occur but are volumetrically minor.

Two types may be distinguished, tremolite-rich ultramafic amphibolite, replacive of websterite and hornblendite and containing abundant tremolite, and an Mg-rich type, replacing dunite veins and harzburgite xenoliths. For Mg-rich amphibolite replacing dunite veins, SiO_2 as well as H_2O must have been introduced by a fluid phase. Mg-rich ultramafic amphibolite is less abundant than the tremolite-rich variety, only occurring within 20 m of contacts between plagioclase-bearing and ultramafic rocks. Commonly, unaltered dunite veins and harzburgite xenoliths occur in a websterite host completely replaced by amphibolite.

Subsolidus, metasomatic transformation of the Big Jim ultramafic rocks also included the formation of narrow, zoned veins. The presence of these veins and ultramafic amphibolite suggests that hydrothermal circulation of an aqueous fluid phase accompanied the cooling of the Big Jim complex. In all, veins of pyroxene, pyroxene-hornblende, hornblende, hornblende-plagioclase, tremolite-hornblende, tremolite-hornblende-chlorite, talc and antigorite have been sampled. These represent a continuum which spans the solidus, products of silicification and hydration of ultramafic rock by infiltrating magma and fluid in a regime of decreasing temperature.

Discussion of chemical analyses

Analyses of the more felsic Big Jim rocks (Tables 1–4) show a smooth trend parallel to typical calc-alkaline variation paths in the literature (Larsen 1948). Big Jim samples are consistently slightly richer in FeO + MnO + 0.9(Fe₂O₃) than the Mt. Stuart average compositions reported by Erikson (1977). If all analyses performed by Erikson (1977) and Pongsapich (1974) are considered, however, Big Jim samples fall within the Mt. Stuart range. The gabbroic rocks



Fig. 10. AFM plots for zoned ultramafic-mafic and ultramafic-felsic plutonic complexes. Not all examples plotted include olivine-bearing rocks. Data from: Irvine 1974 (Duke Island); Ruckmick and Noble 1959 (Union Bay); Lanphere et al. 1968 (Northern Klamaths, Trinity Mountains); James 1971 (Emigrant Gap); Snoke et al. 1981 (Bear Mountain); Hotz 1971 (Chetco River; see also Ramp 1975; Garcia 1982); Findlay 1969 (Tulameen); Springer 1980 (Pine Hill); Walawender 1976 (Los Pinos); Miller 1937 (San Marcos); Walawender and Smith 1980 (Peninsular Ranges); Best 1963 (Guadeloupe); Cawthorn 1978 (Tilting Harbor); and Honegger et al. 1982 (Ladakh batholith; see also Kelemen and Sonnenfeld 1983)

of the complex have M/(M+F) > 0.5, as in most zoned ultramafic-felsic plutonic complexes (Fig. 10).

Aside from the harzburgite xenoliths, the chemical compositions of samples from the Big Jim complex fall along a smooth trend. None of these rocks represent true liquid compositions, but the continuity of the trend suggests that they all crystallized from derivatives of a single parental magma composition. Additional evidence for such a relationship is (1) there are locally gradational contacts between all rock types on outcrop and microscopic scales, (2) no chilled margins were observed along contacts between the different phases, and (3) microprobe analyses of pyroxenes show a smooth compositional gradient from lherzolite through gabbronorite.

Semi-quantitative modelling of assimilation and crystallization in the Big Jim complex

Textural relationships observed in samples from the Big Jim complex indicate reactions between olivine and liquid (and/or fluid) producing orthopyroxene, clinopyroxene, and hornblende; between orthopyroxene and melt (and/or fluid) producing clinopyroxene and hornblende; and between clinopyroxene and melt (...) producing hornblende. The reactions involved show obvious similarities: they all consume phases high in Bowen's (1922a) discontinuous reaction series, plus liquid components, to produce phases lower in the series. Because of the well known peritectic behavior in the Mg₂SiO₄ – SiO₂ system, we might predict



Fig. 11a, b. Calculated volume change, enthalpy change, mass crystallized/mass assimilated, and "instantaneous" solid composition produced during isothermal, isobaric, equilibrium assimilation of olivine (Fo90) in Big Jim quartz diorite (BJ82-50+1.5 wt% H₂O). Input parameters were initial liquid composition, composition of assimilate, temperature (1,100° C), pressure (3 kb), and oxygen fugacity (QFM)

such reactions where a silica saturated magma intrudes olivine-rich rock. Further consideration suggests that all these reactions reduce the total volume and entropy of the system, since they involve transfer of components from the liquid to the solid state; therefore, all should be exothermic.

There is little precedent in the literature for calculating the effects of reactions between solid solutions and silicate liquids. The problem is essentially intractable without knowledge of the thermodynamic properties of components in natural magmas. An empirically calibrated, thermodynamically based solution model for silicate liquids (Ghiorso et al. 1983; Ghiorso 1985; Ghiorso and Carmichael 1985) permits the calculation of component activities, enthalpies and partial molar volumes.

The computer program SILMIN (Ghiorso 1985; Ghiorso and Carmichael 1985) was used to calculate pertinent reactions. Consider equilibrium assimilation of Fo90 by 100 gm of liquid with the composition of Big Jim diorite (BJ82-50). Runs were made with 1.5 wt% H_2O in the melt, at 1,100° C and 3 kb, on the QFM oxygen buffer. Under these conditions, SILMIN predicts the precipitation of 9.75 gm of Opx and 11.50 gm of Cpx from the unaltered liquid. Assimilation of 2 gm of olivine results in the further precipitation of 3.14 gm (0.031 moles) of Opx and 0.35 gm (0.0016 moles) of Cpx. The enthalpy change for the system is -412 joules, equivalent to -118 J/gm reactant.

In this simulation, about 5 mole% of the olivine has reacted to form Cpx (in an Fe free system: $Fo + 2 CaO_{(t)} +$ $3 \operatorname{SiO}_{2(l)} = 2\mathrm{Di}$) while 95% has reacted to form Opx (Fo + $SiO_{2(l)} = 2$ En). The solid – solid reaction enthalpy for this combination, (from data in Robie et al. (1979) for forsterite, clinoenstatite, diopside, tridymite and lime), is -133 J/gmreactant, slightly greater than the enthalpy change predicted by SILMIN. The predicted volume change accompanying the assimilation of 2 gm Fo90 is -10.6% of the reactant volume. Volume change calculated as a combination of the iron-free, end-member reactions, using calculated molar volumes of oxides in the liquid at 1,100° C from Mo et al. (1982), and solid molar volumes from Robie et al. (1979), corrected for temperature and pressure, is -11.3% of reactant volume. We conclude that results of calculations using SILMIN are of the correct magnitude and sign.

Volume change in the system is depicted in Fig. 11. $\Delta V_{\text{total}} = -1.14 \text{ cc}, -10.4\%$ of the volume of the reactants.



The ratio of mass crystallized (Mc) versus mass assimilated (Ma) varies from 1.745 after the first 2 gm of olivine are assimilated, to 1.065 after 40 gm. These values may be predicted in part by end-member reaction stoichiometry: Mc/ Ma is 1.43 for the reaction Fo + melt = 2 En; 3.08 for the reaction Fo + melt = 2 Di; and 1 for the equilibrium assimilation reaction Fo + melt = Fo + melt.

Bowen (1922b) considered the case of isothermal assimilation of forsterite in liquid in equilibrium with clinoenstatite in the binary system $Mg_2SiO_4 - SiO_2$. He predicted that the ensuing reaction would be exothermic and result in a negative volume change. However, his prediction diverges from that by SILMIN in the magnitude of Mc/Ma. Bowen argued that "desilication" of the magma, during stoichiometric conversion of olivine to pyroxene, would lead to further precipitation of clino-enstatite, until the liquid returned to the cotectic composition. He predicted Mc/Ma = 5at 1,550° C, about 20° C below the peritectic temperature in the binary. We have no reason to endorse or criticize this conclusion. Extrapolation from the binary system to natural silicate liquids has been fraught with peril, both for Bowen and his critics. It is difficult to visualize the multi-dimensional shape of the olivine - orthopyroxene peritectic or cotectic "surface". We simply note that, if Bowen is correct, the magnitude of the enthalpy and volume changes would be greater, and their sign the same.

As assimilation of olivine proceeds, calculations indicate a decrease in the concentration of silica in the magma, accompanied by a decrease in the magnitude of ΔH and ΔV . After 20 gm of Fo90 have been assimilated, olivine (Fo 79) appears on the liquidus of the modified model liquid (Fig. 11). The reaction Fo90 +liquid=Fo79 remains exothermic, with a small, negative ΔV , because it continues to produce more crystalline mass than it consumes. The model continues to predict crystallization of small amounts (0.02 to 0.03 gm) of Opx and Cpx. These are negligible in terms of mass balance, but their presence is significant. The discontinuous reaction, Fo + liquid = En, is a continuous reaction, Ol+liquid=Opx, in the iron-bearing system $(Mg_2SiO_4 - Fe_2SiO_4 - SiO_2)$. Opx and olivine become steadily more magnesian, and the amount of Opx produced continuously decreases.

If we assume that pyroxenite is cogenetic with more

Fig. 12. AFM plot comparing chemical composition of rocks from the Big Jim complex and the Mt. Stuart batholith to calculated liquid and solid compositions for isobaric, equilibrium crystallization of Big Jim quartz diorite, with and without combined assimilation. Data for the Mt. Stuart batholith from Pongsapich (1974) and Erikson (1977). Dashed lines enclose fields defined by all available analyses of Big Jim and Mt. Stuart samples. Composition of assimilated olivine was Fo90; composition of pelitic assimilate is given in Table 5. Assimilation rates (2 gm/25° C) are relative to 100 gm initial liquid. Input parameters were initial liquid composition, composition and mass of assimilate at each temperature increment, temperature (1,200 to 1,000° C), pressure (3 kb), and oxygen fugacity (QFM). Calculated paths for fractional crystallization are not significantly different from the equilibrium paths presented here

felsic rocks at Big Jim and other zoned ultramafic-felsic complexes, several problems with this simple-minded model become evident. Isothermal assimilation produces pyroxenite with more Opx than Big Jim websterite, and does not account for chemical variation in felsic rocks peripheral to pyroxenite. Modelling of combined assimilation and crystal fractionation, under conditions of decreasing temperature, produced results more consistent with Big Jim phase compositions.

Figure 12 shows calculated liquid and solid compositions for the crystallization of BJ82-50 (diorite) with 2 wt% H_2O compared to those for the same liquid with no H_2O . In the "wet" run, liquids are closer to the calc-alkaline trend. However, predicted pyroxenite compositions are more iron rich than those at Big Jim and other, similar complexes. The "dry" run, on the other hand, predicts



Fig. 13. AFM plot of calculated liquid and solid compositions during isobaric crystallization of Big Jim gabbronorite (BJ82-51A + 2 wt% H₂O), with and without combined assimilation of olivine (Fo90). Assimilation rates of 2 gm/25° C and 2 gm/10° C are relative to 100 gm initial liquid. Input parameters were initial liquid composition, composition and mass of assimilate at each temperature increment, temperature (1,200 to 1,000° C), pressure (3 kb), and oxygen fugacity (QFM)



Fig. 14a, b. Calculated solid a and liquid b composition for isobaric, equilibrium crystallization of Big Jim quartz diorite +2 wt% H₂O, with and without combined assimilation. Input parameters as for Fig. 12. Diagonally ruled area in b shows the range in Mg# for Big Jim diorite to granodiorite. Solid lines: equilibrium crystallization; dashed: assimilation of olivine; dotted: assimilation of pelitic rock

magnesian gabbro compositions similar to those observed in some ultramafic-felsic complexes, but shows iron enrichment in the liquid. Departures from chemical variation exhibited at Big Jim and in similar complexes are also observed in modelling crystallization of a more mafic "liquid" (BJ82-51A + 2 wt% H₂O). Precipitation of magnesian dunite and websterite causes iron enrichment in the liquid (Fig. 13). These are not trivial discrepancies. It is fractionation of pyroxenes in the "wet" crystallization of diorite, with MgO/(MgO + FeO*) close to that in the liquid, which minimizes iron-enrichment to produce a relatively flat, calcalkaline liquid trend. In many ultramafic-felsic complexes on the other hand, magnesian pyroxenites were produced, apparently without iron enrichment in derivative liquid.

At constant temperature, assimilation of Fo90 in dioritic liquid produced increasing $MgO/(MgO + FeO^*)$ in the liquid, and magnesian websterites similar in composition to Big Jim websterite. We hypothesized that combined assimilation of olivine and crystal fractionation (ACF) of hydrous basaltic liquid, under conditions of decreasing temperature, might produce magnesian pyroxenites and a calcalkaline liquid trend, as observed at Big Jim and other ultramafic-felsic complexes. As shown in Fig. 12, ACF calculations using SILMIN support this hypothesis, with both solid and liquid compositions closer to those observed at Big Jim than those produced by crystal fractionation alone. Figure 13 illustrates the generality of this conclusion. Calculations involving assimilation of olivine in relatively "dry" melts, with plagioclase on the liquidus, also show a calcalkaline trend in the derivative liquids. The nature of the liquidus phases and details of solid-liquid reaction stoichiometry affect the magnitude but not the kind of result.

However, some aspects of this model are not realistic. Figure 14 presents calculated solid and liquid compositions from the "wet" crystallization of diorite liquid (basaltic andesite), with and without assimilation of olivine. In the uncontaminated run, the liquid shows virtually no change in the concentration of SiO₂, so that the more evolved liquids are peralkaline. In the assimilation runs, wt% SiO₂ actually decreases in the liquid with decreasing temperature. Evolved liquids are decidedly alkaline, unlike felsic rocks at Big Jim, which are enriched in silica relative to diorite.

Table 5. Pelitic composition used in assimilation calculations. This composition was derived by averaging the group analyses for shale and slate reported by Clarke (1924), pp. 552 and 631. H_2O , CO_2 , SO_2 , C, P_2O_5 and trace components in the analyses were ignored; other oxides normalized to 100%

	Wt%		Mole%	Wt%
SiO ₂	64.463	Hercynite }	Sp 42	4.935
Al_2O_3	17.107	Enstatite }	En 46	4.795
FeO* MgO	6.691 2.754	Sanidine		7.334 21.015
CaO Na2O	3.105 1.593	Albite } Anorthite }	An 52	13.479 15.404
K₂Ō	3.556	Beta Quartz Ilmenite		28.724 1.388

The reasons for this may be systematic. SILMIN incorporates a solution model for spinel minerals which does not account for several common spinel components, including spinel (sensu stricto), hercynite and chromite. Since the chemical affinity calculated by SILMIN for a phase is the sum of the affinities of the components, SILMIN consistently underpredicts the stability of spinel minerals. More obviously, SILMIN does not include solution models for hornblende, biotite, and ilmenite. Crystallization of all of these phases is evident at Big Jim and similar complexes. Hornblende and biotite have MgO/(MgO+FeO*) ratios approximately equal to, and less silica than, most liquids with which they are in equilibrium.

In summary, thermodynamic modelling shows that isothermal assimilation of olivine-rich country rock in dioritic magma is spontaneous, exothermic, and involves a negative change in volume. Where the mass of assimilate is large enough to affect the liquid composition, zoned reaction assemblages are formed, becoming more magnesian with increasing assimilation. For combined assimilation and fractionation, we calculate that the reaction products will be websterite similar to that at Big Jim. Combined fractional crystallization and assimilation of mafic wall rock in a hydrous magma may prove to be an explanation for chemical variation in ultramafic-felsic plutonic complexes, and, by analogy, for the calc-alkaline liquid trend.

Assimilation of pelitic schist, combined with crystal fractionation, might also be proposed as a way to modify the crystal and liquid line of descent. Bowen (1922b) treated this problem in general, and concluded that such reactions might produce more orthopyroxene-rich crystal products, but would result in little change in the liquid line of descent. We have investigated this possibility using SILMIN. A representative pelitic rock composition was obtained by averaging 178 analyses of shale and slate reported by Clarke (1924, pp. 552 and 631). H₂O, CO₂, SO₂, C, P₂O₅, and trace constituents were ignored. The average composition, in oxides and recast as a set of mineral compositions in pyroxene hornfels facies, is given in Table 5. We modelled assimilation of this phase assemblage in Big Jim quartz diorite (BJ82-50+2 wt% H_2O) under the same conditions as in olivine assimilation calculations. The results, illustrated in Figures 12 and 14, support Bowen's assertion that such assimilation reactions have little effect on the major element composition of derivative liquids.

A qualitative theory

Erikson (1977) modelled the evolution of the Mt. Stuart batholith as a result of fractional crystallization of a liquid with the composition of high aluminum gabbronorite, which accounts for 2% of the exposed area of the batholith. He concluded that the model was internally consistent, that is, all rock types could be produced by successive removal of cumulate phases, but that it required the production of an enormous, perhaps unreasonable quantity of cumulate gabbro, 8 to 10 times the volume of the batholith at the present level of erosion.

A perfect fractional crystallization approach is probably not sufficient to model the evolution of the Big Jim complex for several other reasons as well. First, there is abundant evidence of assimilation of ultramafic rocks in intermediate magmas: trains of harzburgite xenoliths may be derived from continuous, elongate metaperidotite bodies, largely "digested" and replaced by a variety of rock types. Second, almost every rock records reaction relationships in which early, mafic phases reacted with a more felsic and/or cooler and/or more hydrous liquid to produce less refractory, more felsic minerals. The Big Jim complex may be better described as a consequence of combined assimilation of ultramafic country rock and partial fractional crystallization. This hypothesis provides a useful framework for summarizing observations and speculation.

Much of the unusual ultramafic rock in the complex, websterite and hornblendite, formed by the interaction of a cooling, fractionating magma and an ultramafic wall rock. Such interaction occurred on a regional scale where phases of the Mt. Stuart batholith came into contact with lenses of metaperidotite. At shallow crustal levels, the effects were relatively minor; only a few orthopyroxenite veins record silicification of the alpine type Ingalls peridotite along a contact with Mt. Stuart quartz diorite 40 km south of Big Jim (Frost 1973, 1975). Further north (at greater depth), ultramafic blocks underwent considerable modification. Near Stevens Pass, hornblendite bodies with minor pyroxenite near the Mt. Stuart contact probably represent completely digested slices of ultramafic country rock. Between Icicle Ridge and Stevens Pass, at the Big Jim complex, this process achieved its outcrop apogee.

The ultramafic wall rock was a foliated metaperidotite which had been included in the schist prior to a regional deformation event. However, undeformed Big Jim websterite and hornblendite preserves the gross structural features of the foliated host. Elongate xenoliths of hornblendite in diorite, as well as the trend of major contacts between ultramafic and plagioclase bearing rocks in the complex, are aligned subparallel to regional foliation in the Chiwaukum schist. This is thought to be the result of in situ replacement of metaperidotite. Structurally isotropic hornblendite completely replaced the foliated peridotite protolith after it was stoped into felsic liquid. Since much of the magma which formed websterite by reaction with peridotite was injected in narrow dikes along foliation in the host, some pyroxenites preserve a planar flow foliation.

The proposed reactions between wall rock and melt involve large, negative changes in enthalpy, volume and free energy of the magma – wallrock system. Thus they are spontaneous and exothermic. The negative volume change probably caused fracturing parallel to foliation in the metaperidotite, accompanied by the injection of new dikes, as well as the widening of existing dikes. Textural evidence shows that reactants locally penetrated the peridotite on a grain-boundary scale. Infiltration of peridotite by mafic silicate liquids has been experimentally demonstrated (Stolper 1980; Watson 1982), and invoked to explain outcrop scale clinopyroxene veins in alpine-type harzburgite (Evans 1985). Grain boundary diffusion of melt components along the activity gradient between ultramafic solid and hydrous liquid may have been important as well. Even in the absence of a homogeneous fluid phase, H₂O is likely to diffuse rapidly, until its fugacity is equivalent in both xenolith and host (Nockolds 1933). In the presence of intergranular "films" of H₂O as narrow as 10 Å in width, diffusion of other components would be several orders of magnitude faster than "dry" grain boundary diffusion (Walther and Wood 1984).

We infer that the initial Big Jim magma must have contained several wt% H_2O , since the presence of H_2O in melts at 3 to 4 kb supresses the liquidus temperature of plagioclase more than those of pyroxenes and hornblende. Under such conditions, it is possible to derive websterites with little or no plagioclase from melts similar in composition to Big Jim diorite, through much of the crystallization interval. H_2O contents in excess of 3 wt% are necessary to stabilize hornblende in mafic to intermediate liquids (Burnham 1979).

Discordant dunite and wehrlite bodies cutting pyroxenite and peridotite are found in concentrically zoned ultramafic complexes (Irvine 1963, 1974; James 1971); alpinetype peridotite (Dick 1977a, b; Dungan and Ave-Lallement 1977; Quick 1981a, b), and large, layered intrusions (Cameron and Desborough 1964; Schiffries 1982; Raedeke and McCallum 1984). Their origin has been attributed to partial melting of the host, leaving an olivine-spinel restite (Boudier and Nicolas 1972; Dick 1977a, b; Jackson and Ohnenstetter 1981; Nicolas and Jackson 1982), or to incongruent dissolution of pyroxene by an H₂O-rich magma or fluid phase (Bowen and Tuttle 1949; Cameron and Desborough 1964; Dungan and Ave-Lallement 1977; Irvine 1974; James 1971; Raedeke and McCallum 1984; Schiffries 1982). At Big Jim, the latter theory seems much more probable. It seems especially compelling where hornblende dunite veins replace websterite, since websterite is probably more refractory than the vein assemblage. A third possibility, that the dunites are "cumulate dikes" from picritic magma (Quick 1981 b), seems unlikely; there are no discordant dunite bodies cutting rocks other than pyroxenite in the complex.

Crystallization of an infiltrating magma with limited communication to the main magma reservoir would result in increasing concentration of volatiles and incompatible elements in the residual "pore magma". Clinopyroxenes in websterite are riddled with hornblende because they included a large proportion of trapped, hydrous melt. Increasing H₂O and alkali activities in the liquid could lower the liquidus temperature, causing dissolution of ortho- and clinopyroxene, and greatly expand the olivine stability field in composition space (Kushiro 1975). Where such an H_2O and alkali-rich residuum was concentrated, replacive dunites would form at the expense of pyroxenite. This could occur simultaneously with the assimilation of harzburgite xenoliths closer to the main magma reservoir. This hypothesis may explain the puzzling occurrence of replacive dunites in a regime governed essentially by silicification of ultramafic rock.

At temperatures close to the solidus (for basaltic and andesitic melts at 3 to 4 kb) hornblende became the stable ferromagnesian phase crystallizing in the main magma reservoir. At this point, or somewhat earlier where "pore magma" was enriched in H_2O , alumina, and alkalies, reaction between ultramafic rock (metaperidotite, websterite, and dunite veins) and magma began to produce hornblendite. In narrow screens, this process continued to completion, but in the main ultramafic slabs, unaltered websterite and dunite remained. Hornblendite dikes, which are found only in the vicinity of ultramafic rocks though they cut almost all rock types, probably crystallized during this stage.

The proposed hybrid origin of pyroxenite, hornblendite and gabbro in the Big Jim complex might be tentatively extended to similar rock types elsewhere in the Mt. Stuart batholith. The parental magma may have been similar in composition to Erikson's (1977) main phase quartz-diorite (MPQD), by far the most voluminous member of the batholith. While this begs the question of how the MPQD originated, it does provide a satisfactory explanation for the evolution of other members of the batholith. More felsic liquids formed by fractional crystallization of Hb, biotite, plagioclase and oxides from MPQD, while more mafic rocks formed by reaction between MPQD and ultramafic country rock. This accounts for the relative volumes of the various types better than Erikson's model of fractionation, and explains the position of the mafic rocks near the margin and "roof" of the exposed batholith, adjacent to metaperidotite wall rock.

Applications

Characteristics of zoned ultramafic-mafic and ultramaficfelsic plutonic complexes suggest their division into four groups, based on the succession and relative age of associated rock types (Table 6). The ultramafic rocks in Alaskan-type complexes have generally been interpreted as cumulates from undersaturated, or even ultramafic, magmas. Murray (1972) pointed out that phase relations do not preclude the crystallization sequence Ol-Cpx-Mgt-Hb-Plag in tholeiitic magmas at high $P_{\rm H_2O}$. The results of experiments on natural and synthetic andesite, tholeiite and olivine tholeiite, not all of them available to Murray in 1972, confirm that this sequence is common in hydrous, mafic silicate liquids at crustal pressures (Cawthorn 1976; Eggler 1972; Eggler and Burnham 1972; Helz 1973, 1976; Holloway and Burnham 1972; Yoder and Tilley 1962). Phase compositions reported by Helz are not significantly different from those reported by Irvine (1974) for the Duke Island complex. Hence, the Duke Island parental magma need not have been critically undersaturated in silica.

Klamath-type complexes have recently been given general treatment by Snoke et al. (1981, 1982). These authors tend to emphasize similarities with Alaskan-type complexes. However, crucial differences exist. Comparison of AFM plots for Klamath- and Alaskan-types highlight the most important of these: data from Duke Island and Union Bay form a marked iron enrichment trend, whereas Klamathtype complexes show a calc-alkaline trend. In some Klamath-type complexes, pyroxenite bodies lie directly along the contact between plutonic rocks and alpine-type harzburgite (Davis et al. 1965; Ramp 1975; Snoke et al. 1981). Indeed, most Klamath-type complexes intrude alpine peri-

	Characteristic zones	Other distinguish- ing features	Well characterised examples; range of Ol comp'n; most calcic Plag; comments
Alaskan-type	dun; wehr; Ol cpxte; Hb cypxte; hbte; gbnte; Hb gb	Plag, Opx absent in UM; abundant Mgt in Hb cpxte; gb gen'ly interp. older than UM	Union Bay (Ruckmick and Noble 1959); Fo93-78; Plag sausuritized, x-cutting dun & wehr "sills"
			Duke Island (Irvine 1963, 1974); Fo95-85; An>90; replacive dun and wehr
			Tulameen (Findlay 1969); Fo89-69; Plag sauss.; assoc'd alkalic gb and di
Klamath- type	dun; wehr; Ol cpxte; Hb cpxte; hbte; gbnte; Hb gb; di; grdi	minor Opx in UM; Mgt not abundant; Plag-bearing rks interp. younger than or coeval with UM	Emigrant Gap (James 1971); Fo85-72; An93; replacive dun; tectonite fabrics in wehr, absent in cpxte
			Bear Mountain (Snoke et al. 1981); Fo83-67; An93; tectonite fabrics in wehr, absent in pxte; minor Mgt-rich Hb cpxte
Peninsular- type	Hb Plag lherz; Hb Plag webst; troct; gbnte; Hb gb; di; ton; grdi	abundant Plag, Opx; Mgt not abundant	Los Pinos (Walawender 1976); Fo90-86 An88; UM interp. younger than more felsio rks
			Tilting Harbor (Cawthorn 1978); Fo?; An?; 2 magma series interp., both producing webst; some Mgt-rich gb
			Ladakh batholith (Honegger et al. 1982; Kelemen and Sonnenfeld, 1983); Fo80; An90; Hb abundant, Cpx rare; UM interp. older than more felsic rks
Mg-rich type	dun; webst; hbte; gnte; Hb gb; di; grdi	abundant Opx, no Plag in UM; Mgt not abundant; Plag-bearing rks interp. younger than or coeval	Giant Mascot (Aho 1956); Fo90; An85 replacive dun; sulfides assoc'd w/dun (nickel deposit); incl. opxte
		with UM	Trinity plutons (Quick 1981); Fo90-86; An97(!); incl. dun, wehr, webst, cpxte, gb(s.s.), gbnte, Hb di
			Big Jim (this paper)

Table 6. Proposed classification of related zoned ultramafic-mafic and ultramafic-felsic plutonic complexes

Key to abbreviations. Ol, olivine; Cpx, clinopyroxene; Opx, orthopyroxene; Hb, hornblende; Plag, plagioclase; Mgt, magnetite; dun, dunite; wehr, wehrlite; cpxte, clinopyroxenite, webst, websterite; hbte, hornblendite; gb, gabbro; gbnte, gabbronorite; di diorite; grdi, granodiorite; ton, tonalite; UM, ultramafic rock

dotite, and ultramafic rocks within the complexes are near the periphery, rather than in the center. As noted in the introduction, Snoke et al. (1981) and James (1971) report the presence of deformed wehrlite blocks within undeformed clinopyroxenite. Finally, while gabbro and diorite associated with Alaskan-type complexes has generally been interpreted as older than ultramafic rocks, gabbro, diorite and granodiorite associated in Klamath-type complexes are said to be coeval with, or younger than, ultramafic rocks.

We feel that our qualitative model, of combined assimilation of peridotite and partial, fractional crystallization, could be exported to Klamath-type complexes with little change. The major difference between Klamath-type complexes and Big Jim is the abundance of orthopyroxene in Big Jim pyroxenite. This is a function of silica and magnesium activity in the magma – host rock system. Parental melts in most complexes must have had olivine and Cpx on the liquidus, rather than Opx and Cpx as at Big Jim.

Application of the model to other zoned complexes may be less valid. The ultramafic rocks in Alaskan-type complexes may well be cumulate products of crystal fractionation alone, as proposed by Murray (1972), Irvine (1963, 1974), Conrad and Kay (1984). Many Peninsular-type complexes lie suggestively close to major belts of alpine-type peridotite. Reaction zones similar to those in the Big Jim complex are likely where arc magmas and mantle are juxtaposed. Early crystallization of plagioclase may be explained by lower water fugacities in Peninsular-type magmas, which would stabilize plagioclase relative to clinopyroxene in many mafic to intermediate compositions.

In suggesting the general application of our model, we do not wish to imply that alpine-peridotite was involved as a reactant in every case. Early formed olivine and olivine-Cpx cumulates are better candidates for the ultramafic end-member in most complexes. In a magma chamber in which evolved liquids periodically reacted with cumulates, textures and zoning similar to those at Big Jim could develop. Imagine a basaltic magma in a deforming magma chamber, or perhaps a conduit, in which dunite cumulate blocks are periodically stoped into the magma. If this occurs when one or more pyroxenes are on the liquidus, the blocks will react with the magma to form some hybrid along their perimeter. In fact, negative volume changes associated with reactions forming pyroxene from olivine+melt (or hornblende from pyroxene+melt) might lead to stoping and disagregation of early formed cumulates.

In the upper mantle above subduction zones, fractionating magmas must assimilate both harzburgite and lherzolite wall rock, and later, hybrid types lining magma conduits. If magma volumes are large enough, and the subduction zone is operative for a long enough time, this process must result in the wholesale hybridization of large portions of lithosphere beneath volcanic arcs.

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