ULTRAMAFIC INTRUSIVES AND ASSOCIATED MAGNETITE DEPOSITS AT UNION BAY, SOUTHEAST ALASKA

Thesis by

John Christian Ruckmick

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ABSTRACT

An intrusive body of ultramafic rocks, which crops out over an area of 7 square miles at Union Bay, southeast Alaska, has been mapped and studied petrographically. The ultramafic rocks are probably Jurassic or Cretaceous in age, and constitute a spoon-shaped lopolith with a dunite feeder plug at the east end. The rocks of the lopolith are composed of various proportions of diopside and forsteritic olivine, with some magnetite and hornblende, and no feldspar. The most basic rocks, dunite and peridotite, occur in the central portion of the lopolith, and are enveloped by olivine-pyroxenite, pyroxenite, and hornblende-pyroxenite in that order. The peridotite rocks in the central portion of the complex are composed of olivine-pyroxenite intruded by sills and irregular bodies of dunite. Attitudes of the dunite sills conform to the spoon-shaped structure of the lopolith. Large areas of pyroxenite containing 10% to 25% of primary magnetite crop out around the periphery of the lopolith. An intrusive body of gabbro adjoins the south side of the ultramafic lopolith. The gabbro is earlier than, and has been intruded by, the ultramafic rocks.

The structure and petrology of the ultramafic lopolith are explained by an hypothesis of successive injections of increasingly basic magmas composed essentially of: (1) a cotectic blend of diopside and magnetite; (2) a cotectic blend of diopside and forsteritic olivine; and (3) forsteritic olivine. The intrusion of the magmas in that order, the reverse order of crystallization of the component minerals, is a reflection of the differential melting of the ultramafic source in the mantle of the earth. Each arriving magma must have found the hot, still crystallizing, central portion of the preceding magma the most accessible locus of intrusion.

The lack of a very high grade of contact metamorphism in the pelitic sediments adjacent to the ultramafic rocks is explained by the assumption that the ultramafic magmas contained very little or no water, and, therefore, expelled no significant amounts of volatile phases during crystallization.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLES

FIGURES

TABLE OF CONTENTS (Cont'd)

TABLE OF CONTENTS (Cont'd)

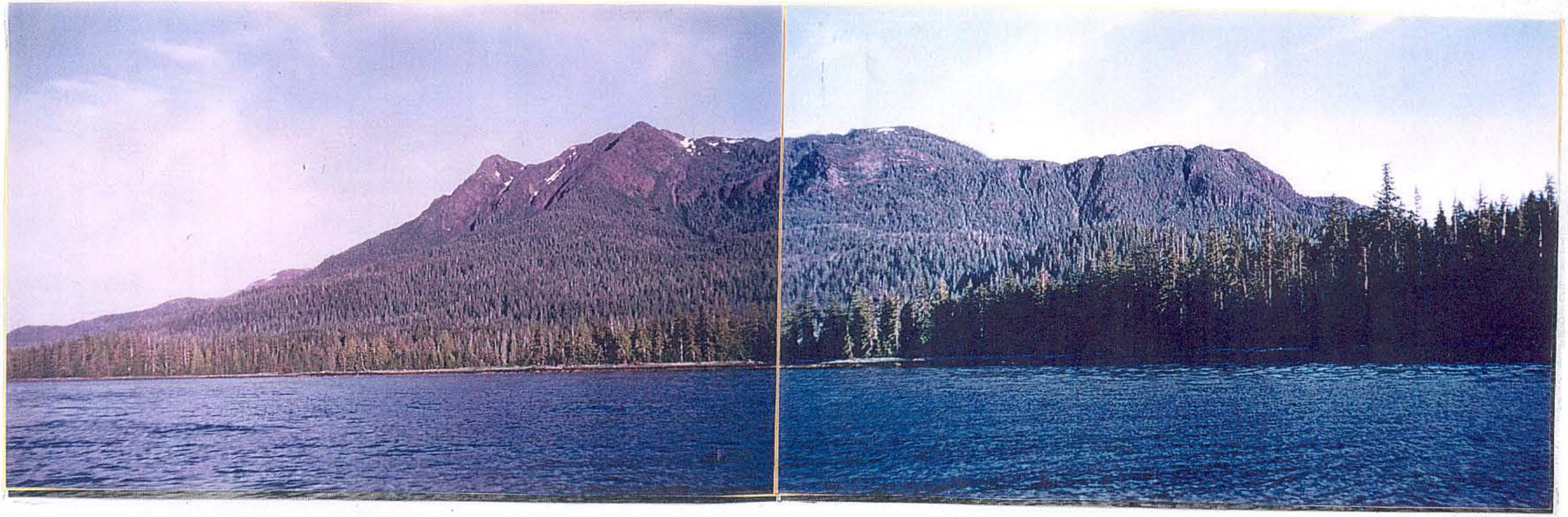

Figure 1. View of Mount Burnett looking southeast from Ernest Sound.

I. INTRODUCTION

REGIONAL SETTING

The Union Bay ultramafic complex is one of a northwest trending belt of ultramafic intrusives which crop out west of the Coast Range batholith throughout southeastern Alaska (Figure 2). Ultramafic intrusives also crop out east of the Coast Range batholith from near the 49th parallel well into the Yukon Territory (25, p. 396). All these ultramafic intrusives are relatively small (most are approximately 20 square miles in area, or smaller). They are of striking lithologic similarity, and are probably related in both age and genesis.

GENERAL DESCRIPTION OF UNION BAY

Union Bay is located at the northwest extremity of Cleveland Peninsula, about 35 miles by air, or 40 miles by boat, northwest of Ketchikan. The ultramafic intrusive lies along the east shore of the bay and extends eastward along a high east-west ridge for $6\frac{1}{2}$ miles. The highest elevation on the ridge is Mount Burnett, 2,874 feet above sea level. The outcrop of the ultramafic is roughly elliptical in plan, covering an area of approximately 15 square miles. An intrusive body of gabbro crops out immediately south of the ultramafic and is in contact with it. The gabbro occupies an area of 12 square miles and forms a high mountain (3,100 feet above sea level) which is referred to in the text as "South Mountain." The low, east-west valley of Cannery Creek lies between South Mountain and the high ridge of Mount Burnett.

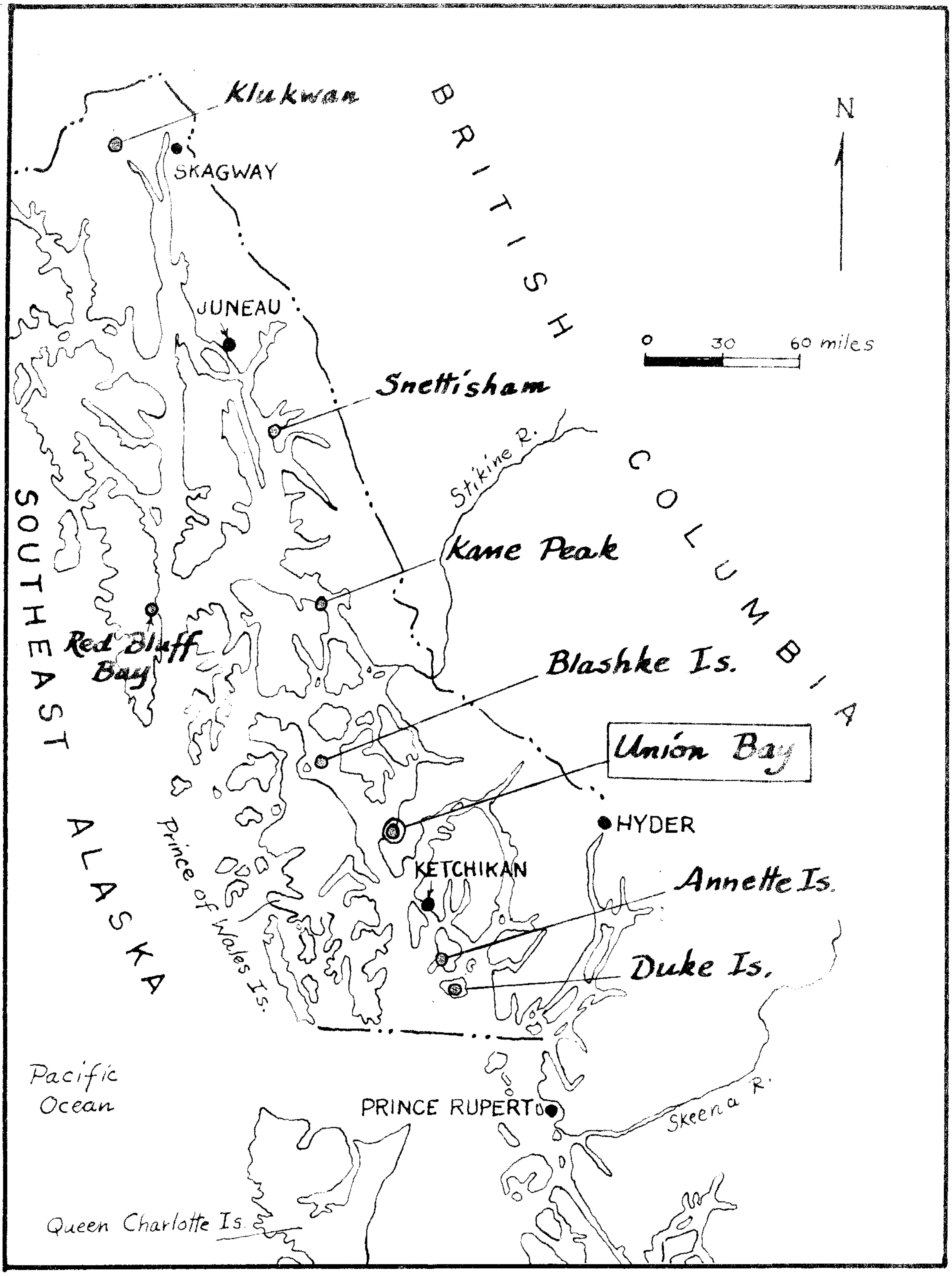

Figure 2. Location of Union Bay and other ultramafic intrusives in southeast Alaska.

The shore line is generally rocky, especially on the west side of the ultramafic where the intrusive passes into the bay. Near the mouths of major streams the shore is composed of sand and gravel. The topography is steep, and the mountain slopes are covered by dense, virgin stands of cedar, hemlock, spruce, and pine up to an elevation of 1,000 feet. Above this elevation, dwarfed and contorted lodgepole pine and cedar are predominant, except for areas of dunitic rock which support practically no vegetation. Relatively flat and poorly drained areas, or benches, support only a muskeg type of growth with no trees other than a few contorted lodgepole pine. This is especially true of the relatively low and gently sloping bench of metasediments along the north side of the ultramafic.

There are excellent exposures of rock along the shore line (in part because of 20 foot tides), and at higher elevations where timber is sparse. On the heavily forested slopes below 1,000 feet, the degree of exposure is variable and somewhat dependent upon the steepness of the slope. There are many vertical, or nearly vertical, clean exposures on joint faces which range in height from several feet to 200 feet. On the more gently sloping, heavily timbered slopes, exposures may be absent or poor throughout large areas, although in many places the only cover is a deep layer of moss and forest litter. Some of the major streams afford narrow exposures along their beds for considerable distances, and offer the only clean, but quite limited, exposures of contacts between intrusives and wall rocks.

The general form of the topography is that of a heavily glaciated region with cirques and U-shaped valley cross-sections, often with a shoulder, or break in slope, which is not controlled by lithology. Coarse, locally derived glacial drift mantles the ridges and valley floors in places, and extensive deposits of coarsely bedded till have been mapped in two of the stream valleys. The dioritic composition of a few erratics scattered throughout the area suggests that they have been carried from the Coast Range 12 miles to the east. The presence of glacial debris of sizes ranging up to very large boulders renders the use of float for geologic mapping unreliable.

Snow fields of considerable size often remain at altitudes above 1,500 feet until late June or early July. The summer climate is typically wet, and dry spells of more than 3 or 4 days duration are rare. Annual precipitation is reported to be between 150 and 200 inches per year for this region.

PREVIOUS WORK

Several of the ultramafic intrusives in southeastern Alaska, including Union Bay, were briefly described by Buddington and Chapin (10, pp. 190-194) in the course of their reconnaissance of southeastern Alaskan geology. Union Bay was also examined, and some features of the intrusive described, by Kennedy and Walton during the course of a U. S. Geological Survey war minerals investigation in the summer of 1943 (28). Walton again visited Union Bay during the course of his study of the Blashke Islands ultramafic body, which work constituted a Ph. D. thesis at Columbia University (47).

II. GEOLOGY OF UNION BAY

GENERAL GEOLOGIC DESCRIPTIONS

The geology of the Union Bay area is given on the geologic map, Figure 3, and on the geologic sections, Figure 4. The broad geologic features are outlined below, followed by detailed descriptions and interpretations of the rocks in succeeding sections of the text.

Metasedimentary Rocks

The ultramafic and gabbro intrusives at Union Bay crop out 12 miles west of the western contact of the Coast Range batholith and are intruded into a belt of metasediments mapped and referred to as the Wrangell-Revillagigedo metamorphic series by Buddington and Chapin (10, pp. 49-74). These rocks have undergone low grade regional metamorphism to marbles, slates, phyllites, and chloritic and amphibolitic volcanic greenstones. At Union Bay the intrusive rocks are emplaced in a sequence of phyllites with a very few intercalated tuffs.

Problems of correlation of the Wrangell-Revillagigedo members have caused their age to remain somewhat speculative, and Buddington refers to the sequence as "probably Ordovician to Jurassic or later." The Union Bay metamorphics are probably best correlated with the belt of slates, graywackes, and greenstones in the vicinity of Ketchikan. Here Triassic slates and Cretaceous greenstones have been reasonably well dated on the basis of lithologic, structural, and some paleontological evidence.

The Gabbroic Rocks

Although the main body of gabbro lies to the south of the ultramafic, a portion of it crops out to the north along most of the high east-west ridge north of Cannery Creek, forming a relatively thin cap over part of the ultramafic complex. Areas of gabbro of variable size also crop out along or near portions of the north, northeast, and southwest margins of the ultramafic. In many places along the margin of the main body of gabbro, where it is in contact with metasediments or ultramafic rocks, the gabbro has been partially saussuritized. All the smaller bodies of gabbro which are separate from the main body of gabbro are completely saussuritized.

The Ultramafic Intrusive Complex

The over-all form of the ultramafic complex is that of a spoon-shaped lopolith with a feeder. A cylindrical plug of dunite, with a diameter of one mile, constitutes the feeder conduit at the east end of the intrusive. On three sides (north, east, and south), the dunite plug is enclosed in peridotite, olivine-pyroxenite, and pyroxenite (in that order) which dip steeply away from the dunitic core. To the west, the dunite passes gradationally through peridotite into the central portion of the main body of the lopolith. The spoon-shaped lobe, which forms the main body of the lopolith, exhibits a pronounced, sub-horizontal, compositional layering in terms of features measured from inches to hundreds of feet in thickness. The layering is a primary feature which is an expression of the difference between one layer and another in the relative proportions of the two principal minerals, diopside and olivine. The more olivine-rich rocks, dunite and peridotite, are involved in the most conspicuous layering and constitute the more central portions of the lopolith. These units pass outward and gradationally (in three dimensions) through olivine-pyroxenite to pyroxenite which constitutes a continuous shell or envelope, encasing the olivine-rich rocks. Hornblende becomes an important mineral in the outer margin of the pyroxenite shell, forming a hornblende-pyroxenite rock. This rock lies between pyroxenite and saussurite-gabbro or schist, and constitutes the outermost ultramafic unit in most places.

The hornblende-pyroxenite, pyroxenite, and much of the olivine-pyroxenite are essentially devoid of primary layering within the respective units, with the exception of one feature. Locally in the pyroxenite and in the olivine-pyroxenite,regular, parallel bands of magnetite occur from a fraction of an inch to several inches in thickness and from an inch to one foot apart. These magnetite bands or layers are especially prevalent in the western portion of the pyroxenite, and, in places, show continuity for distances of 100 feet or more along the strike. The greatest continuity is exhibited in the higher, more central region of the lower pyroxenite unit on the western slopes. Here the attitude of the magnetite bands is concordant with the attitude of the peridotite layering higher in the intrusive.

Primary magnetite is present to some extent in all the igneous rock units at Union Bay. However, the most concentrated occurrence is in the pyroxenite unit. The largest concentration of magnetite lies in a pocket in the lower pyroxenite and hornblende-pyroxenite units along the west and northwest sides of the ultrabasic.

Over an area of approximately 3 square miles, the magnetite content of the rock is remarkably constant, averaging approximately 20% of the rock by weight.

Chromite occurs as a minor constituent of the dunite, and there are minor amounts of sulfide mineralization, mostly pyrite with some chalcopyrite and pyrrhotite, sporadically distributed throughout the peripheral rocks of the ultramafic intrusive. Neither of these types of mineralization appears to be of economic interest.

Tertiary Rocks

At the mouth of Cannery Creek, and at the northwest extremity of the ultramafic complex near Union Point, the ultramafic rocks and the Wrangell-Revillagigedo metamorphics are unconformably overlain by a coarse conglomerate. The matrix of the conglomerate is composed of ultramafic material, and most of the fragments are ultramafic rocks. Where the conglomerate crosses the ultramafic-metasediment contact near Union Point, it exhibits an abrupt facies change northward, in a distance of 30 feet, to arkosic sandstone. Farther to the north, the sandstone grades abruptly back to a coarse conglomerate on Union Point. Bedding is indistinct in the conglomerate, but moderately well developed in the sandstone. The sandstone probably represents a shore line or stream deposit rather than a facies change controlled by the ultramafic-metasediment contact.

The conglomerate contains some plant remains and has been correlated with the Port Camden basal Eocene by Buddington (10, pp. 10-37). If this correlation is correct, an upper age limit (Cretaceous?) is thereby established for the ultramafic complex.

The conglomerate, metasediments, and ultramafic rocks are cut by basalt dikes and sills which are generally 3 feet to 8 feet wide. The basalt is fine-grained with randomly oriented phenocrysts of augite and plagioclase (zoned from An_{75} in the center to An_{60} at the rim), approximately 1 mm in the longest dimension. The very fine-grained groundmass contains a great deal of ankerite.

Dike rocks of pegmatitic nature crop out in the metasediments midway along the north shore and at the head of Vixen Inlet. The attitudes of these dikes parallel both the predominant foliation in the metasediments and the attitudes of nearby basalt dikes. The pegmatitic rocks are leucocratic, medium to coarse-grained, and are composed of 40% anhedra of quartz, 40% anhedra of albite (An_5), 10% euhedra of clinozoisite, 10% muscovite, traces of almandite garnet, and, locally, some biotite. Relationships between these dikes and rocks other than the metasediments which they intrude are unknown.

Joints and Faults

The attitudes of joint surfaces show considerable variation from place to place, but generally predominant in all rock types at Union Bay are two joint directions striking approximately N20°W and N20°E, and dipping steeply at 60° to 90°. In the aerial photographs, this set of joints is remarkably evident in outcrops above timberline, and on the forested slopes, where the joints control drainage. Because this predominant joint set occurs in all rock types, it is most probably a regional pattern, and no statistical study was made of it.

Nine faults were mapped in the ultramafic complex. None of them appears to have caused displacement of more than 1, 000 feet in any direction. Fault breccia, composed of angular fragments of ultramafic rock in a quartz matrix, occurs in many places along outcrops of the faults. The faults are also commonly host to small quartz veins and small basalt stringers.

DETAILED DESCRIPTIONS OF ROCKS

The mineralogical compositions of representative rock specimens in Table 1 were determined by grain counts made with an ocular grid. The compositions of plagioclase grains were determined by measurement of extinction angles using the statistical method of Michel-Levy, and by correlation of these angles with data published by Kennedy (29, p. 562). The indices of refraction of olivine and pyroxene grains were determined with immersion oils. The compositions of olivines and orthorhombic pyroxenes were established from graphs published by Kennedy (29, pp. 567 and 564), and the compositions of monoclinic pyroxenes were determined from graphs published by Hess (24, pp. 634 and 641). The optic angles of representative diopside grains were determined with a universal stage. Optic angle determinations and chemical analyses of representative diopside mineral separates (Figure 13) establish the composition of the monoclinic pyroxenes within the approximate range of the diopside-hedenbergite solid solution

SPEC. COMPONENTS	400 Ph	111 Sch	192c Sch	222 Sch	160 Gb	164 Sgb	223 Sgb	130 Sgb
SiO_2	66.34	58.66	59.36	60.14	49.94	48.70	48.76	45.96
Al_2O_3	15.08	17.68	17.94	17.93	20.24	18.14	17.54	19.38
FeO	4.95	6.96	7.08	6.12	7.63	6.61	4.94	6.42
Fe_2O_3	.64	.92	.94	.74	2.58	4.58	5.66	5.17
TiO_2	.65	.90	.72	.88	.56	.96	.68	.88
MnO	.07	.13	.14	.14	.18	.20	.19	.24
CaO	1.56	1.83	2.88	3.92	9.46	9.54	10.36	11.35
MgO	2.88	3.69	3.72	2.93	5.13	5.06	5.74	5.22
K_2O	1.48	2.49	1.68	1.74	.62	.95	.43	.83
Na_2O	3.34	3.05	3.54	3.58	2.74	2.23	3.87	2.74
H_2O - 105°c	.23	.24	.42	.10	.05	.34	.06	.06
H_2O + "	2.80	2.95	1.23	1.35	.35	2.44	1.30	1.04
CO_2	nil	nil	nil	nil	nil	nil	nil	nil
P_2O_5	.23	.22	.13	.17	.33	.37	.27	.53
Cr	na	na	nil	nil	na	na	tr.	nil
TOTAL	100.25	99.72	99.78	99.74	99.81	100.12	99.80	99.82
olivine								
diopside					12			
hornblende				6		21	45	33
hypersthene					14			
actinolite								tr.
biotite		31	29	42	4	3	tr.	tr.
chlorite (penn.)	26	4				12		10
serpentine								
epidote + clinozoisite				1		37	20	36
plagioclase	12	18	38	25	64	16	28	18
(comp. of ")	An_{10}	An_{30}	An_{15-40}	An_{28-30}	An_{55}	An_5	An_5	An_5
quartz	27	12	28	18		2	5	
sericite	32	34	tr.	3		6	tr.	tr.
orthoclase				tr.	tr.			
carbonate			1				tr.	
almandite gnt.			3	3				
apatite	2					1		tr.
hercynite								
sphene						1	1	
magnetite	tr.	tr.			5	tr.	tr.	
ilmenite								
chromite								
sulfides	tr.	1	tr.	1		tr.	tr.	2
TOTAL	99+	100	99+	99+	99+	99+	99+	99+

Table 1. Chemical and mineralogical analyses of representative specimens. Locations of specimens are given on the index map, Figure 42. Chemical analyses by W. H. Herdsman, Glasgow, Scotland.

SPEC. / COMPONENTS	193 Sgb	192a Hpx	95 Hb min. sep.	32a diop. min sep.	32a Px	109 diop. min. sep.	183b diop. min. sep.	9 Opx
SiO_2	52.34	43.57	39.82	47.42	37.54	48.66	51.94	49.24
Al_2O_3	18.93	17.88	16.64	5.98	5.35	5.88	1.52	2.42
FeO	5.85	7.83	8.93	3.96	9.64	5.43	2.79	6.75
Fe_2O_3	2.86	3.16	4.37	2.48	15.52	2.33	.83	2.00
TiO_2	.66	.56	1.24	.86	2.23	.38	.13	.21
MnO	.18	.24	.18	.13	.16	.19	.14	.19
CaO	9.46	18.42	12.09	23.36	17.40	23.02	22.82	18.90
MgO	3.72	4.83	12.63	14.62	11.85	13.63	18.56	19.12
K_2O	.39	tr.	.96	tr.	tr.	.06	.04	.07
Na_2O	3.48	1.04	1.62	tr.	tr.	.18	.09	.18
H_2O - 105°C	.24	.25	.26	.20	.32	.09	.19	.19
H_2O + "	1.87	1.82	1.38	.76	.28	.31	.62	.64
CO_2	nil	nil	nil	nil	nil	nil	nil	nil
P_2O_5	.21	.56	tr.	tr.	tr.	tr	tr.	tr.
Cr	na	na	na	na	na	nil	.22	.26
TOTAL	100.19	100.16	100.12	99.77	100.29	100.16	99.89	100.17
olivine							3	16
diopside		16	tr.	98	72	93	92	80
hornblende	12	30	97	tr.	4	2	1	1
hypersthene								
actinolite	10	5	2					
biotite								
chlorite (penn.)	8	3						
serpentine							1	tr.
epidote + clinozoisite	35	32						
plagioclase	22	10						
(comp. of ")	An5	An5						
quartz	10							
sericite	1							
orthoclase								
carbonate								
almandite gnt.								
apatite		tr.						
hercynite					2			
sphene		tr.						
magnetite		tr.	tr.	1	21	5	2	2
ilmenite					1			
chromite							tr.	
sulfides	1	3						
TOTAL	99	99+	99+	99+	100	100	99+	99+

Table 1: Continued

SPEC. COMPONENTS	200 Pd	6 Du	183a Du	231 Du
SiO_2	39.06	37.25	38.48	40.22
Al_2O_3	1.42	.97	1.06	1.69
FeO	7.24	12.34	8.42	9.28
Fe_2O_3	5.75	4.58	1.08	.88
TiO_2	tr.	nil	nil	tr.
MnO	.23	.27	.17	.18
CaO	4.78	.38	.19	nil
MgO	34.39	39.42	46.88	47.46
K_2O	tr.	.11	nil	tr
Na_2O	.12	.36	nil	.04
H_2O - 105°C	.49	.48	.68	.09
H_2O+ "	6.31	3.96	2.94	.30
CO_2	nil	nil	nil	nil
P_2O_5	tr.	tr.	tr.	tr.
Cr	nil	.26	na	nil
TOTAL	99.79	100.12	99.90	100.14
olivine	57	80	92	97
diopside	12	4		
hornblende		tr.		
hypersthene				
actinolite				
biotite				
chlorite (penn.)				
serpentine	28	15	6	
epidote + clinozoisite				
plagioclase				
(comp. of ")				
quartz				
sericite				
orthoclase				
carbonate				
almandite gnt.				
apatite				
hercynite				
sphene				
magnetite	2	tr.	1	2
ilmenite				
chromite	tr.	tr.	1	1
sulfides				
TOTAL	99+	99+	100	100

KEY :

Ph = phyllite
Sch = schist
Gb = gabbro
Sgb = saussurite-gabbro
Hpx = hornblende-pyroxenite
Px = pyroxenite
Opx = olivine-pyroxenite
Pd = peridotite
Du = dunite

Table 1: Continued

series. Therefore, the composition of the diopsides are noted as D_nH_{100-n} in the text. Optical data and corresponding compositions of the minerals are given in Table 2.

Metasedimentary Rocks

With the exception of a very few tuff beds, the Wrangell-Revillagigedo series is represented at Union Bay by the low grade metamorphic equivalents of pelitic sediments, most probably shales and fine-grained graywackes. These sediments have suffered regional metamorphism to fine-grained friable black graphitic slates and sericitic phyllites analogous in a general way to the biotite zone of the Scottish Highlands (21, pp. 214-218). Around the gabbroic and ultramafic intrusive bodies, the rocks show an increase in metamorphic grade to recrystallized garnetiferous quartz-oligoclase or andesine (An_{15} to An_{40})-biotite, or sericite-biotite schists analogous to the almandine zone described by Harker (21, pp. 218-224). The development of garnet is readily observed in the field in a zone 400 to 1,500 feet wide adjacent to intrusive rocks.

Only a few limited points of exposure, about 8 in number, of contacts between intrusive rocks and metasedimentary rocks can be found in the field. Each of these areas is described in detail.

On the southeastern periphery of the ultramafic intrusive, due south of the dunite core, a continuous but narrow section is exposed in a creek for several thousand feet on each side of the intrusive contact. Three quarters of a mile from the intrusive, the rock is fine-grained, highly schistose sericitic phyllite. This rock grades into medium-grained garnetiferous quartz-oligoclase-biotite

ROCK TYPE	SPEC. NO.	MINERAL	INDICES	COMP.	REMARKS
Px (+mag.)	109	diopside	Z 1.713 Y 1.693 X 1.684	D_{73} H_{27}	2V = 58°
"	76b	"	Z 1.712 Y 1.690 X 1.684	D_{74} H_{26}	
"	150	"	Z 1.712 Y 1.691 X 1.684	D_{74} H_{26}	
"	218	"	Z 1.710 Y 1.688 X 1.682	D_{77} H_{23}	
"	309	"	Z 1.710 Y 1.688 X 1.682	D_{77} H_{23}	
"	233a	"	Z 1.710 Y 1.688 X 1.682	D_{77} H_{23}	
"	32a	"	Z 1.710 Y 1.688 X 1.682	D_{77} H_{23}	2V = 58½°
"	126a	"	Z 1.708 Y 1.687 X 1.679	D_{80} H_{20}	2V = 59°
"	316	"	Z 1.709 Y 1.686 X 1.679	D_{80} H_{20}	
"	161	"	Z 1.705 Y 1.683 X 1.676	D_{86} H_{14}	
Px	235	"	Z 1.710 Y 1.688 X 1.682	D_{77} H_{23}	
"	46	"	Z 1.708 Y 1.687 X 1.680	D_{80} H_{20}	
"	168	"	Z 1.707 Y 1.684 X 1.677	D_{84} H_{16}	

Table 2. Correlation of optical indices and composition of representative specimens according to charts published by Hess (23) and Kennedy (29).

ROCK TYPE	SPEC. NO.	MINERAL	INDICES	COMP.	REMARKS
Hpx	98	diopside	Z 1.713 Y 1.692 X 1.684	$D_{73} H_{27}$	
"	51	"	Z 1.713 Y 1.692 X 1.684	$D_{73} H_{27}$	
"	156	"	Z 1.714 Y 1.693 X 1.686	$D_{70} H_{30}$	2V = 60°
Opx	144	"	Z 1.710 Y 1.690 X 1.682	$D_{77} H_{23}$	
"	305	"	Z 1.710 Y 1.688 X 1.682	$D_{77} H_{23}$	from ore zone, spec. assoc. with 20% mag., some hematite
"	155	"	Z 1.707 Y 1.686 X 1.678	$D_{82} H_{18}$	from Struct. pd. unit; spec. assoc. with 20% mag.
"	8	"	Z 1.705 Y 1.683 X 1.676	$D_{86} H_{14}$	
"	9	"	Z 1.705 Y 1.684 X 1.676	$D_{86} H_{14}$	2V = 58°
"	85a	"	Z 1.705 Y 1.682 X 1.676	$D_{86} H_{14}$	spec. contains 10% of hornblend.
"	87a	"	Z 1.705 Y 1.682 X 1.676	$D_{86} H_{14}$	" " "
"	226	"	Z 1.703 Y 1.681 X 1.674	$D_{88} H_{12}$	2V = 57°
"	224	"	Z 1.702 Y 1.679 X 1.673	$D_{90} H_{10}$	all oliv. serpentinized
Pd	200	"	Z 1.699 Y 1.677 X 1.670	$D_{94} H_{6}$	textural Pd

Table 2: Continued

ROCK TYPE	SPEC. NO.	MINERAL	INDICES	COMP.	REMARKS
Pd	225	diopside	Z 1.698 Y 1.677 X 1.670	$D_{94} H_6$	Structural Pd
"	183d	"	Z 1.698 Y 1.675 X 1.669	$D_{96} H_4$	Textural Pd
Du	183a	"	Z 1.696 Y 1.672 X 1.667	$D_{99} H_1$	
"	183b	"	Z 1.696 Y 1.672 X 1.667	$D_{99} H_1$	2V = 59°
Opx	8	olivine	Z 1.714 Y 1.696 X 1.676	$Fo_{78} Fa_{22}$	Opx wall-rock adjacent to dunite sill; see spec. no. 8 below. Opt. —
"	9	"	Z 1.714 Y 1.696 X 1.676	$Fo_{78} Fa_{22}$	2V = 88°; opt. —
"	87a	"	Z 1.713 Y 1.696 X 1.676	$Fo_{78} Fa_{22}$	Spec. contains 10% + hornblende. Opt. —
"	144	"	Z 1.713 Y 1.695 X 1.675	$Fo_{79} Fa_{21}$	opt. —
"	305	"	Z 1.713 Y 1.695 X 1.675	$Fo_{79} Fa_{21}$	opt. — ; from ore zone; assoc. with mag. + hematite.
"	6	"	Z 1.713 Y 1.695 X 1.675	$Fo_{79} Fa_{21}$	Opx wall-rock adjacent to dunite sill; compare with Pd spec. no. 6 below.
"	226	"	Z 1.693 Y 1.677 X 1.658	$Fo_{88} Fa_{12}$	Opt. —
Pd	8	"	Z 1.710 Y 1.692 X 1.672	$Fo_{81} Fa_{19}$	spec. of dunite sill intrusive into spec. no 8 above. Opt. —
"	155	"	Z 1.709 Y 1.692 X 1.672	$Fo_{81} Fa_{19}$	Opt. — ; from dunite sill in Structural Pd.
"	6	"	Z 1.703 Y 1.686 X 1.666	$Fo_{83} Fa_{17}$	spec. of dunite sill intrusive into spec. no. 6 above. Opt — .

Table 2: Continued

ROCK TYPE	SPEC. NO.	MINERAL	INDICES	COMP.	REMARKS
Pd	200	olivine	Z 1.694 Y 1.678 X 1.660	$Fo_{87} Fa_{13}$	textural Pd.; Opt. −
"	225	"	Z 1.695 Y 1.679 X 1.661	$Fo_{87} Fa_{13}$	" "
"	227	"	Z 1.695 Y 1.679 X 1.661	$Fo_{87} Fa_{13}$	" "
"	183d	"	Z 1.686 Y 1.667 X 1.650	$Fo_{93} Fa_{7}$	" Opt. +
Du	231	"	Z 1.690 Y 1.671 X 1.654	$Fo_{90} Fa_{10}$	Opt. + ; 2V = 88°
"	183a	"	Z 1.688 Y 1.670 X 1.654	$Fo_{91} Fa_{9}$	Opt. +
"	220	"	Z 1.685 Y 1.668 X 1.651	$Fo_{93} Fa_{7}$	2V = 90°
"	210	"	Z 1.687 Y 1.669 X 1.650	$Fo_{93} Fa_{7}$	2V = 90°
Hpx	115	apatite	N_e 1.634 N_o 1.638		biaxial, small 2V.
Sch	205	garnet	N > 1.770	probably almandite	red; isotropic.
Px	316	ankerite	N_e 1.516 N_o 1.696		in veins in Px.
Sgb	203	diopside	Z 1.714 Y 1.693 X 1.686	$D_{70} H_{30}$	
Gb	189	hypersthene	Z 1.713 Y 1.710 X 1.699	$En_{64} Fs_{36}$	central portion of main body of Gb. 2V = 52

Table 2: Continued

ROCK TYPE	SPEC NO.	MINERAL	INDICES	COMP.	REMARKS
Gb	221	diopside	Z 1.718 Y 1.697 X 1.690	$D_{64}H_{36}$	spec from within 900 ft. of ultramafic contact near dunite core.
"	189	"	Z 1.715 Y 1.695 X 1.687	$D_{68}H_{32}$	central portion of main body of Gb.
"	159	"	Z 1.715 Y 1.695 X 1.687	$D_{68}H_{32}$	from within 500 ft. of ultramafic contact on ridge west of Mt. Burnett.
"	206	"	Z 1.717 Y 1.696 X 1.688	$D_{65}H_{35}$	collected 300 ft. from contact with Sch south of Cannery Creek.
"	159	hypersthene	Z 1.708 Y 1.706 X 1.695	$En_{67}Fs_{33}$	see 159 above
"	206	"	Z 1.725 Y 1.723 X 1.712	$En_{54}Fs_{46}$	see 206 above

Table 2: Continued

schist 1,000 feet from the contact. Within 500 feet of the intrusive, the schist becomes coarser grained, more strongly foliated and indurated, and highly contorted. The contorted foliation consists of biotite-rich bands between bands of recrystallized, granulose quartz and oligoclase (An_{28} to An_{30}). The leucocratic bands also contain a few subhedral crystals of epidote and sphene, a few ragged, anhedral grains of hornblende, and traces of interstitial orthoclase. In thin section, the regular orientation of the biotite is deflected around medium-grained, fractured, subhedral garnets and, to a lesser degree, around larger grains of quartz and andesine. Garnets also include circular or spiral patterns of fine-grained biotite typical of porphyroblastic crystal development. The garnets are deep red in hand specimen and, on the basis of very high indices and complete lack of birefringence, are judged to be almandite. The mineralogy and a chemical analysis of a typical specimen of this rock (no. 222) appear in Table 1.

In abrupt contact with the garnetiferous-biotite schist, and separating it from the nearest ultramafic unit at this exposure (slightly serpentinized olivine-pyroxenite), is a 100 foot width of medium-grained albite-epidote-hornblende schist. The abrupt contacts, mineralogy, and chemical analysis of this unit (specimen no. 223, Table 1) indicate that this rock, mapped as saussurite-gabbro, is the metamorphic equivalent of gabbro, and it is considered in the next section of the text.

At the eastern margin of the ultramafic, two miles northeast of the outcrop just described, good exposures of the metasediments enclosing the intrusive are afforded by Vixen Creek and one of its larger tributaries. Here the wall rock in abrupt contact with a somewhat serpentinized, medium-grained pyroxenite is a fine-grained, thinly foliated, indurated and contorted schist of the following composition: 20% penninite, 20% quartz, 20% biotite, 15% sericite, 15% clinozoisite, 5% albite (An_5), 3% pyrite and magnetite, and 2% to 3% sphene. The coarsest grain of the rock is seen in aggregates of penninite and fine-grained magnetite up to 0.3 mm and anhedral to subhedral crystals of sphene up to 0.2 mm. Biotite, sericite and small euhedral prisms of clinozoisite are all well oriented in the plane of foliation. The foliation of the rock is regularly deflected around the pods of penninite and magnetite, which are probably retrogressive relics of porphyroblastic almandite garnets.

Included in the pyroxenite 20 feet inside the contact is a lenticular fragment of schist 6 feet wide and approximately 30 feet long. This inclusion is of the same composition and texture as the schist at the contact and also has abrupt margins against the pyroxenite.

Intrusive into the schist near the contact at this exposure are small, lenticular pods of hornblende-rich saussurite-gabbro from 2 inches to 10 feet in the longest dimension, around which the schistosity and foliation of the schist are regularly deflected. Similar intrusive pods occur in other places as outliers in schist around bodies of saussurite-gabbro, and around the west and southwest margins of the main body of gabbro comprising South Mountain.

The contact between ultramafic rocks and schist is irregular around the northeast margin of the ultramafic intrusive, where an apophysis of wall-rock projects into the pyroxenite unit. Where exposed, the contact between schist and pyroxenite is abrupt. A great deal of hornblende (up to 70°/o of the rock) and some clinozoisite (5°/o of the rock) have been developed in the pyroxenite in a narrow zone from 20 to 50 feet wide at the wall-rock contact. Within 1,000 feet to 1,500 feet of the ultramafic rocks, the wall-rocks are composed of highly contorted, strongly foliated, and well indurated garnetiferous biotite and sericite-biotite schists, many of which are almost gneissic in texture by irregular banding of relatively coarse, recrystallized quartz and oligoclase (An_{28}), or quartz, clinozoisite, and albite (An_5).

An elongate, lenticular body of saussurite-gabbro approximately one mile long crops out in the schist in this area 1/4 mile northeast of the ultramafic-schist contact. The contact between schist and saussurite-gabbro is complex and transitional over a distance of several hundred feet. Many apophyses of saussurite-gabbro cut across the metasediments near the contact. In contact with saussurite-gabbro in several places are metasedimentary rocks of hornfelsic texture and the following composition: 40°/o hornblende, 25°/o sericite, 15°/o penninite, 10°/o clinozoisite and epidote, 5°/o albite (An_5), 3°/o quartz, and traces of pyrite and magnetite.

Along most of the northern margin of the ultramafic intrusive, the metasediments are separated from the ultramafic by a continuous, lenticular body of saussurite-gabbro up to 2,000 feet in thickness. Outcrops in a stream show the usual transition from sericitic phyllite to garnetiferous sericite-biotite schist 1,000 feet from the gabbro. As the gabbro is approached the fine-grained schist becomes increasingly indurated, contorted, and strongly foliated. Two hundred feet from medium-coarse grained rock that can be readily identified as saussurite-gabbro, the schist loses obvious schistosity and foliation and, through an increase in grain size and the gradual addition of hornblende and clinozoisite, appears to grade into the saussurite-gabbro through a transitional, massive rock composed largely of penninite and muscovite. The transitional contact-rock has the following composition and texture: 20°/o ragged patches of penninite up to 1 mm (probably a replacement of garnet), 20°/o medium-grained muscovite in unoriented, interstitial aggregates, 15°/o fine-grained subhedral clinozoisite, 8°/o subhedral crystals of epidote up to 1 mm, 10°/o quartz, 5°/o cummingtonite in oriented aggregates up to 1 mm, 5°/o carbonate (ankerite) in very fine-grained pockets, 5°/o fine-grained albite (An_5), 3°/o ragged biotite, 3°/o fine-grained, disseminated pyrite and magnetite, 3 to 5°/o clay minerals (associated with clinozoisite), and 2°/o sphene, intimately associated with magnetite. In some parts of the rock, quartz has crystallized in small, pegmatitic pockets up to 1 cm in diameter. In these pods the quartz crystals are from 1 mm to 3 mm in length. They exhibit euhedral crystal faces and have very irregular extinctions. The quartz crystals poikilitically enclose subhedral crystals of green hornblende up to 1 mm in length and subhedral crystals of albite (An_5) up to 2 mm. Small pockets up to 1 mm in diameter of very fine-grained anhedral ankerite are successively rimmed by fine-grained clinozoisite and muscovite, in that order.

One mile west of the stream just mentioned, an inclusion of schist 75 feet wide and several hundred feet long crops out in the body of saussurite-gabbro which is marginal to the north side of the ultramafic. The schist is generally fine-grained, strongly foliated, highly contorted, and of the following composition: 30% anhedral quartz, 20% fine-grained epidote and clinozoisite, 15% biotite, 12% penninite, 10% ragged, green hornblende, 5% anhedral albite (An_5), 5% sericite, and 3% fine-grained disseminated magnetite and pyrite. The best exposure of contact relationships between the inclusion and saussurite-gabbro shows a considerable increase in the amounts of clinozoisite and sericite in the schist near the contact.

South of Union Point, at the northwest extremity of the ultramafic intrusive, the contact between ultramafic and schist is obscured by float. However, the schist which crops out along the beach must be within 30 feet of the ultramafic intrusive, leaving little room for saussurite-gabbro here. Some faulting may have occurred, but, with reference to the east and northeast margins of the ultramafic, is not required to explain the absence of the gabbro. The wall-rock essentially in contact with the ultramafic here (magnetiferous pyroxenite) is a fine-grained, thinly foliated, garnetiferous quartz-andesine (An_{30})-sericite-biotite schist quite similar to wall rock in contact with the east and southeast portions of the ultramafic complex. However, the foliation at this outcrop shows considerable continuity and is not contorted in the manner frequently observed close to intrusive contacts in other localities. Except for the development of garnets (largely altered to penninite) within 1,000 feet of the ultramafic, the rock near the contact appears identical in hand specimen with metasediments cropping out around Union Point more than 1/2 mile to the north of the intrusive. The mineralogy and a chemical analysis of a specimen representative of schist close to the contact appears in Table 1 (specimen no. 111).

Immediately south of Cannery Creek at the abandoned cannery site on the west shore, the metasedimentary wall-rock near the contact between ultramafic and the main body of gabbro is strongly indurated and foliated, highly contorted, medium-grained, garnetiferous quartz-oligoclase-biotite schist. This rock has suffered considerable recrystallization as evidenced by medium-grained leucocratic bands of quartz and oligoclase up to several centimeters in thickness. A considerable range in composition of the plagioclase is present in transitional textures. The largest grains (1 to 2 mm) are zoned from An_{40} (center) to An_{25} (rim). The smallest grains (ca. 0.3 mm) are subhedra of the composition An_{32} to An_{25}. Medium to large (up to 0.8 mm), very irregular, interstitial areas are An_{25} to An_{15}. The mineralogy and a chemical analysis of a representative specimen of this schist (specimen no. 192c) appears in Table 1.

One mile south of Cannery Creek, on the west flank of South Mountain, a large land-slide scar has created a clean exposure of the intrusive contact between schist and the main body of gabbro. The contact is somewhat irregular but of knife-edged abruptness. A specimen of schist collected from the contact is composed of 40%

biotite, 25% quartz, 25% andesine, 8% garnet, and 2% pyrite. The rock is foliated, highly schistose, and generally fine-grained. Relatively large (0.7 to 2 mm) almandite garnets, quartz and zoned plagioclase grains show porphyroblastic development with inclusions and local deflection of the biotite orientation. The porphyroblastic plagioclase is zoned from An_{37} (center) to An_{30} (rim) probably indicating a steep temperature gradient at the contact, and reflecting the related lack of equilibrium during metamorphism. There is no evidence here of any development of clinozoisite or epidote either in the gabbro or in the wall rock.

Three quarters of a mile southeast of the slide scar mentioned above, the gabbro near the contact with schist exhibits some saussuritization and contains many small inclusions of schist from 1 inch to several feet in length. One of the smallest inclusions was examined under the microscope and found to consist of 50% almandite garnet, 20% epidote and clinozoisite, 20% albite (An_5), 10% quartz, and traces of pyrite and magnetite, all constituents very fine-grained. There is a rim around the inclusion composed of fine-grained, anhedral epidote with some carbonate. The plagioclase grains in the gabbro surrounding the inclusion show clusters of fine-grained, euhedral prisms of zoisite and clinozoisite.

The metasedimentary country rocks beyond the aureole of contact metamorphism are thinly foliated, friable, and generally very fine-grained phyllite composed of quartz, sericite, penninite and albite (An_{10}), with some graphite and traces of apatite, pyrite and magnetite. A representative specimen of this rock was collected from a small island 2 miles north of the ultramafic complex. The mineralogy and chemical analysis of this rock (specimen 400) are given in Table 1. Comparison of the chemical analyses of specimen 400 and representative specimens of the garnetiferous quartz-oligoclase-biotite schists (specimens 192c and 222, Table 1) indicate that the phyllite has suffered little chemical change during metamorphism to schist by the ultramafic and gabbro intrusives. The schists contain somewhat less silica and water, and slightly more total iron, calcium, and alumina than the phyllite (the relative chemical composition is graphically illustrated in Figure 5).

No general summary of contact metamorphism around the ultramafic and gabbro intrusives can be undertaken until the saussurite-gabbro rocks are considered in the next portion of the text. However, it is emphasized here that: (1) the mineralogy, textures, and general width of the zones of contact metamorphism are the same around both the main body of gabbro and the ultramafic complex, and (2) although the phyllitic country rock shows evidence of considerable dynamothermal recrystallization to garnetiferous quartz-oligoclase-biotite schists near contacts with ultramafic and gabbroic intrusive rocks, these schists are considered to be low-intermediate to intermediate rank metamorphic facies by Eskola (16), Harker (21), and Turner (43).

Gabbro and Saussurite-Gabbro

With the exception of marginal areas of one to several hundred feet in width, the main body of gabbro comprising South Mountain and its northward extension, as a cap over the ultramafic intrusion, are essentially homogeneous texturally and mineralogically. An average composition is 60% plagioclase (An_{56} to An_{43}), 15%

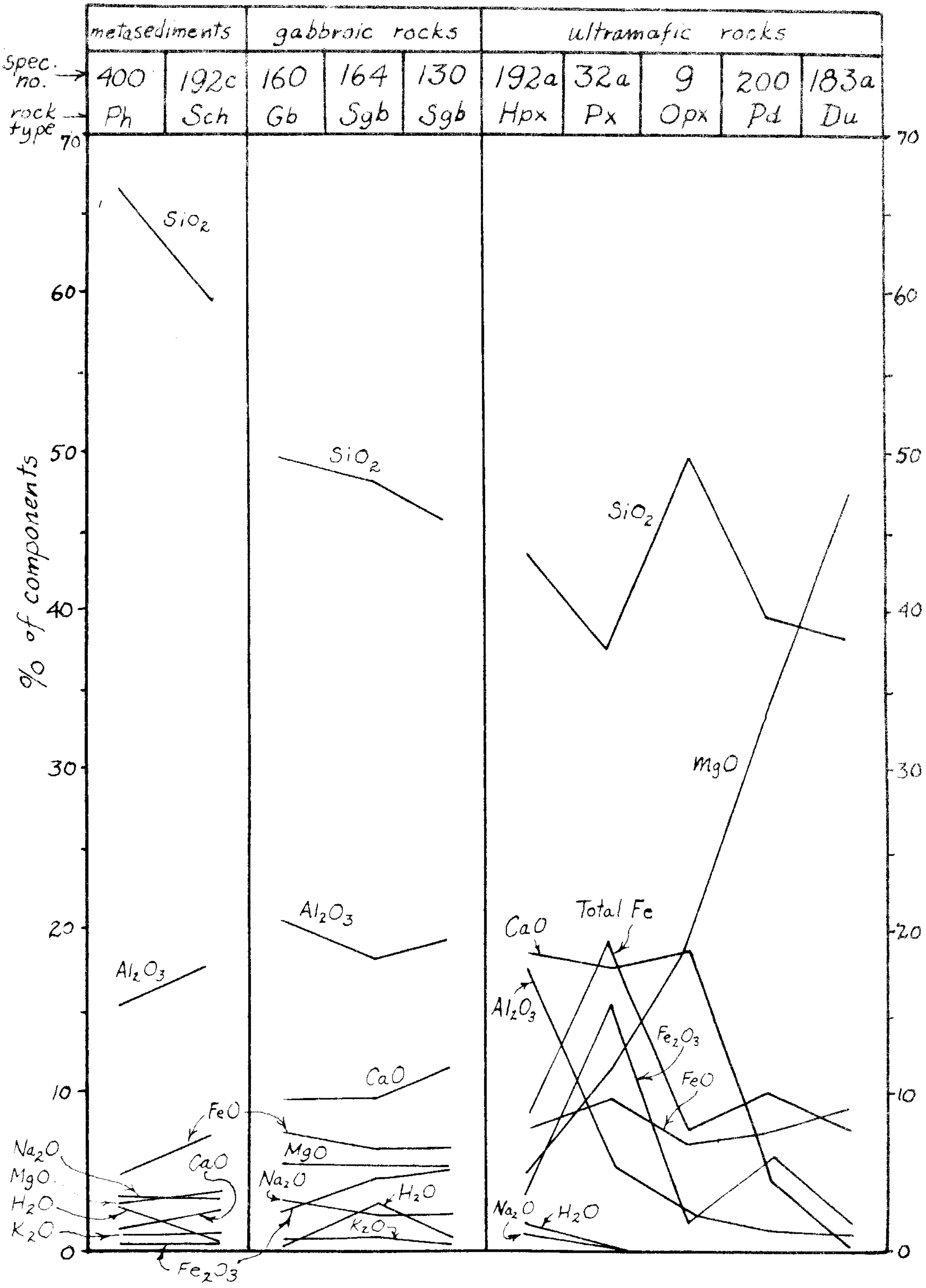

Figure 5. Comparative chemical analyses of all rock units.

hypersthene ($En_{67}Fs_{33}$), 10% diopside, 5% biotite, 5% magnetite, and traces of orthoclase, clays, sericite, apatite and hydrous iron oxides. The rock is everywhere medium-grained with plagioclase crystals ranging in size from 1 mm to 4 mm, and pyroxene crystals from 0.5 mm to 2 mm. Most outcrops exhibit sub-parallel orientation of pyroxene and plagioclase crystals. This foliation shows more continuity in marginal areas than toward the center of the intrusive, where it either shows local variation or is too inconspicuous to map. The chemical composition and mineralogy of a specimen representative of the central portion of the main body of gabbro underlying South Mountain are given in Table 1 (specimen no. 160). Figure 6 is a photomicrograph of a thin section cut from this specimen.

The marginal portions of the main gabbro intrusive are dioritic in composition for several hundred feet adjacent to the contacts with schist on the west, southwest and south slopes of South Mountain. In these areas the mafic minerals are hornblende and biotite, and the composition of the plagioclase ranges from An_{50} to An_{30}. A specimen collected from the contact with schist at a landslide scar on the west flank of South Mountain has the following composition: 60% andesinre, 15% biotite, 10% quartz, 10% tremolite and actinolite, 2% penninite, a few anhedral garnets, and traces of magnetite, apatite, and carbonate. Many of the larger plagioclase grains are zoned from An_{47} (center) to An_{30} (rim). Tremolite and actinolite occur together in clusters, probably as a replacement of hornblende. The actinolite is intimately associated with small, anhedral grains of magnetite.

The indices of refraction of both monoclinic and orthorhombic pyroxenes from four selected specimens were compared in an

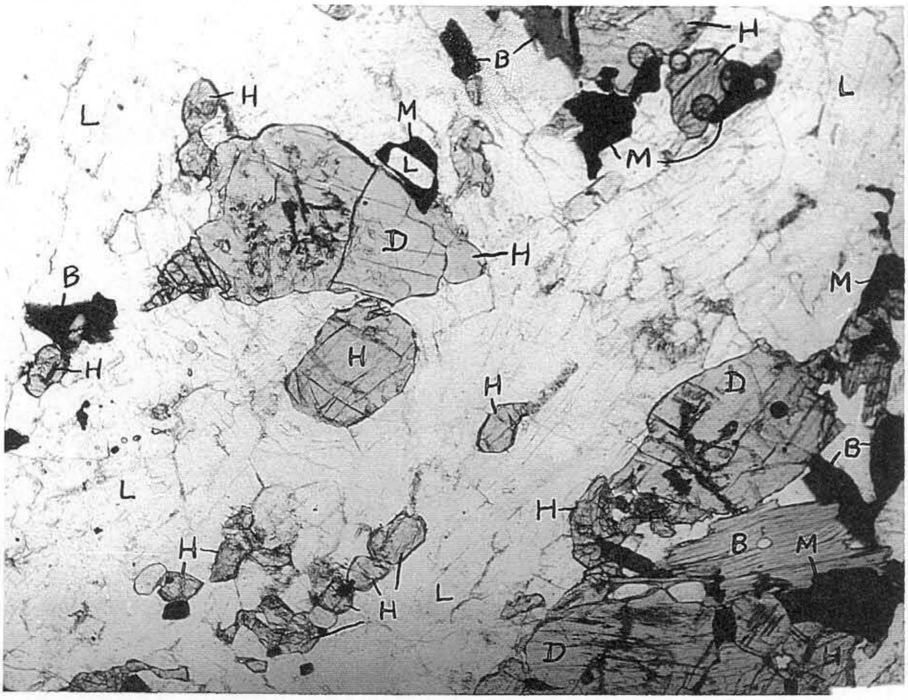

Figure 6. Photomicrograph of a representative thin section of gabbro (x30). B-biotite, D-diopside, H-hypersthene, L-labradorite, M-magnetite.

attempt to study the variation in composition throughout the gabbro intrusive. It was discovered that the variation in composition of the monoclinic pyroxene was very small, almost within the limits of error of the oil immersion method. The hypersthene, however, showed the following variation: in two specimens collected from the cap of gabbro overlying the ultramafic, 3½ miles apart, but both within 500 feet of the contact with the ultramafic, the composition of the hypersthene is $En_{67}Fs_{33}$. The composition of the hypersthene in a specimen collected from the central portion of the main gabbro intrusive is $En_{64}Fs_{36}$; hypersthene in a specimen collected 500 feet from the contact with schist on the west slope of South Mountain is $En_{54}Fs_{46}$. This trend of decreasing percentage of the magnesian molecule (enstatite) from the ultramafic contact (to the north) to the contact with metasediment (to the southwest) is difficult to interpret unless it is assumed that the ultramafic is younger, and has intruded the gabbro.

The only clean, but very limited, exposure of the contact between the main body of gabbro and the ultramafic intrusive occurs in Cannery Creek ½ mile east of tidewater. Nowhere has the writer observed a cleanly exposed contact where the cap of gabbro overlies the ultramafic, although many outcrops of both intrusives occur at higher elevations near (within 200 or 300 feet of) the contact. All the field evidence indicates that the contact relationships between these two intrusives are similar everywhere. Figure 7 is a graphic generalization of these contact relationships.

In all areas, the ultramafic unit in contact with the gabbro

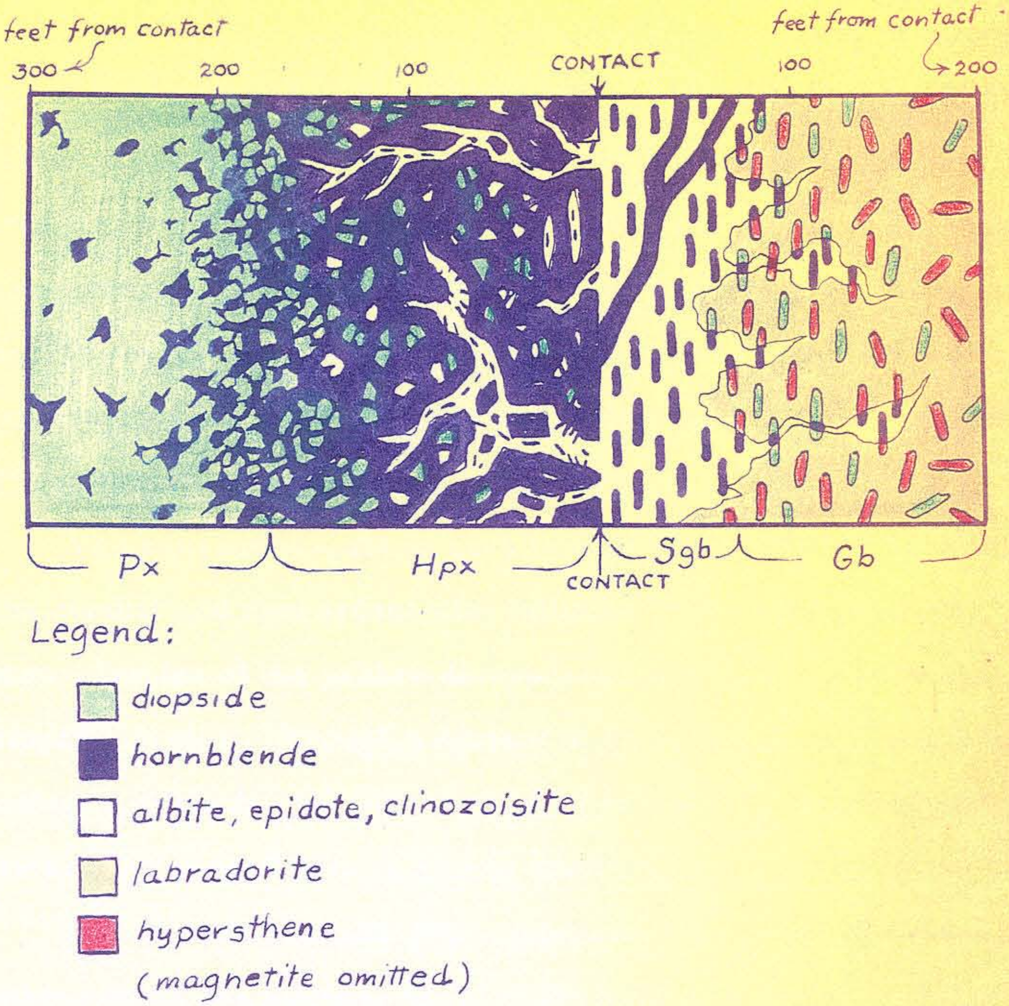

Figure 7. Contact between ultramafic and gabbro intrusives, generalized. The scale of the veins and mineral grains is much larger than the scale of the distance, in feet, from the contact.

is hornblende-pyroxenite, in which the relative amount of hornblende increases toward the contact to such proportions (over 75°/o) that the rock can be termed hornblendite. Generally within 100 to 200 feet of the gabbro, the hornblende-pyroxenite exhibits many irregular veinlets of all sizes up to several feet in width composed of clinozoisite, epidote, and albite, with or without elongate prisms of black hornblende (generally partially or wholly actinolitized). Some quartz, carbonate, and sericite are commonly present in the veins. At the contact with gabbro, the texture and relative proportions of minerals change abruptly to the rock unit mapped and referred to as saussurite-gabbro (25°/o to 50°/o hornblende and actinolite, 50°/o to 75°/o albite, clinozoisite and epidote).

The saussurite-gabbro usually exhibits a foliation parallel to the contact and concordant with foliation in the gabbro nearby. Saussuritization of the gabbro disappears inward, away from the ultramafic contact, through a system of veins and pods in which the orientation of the hornblende is parallel to the orientation of plagioclase and pyroxene in the adjacent, unaltered rock (see Figure 7).

Due to lack of continuous exposures, the extent of saussuritization around the margins of the main body of gabbro in contact with the ultramafic cannot be accurately determined. Its distribution appears to be sporadic, and, in a number of places near the periphery of the gabbro cap overlying the ultramafic, unaltered gabbro crops out within 100 to 200 feet of the ultramafic rocks (see the geologic map, Figure 3).

One specimen of unaltered gabbro collected 100 feet from the ultramafic contact near Mount Burnett contains, besides the normal plagioclase and pyroxenes, an unusual amount of orthoclase (15°/o of the rock). At the northeastern extremity of the main body of gabbro, in the vicinity of the dunitic core of the ultramafic, the gabbro is unusually mafic and contains up to 60°/o pyroxene (approximately equal amounts of diopside and hypersthene).

On both sides of Cannery Creek $\frac{1}{2}$ to 1 mile east of tidewater, the gabbro is saussuritized over an area of $\frac{1}{2}$ square mile, extending several thousand feet away from the ultramafic contact. The structure sections suggest that this portion of the gabbro may have been close to (under) the floor of the ultramafic intrusion before erosion.

Southeast of the contact in Cannery Creek, the saussurite-gabbro is cut by several hornblendite dikes approximately 3 feet wide. These dikes are vertical and strike N40°W. The saussurite-gabbro in this area also contains many podlike segregations from 1 inch to 10 feet in diameter of magnetite surrounded by successive rims of diopside and hornblende, in that order.

The marginal portions of the dioritic gabbro in contact with schist on the west and southwest slopes of South Mountain exhibit minor areas of saussuritization. However, the distribution of saussurite-gabbro around this contact is not continuous. Some saussuritization is evident near the gabbro-schist contact $1\frac{1}{2}$ miles southeast of the cannery. Otherwise most outcrops along the west and southwest periphery of the gabbro, including one clean exposure of the contact at a land-slide scar (previously described), show no evidence of saussuritization.

The development of saussurite-gabbro in the main body of gabbro can be considered essentially, but not entirely, a marginal feature. In two or three places in the more central portions of the unaltered gabbro, small veins and patches of saussurite-gabbro were observed.

At the southeastern extremity of the ultramafic intrusion, the main gabbro body pinches out between ultramafic and schist. The gabbro here is represented by a medium-coarse-grained albite-clinozoisite-epidote-hornblende schist, briefly mentioned in the preceding section of the text. The mineralogy and a chemical analysis of this rock (specimen no. 223) appear in Table 1. The chemical analysis of this schist is very similar to that of unaltered gabbro (specimen no. 160).

Included in the hornblende-pyroxenite in some places near (within 200 feet of) the contact with the cap of gabbro which overlies the ultramafic complex are tabular bodies of saussurite-gabbro from 6 inches to 20 feet in length oriented parallel to the contact. These inclusions are best exposed near the western extremity of the gabbro cap.

Bodies of saussurite-gabbro of all sizes from several inches to several hundred feet long appear to be included in the hornblende-pyroxenite along the shore for one mile north of the cannery site. The larger inclusions are lenticular in plan, dip steeply, and trend northwest (see geologic map, Figure 3). The largest of these inclusions crops out 500 feet north of the mouth of Cannery Creek. At the southeastern extremity of the outcrop, the rock is fine-grained, well indurated, and vaguely exhibits a thin banding. This rock is composed of hornblende partly altered to actinolite, clinozoisite, epidote, quartz, albite (An_5), penninite, and minor amounts of sericite, apatite, and pyrite. The amount of quartz ranges from less than 5% to 20% of the rock in different specimens. The mineralogy and a chemical analysis of a representative specimen of this outcrop are given in Table 1 (specimen no. 193).

Although continuous exposure is interrupted by 200 feet of stream gravel, the fine-grained, banded rock appears to grade, over a distance of 600 feet along the shore, through a coarsely banded, gneissic rock into medium to coarse-grained saussurite-gabbro without any change in mineralogy other than a decrease in the amount of quartz.

Specimen no. 130 was collected from a strongly banded, fine-grained, granulose inclusion of saussurite-gabbro in hornblende-pyroxenite 3/4 mile north of Cannery Creek. The mineralogy and a chemical analysis of this rock are given in Table 1.

There are three other areas at Union Bay where bodies of saussurite-gabbro are separate from each other and from the main gabbro intrusive at the present level of erosion (see the geologic map). They are: (1) two bodies approximately 1,300 feet in the longest dimension which crop out within the northwestern portion of the hornblende-pyroxenite south of Union Point; (2) an elongate, lenticular body 3 miles long and as much as 1/2 mile wide which crops out along the northern margin of the ultramafic, and separates that intrusive from the metasediments to the north; (3) an outlying, lenticular body one mile long and as wide as 1,000 feet which crops out in the metasediments 1/4 mile to the northeast of the ultramafic near Vixen Inlet.

All these bodies of saussurite-gabbro exhibit essentially identical mineralogy, textures, and contact relationships (against the same rock types). An average composition for all saussurite-gabbro is approximately 30% hornblende, 30% epidote and clinozoisite, 15% albite (An_3 to An_{10}), and minor and variable amounts of diopside, quartz, actinolite, apatite, carbonate (ankerite), sphene, chlorite (penninite), biotite, sericite, magnetite, sulfides (pyrite, chalcopyrite, pyrrhotite), and hydrous iron oxides. Except for some fine-grained inclusions north of Cannery Creek, the rock is generally composed of relatively coarse grains of hornblende and fine-grained albite, epidote, clinozoisite, and minor constituents. Pronounced foliation is observed only in some inclusions, or within a short distance (approximately 100 feet) of the contact with ultramafic rocks.

In most specimens hornblende exhibits elongate, sub-prismatic form, although in thin section even the best developed prisms have ragged, interlocking boundaries. Many hornblende grains poikilitically enclose fine-grained quartz and apatite. Where diopside grains are observed, they are very ragged remnant grains almost completely replaced by hornblende. Albite is usually present in two generations. Medium-grained anhedra are an essential constituent, comprising 30% to 60% of the area of a thin section. These grains contain many fine-grained subhedral to euhedral clinozoisite and epidote crystals, and usually some sericite. A later generation of fine-grained, unaltered albite commonly cuts across and rims the larger grains of albite and hornblende. Both clinozoisite and epidote are present in most specimens. Clinozoisite is the most ubiquitous of the two and occurs as very fine grains in albite. Although epidote also occurs in this way in some specimens, it is more commonly developed as larger, individual, subhedral grains associated with hornblende and magnetite. Also invariably observed in thin sections, in fields of fine-grained clinozoisite, is an increase in birefringence and pleochroism of the clinozoisite to that of epidote adjacent to grains of hornblende and magnetite. Grains of anhedral quartz generally make up 3% to 5% of the rock. Subhedral to euhedral sphene is often observed in intimate association with grains of magnetite. Paragenetically, the sphene is the later mineral, rimming and cutting the magnetite.

The above textures are illustrated in Figure 8 which is a photomicrograph of a thin section of saussurite-gabbro. The mineralogy and a chemical analysis of a representative specimen (no. 164), collected from the saussurite-gabbro marginal to the north side of the ultramafic, appears in Table 1.

In all specimens of saussurite-gabbro studied, albite (An_3 to An_{10}) is the only plagioclase present. Therefore, if this mineral assemblage is representative of metamorphism (saussuritization) of a gabbroic rock originally containing a more calcic plagioclase, the metamorphism has been so complete that no relic grains of the original plagioclase are evident in thin section.

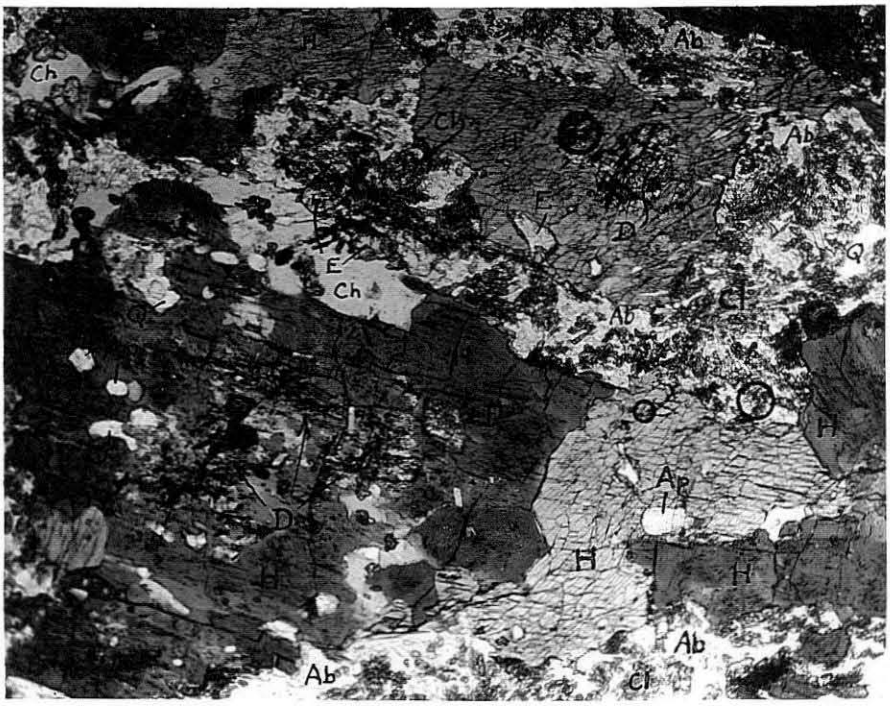

Figure 8. Photomicrograph of a representative thin section of saussurite-gabbro (x90). Remnant diopside grains are enveloped by hornblende. The field between grains of hornblende is composed of many fine-grained, euhedral crystals of clinozoisite (high relief) in anhedral, medium-sized grains of albite (low relief). Ab-albite, Ap-apatite, Ch-chlorite (penninite), Cl-clinozoisite, D-diopside, E-epidote, H-hornblende.

The contact relationships between saussurite-gabbro and metasedimentary rock have been presented in the preceding section of the text. In a stream channel midway along the north side of the ultramafic body, and along the shore north of the cannery, contacts between saussurite-gabbro and ultramafic rocks are exposed. These outcrops, plus other less continuous exposures in other places, show that the contact relationships between the separate bodies of saussurite gabbro and ultramafic rocks are identical to the relationships which have been described between the margin of the main body of gabbro and the ultramafic complex (see Figure 7). However, the main gabbro intrusive exhibits only peripheral saussuritization over a distance of several hundred feet against the ultramafic, while the outlying bodies are completely saussuritized.

At the time of the ultramafic intrusions, the outlying bodies of gabbro, which now crop out along the north and northeast margins of the ultramafic, probably were not completely saussuritized, and therefore, contained less water than the surrounding metasediments. The complete saussuritization of these gabbros may be due to the diffusion of water into them from the relatively wet metasediments at elevated temperatures caused by the ultramafic intrusions. The feasibility of this phenomenon has been recently emphasized by Thompson (42, pp. 98-99). On the other hand, the contact between the ultramafic intrusives and the main body of gabbro would have been a relatively dry environment.

The possibility is not precluded that some portions of the rocks mapped as saussurite-gabbro represent sediments highly metamorphosed and mobilized by the ultramafic intrusions, especially the fine-grained banded inclusions in hornblende-pyroxenite near the mouth of Cannery Creek. However, the evidence listed below supports the conclusion that individual bodies of saussurite-gabbro are metamorphic (saussuritized) portions of a single gabbro intrusion, having been separated from the main body of gabbro by the ultramafic intrusions:

1. Except for 1.5% to 2% water, the chemical analyses of all specimens of saussurite-gabbro (130, 164, 193, and 223, Table 1) are essentially identical to the chemical analysis of a specimen from the unaltered portion of the main gabbro intrusive (specimen no. 160).

2. The textural and mineralogical identity of outlying bodies of saussurite-gabbro with that portion of the main body of gabbro which has been saussuritized along the ultramafic contacts.

3. The identity of contact relationships between outlying bodies of saussurite-gabbro and ultramafic rocks with contact relationships between the main gabbro intrusive and ultramafic rocks.

4. The textural and mineralogical similarity between the saussurite-gabbro at Union Bay and metamorphosed basic intrusive rocks in other regions (e.g., the albite-epidote, hornblende schists or "epidiorites" of the Scottish Highlands described by Harker and others (21, pp. 278-280). Most authors assign these rocks to the albite-epidote amphibolite facies, embracing a grade of metamorphism corresponding to the almandine zone as defined for pelitic schists (43, p. 88). Therefore, the saussurite-gabbro at Union Bay

can be considered correlative in metamorphic rank with the zone of garnetiferous biotite schist which has been developed in the metasedimentary rocks around the gabbro and ultramafic intrusives.

The Ultramafic Intrusive Rocks

Definitions of the ultramafic rock units at Union Bay are given in Table 3. Distinctions between units are purely mineralogical, and the terminology employed is intended to be descriptive of the mineralogy. Divisions between the units are based upon the best distinctions which can be made in the field.

1. Pyroxenite:

In broad terms the pyroxenite is a peripheral unit, encasing the spoon-shaped, lopolithic portion of the ultramafic body. However, the thickness of the pyroxenite shell is not symmetrical about the lopolith. The largest areas of pyroxenite outcrop, and the greatest thickness of the unit, lie around the north and west margins of the intrusive. The upper portion of the pyroxenite shell (under the cap of gabbro) is thinner in section than the lower portion but exhibits identical textures and mineralogy. With an increase in amount of hornblende, the pyroxenite grades outward to hornblende-pyroxenite in many areas, and with an increase in the amount of olivine it grades inward to olivine-pyroxenite everywhere. Except for thin bands of magnetite (generally 1 to 5 cm thick) in some areas, the pyroxenite exhibits no structure other than joints and is of monotonous composition over large areas. It is essentially composed of diopside with some hornblende and magnetite. Fresh surfaces of the rock show

mineral components rock units	diopside	hornblende	olivine	albite, clinozoisite, epidote.	magnetite	serpentine minerals
PYROXENITE (Px)	45-95	0-15	0-10 locally	0-10 locally	1-40+	tr.
mode	75	5	nil	nil	5-20 variable	nil
HORNBLENDE-PYROXENITE (Hpx)	10-85	15-90	0-10 locally	0-30+	tr.-20	tr.
mode	40	40	nil	10	10	nil
OLIVINE-PYROXENITE (Opx)	40-90	tr.-10	10-40	nil	tr.-10	tr.-20
mode	75	tr.	20	nil	3-5	2-3
PERIDOTITE (Pd)	10-60	tr.	40-90	nil	1-5	tr.-30
mode	45	tr.	45	nil	1-2	5
DUNITE (Du)	0-10	tr.	90+	nil	tr-3*	0-30
mode	2	nil	95	nil	1*	3-5

all figures are estimated vol. %.

* magnetite and chromite.

Table 3. Definitions of ultramafic rock units.

dark green, vitreous grains of diopside and black, metallic grains of magnetite. Weathered surfaces are medium gray-green with blue-gray, metallic magnetite standing out in relief. The grain size of the rock ranges locally from medium (1 mm) to coarse (1 to 3 cm). Pyroxene grains as large as 10 cm are not infrequently observed, but these very coarse grains are generally in irregular clots or veins which cut the finer grained pyroxenite. The rock is typically equigranular with randomly oriented, equant, subhedral grains of diopside. The grain sizes of magnetite and diopside generally vary in a direct relationship because the magnetite is interstitial to the pyroxene grains.

Variations in the grain size of the rock are randomly distributed throughout the pyroxenite unit. From lack of adequate exposures, it is not known whether there are textures in the pyroxenite and hornblende-pyroxenite units which could be interpreted as chilled margins where these rocks are in contact with schist. However, there are enough exposures of medium to coarse grained hornblende-pyroxenite at or near contacts with gabbro and saussurite-gabbro to infer that there is no chilled zone between the ultramafic and gabbroic rocks.

Although some thin sections of pyroxenite contain two or three grains of diopside which exhibit undulose extinction or strain shadows, more than 90% of the grains studied in thin section show sharp extinctions. Features which could be interpreted as mortar texture (granulated and sutured grain boundaries) are rare. Thin sections of two specimens collected from within 300 feet of the upper contact between ultramafic and the overlying gabbro cap do show a mortar texture. This feature is not typical of the contact zone of the ultramafic. The majority of specimens collected along the outer margin of the pyroxenite exhibit no evidence of strain. Mortar textures are evident in all thin sections of pyroxenite intimately associated with bands of magnetite. These are discussed in more detail under the heading of "Ore Mineralization."

Photomicrographs of representative thin sections of pyroxenite appear in Figures 9 and 10. Some specimens show considerable diallage twinning on the 100 plane (Figure 10). Most of the magnetite occurs in the interstices between diopside grains, but many grains of diopside exhibit tiny, brownish, translucent inclusions of magnetite regularly oriented parallel to the 100, 001, 011, and 122 crystallographic directions in the pyroxene. These inclusions, which in some grains are so concentrated that the pyroxene has a "dusty" appearance in thin section, are clustered in the central portions of the pyroxene grains and are absent from the periphery (see Figure 11). It can be deduced from this feature that the magnetite inclusions are not replacement phenomena but rather represent ferric iron trapped in the diopside lattice at the time and temperature of crystallization of the pyroxene and later exsolved as magnetite at lower temperature as the diopside grains cooled.

A few small (0.2 mm) anhedral grains of hercynite spinel are almost always present in magnetite which is interstitial to diopside grains. Also invariably associated with the magnetite is some hornblende which is black in hand specimen and pleochroic green

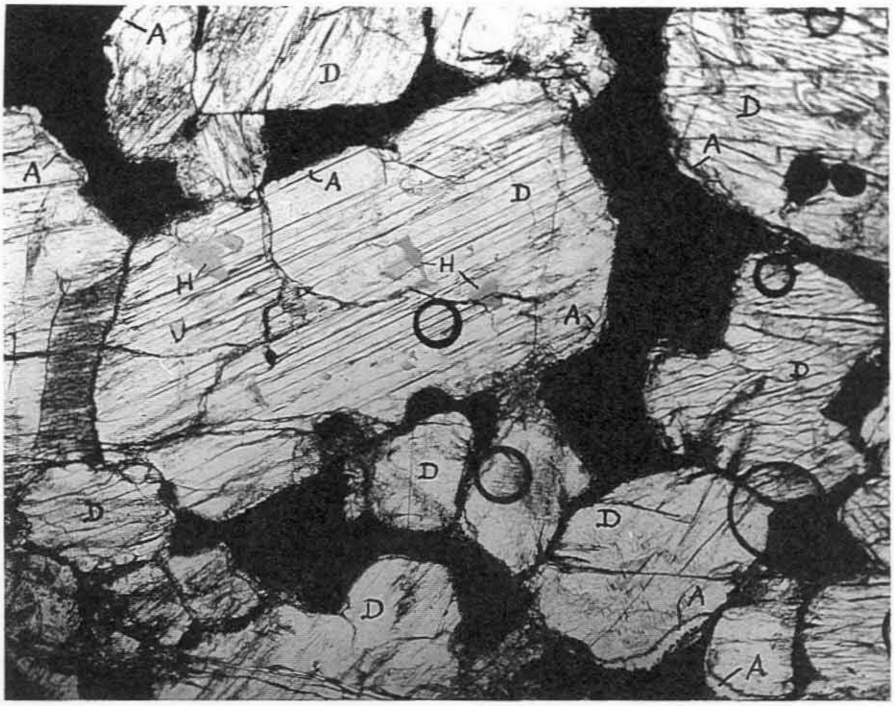

Figure 9. Photomicrograph of a thin section of magnetiferous pyroxenite from the ore zone (x30). Subhedral to euhedral grains of diopside with interstitial magnetite (black areas). A narrow rim of antigorite is commonly developed between diopside and magnetite. A-antigorite, D-diopside, E-epidote, H-hornblende.

Figure 10. Photomicrograph of a thin section of magnetiferous pyroxenite showing diallage twining in diopside crystals (x30), crossed nicols).

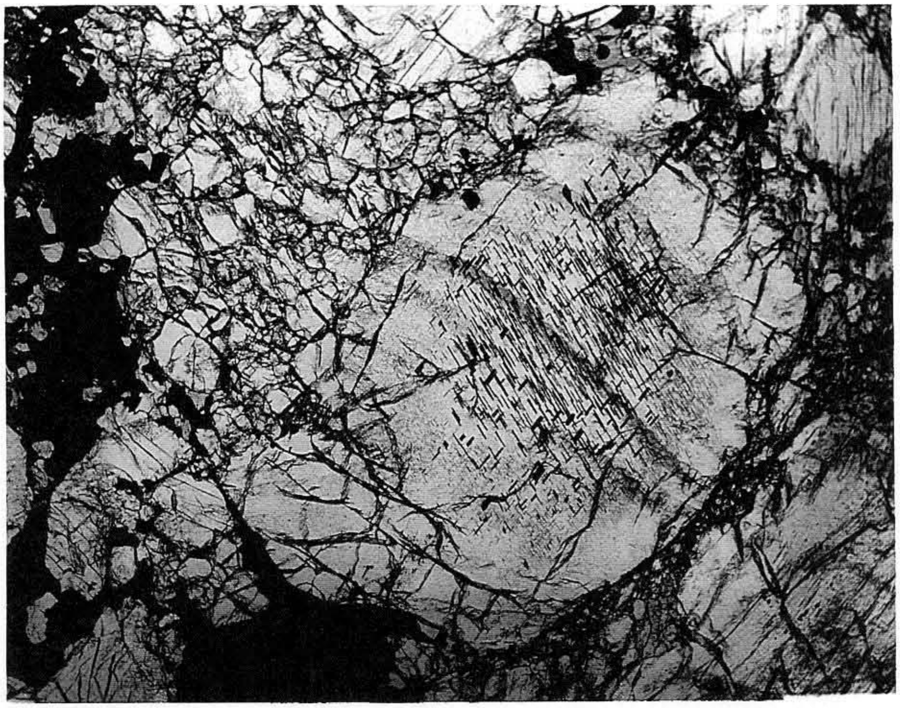

Figure 11. Photomicrograph of a thin section cut across a band of magnetite in pyroxenite (x30). The black areas are magnetite at the edge of the band. The remainder of the field is diopside with traces of hornblende. Note the granulation around the large grain of diopside and the tiny, oriented inclusions of magnetite near the center of the grain.

to brown in thin section. In sections which contain only a very small amount of hornblende (1°/o or 2°/o of the rock), this mineral occurs as a fine-grained deuteric alteration of diopside, typically at the contact between diopside and magnetite but in some instances in the interior and along the C directions of the pyroxene grains. With an increase in the amount of hornblende (5°/o to 15°/o of the rock), the hornblende also appears as medium to coarse grained, anhedral, ophitic patches in the interstices between diopside grains with (in thin section) many separate anhedral areas of hornblende in parallel orientation. In such rocks, a narrow (0.05 mm) rim of very fine-grained antigorite is frequently observed as an alteration of diopside grain boundaries in contact with interstitial magnetite. Narrow rims of penninite are also commonly developed between magnetite and hornblende in the same rocks.

In places small, secondary veins of ankerite, generally 3 mm to 10 mm wide, cut through the pyroxenite and hornblende-pyroxenite. Diopside and hornblende grains exhibit local alteration to actinolite, and magnetite shows secondary development of earthy hematite adjacent to these carbonate veins.

All pyroxenite hand specimens and thin sections studied contain magnetite in amounts from 1°/o to over 50°/o. However, the magnetite content of the rock is constant throughout large areas of outcrop, as shown on the map, Figure 3. The largest areal concentration of magnetite crops out around the west and northwest exposures of the lower pyroxenite and hornblende-pyroxenite units. Here, in what is referred to as the "ore zone," the magnetite content of the rock averages 20°/o by weight over many portions of this area.

The portions of the lower pyroxenite unit which crop out around the north, northwest, and west sides of the ultramafic and the upper pyroxenite unit under the gabbro cap contain essentially no olivine 200 feet or so away from the olivine-pyroxenite unit. In these portions of the pyroxenite, olivine is found in amounts up to 10°/o of the rock in only a very few, small areas where its occurrence cannot be traced for more than 100 feet or so in any direction.

The pyroxenite around the northeast, east, and south periphery of the ultramafic in the vicinity of the dunite core contains generally 5°/o and locally between 8 and 10°/o olivine. Due south of the dunite core the outer margin of the ultramafic is olivine-pyroxenite which contains from 15 to 20°/o olivine at the contact with albite-clinozoisite-epidote-hornblende schist.

Olivine in the pyroxenite unit has the same optical properties and textural relationships as the olivine of the olivine-pyroxenite unit. However, the olivine in the olivine-pyroxenite is relatively fresh, and that found in the pyroxenite unit is commonly altered to antigorite, chrysotile, and bowlingite, especially within several hundred feet of the outer margin of the ultramafic. A representative specimen of pyroxenite collected at the contact between ultramafic and wall-rock due east of the dunite core contained 72°/o diopside, 20°/o magnetite, and 8°/o olivine which has been completely altered to antigorite, chrysotile, and bowlingite. The alteration of this rock has been highly selective. All the diopside grains are fresh and unaltered.

The indices of refraction of 30 diopside specimens collected from various parts of the ultramafic intrusive were determined by immersion oils. The relative proportions of the diopside and hedenbergite molecules (D_nH_{100-n}) were established from charts correlating this relative molecular composition and optical properties published by Hess (24, p. 641). These determinations are listed in Table 2. The results of this study indicate a regular pattern of variation in the composition of the diopside throughout the ultramafic body. The two extremes in composition in Table 2 are represented by specimen no. 156 ($D_{70}H_{30}$) collected from the peripheral hornblende-pyroxenite unit and specimen no. 183b ($D_{99}H_1$) collected from the dunite core. The average molecular composition of the diopside in each ultramafic unit in the order: hornblende-pyroxenite, pyroxenite, olivine-pyroxenite, peridotite, dunite, is successively richer in $CaMgSi_2O_6$ and poorer in $CaFeSi_2O_6$. This is illustrated in Figure 12, which also indicates a parallel trend in the relative proportions of MgO and FeO in the olivine of the olivine-pyroxenite, peridotite, and dunite units.

Thirteen of the 30 diopside specimens in Table 2 were collected from the pyroxenite unit and show a variation in composition from $D_{73}H_{27}$ to $D_{86}H_{14}$. The variation within the magnetite ore zone is from $D_{73}H_{27}$ to $D_{80}H_{20}$. The lowest value for the diopside molecule ($D_{73}H_{27}$; specimen no. 109) was collected from within 50 feet of the schist contact at the northwest edge of the ultramafic. The more hedenbergitic pyroxenes in every portion of the pyroxenite sampled are those which are associated with approximately 20% or more magnetite and which are closest to the outer margin of the ultramafic. No more detailed pattern of variation in composition of the diopside within the pyroxenite unit could be determined from the specimens collected.

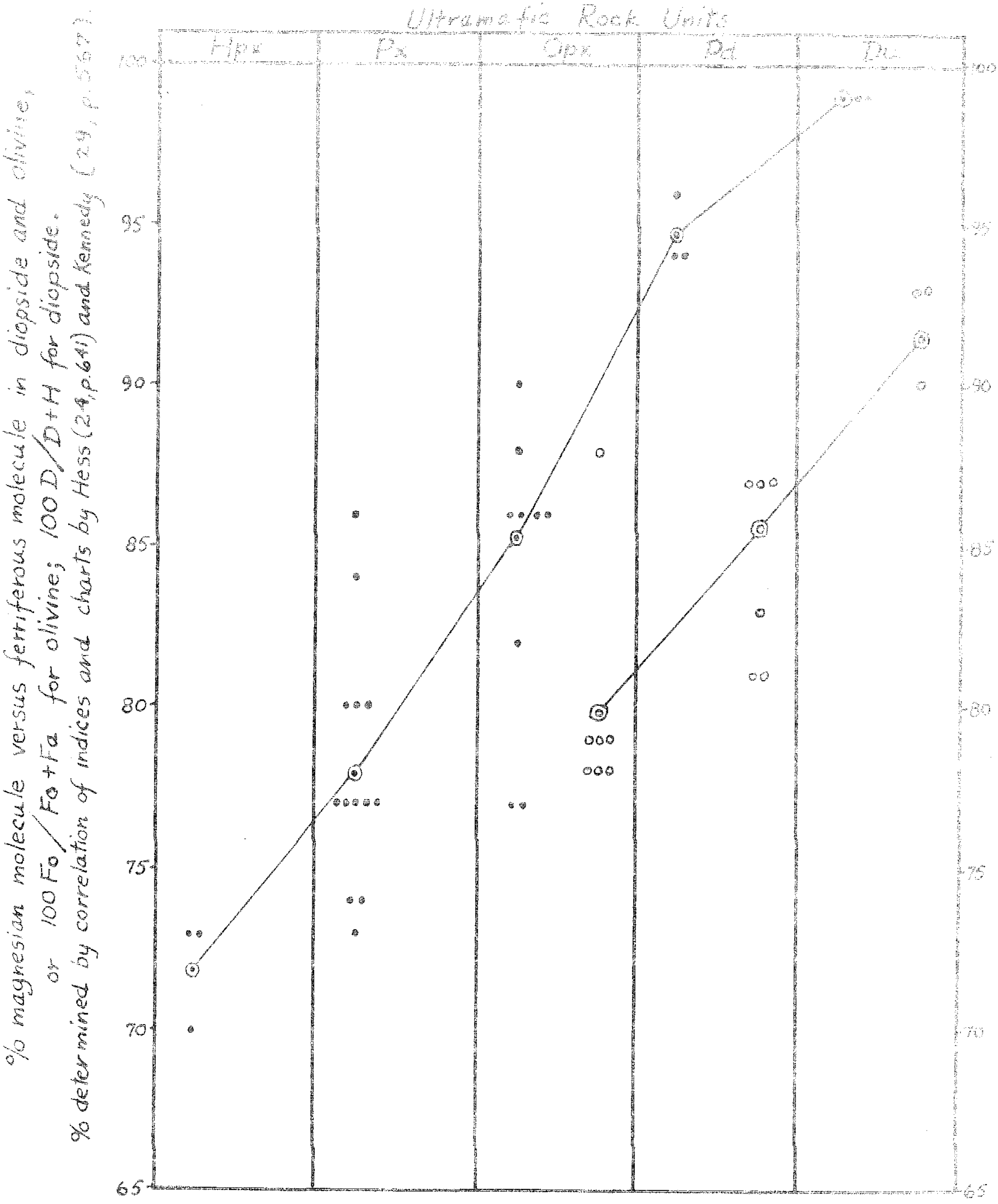

Figure 12 : Correlation of indices and composition for olivine and diopside in ultramafic rock units.

Legend:
• diopside determinations
⊙ ave. of each unit
○ olivine determinations
⊙ ave. of each unit
——— trends of ave. composition

Mineral and chemical analyses of a representative pyroxenite specimen collected from the central part of the ore zone are given in Table 1 (specimen no. 32a). The diopsides of this specimen and specimen 109 (above) were separated, except for approximately 3°/o contamination by mostly magnetite and some hornblende, and analyzed. The atomic percentages of Ca, Mg, and Fe were calculated from these two diopside separates plus one other diopside separate from the dunite core (specimen no. 183b). These determinations are plotted on a ternary diagram in Figure 13. Amounts of FeO and Fe_2O_3 were subtracted from the chemical analyses to correspond with the amount of magnetite contamination in the separates. Remaining Fe_2O_3 was assumed to be in octahedral (6-fold) coordination in the diopside lattice and was recalculated as ferrous iron in the diagram.

Specimens no. 183b and 109 represent respectively the magnesian and ferriferous ends of the spectrum of composition of diopside in the ultramafic. Curve A in Figure 13 is drawn through the plots of specimens 183b, 32, and 109 to represent the trend of composition of the diopside in the intrusive. Curve B in Figure 13 represents the trend of composition of the monoclinic pyroxene in the Blashke Island ultramafic, as worked out by Walton (47, p. 65). Curve C shows the trend of composition of monoclinic pyroxenes crystallizing from the more common mafic magmas (gabbro, norite, and diorite) according to Hess (23, p. 585). The trend of composition of diopside at Union Bay is 7 to 8°/o more calcic than the trend in the more common mafic magmas (curve C) and 3 to 5°/o more calcic

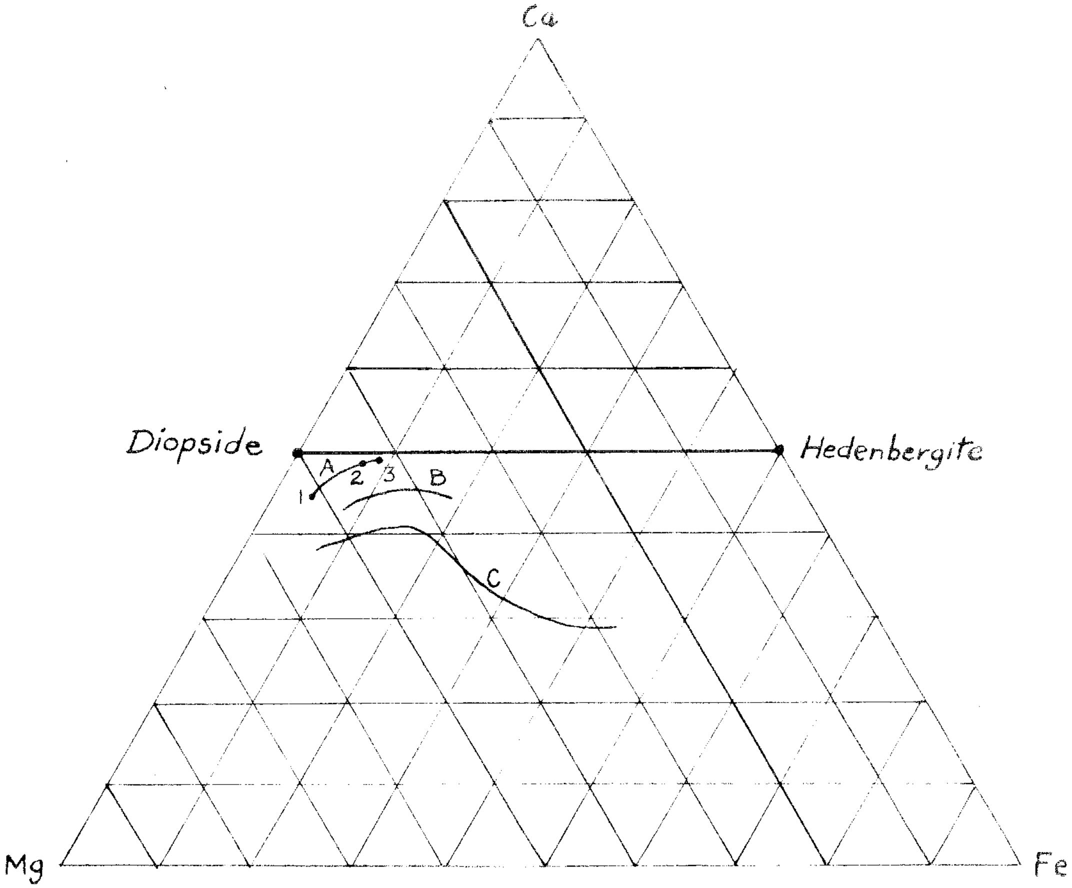

Figure 13. Chemical composition of monoclinic pyroxenes in terms of percentages of Ca, Mg, and Fe.

Points:

1. Specimen 183b (diopside from the dunite core).
2. Specimen 32a (diopside from the ore zone).
3. Specimen 109 (diopside from outer ultramafic contact with schist near the ore zone).

Curves:

A. Trend of composition of diopside in the Union Bay ultramafic complex, as determined by chemical analyses.

B. Trend of composition of monoclinic pyroxenes in the Blashke Islands ultramafic complex, after Walton (47, p. 65).

C. Trend of composition of monoclinic pyroxenes crystallizing from common mafic magmas, after Hess (23, p. 585).

than the monoclinic pyroxenes at the Blashke Islands (curve B). Curve A does fall within the relatively limited range of composition for porphyritic pyroxenes in many basaltic rocks (2, p. 195).

An increase in the amount of Al_2O_3 from the dunite core to the pyroxenite unit of the lopolith is conspicuous in the chemical analyses of diopside separates from specimens no. 109, 32, and 183b.

A discrepancy is exhibited in Figure 13 between the plots by atomic per cent of the more alumina-rich diopsides of the pyroxenite unit (specimens no. 32a and 109) and their relative position on the diopside-hedenbergite line according to the position on the line predicted by the use of Hess's optical data (24, p. 641). This discrepancy must be due to the amount of Al_2O_3 in the diopside, which increases the indices of refraction.

Chemical analyses of the diopside in the pyroxenite unit at Union Bay indicate less SiO_2 and more Al_2O_3, Fe_2O_3, and CaO than most chemical analyses of diopsides in the literature (see Hess, 24, pp. 645-666). Analyses of chromian diopsides from peridotitic inclusions in basalts (published by Ross, Foster, and Myers; 40, p. 709) are very similar to analyses of the Union Bay diopsides, especially with respect to the relatively high Al_2O_3 content. Analyses of the pyroxenite and diopside, as well as other ultramafic rocks, at Union Bay are practically identical to analyses published by Camsell from his work on the Lodestone Mountain ultramafic body near Tulameen, British Columbia (12, pp. 53 and 61). The Lodestone ultramafic crops out near the southern extremity of the Coast Range batholith. It does not exhibit lopolithic structure but is similar to the Union Bay ultramafic in most other respects.

2. Hornblende-Pyroxenite

The hornblende-pyroxenite unit represents a peripheral and compositional modification of the pyroxenite unit at the contact between pyroxenite and wall-rock (schist, gabbro, and saussurite-gabbro) around the perimeter of the lopolithic portion of the ultramafic intrusion. The essential compositional and textural relationships between pyroxenite and hornblende-pyroxenite in contact with gabbro have been diagrammatically summarized in Figure 7.

Specimens of pyroxenite representative of the more central portions of the pyroxenite unit contain an average of approximately 5°/o hornblende. The amount of hornblende associated with pyroxenite commonly increases outward toward the wall-rock contact to an extent (up to 90°/o of the rock) that in some places the rock can be termed hornblendite. Also associated with the hornblende-pyroxenite near the contact are veins and dikes composed primarily of hornblende and clinozoisite. For these reasons the mineralogical definition of the hornblende-pyroxenite unit in Table 3 shows the most variation in composition of any of the ultramafic rock units.

Because of its gradational nature (Figure 7), the contact between pyroxenite and hornblende-pyroxenite is the most ambiguous contact mapped within the ultramafic body. The relative composition of approximately 15°/o hornblende and 85°/o diopside was found to be the most convenient mineralogical field boundary between these two rock types.

The width of the hornblende-pyroxenite generally varies from 200 to 500 feet in thickness and is relatively uniform around most of the perimeter of the lopolith (see the geologic map, Figure 3). Only traces of hornblende (1% to 2%, or less, of the rock) are present locally in the pyroxenite around the eastern periphery of the ultramafic in the vicinity of the dunite core, and there is no hornblende-pyroxenite in this area. Hornblende-pyroxenite, enclosing small areas of saussurite-gabbro, crops out over a large area of approximately one square mile along the northern portion of the magnetite ore zone at the northwest periphery of the lopolith. That this relatively large area of hornblende-pyroxenite outcrop is close to the floor of the intrusion (within 1,000 vertical feet) is an interpretation suggested by the structure cross-sections.

Hornblende-pyroxenite at or near contacts with schist around the northeastern periphery of the ultramafic is generally composed of approximately 40% hornblende, 40% diopside, 15% magnetite, and a few small veins from 1 mm to several cm in thickness of hornblende, clinozoisite, epidote, and albite. In areas which are in contact with gabbro or saussurite-gabbro, the hornblende-pyroxenite contains more hornblende relative to pyroxene than in other areas, and generally from 20 to 30% of the rock is composed of hornblende-clinozoisite-epidote-albite veins and dikes up to several feet in thickness. Good exposures of hornblende-pyroxenite of this nature crop out along the shore-line for a distance of 1/2 mile north of the cannery site at the southwest edge of the ultramafic. The rock in this area locally contains from 70 to 90% coarse hornblende, 10 to 30°/o clinozoisite, epidote and albite which are either interstitial to the hornblende crystals or in separate veins, and only traces of diopside and magnetite (see Figure 14). The veins and dikes which cut the hornblende-pyroxenite in this area are composed primarily of ragged hornblende crystals, interstitial clinozoisite with some epidote and albite, and minor amounts of apatite, carbonate, sericite, quartz, magnetite, and sulfides (mostly pyrite with some chalcopyrite and pyrrhotite). The porphyritic hornblende crystals are commonly in random orientation, but radiating groups of crystals and crystals oriented perpendicular to the walls of the veins or dikes are sometimes observed. Some of the hornblende in the vein material is partially or completely altered to actinolite and penninite. The mineralogy of these veins and dikes cannot be distinguished from saussurite-gabbro rock in either hand specimen or thin section. Figures 14, 15 and 16 illustrate textures in the hornblende-pyroxenite north of the cannery site.

Exposures of hornblende-pyroxenite which crop out at the cannery site, on the southwest margin of the ultramafic complex, are separated from the closest exposures of metasedimentary schist by approximately 250 feet of stream gravel. Hornblende-pyroxenite which crops out in the bed of Cannery Creek is unusually fine-grained (largest grains are hornblende, approximately 1 mm) and may be within a few feet of the metasedimentary contact. The mineralogy and a chemical analysis of this fine-grained rock (specimen 192a) are given in Table 1.

On the weathered surface of a typical hornblende-pyroxenite specimen, the black hornblende contrasts with the gray-green

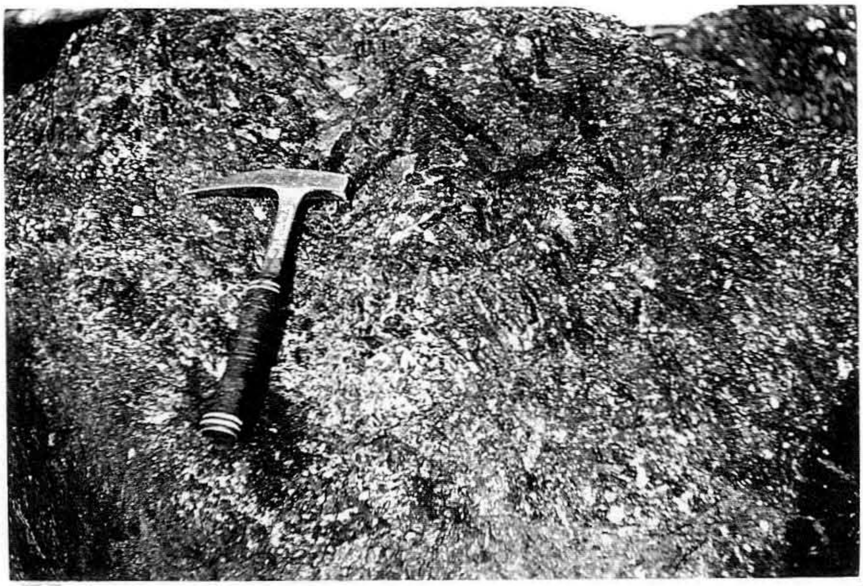

Figure 14. An outcrop of coarse-grained hornblendite with interstitial albite and clinozoisite (white).

Figure 15. Hornblendite cut by veins containing hornblende, albite, clinozoisite, epidote, and traces of quartz.

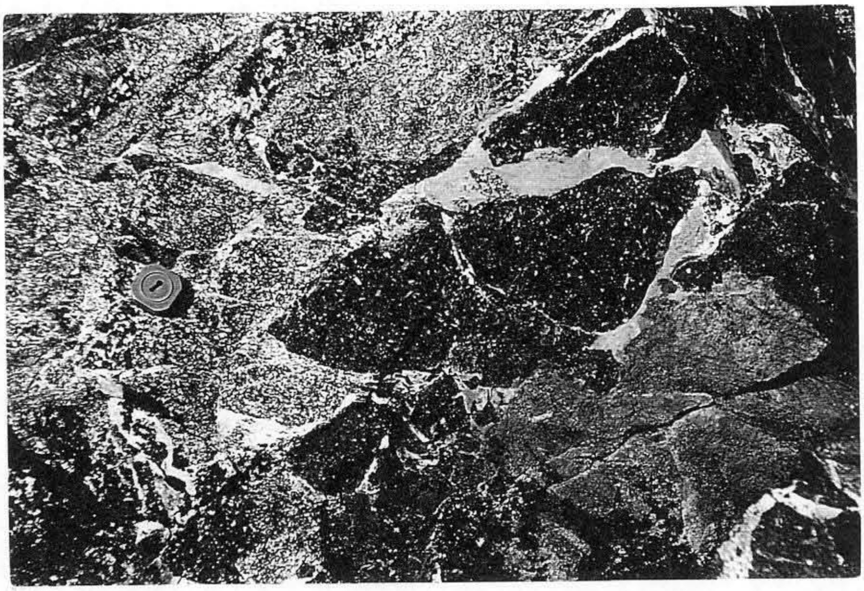

Figure 16. Hornblendite (black) containing a flow-banded inclusion of saussurite-gabbro (rusty). The hornblendite is cut by a large, irregular dike and small veins of gabbroic material essentially identical in composition to the inclusion. The white veins are composed of albite and clinozoisite.

weathered surfaces of diopside grains. However, on a freshly broken surface of medium or fine-grained rock, the hornblende usually can be distinguished from the dark green diopside only with the use of a hand lens. In thin section the hornblende exhibits all the features of common black hornblende and is pleochroic: X = pale yellow brown; Y = medium brownish green; Z = dark brownish green; absorption $X < Y < Z$. Approximately 10% of the hornblende grains studied in thin section are twinned on the 100 crystallographic plane.

The textural association between hornblende and diopside in all the hornblende-pyroxenite specimens studied indicates that the hornblende crystallized after diopside. In specimens which contain more diopside than hornblende, the hornblende occurs both as a fine-grained replacement of diopside, generally along the C-directions and around the perimeter of diopside grains, and as relatively coarse, anhedral patches interstitial to diopside grains. In a typical specimen of hornblende-pyroxenite of this composition which contains medium-grained diopside (grains up to 1 cm), ophitic, interstitial patches of hornblende exhibit parallel cleavage surfaces over areas as large as 15 cm in the longest dimension. The hornblende commonly encloses subhedral and euhedral crystals of diopside as illustrated in Figure 17. In many thin sections in which hornblende encloses diopside grains, the diopside grains are peripherally altered to actinolite, which occurs either as a fine-grained separate mineral phase or as a gradational, compositional variation of the enclosing hornblende crystal.

Textural relationships between hornblende and diopside

Figure 17. Photomicrograph of a thin section of hornblende-pyroxenite (x30). In this section, a relatively large, anhedral, interstitial area of hornblende (gray mineral) encloses an euhedral crystal of diopside (transparent) mineral). Two 100 twin lines are evident in this crystal. The black mineral is magnetite. Penninite and some epidote occur at the borders between magnetite and hornblende.

indicate that only a very minor portion of the hornblende is a deuteric alteration formed at the expense of diopside grains. The majority of the hornblende can be considered primary in that it has crystallized in the interstices between diopside crystals. Therefore, exclusive of gabbroic veins and dikes, hornblende, plus some magnetite, represents the last ultramafic fraction to crystallize in the peripheral regions of the lopolith.

Specimen no. 95 is a mineral separate of hornblende from the hornblendite in Figure 14. The chemical analysis of this hornblende separate appears in Table 1.

3. Olivine-Pyroxenite:

Through an increase in the amount of forsteritic olivine, the pyroxenite unit everywhere grades inward toward the central portions of the ultramafic to olivine-pyroxenite. This contact is transitional, generally over a distance of approximately 200 feet measured in a direction approximately perpendicular to the main structure of the intrusive. In the lopolithic portion of the intrusive, erosion has exposed upper and lower segments of the olivine-pyroxenite which exhibit sub-horizontal attitudes, and which are essentially symmetrical above and below the peridotitic central portion of the lopolith. The general distribution of the olivine-pyroxenite unit throughout the lopolith reflects the spoon-shaped structure of the intrusive body. In the eastern portion of the ultramafic, the olivine-pyroxenite crops out as a sheath, dipping steeply outward, around the dunite feeder but separated from the dunite by peridotite rock. Several relatively small, isolated areas of olivine-pyroxenite crop out as inclusions in the dunite core. Relationships between these inclusions and the dunite are discussed in the description of the dunite unit. Much of the rock included in the peridotite unit, which is described in the next section of the text, is of the same composition as olivine-pyroxenite.

The olivine-pyroxenite is generally composed of approximately 80% diopside and 20% forsteritic olivine, and this composition is remarkably constant throughout the intrusive. The variation in composition expressed in the definition of the unit in Table 3 is confined to the margins of the olivine-pyroxenite where it grades into peridotite with an increase in the olivine content or into pyroxenite with a decrease in the olivine content.

Olivine weathers more rapidly than diopside and appears as brownish yellow depressions on the weathered surfaces of olivine-pyroxenite outcrops. The rock is generally medium grained and equigranular (grains from 1 to 8 mm). In either hand specimen or thin section, the textural relationships between diopside and olivine are the same. Individual grains and clusters of several grains of olivine are scattered evenly throughout the rock. Grains of both diopside and olivine range from anhedral to euhedral, and no convincing age relationships can be deduced from observation of their mutual boundaries. Both the general texture and the relative mineralogical composition of the olivine-pyroxenite strongly suggest that the diopside and the olivine crystallized simultaneously along a cotectic curve.

The olivine grains in the olivine-pyroxenite are generally altered to bowlingite along fractures and around grain boundaries.

Many olivine grains are also partly or completely altered to antigorite, chrysotile, talc, and very fine-grained, secondary magnetite, especially where the olivine-pyroxenite constitutes, or is close to, the periphery of the ultramafic (around the eastern and southwestern portions of the intrusive). Although minor amounts of bowlingite follow fractures in the diopside grains, particularly where they are adjacent to partly or completely serpentinized grains of olivine, the pyroxene is always relatively fresh and unaltered. In thin section, relatively unaltered grains of olivine in a few specimens exhibit regular bands of bowlingite which do not follow fractures and which contain very fine-grained "graphic" magnetite oriented parallel to crystallographic directions in the olivine. Figure 18 is a photomicrograph of a representative thin section of olivine-pyroxenite which illustrates some of the above features.

The indices of refraction of the diopside and the olivine from several specimens of olivine-pyroxenite are listed in Table 2 and Figure 12. The range in molecular composition of diopside and olivine is from $D_{77}H_{23}$ in specimen no. 144 to $D_{90}H_{10}$ in specimen no. 224 and from $Fo_{78}Fa_{22}$ in specimens no. 8 and 9 to $Fo_{88}Fa_{12}$ in specimen no. 226. In the cases of both diopside and olivine, the relatively ferriferous minerals were collected from the western portion of the lopolith and the relatively magnesian specimens from within 300 feet of the southeastern contact of the ultramafic in the vicinity of the dunite core.

A chemical and mineralogical analysis of a representative specimen of olivine-pyroxenite collected from the western portion of the lopolith, specimen no. 9 ($D_{86}H_{14}$; $Fo_{78}Fa_{22}$), appears in

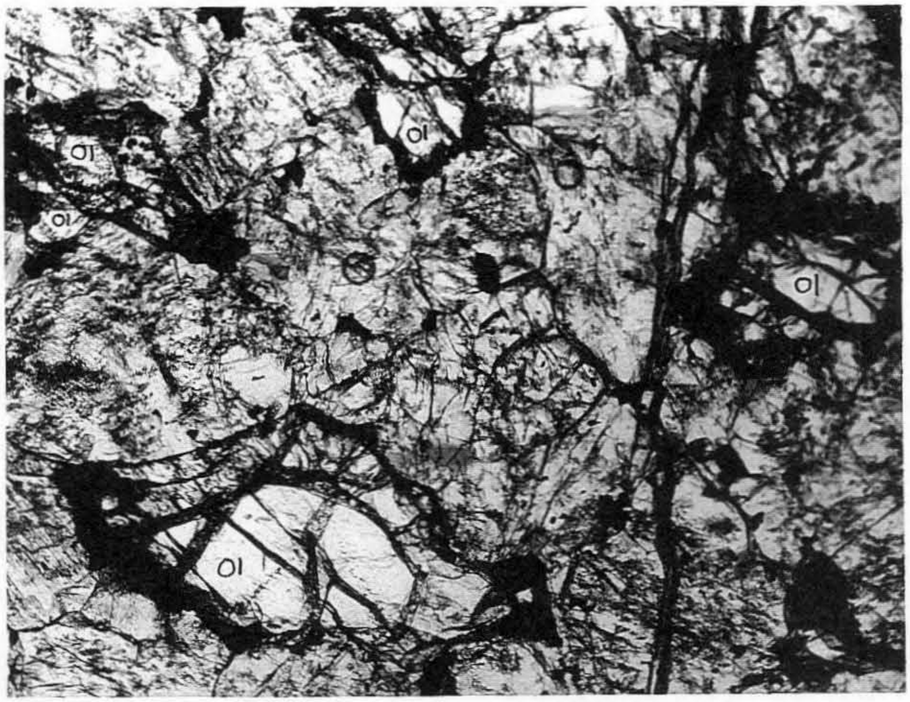

Figure 18. Photomicrograph of a thin section of olivine-pyroxenite (x30). The relatively clear areas bordered and crossed by dark fractures are olivine (Ol). The remainder of the field is diopside with some magnetite. Bowlingite and traces of secondary magnetite occur in the fractures in the olivine grains.

Table 1.

4. Peridotite

The peridotite unit constitutes the central section of the lopolithic portion of the ultramafic and crops out as a sheath, dipping steeply outward, around the north, east, and south periphery of the dunite core. Along the axis of the lopolith to the west of the dunite core, the peridotite grades to the east, with decreasing amount of diopside, into dunite. In the lopolith, the over-all structure of the peridotite unit and smaller scale structures within the unit generally exhibit sub-horizontal attitudes and reflect the spoon-shaped structure of the intrusive body.

The mineralogical definition of the peridotite unit is given in Table 3. Rocks mapped in the field as peridotite fall into two categories: (1) "textural peridotite", rocks composed of evenly scattered grains of forsteritic olivine and diopside in approximately equal proportions (see Figure 19); (2) "structural peridotite", rocks which have the composition and texture of olivine-pyroxenite but which are host to many irregular and sill-like intrusions of dunitic material such that the bulk mineralogical composition of the rock, over an outcrop area of several hundred square feet, is within the limits prescribed for the peritotite unit (see Figure 20).

Most of the peridotite unit which crops out around the dunite core is textural peridotite. Structural peridotite is typical of the lopolithic portion of the intrusive, and constitutes most of the primary structural features mapped within the lopolith.

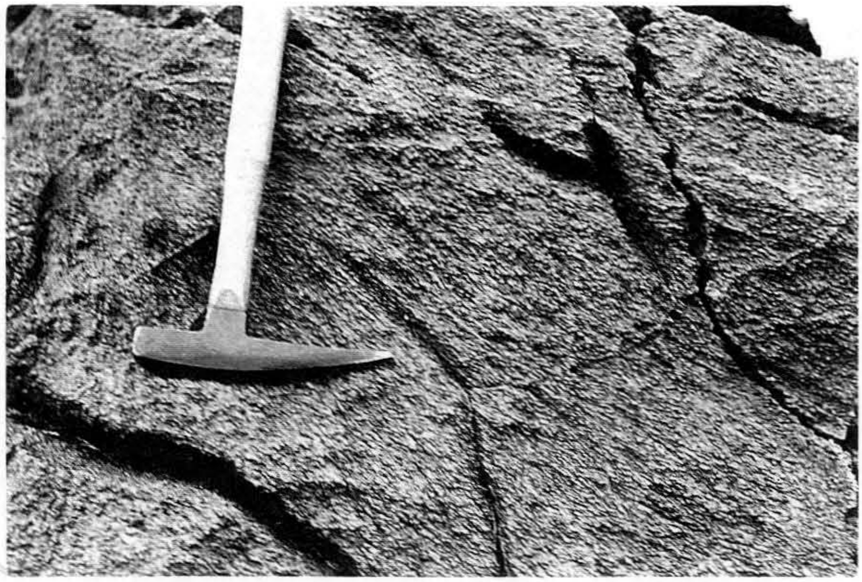

Figure 19. An outcrop of textural peridotite containing approximately 60% forsteritic olivine and 40% diopside.

Figure 20. Looking north at an outcrop of structural peridotite in the western portion of the lopolith. The dark rock is olivine-pyroxenite, and the light-colored rock is relatively pure dunite. The outcrop behind and below Mr. Stebbins exhibits several veins and sills of dunite dipping from 30 to 45 degrees to the right, or east. The rock Mr. Stebbins is inspecting is the lower portion of a large sill of dunite dipping in the same direction, and containing irregular inclusions of olivine-pyroxenite.

Individual bodies of dunitic material in the structural peridotite are of all sizes and shapes. Many have the dimensions and attitudes of sills with somewhat irregular but knife-sharp contacts and attitudes displaying considerable continuity in both vertical and horizontal directions within the peridotite unit. The thickness of these sills ranges from less than an inch to more than 50 feet. In several places sills of dunite approximately 75 feet thick were considered large enough to map as individual units on the scale employed. Figure 21 is a photograph of two parallel sills of this size which crop out in olivine-pyroxenite across the crest of a ridge one mile west of the dunite core. The uppermost of these relatively large sills separates pyroxenite from olivine-pyroxenite and creates an anomaly in the usual gradational sequence of these two units.

Many outcrops of peridotite along the north and west flanks of the lopolith contain many relatively small sill-like and veinlike bodies of dunitic material from less than one inch to several feet in thickness. Although many of the smallest of these exhibit regular continuity along the strike, many are in the form of irregular veins which may or may not follow the general attitude of the larger sills in the area. In a few of the smaller sills and veins, small veins of diopside generally one or two crystals, or 5 to 10 cm, thick cut across the dunitic sills from wall to wall and create contradictory age relationships.

Figures 20, 21, 22, and 23 illustrate examples of dunitic sills in outcrops of peridotite. The type of structure illustrated in Figure 24 presents especially convincing evidence that the dunitic

Figure 21. Looking southwest at the high ridge east of Mount Burnett. In the saddle on the skyline may be seen two relatively large dunite sills approximately 75 feet thick, dipping to the left, or south, and away from the camera. Other, similar compositional features can be distinguished in the same attitude. The darker rock is olivine-pyroxenite and peridotite.

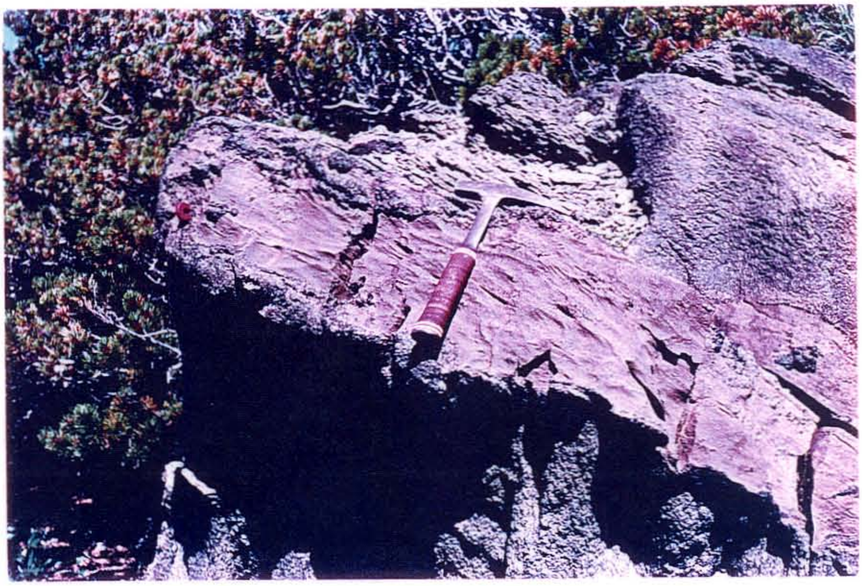

Figure 22. A dunite sill cutting olivine-pyroxenite in the western portion of the lopolith. The sill contains some magnetite at the right of the photograph and where the magnet is clinging.

Figure 23. An outcrop of structural peridotite containing olivine-pyroxenite and many regular dunite sills from an inch to several feet in thickness, all dipping at 45 degrees to the left, or south, and away from the camera.

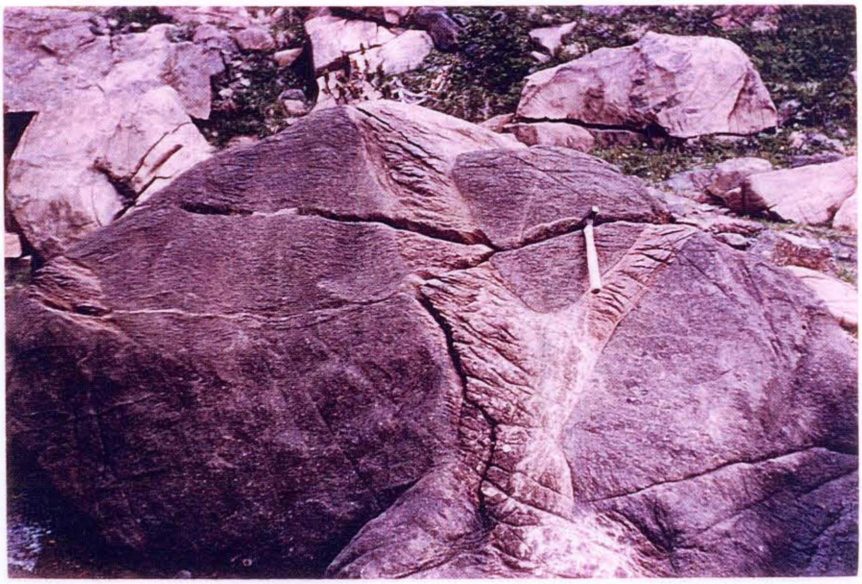

Figure 24. A bifurcating dike or sill of dunite cutting olivine-pyroxenite. This is a large boulder, not in place.

material has invaded the olivine-pyroxenite host rock. Figure 25 illustrates an example of peridotite outcrop in which the structural relationships are very uncertain.

The pyroxene-rich portion of the structural peridotite is generally composed of approximately 80°/o diopside and 20°/o forsteritic olivine and cannot be distinguished in either hand specimen or thin section from specimens of the olivine-pyroxenite unit. The dunitic material is composed of from 85 to 95°/o forsteritic olivine and from 5 to 15°/o diopside. Some fine-grained, disseminated magnetite is generally present in the rocks, especially in the pyroxene-rich rocks. Locally magnetite is concentrated in irregular patches or veins up to several feet long in either rock type, and in some places the larger veins cut across both. Traces of hornblende (generally less than 1°/o of the rock) occur in all portions of the peridotite as alteration of diopside grains.

The texture of the dunitic material is more constant than that of the pyroxene-rich rocks. The grain size of olivine varies between 0.2 and 1.5 mm, and diopside ranges from approximately 1 mm to 2 cm in the olivine-pyroxenite rock. In the dunitic material, grains of olivine are generally equant and display anhedral to generally subhedral crystal outlines. Diopside in this portion of the rock varies from anhedral to subhedral and occurs either as individual grains or clusters of several grains in most specimens. Practically all the magnetite in the dunitic material is concentrated in these clusters of diopside grains (see Figure 26).

Most of the individual bodies of dunitic rock exhibit patterns of closely spaced, parallel fractures in which one or two directions

Figure 25. Structural peridotite illustrating uncertain age relationships between dunite and olivine-pyroxenite. Note the radial fractures in olivine-pyroxenite around circular cross-sections of dunite.

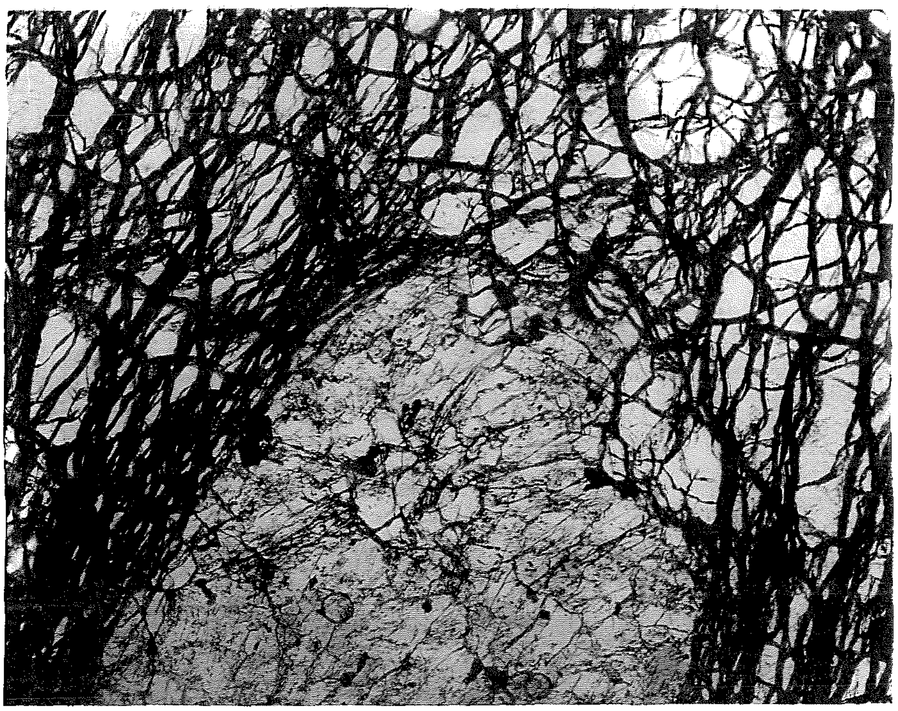

Figure 26. Photomicrograph of a thin section cut from a small dunite sill in olivine-pyroxenite (x30). The fractured, but undisturbed, subhedral olivine grains enclose an aggregate of anhedral diopside grains. The black, opaque mineral associated with the diopside is magnetite. The olivine grains are approximately 1 mm in size. The fractures, which curve around the inclusion of diopside grains, contain bowlingite.

are predominant. In most of the more regular sills, the predominant set of fractures is parallel to the walls of the sills. Megascopically these fracture patterns flow around inclusions of olivine-pyroxenite and bear a remarkable, but false, similarity to flow lines. In thin section, the fractures cross through olivine grains in all directions without disrupting the orientation of individual portions of each grain. The predominant set of fractures is deflected around grains of diopside in thin section in the same manner as around the megascopic olivine-pyroxenite inclusions (see Figure 26).

The dunitic portion of the structural peridotite is serpentinized to different degrees in different places. In general, the rock is relatively fresh, with only minor alteration of olivine to bowlingite along fractures. However, in some specimens as much as 50°/o of the olivine has been altered to antigorite, chrysotile, bowlingite, and secondary magnetite along fractures.

Seven thin sections (including the section illustrated in Figure 26) were cut at various orientations across three specimens of small, regular dunitic sills. A study of these sections indicates that the olivine grains in these specimens show no preferred crystallographic orientation with respect to the dimensions of the sills.

Peridotite rock of the relative composition and texture designated as the textural type (Figure 19) occurs in places in the central portions of the lopolith but is especially typical of the peridotite which crops out around the dunite core. The textural relationships between diopside and olivine in this rock are identical to the relationships between hornblende and diopside in the hornblende-pyroxenite unit. Diopside grains are typically irregular, anhedral, and interstitial to equant, subhedral and euhedral crystals of olivine (see Figure 27). In most specimens the olivine is medium-grained (from 1 to 5 mm), and interstitial, ophitic patches of diopside commonly display parallel crystallographic orientation over areas as large as 10 cm in the longest dimension. In some local pyroxene-rich facies of the textural peridotite near the dunite core, the diopside is even coarser grained and exhibits subhedral crystal shapes. Both the coarse, subhedral grains and the interstitial grains of diopside poikilitically enclose euhedral crystals of olivine, as illustrated in Figure 28. The poikilitic inclusions of olivine exhibit more perfect crystal development and are finer grained than most of the olivine in the rock.

In many places in the structural peridotite where dunitic material exhibits a rounded, convex contact against the olivine-pyroxenite, radial fracture patterns occur in the pyroxene-rich rock adjacent to the contact. This feature is especially obvious where small bodies of dunitic rock show a circular cross section, as illustrated in Figures 25 and 29. The nature of this secondary (post solidification) fracture pattern indicates either that the olivine has increased in volume relative to the pyroxene or that the pyroxene has decreased in volume relative to the olivine. Because the coefficient of expansion with temperature is greater for olivine than for diopside (4, pp. 32-33) the fractures were probably not caused by differential contraction as the intrusive cooled. All the dunitic rocks associated with this feature contain approximately

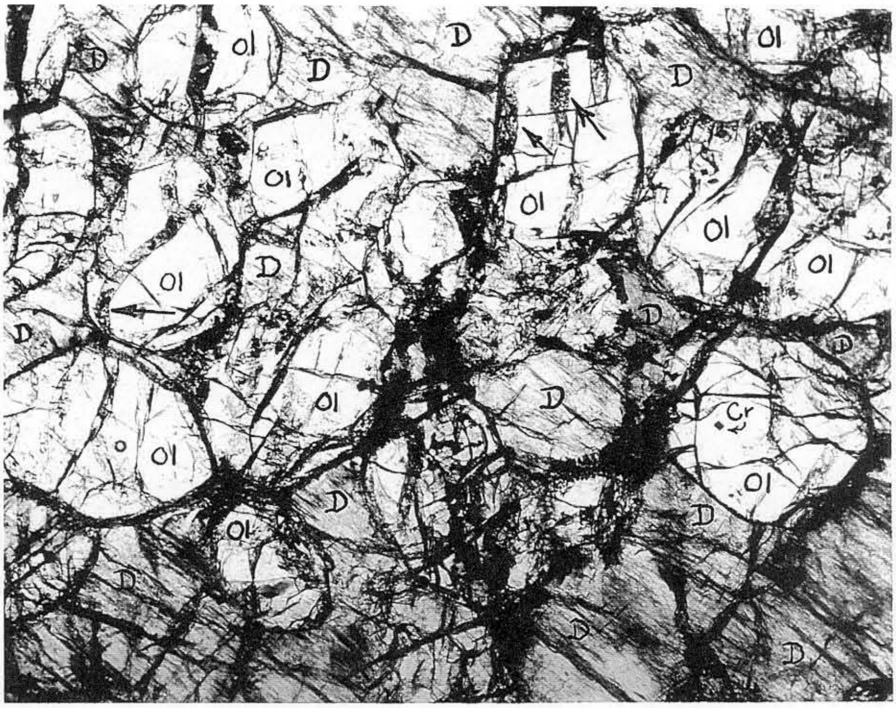

Figure 27. Photomicrograph of a thin section of textural peridotite (x30). Anhedral diopside (D) interstitial to subhedral and euhedral crystals of forsteritic olivine (Ol). All of the diopside in this photograph has parallel extinction. Several of the olivine crystals contain bands of bowlingite and tiny, graphic grains of magnetite (see arrows). One olivine crystal contains a small, euhedral crystal of chromite (Cr).

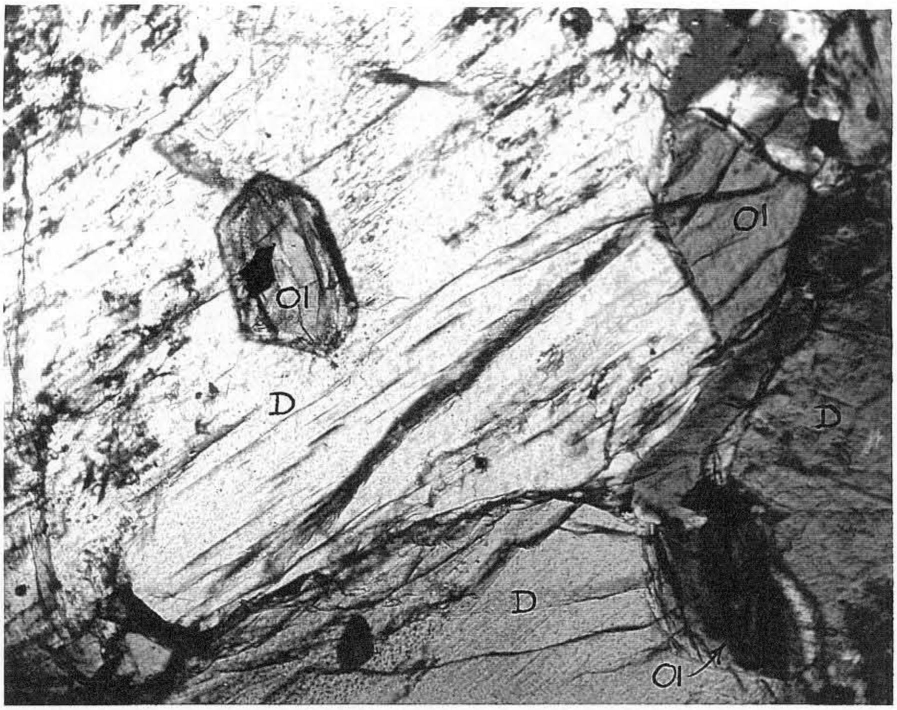

Figure 28. Photomicrograph of a thin section of peridotite (x90). A small, euhedral crystal of olivine (Ol) is poikilitically enclosed in a larger grain of diopside (D). The black mineral in the olivine crystal is either magnetite or chromite.

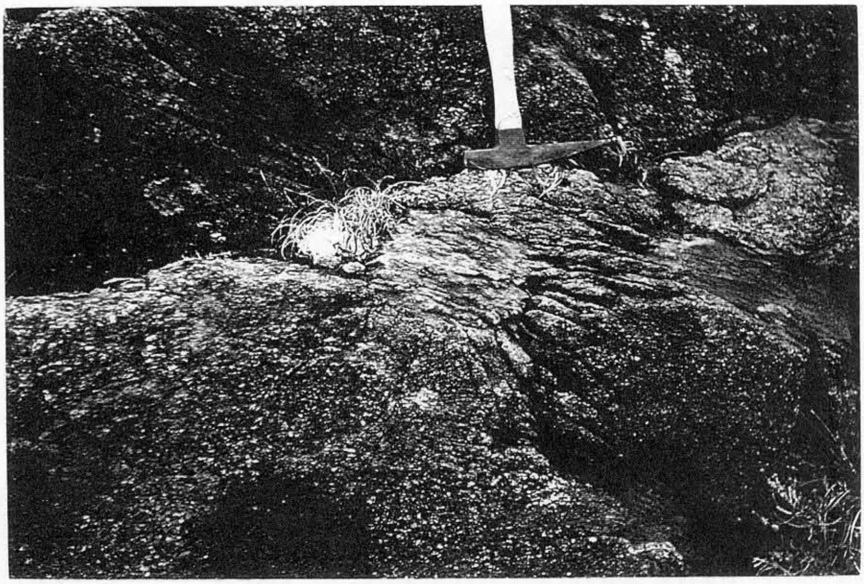

Figure 29. Radial fractures in olivine-pyroxenite around a circular cross-section of dunite.

10°/o or more serpentine minerals, and possibly the fractures were caused by relative expansion of the dunitic material during serpentinization of the olivine. The same fracture pattern is seen in thin section where interstitial areas of diopside enclose partially serpentinized grains of olivine. This is illustrated in Figure 30, in which the olivine is moderately serpentinized, and radial fractures in the diopside are filled with chrysotile.

Figure 31 is a photograph of a dike of peridotitic material which has cut textural peridotite in the vicinity of the dunite core. The dike is composed of approximately 50°/o medium-grained olivine, most of which has crystallized along the walls of the dike, and 50°/o coarse-grained diopside which has crystallized in the central portion of the dike. Both dike and wall rock are of very similar bulk composition.

The indices of refraction and relative molecular compositions were determined for several specimens of olivine and diopside collected from both textural and structural types of peridotite from various portions of the ultramafic (Table 2 and Figure 12). The indices indicate that the olivine and diopside in the textural peridotite near the dunite core contain more of the magnesian molecule relative to the ferriferous molecule than specimens from the structural peridotite of the lopolith.

Specimens no. 6 and 8 (Table 2) are specimens of structural peridotite which were collected from the western portion of the lopolith and which consist of olivine-pyroxenite wall-rock and small, regular sills of dunitic material approximately one inch

Figure 30. Photomicrograph of a thin section of partially serpentinized peridotite (x30). A subhedral crystal of olivine (Ol) has been partly altered to antigorite (A) and bowlingite (B). Diopside (D) containing much very fine-grained magnetite is interstitial to the olivine. Fractures filled with chrysotile (C) occur radially distributed in the diopside around the olivine crystal.
Black areas are magnetite.

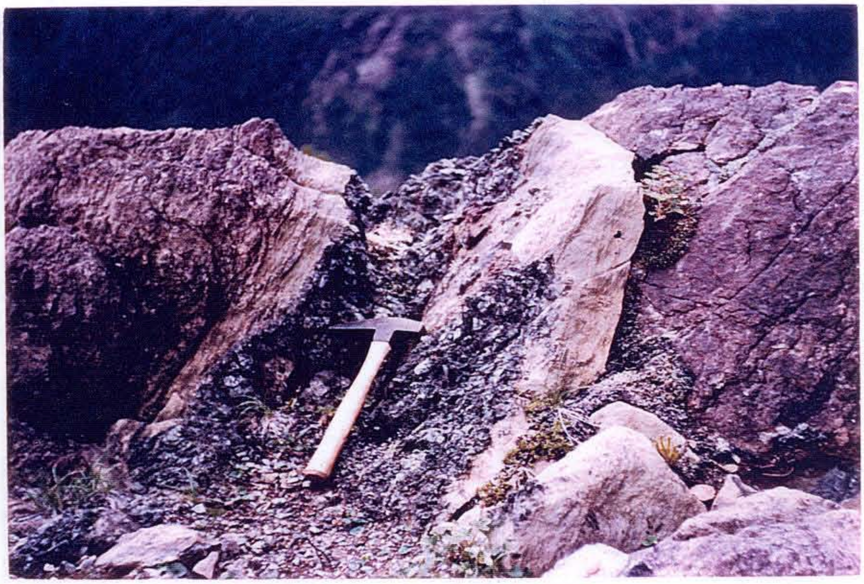

Figure 31. A differentiated peridotite dike cutting peridotite. In the dike, most of the olivine has crystallized along the walls, and most of the diopside has crystallized in the center.

thick. Two determinations of the olivine constituent were made of each specimen; one from the sill of dunitic material and one from the olivine-pyroxenite wall-rock. The olivine of the dunitic portions of specimens 6 and 8 contain respectively 4% and 3% more of the forsterite molecule than does the olivine of the wall-rock in the same specimen. This difference definitely exceeds the limits of error of the oil immersion method, and suggests the possibility of a hiatus between the olivine of the wall-rock and the olivine in the dunitic sills.

A chemical and mineralogical analysis of a specimen of textural peridotite collected from near the dunite core appears in Table 1 (specimen no. 200, which is illustrated in thin section in Figure 30). Also in Table 1 is given a chemical and mineralogical analysis of specimen no. 6, which is dunitic material collected from a sill in structural peridotite in the western portion of the lopolith. An approximate average composition of the structural peridotite in this area can be calculated from an average between the analyses of specimens no. 6 and 9 (the latter is olivine-pyroxenite from this area) using a one to one ratio.

5. Dunite:

The dunite core, which crops out over an area slightly larger than one square mile, constitutes the predominant feature of the eastern portion of the ultramafic intrusive. The general shape of the dunite outcrop is that of a vertical plug which is essentially circular in plan, although it grades to the west into the peridotitic, central portion of the lopolith. Judged from its intersection with the topography, the outer contact of the dunite is either vertical or steeply dipping outward to the north, east, and south. This contact is everywhere abruptly gradational to peridotite through an increase in the amount of diopside relative to olivine in the rock.

The mineralogical definition of the dunite unit is given in Table 3. The bulk mineralogical composition of the dunite plug is approximated by the mode given in the table. The olivine is generally equant and subhedral and is medium-grained throughout the entire unit (grains from 1 mm to 5 mm). Diopside varies from medium to coarse grained and generally occurs as scattered anhedral grains interstitial to the olivine. In some places veins of diopside from less than an inch to several inches in width cut the dunite. The diopside crystals in these veins are medium to coarse grained and are generally subhedral. In one locality in the northern part of the dunite core, the dunite contains many closely spaced, parallel layers of subhedral, medium-grained diopside crystals. These layers, which vary from 1/4 inch (one or two crystals) to several inches in thickness, exhibit a remarkable continuity over a distance of 300 feet along their strike. The layers strike north-south and dip 38 degrees to the west. They are illustrated in Figures 32 and 33. The layers in Figure 33 show a gradation upward in the amount of diopside relative to olivine (decreasing upward) but not in the size of the diopside crystals. These features resemble the primary layering described in a number of basic intrusives such as the Skaergaard (45), and they imply gravitational settling of crystals from a crystallizing magma.

Figure 32. Layers of diopside crystals in dunitic rock.

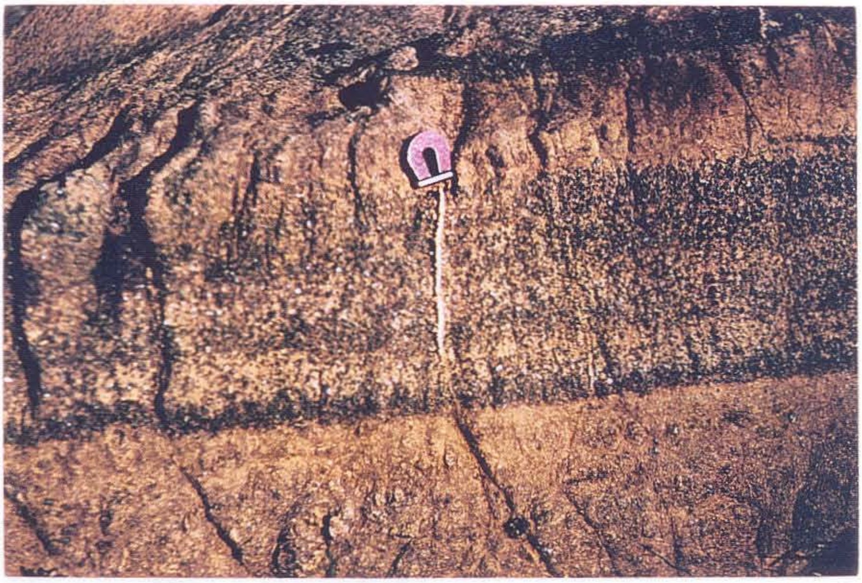

Figure 33. Layers of diopside crystals in dunitic rock. In the lower layer especially, there is a gradation upward in the amount of diopside crystals. There is no apparent gradation in the size of the crystals.

Both chromite and magnetite occur in the dunite in finely disseminated, subhedral to euhedral grains, many of which are poikilitically included in grains of both olivine and diopside. In a few places in the dunite plug, chromite is concentrated in small, irregular veins from 6 inches to 3 feet in the long dimension (see Figure 34).

Fifteen separate bodies of olivine-pyroxenite, large enough to map on the scale employed, crop out within the dunite core. These appear to be inclusions. The largest body of olivine-pyroxenite is approximately 650 feet in the longest dimension exposed, and is illustrated in Figure 35. One of the olivine-pyroxenite inclusions is tabular in shape and dips northeast at 40 degrees. The other bodies are irregular. Contacts between the olivine-pyroxenite and the dunite are sharp and highly irregular, with many irregular apophyses of dunite extending into the olivine-pyroxenite around the perimeters of the inclusions.

The dunite is serpentinized to different degrees in different places, but the majority of the rock is relatively fresh, as indicated in Table 3. Two distinct colors of weathered surfaces are seen throughout the dunite core (see Figure 35). Olivine which has been partially altered to serpentine minerals weathers a light brownish yellow and that which is fresh and unaltered weathers to a darker reddish brown. Probably 60°/o of the exposed surface of the dunite plug has been partially serpentinized and weathers yellow, and approximately 40°/o is fresh and weathers brown. The irregular areas of different colored rock vary in size but are generally as large as 500 to several thousand feet in one dimension. There is no pattern

Figure 34. Chromite disseminated, and in an irregular vein, in dunite.

Figure 35. A view looking north at the dunite core. A large inclusion of olivine-pyroxenite can be seen. Two color shades of dunite are evident: light dun around the olivine-pyroxenite inclusion, and darker brown near the highest elevation. The lighter color indicates the presence of some serpentine.

to their distribution except that the periphery of the plug and the areas of dunite surrounding the olivine-pyroxenite inclusions are invariably somewhat serpentinized for a distance of 200 feet or more away from the contact.

In a typical specimen of partially serpentinized dunite, only from 5 to 10°/o of the olivine has been altered to bowlingite, antigorite, chrysotile, and secondary magnetite along fractures. In a few specimens, the serpentine minerals constitute between 20 and 30°/o of the rock. In thin sections of fresh dunite, many of the olivine grains have subhedral to euhedral outlines. Some grains have irregular, interlocking boundaries and exhibit wavy extinctions or strain shadows, as illustrated in Figure 36. One or two grains in each thin section generally exhibit true mortar texture with granulated grain boundaries.

The depth of weathering of the dunite is approximately the same, about 1 cm, in all outcrops of both fresh and partially serpentinized rock. Freshly broken surfaces of the dunite are black, but the edges of olivine grains are clear and vitreous under a hand lens. The diopside associated with the dunite core and the peridotite in the vicinity of the core is a brighter green and can be distinguished from the dark green diopside of other portions of the ultramafic. As indicated in the chemical analysis of specimen no. 183b in Table 1, a chromium content of approximately 0.2°/o is at least partly responsible for the brighter green color.

Both the diopside and the olivine in the dunite plug are the most magnesium-rich varieties collected from anywhere in the

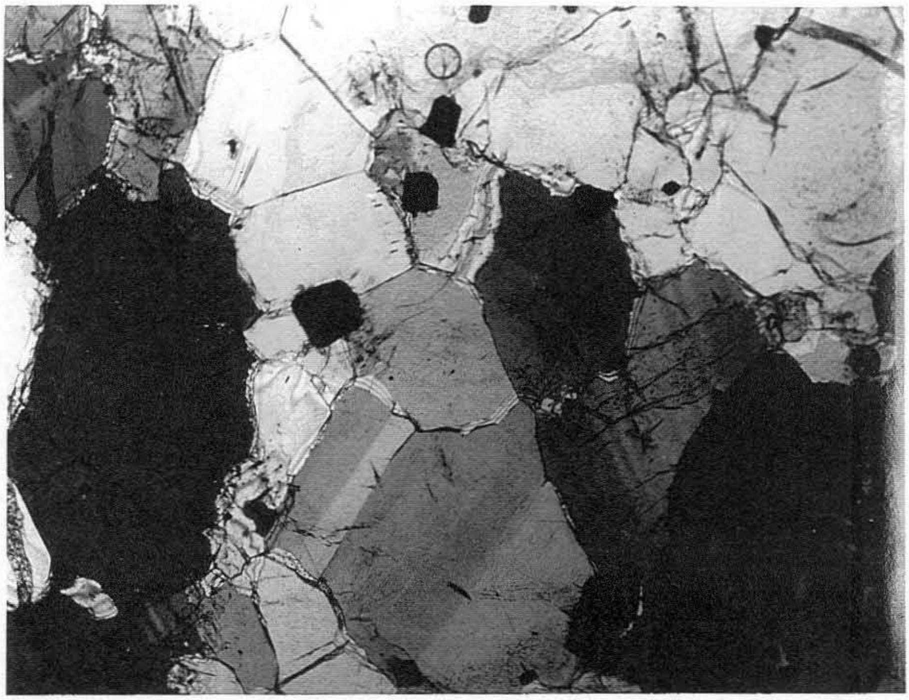

Figure 36a. Photomicrograph of a thin section of fresh dunite (x30, crossed nicols). Strain shadows are evident in several of the olivine grains in the lower center portion of the photograph. Note that some olivine grains have irregular boundaries, and that others exhibit euhedral crystal faces. See also Figure 36b (next page).

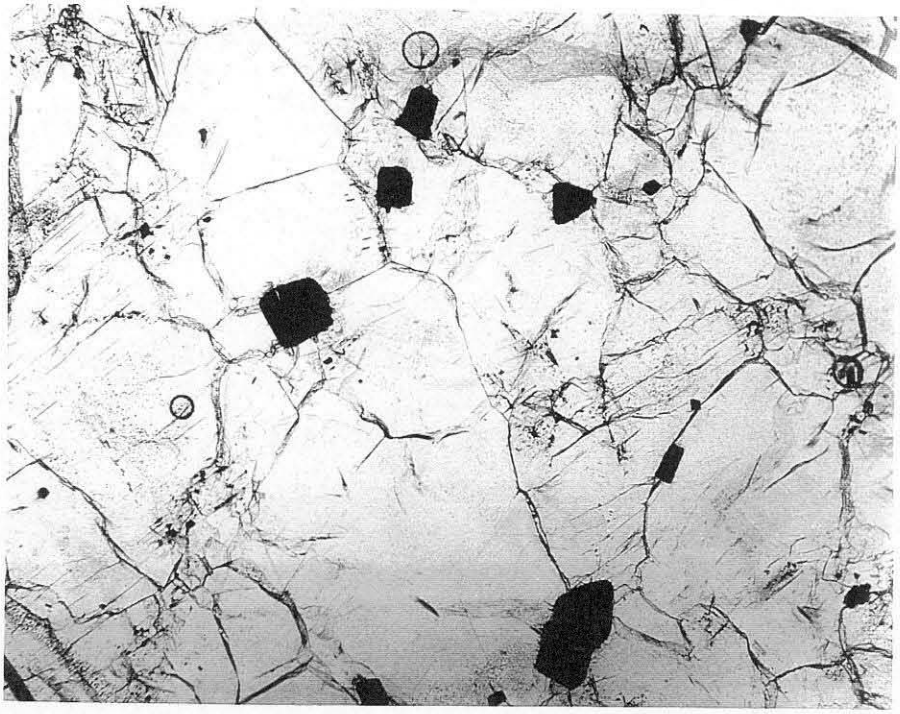

Figure 36b. Photomicrograph of a thin section of fresh dunite (x30, plane light). Same as Figure 36a. Black subhedra and euhedra are chromite and magnetite.

ultramafic. The relative molecular composition of two specimens of diopside collected from the dunite core is $D_{99}H_1$, as determined from their indices of refraction (specimens no. 183 and 183b in Table 2). The range in composition of 4 specimens of olivine collected from various parts of the dunite core is from $Fo_{90}Fa_{10}$ (specimen no. 231) to $Fo_{93}Fa_7$ (specimens no. 183a, 210, and 220, Table 2).

A chemical analysis of a pyroxene mineral separate from specimen no. 183b is given in Table 1. Also given in Table 1 are chemical and mineralogical analyses of a specimen of fresh, unaltered dunite (specimen no. 231) and a specimen of partly serpentinized dunite (specimen no. 183a), both collected from the dunite plug.

Ore Minerals

As the preceding descriptions have indicated, all the ultramafic rock units and most portions of the gabbro and saussurite-gabbro units contain some magnetite. However, the only concentrations of magnetite which are large enough to be considered of economic interest at the present time are confined to the pyroxenite and hornblende-pyroxenite units. Although there are local anomalies on a large scale, the content of magnetite in the rock is relatively constant throughout large areas of pyroxenite outcrop in all parts of the ultramafic intrusive. The largest areal concentration of magnetite crops out in what is referred to as the "ore zone," an area of approximately 3 square miles around the west and northwest portions of the lower pyroxenite and hornblende-pyroxenite units. Most of the rock in the ore zone contains approximately 20% magnetite by weight.

For detailed information regarding the distribution of magnetite in various parts of the ultramafic, the reader is referred to the geologic map (Figure 3). The percentages of magnetite graphically indicated on the map are based upon visual estimates of outcrops, supported by the use of a hand magnet only. Subsequent drilling and analyses have in part substantiated the visual estimates of amounts of magnetite in portions of the ore zone.

Twenty-five polished section mounts of various types of magnetite distributions were studied. Sixteen of these 25 mounts were made from specimens collected from the ore zone. The textures and distribution of the magnetite throughout the ultramafic clearly indicate that the magnetite is a primary constituent of the ultramafic rocks, except that magnetite which is a product of serpentinization of olivine.

The textural relationships between magnetite and rocks with which it is associated are of 4 types: (1) fine-grained, euhedral magnetite disseminated in, but constituting only a very minor amount of, the dunite core; (2) regular, closely spaced, parallel bands; (3) large, irregular clots and irregular veins up to several feet in the longest dimension; (4) disseminated fine to coarse-grained, anhedral magnetite interstitial to diopside and usually rather evenly distributed throughout the rock.

The first type of textural association is present only in specimens collected from dunitic material in the vicinity of the dunite plug. Chromite is found in the same specimens in the same texture and in approximately the same amounts. Because most of the magnetite in the ultramafic is associated with pyroxenite in textures which indicate that most of the magnetite has crystallized after the diopside, different physico-chemical conditions are indicated by the fine-grained magnetite which has crystallized euhedrally and apparently either before or contemporaneously with the olivine in the vicinity of the dunite core.

Regular, thin bands or layers of magnetite crop out in only a few places in the pyroxenite and olivine-pyroxenite units. They are generally from 0.5 to 4 cm thick and are remarkably parallel and continuous over distances of several hundred feet. In some places near the periphery of the intrusive, the bands exhibit undulations or open folds. The diopside grains near the bands show granulation and some irregular extinctions or strain shadows. Diopside grains immediately adjacent to or included in the bands are anhedral and generally less than 0.5 mm in size. Figure 11 is a photograph of a thin section cut perpendicular to a band of magnetite.

Probably 90% or more of the magnetite in the ultramafic intrusive is present in the pyroxenite and hornblende-pyroxenite units in the textural association of the fourth type. In a representative specimen of fine-grained rock from the ore zone, the pyroxenes vary from 1 to 4 mm and the magnetite from 0.07 to 2 mm. In the coarser grained rock, pyroxene ranges from 2 to 15 mm and the magnetite from 1 to 10 mm. Areas of magnetite which exceed 1 mm in size are almost always composed of several irregular grains, rarely larger than 3 mm. The pyroxene grains in all grain sizes range from anhedral to euhedral but are generally subhedral and equant. The interstitial magnetite is very irregular and inequant (Figure 9). The primary textural relationship indicates that the most of the magnetite has crystallized in the interstices between diopside grains.

In several specimens of pyroxenite collected from, or near, the contacts between pyroxenite and schist, most of the magnetite is irregular and interstitial to diopside, but grains of diopside poikilitically enclose small, subhedral grains of magnetite. This texture indicates that some magnetite had commenced crystallization during crystallization of diopside. This texture is peculiar to these specimens and is probably the result of especially rapid crystallization of the rock at the contact with schist.

Most of the polished mounts of magnetite contain some ilmenite, both as independent grains and as exsolution lamellae in the magnetite. Independent ilmenite grains are generally irregular, anhedral, and peripheral to larger grains of magnetite. The textures in some mounts indicate that ilmenite has replaced magnetite along crystallographic directions in the latter. Individual grains of ilmenite compose approximately 1°/o to 3°/o of the opaque minerals in those mounts in which they occur and range in size from 0.06 mm to 0.6 mm. The most usual size is 0.15 mm. Approximately 75°/o of the magnetite grains exhibit exsolved blades of ilmenite along octahedral directions in the magnetite. In a typical example, there are a few larger blades which may run the length of the magnetite grain (up to 3 mm) but are never more than

0.005 mm in width, plus swarms of smaller, oriented blades grading in size from 0.04 mm in length down to the limits of resolution of the microscope. The ilmenite present as blades of all sizes is visually estimated to compose between 2°/o and 5°/o of the opaque material. Small (0.02 mm) blades of a gangue mineral are also present in amounts of approximately 1°/o to 2°/o, oriented along cubic directions in the magnetite. The identification of this mineral in polished mounts is difficult, but extrapolation from thin section studies indicates that it is most probably hercynite spinel.

Since there are all gradations in size of ilmenite blades in the magnetite, there is reason to believe that there are ilmenite blades below the limits of resolution of the microscope. Approximately 20°/o of the magnetite grains appear slightly anisotropic. This probably indicates that TiO_2 is present either as submicroscopic lamellae or actually substituting for Fe_2O_3 in the magnetite lattice.

Local and minor amounts of earthy hematite are associated with ankerite veinlets in some areas of hornblende-pyroxenite and pyroxenite. Both megascopic and microscopic textural relationships show that this is a secondary alteration of magnetite. There are also minor amounts of sulfide mineralization around the periphery of the ultramafic. Most of the sulfide minerals are in the ultramafic rocks, generally hornblende-pyroxenite, but minor concentrations occur locally in saussurite-gabbro.

The sulfides are mostly pyrite with some pyrrhotite and chalcopyrite and traces of marcasite. Some magnetite is intimately associated with the sulfide minerals.

The sulfides generally occur as individual grains disseminated throughout portions of the rock, but there are a few irregular and discontinuous veins. In the ultramafic rocks, pyrite is the only sulfide mineral which shows euhedral crystal development. Pyrrhotite and chalcopyrite occur as irregular grains, generally interstitial to silicate minerals. The texture studies in polished mounts indicate the following general paragenetic relationships:

$$\left.\begin{array}{r}\text{ilmenite}_{\text{I}}^{*}\\ \text{(exsol'n)}\\ \text{magnetite}_{\text{I}}\end{array}\right\}\text{-ilmenite}_{\text{II}}^{*}\text{-pyrrho}\underset{\diagdown\ \text{marcasite}}{\text{tite-}}\text{?-pyrite}^{**}\text{—chalcopyrite-magnetite}_{\text{II}}$$

$\text{magnetite}_{\text{I}}$ = primary magnetite

$\text{magnetite}_{\text{II}}$ = secondary magnetite, a product of serpentinization.

* exsolved ilmenite and peripheral grains of ilmenite are most logically explained by two separate generations.

** only definite relationship between pyrite and other opaque minerals is that chalcopyrite veins pyrite. Chalcopyrite also veins pyrrhotite.

III. GENETIC THEORY

RELATIONSHIPS BETWEEN GABBRO AND ULTRAMAFIC ROCKS

In other localities in southeastern Alaska, and in other regions of the world, relatively small, intrusive ultramafic bodies of the type exposed at Union Bay invariably show space relationships with gabbro intrusions generally similar in size and mineralogy with the rocks described here (see 1, 12, 16, 19, 26, 27, 33, 47, 51).

From his study of the ultramafic complex at the Blashke Islands, southeastern Alaska, Walton concludes that the "gabbro ring" peripheral to that ultramafic plug, although discontinuous, has been developed by fusion and mobilization of metasedimentary wall-rock by the ultramafic intrusion (47, p. 176). This hypothesis fails to explain the relationships at Union Bay. The igneous textures, intrusive relationships, and peripheral metamorphism of metasedimentary wall-rocks around the main body of gabbro at Union Bay indicate that the gabbro was emplaced as a magma. The ultramafic magma probably did not contain enough heat in excess of the latent heat of fusion to melt a volume of wall rock approximately equal to or possibly even greater than the volume of the ultramafic. There is no evidence at contacts between ultramafic rocks and schist that more than minor amounts of a few components of the wall-rocks, mostly water, were mobilized by heat from the ultramafic intrusion.

Although the composition of the mineral diopside, as determined by refractive indices, and the general chemical composition of the rocks are somewhat similar on both sides of the contacts between hornblende-pyroxenite and saussurite-gabbro (see Table 1 and

Figure 5), there is no other evidence that the ultramafic and gabbro rocks could have been differentiated from a common magma, either in the site of intrusion or anywhere else. Any mechanism of differentiation would fail to explain the distribution of the gabbro around the ultramafic, the intrusive relationships between ultramafic and gabbro, and the absence of complementary, intermediate, or gradational rock types. Except for inclusions of saussurite-gabbro and veins of material similar to saussurite-gabbro in the hornblende-pyroxenite, which are marginal, essentially contact, features, not one plagioclase grain has been observed in 7 square miles of outcrop within the ultramafic intrusive.

The only tenable explanation of the relationships between ultramafic and gabbroic rocks at Union Bay must incorporate an hypothesis of two intrusions separated by enough time to allow the earlier intrusive to become largely or wholly crystalline. The lack of chilled margins in either gabbro or ultramafic rocks at their mutual contacts implies that the time-gap separating the two intrusions was relatively short.

A straightforward interpretation of age relationships between gabbro (and saussurite-gabbro) and ultramafic rocks is not obvious from their contact relationships (see Figure 7). Veins of albite, clinozoisite, epidote and hornblende which cut through the hornblende-pyroxenite at or near the contact cannot be taken as criteria that the gabbro is the younger of the two intrusives. Dikes of hornblendite, which cut the gabbro near the contact, are contradictory evidence, and the development of saussuritization of gabbro along the ultramafic contact is a feature clearly superimposed upon the main gabbro intrusive. Furthermore, in the general case of an ultramafic magma intruding hot, gabbroic rocks, a eutectic or cotectic mixture of the least refractory constituents of the gabbro would be the first material (if any) to be mobilized by temperature and pressure conditions at the contact (with or without the presence of water), and these would normally be expected to recrystallize after the more refractory minerals of the ultramafic had crystallized, in which case the apparent age relationships would be reversed and misleading.

A conclusion that the gabbro is earlier than, and intruded by, the ultramafic is the preferred one. The alternative hypothesis that the gabbro is later than the ultramafic would fail to explain the following features:

1. Inclusions of saussurite-gabbro in the hornblende-pyroxenite, in some cases close to and oriented parallel to the contact with the main body of gabbro.

2. Dikes of hornblendite cutting the gabbro at or near the contact with hornblende-pyroxenite.

3. Mineralogical asymmetry of the main gabbro intrusive: the apparent interruption by the ultramafic of both the general trend towards a dioritic periphery and the trend of composition of the mineral hypersthene (see the detailed description of the gabbro rocks).

4. The pattern of distribution of the gabbroic rocks around the ultramafic and the three dimensional symmetry of the ultramafic intrusion against the gabbro contacts. Nowhere can it be demonstrated that the gabbro has cut out or cut across a unit of the ultramafic intrusive.

THE NATURE OF THE ULTRAMAFIC MAGMA

In the geologic literature of the past 30 years, there has been considerable discussion about the physical nature of ultramafic magmas. The experimental work of Bowen and Schairer (8) with the system $MgO-FeO-SiO_2$ indicates that magnesian olivine of the type commonly occurring in intrusive bodies of peridotite and dunite begins to melt at approximately 1600^o and becomes completely molten at approximately 1800^o. In spite of these high temperatures, an anomalous lack of high-grade metamorphism of the adjacent wall-rocks is usually associated with the ultramafic intrusions. Consideration of this problem has forced Bowen (8) and others to conclude that there must be a special mechanism of solid intrusion for peridotitic and dunitic rocks. However, many observers have found it difficult or impossible to reconcile a great deal of field evidence with any hypothesis other than intrusion of a relatively liquid magma of peridotitic or dunitic composition (Camsell, 12; Cooke, 14; Hess, 22; Walton, 47; and others).

The abundance of igneous relationships associated with both large and small scale features of the ultramafic rocks at Union Bay definitely precludes any mechanism of solid intrusion. Briefly summarized below are features of the ultramafic rocks which have been described in detail in earlier portions of the text, and which can be explained only by an intrusion of a liquid magma:

1. General intrusive relationships such as dikes of hornblendite cutting the gabbro around the margin of the ultramafic.

2. Regular sills of dunitic rock of all sizes from 75 feet to less than one inch thick with sharp contacts and a great deal of continuity.

3. The general unsheared and ungranulated allotriomorphic texture of all the rock types, plus detailed textures which can be explained only by crystallization of the rock in place.

4. Evidence of crystal settling in peridotitic rocks (see Figures 32 and 33).

Evidence of crystal settling much more spectacular than that at Union Bay appears in an ultramafic intrusive of similar size and identical mineralogy on Duke Island, southeastern Alaska (see Figure 2). Here, a mechanism of rhythmic precipitation has produced thick "sedimentary" sections of layered peridotite rock composed of diopside and forsteritic olivine (see Figures 37 to 40). Individual beds composed of a diopside-rich layer grading upward into an olivine-rich layer can be followed for hundreds of feet. In many layers, the diopside crystals show a conspicuous gradation in size, decreasing upward (see Figure 38). There can be no doubt that these rocks crystallized from a liquid, peridotite magma.

EXPLANATION OF THE DISTRIBUTION OF ULTRAMAFIC ROCK TYPES

Although there are local features of some of the ultramafic rocks at Union Bay that require explanation by crystal settling (evidence cited above), a mechanism of differentiation by crystal settling cannot explain the general petrologic structure of the ultramafic intrusive. As Wager and Deer (45, pp. 117-123) have pointed out, a crystal accumulation from a crystallizing magma contains approximately 20% interstitial material representing the composition of the magma from which the crystals have separated. An hypothesis explaining crystallization

Figure 37. Mineral banding in peridotitic rock on Duke Island, southeast Alaska. The rock is composed of diopside and forsteritic olivine, and these minerals have segregated in alternate layers rich in each. The diopside-rich layers weather out in relief.

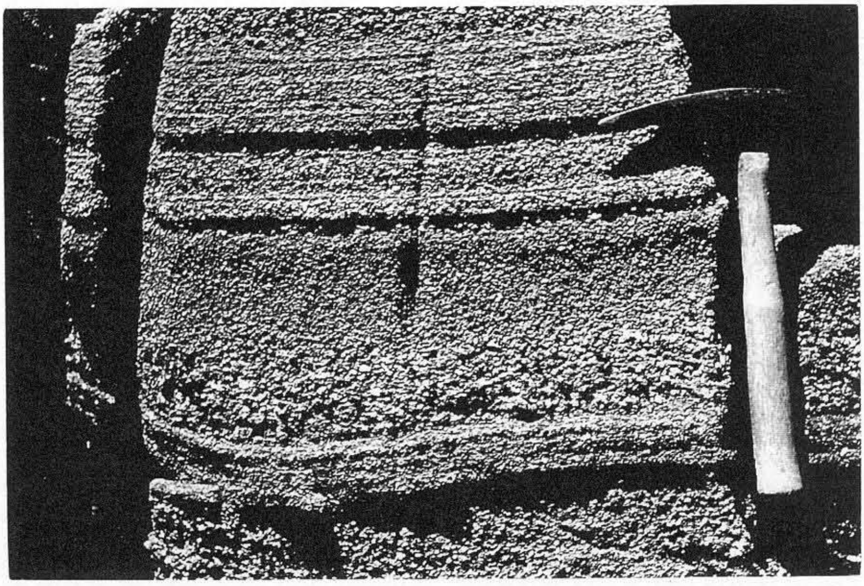

Figure 38. Graded bedding in diopside-rich layers on Duke Island. The size of the diopside crystals decreases upwards in individual layers.

Figure 39. An angular unconformity, and draped bedding on Duke Island. The block upon which the pick is resting was rotated prior to deposition of the draped bedding to the right.

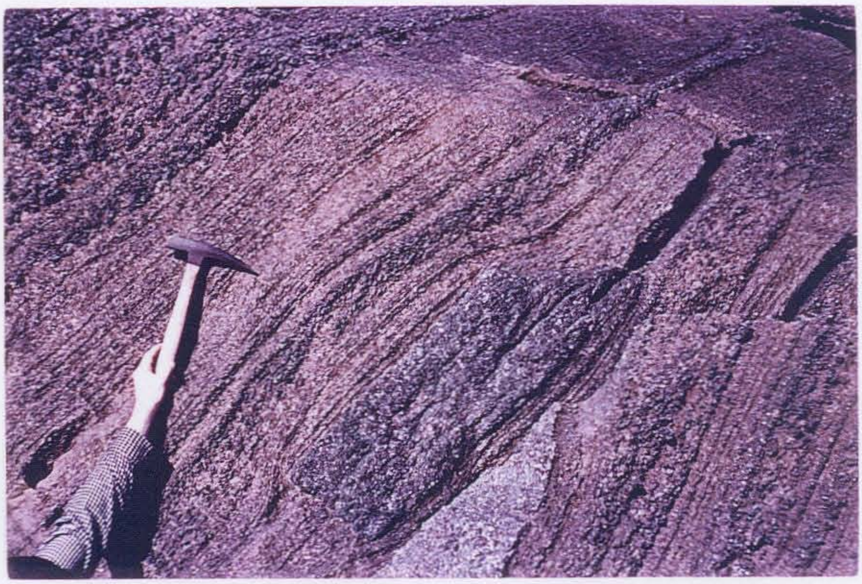

Figure 40. A block of olivine-pyroxenite in the bedding on Duke Island. The beds under the block (to the right) are slightly compressed. The beds above the block (to the left) are draped over it. The block must have settled onto the floor of the crystallizing intrusive during precipitation of the bedding.

of all the ultramafic rocks from a single magma would fail to explain the presence of a large body of dunite, which is essentially monomineralic rock. This rock requires a separation of mineral phases which is more complete than is possible by crystal accumulation from a compound magma represented by the total composition of all the ultramafic rock types or the ultramafic plus the gabbro rocks.

If a process of differentiation by crystal accumulation had controlled the distribution of ultramafic rock types, the lopolithic portion of the intrusive should show a definite gradation in composition from bottom to top. Assuming that the initial composition of the magma would have to be on the olivine side of a binary eutectic mixture of diopside and olivine, dunite, the early crystallizing phase, should be concentrated near the floor of the lopolith with an increasing amount of diopside (in cotectic proportion) near the roof. There is no mechanism of differentiation by a gravity controlled crystal accumulation which can explain the fact that the most refractory ultramafic rocks, dunite and peridotite, constitute the central portion of the intrusive complex, and are surrounded on all sides (above and below) by the less refractory pyroxenite and hornblende-pyroxenite units.

As an explanation of the concentric zoning of the Blashke Island ultramafic intrusive plug, Walton (47) advanced an hypothesis of differentiation by thermal diffusion in part, or wholly, in a supercritical gas (water vapor) phase, and operating along strong thermal and concentration gradients within the magma. Many portions of the ultramafic rocks and the wall-rocks at Union Bay do not show evidence of a sufficient quantity of water, or any other volatile component, for the large-scale operation of a mechanism of this type.

There is no field or experimental evidence that rates of diffusion through the liquid state are sufficient to operate as a mechanism of differentiation throughout an intrusive body as large as the ultramafic at Union Bay. From his experimental work, Bowen (6) calculates the rate of diffusion of liquid diopside through liquid plagioclase (An_{66}) at a temperature of 1500° to be 2.31×10^{-6} cm^2/sec. At this rate, the diffusion of diopside through plagioclase would take over 300 years to be significant (half saturation) over a linear distance of 2 meters.

Any hypothesis based upon a mechanism of differentiation of the ultramafic magma in the site of intrusion appears to be further burdened with the explanation of the crystallization of the intrusive from the center outward. The most refractory minerals (olivine and chromite) are concentrated in the central portions of the intrusive, and the less refractory minerals (hornblende and diopside) occur peripherally. This distribution is the reverse of that which would be expected assuming a single stage intrusion of ultramafic magma and realistic temperature gradients between intrusive and wall-rock. The expected differentiation is illustrated by the peridotite dike in Figure 31. Here most of the olivine has crystallized along the walls of the dike and most of the diopside occurs in the center.

A mechanism based on water vapor pressure gradients has been proposed by Kennedy (31), whereby sufficient quantities of water vapor and other volatile components may concentrate around the periphery of a magma chamber to reduce the melting points of local components far enough below the existing temperature gradient to promote crystallization of an intrusive from the center outward. This plausible mechanism may help to explain the peripheral concentration of magnetite and hornblende, but it is doubtful that the ultramafic intrusive ever contained enough water, or other volatiles, for this mechanism to control crystallization of the whole body. Furthermore, crystallization from the center outward is a phenomenon which is mechanically unstable in a normal gravity field, and would imply accumulation of the first material to crystallize (dunite) on the floor of a sub-horizontal lopolith. Therefore, it is impossible to explain the concentric petrology of the lopolith at Union Bay by any mechanism requiring crystallization of the ultramafic body from the center outward.

The most plausible explanation of the structure and petrology of the Union Bay ultramafic complex is an hypothesis of successive injections of an ultramafic magma changing in composition with time and intruded in the reverse order of crystallization of the component minerals.

Postponing the discussion of the derivation of the magma, the proposed history of the ultramafic intrusions is outlined below. In the most simplified form, the successive intrusions may be considered to constitute essentially a three-stage phenomenon:

1. Lopolithic, or probably initially sill-like, intrusion into metasediments and a part of the completely, or almost completely, crystalline gabbro of a relatively liquid magma equal in composition

to approximately 80% diopside (approximately $D_{75}H_{25}$), 15% magnetite, and 5% forsteritic olivine (approximately $Fo_{80}Fa_{20}$).

a.) Some peripheral contaminations of this magma by H_2O, SiO_2, Al_2O_3, and Na_2O, mostly from gabbroic wall-rock, and minor amounts, mostly H_2O and, possibly, some SiO_2 from metasedimentary wall-rocks.

b.) Almost complete crystallization of this magma to form the hornblende-pyroxenite unit and magnetiferous portions of the pyroxenite unit.

2. Intrusion into the hot, still crystallizing, central portions of the first intrusive of a relatively liquid magma approximately equal in composition to a binary eutectic mixture of diopside (approximately $D_{80}H_{20}$) and forsteritic olivine (approximately $Fo_{80}Fa_{20}$): probably 80% diopside and 20% forsteritic olivine, but probably also containing several per cent ferric iron.

a.) Some remobilization of the still hot, crystalline, magnetiferous pyroxenite rocks. Some assimilation of the still liquid, initial magma and mixing with the second intrusive.

b.) Almost complete crystallization of the second magma to form the olivine-pyroxenite rock and some less magnetiferous portions of the pyroxenite unit.

3. Intrusions of relatively liquid dunitic material into the central portions of the lopolith, exhibiting generally concordant, but some cross-cutting, intrusive relationships with other ultramafic units.

a.) Some remobilization and assimilation of the recently crystallized and hot olivine-pyroxenite rocks and local contamination of the dunite to form textural peridotite rocks.

b.) Crystallization of peridotitic and dunitic rocks and subsequent cooling of the intrusive. Local formation of serpentine minerals when the cooling intrusive reached the temperature range of 500 to 600 degrees (9).

Unfortunately, there are no physico-chemical data known to the writer on any system approximating the composition of the initial magma postulated. On the basis of the assumptions outlined above, it must be further assumed that there are binary and ternary eutectic relationships between diopside and magnetite and diopside, olivine, and magnetite. The texture and composition of the pyroxenite unit indicate that the eutectic point between diopside and magnetite lies toward the magnetite side of the system. If this inference is correct, and if the initial magma was of the composition assumed above, most of the diopside would have crystallized before any magnetite started to crystallize at the eutectic point, creating the textural relationships between diopside and magnetite observed in the pyroxenite unit.

Because of heterogeneity of the source material, the initial magma must have been composed of diopside and magnetite with some olivine. There is no olivine in many portions of the pyroxenite unit which contain from 10% to 20% magnetite. Therefore, a local mechanism must be postulated to change the composition of the melt away from the stability field of olivine. Such a mechanism may have been furnished by contamination of the magma by material derived from the wall-rocks, especially H_2O and SiO_2.

Water diffusing into the magma from the wall-rocks would have been partially dissociated at the temperature of the environment and would have probably oxidized proportional amounts of ferrous iron in the melt according to the equation (18, p. 657):

$$Fe^{++} + H_2O \rightarrow Fe^{+++} + H_2 + OH^- .$$

Olivine can be converted to magnetite and pyroxene (enstatite or clinoenstatite) by water according to the equation (13, p. 80):

$$3Fe_2SiO_4 + 3Mg_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 2H_2 + 6MgSiO_3 .$$

For this reaction, the calculated change in free energy at 298° is -59,000 cal., and at 1000° is -95,000 cal. These data indicate that, with increasing temperature, water is increasingly capable of oxidizing ferrous iron in olivine to ferric iron in magnetite. To simulate the composition of the initial magma postulated, the solid solution series diopside-hedenbergite would have to be added to both sides of the above reaction, complicating it considerably. However, there is solid solution between diopside and clinoenstatite (7, p. 49), and it is quite probable that any addition of water to the ultramafic magma would have favored the formation of proportional amounts of diopside and magnetite and may have prevented the crystallization of olivine.

The above reaction probably means that oxidation of ferrous iron on the left hand side of the equation has increased the ratio (relative saturation) of SiO_2 to M_gO beyond the field of stability of olivine. Because ferric iron would not have been stable in the silicate lattice in amounts of more than a few per cent, oxidation of ferrous iron in the ultramafic melt would have increased the stoichiometric proportions, and relative saturation, of SiO_2 in the melt, inhibiting the crystallization of olivine.

In the course of experimental work, Bowen and Tuttle (9) and Kennedy (30) have noted the facility with which silica has been transported in supercritical water vapor at temperatures above the critical temperature of water and pressures above 140 atmospheres. Therefore, water diffusing into the ultramafic magma from the wall-rocks may have carried some silica. This phenomenon plus the oxidation of ferrous iron by water constitute additive mechanisms which may have increased the relative saturation of SiO_2 in some portions of the initial ultramafic magma, locally inhibiting the precipitation of olivine and causing the crystallization of bimineralic rock composed of diopside and magnetite.

It is not entirely clear whether the chemical components of the mineral hornblende and the gabbroic veins in the hornblende-pyroxenite represent primary constituents of the ultramafic magmas concentrated in late, pegmatitic phases of intrusion, or whether this material largely represents contamination of the ultramafic by material derived from wall-rocks, or both. However, the absolute confinement of the hornblende-pyroxenite unit to the periphery of the complex and the intimate association between hornblende-pyroxenite and inclusions of both schist and gabbroic material strongly indicate that the H_2O, Al_2O_3, Na_2O, K_2O and much of the SiO_2 were derived from the wall-rocks.

If a relatively short time separated the crystallization of the gabbro and the initial intrusion of ultramafic material, the minerals of the gabbro would have remained very close to (just below) the temperature of crystallization. In this case, only a relatively small contribution of heat energy from the ultramafic magma would have caused mobilization of a eutectic blend of the least refractory constituents of the gabbro wall-rock, and, as previously discussed, this material would have crystallized after the more refractory minerals of the ultramafic had crystallized.

The equilibrium diagram of Bowen (5, p. 212) shows that eutectic proportions of pure diopside and pure forsterite are 87.5% diopside and 12.5% forsterite (Figure 41). The diopside and olivine of the olivine-pyroxenite rocks contain approximately 20% to 25% of the respective iron molecules, hedenbergite and fayalite. The general composition of the rock indicates that eutectic proportions of this mineralogy are in the range of 80% to 85% diopside and 15% to 20% olivine (Figure 41).

The composition of the second stage of ultramafic intrusion must have approximated the lower temperature eutectic point in Figure 41, but in addition probably contained 1% to 3% ferric iron. The invasion of this material would have found the hotter, probably still crystallizing, central portion of the preceding intrusion the most accessible locus for intrusion. This phenomenon has been outlined by Harker and Bowen (7, pp. 157-158) as a mechanism of intrusion for composite dikes in the Hebrides.

At the time of intrusion of the second ultramafic magma

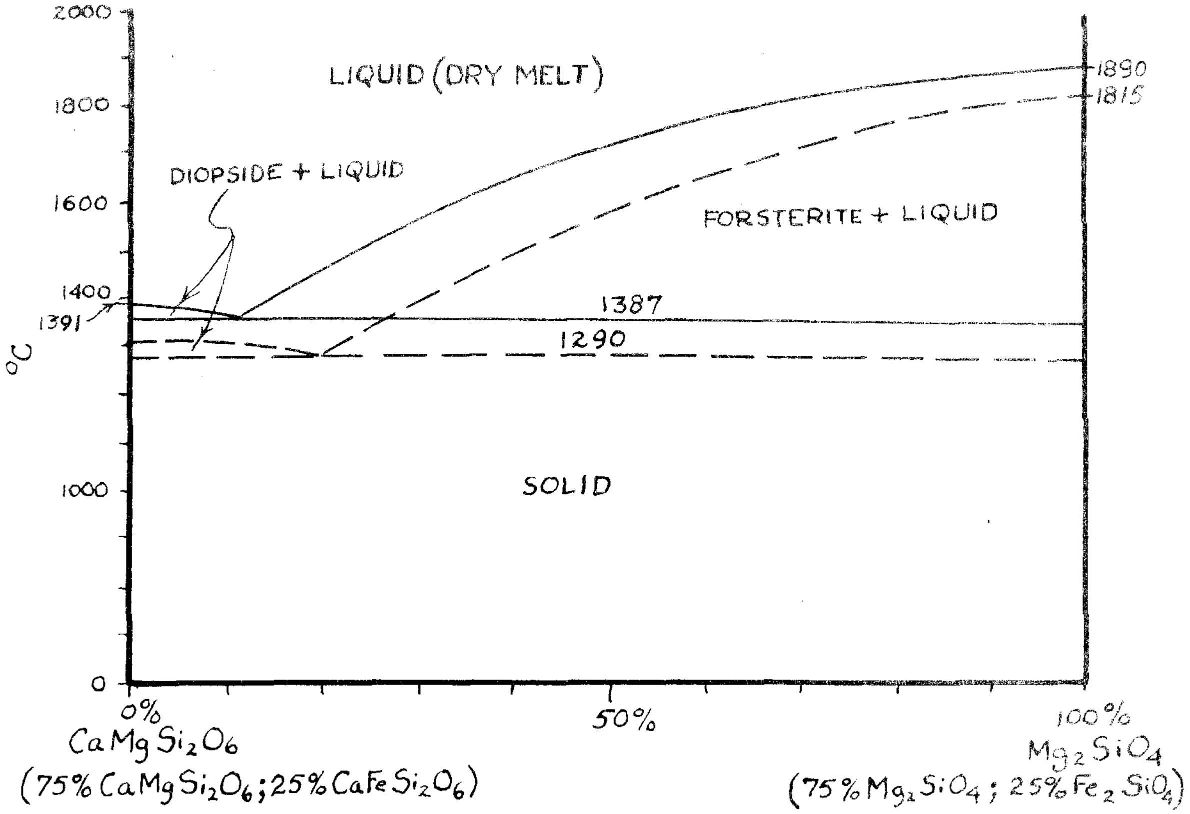

Figure 41. Solid lines: The binary system diopside-forsterite after N. L. Bowen (5, p. 212).
Dashed lines: Proposed binary system diopside-forsterite, each mineral containing 25°/o of the ferriferous molecule, hedenbergite and fayalite, respectively.

(olivine-pyroxenite), crystalline portions of the initial intrusive (diopside and magnetite) must have been just below the temperature of crystallization. Therefore, in addition to some mixing of still liquid portions of the initial magma in the second magma, there would have been some remobilization and assimilation of diopside and magnetite by the second magma. If this assumption is correct, and if consideration of magnetite is neglected in order to simplify the system, the composition of the second magma would have shifted away from the eutectic point (Figure 41) toward the diopside portion of the system. In this case, only diopside would have crystallized around the periphery of the second magma until the composition of the liquid returned to the eutectic point. Then the central portions of the magma would have precipitated eutectic proportions of diopside and olivine, forming the olivine-pyroxenite unit.

Because of assimilation and mixing phenomena, the possibility of precipitation of some pyroxenite by the second stage of intrusion, and the lack of chilled boundaries within the ultramafic complex, it is not possible to make sharp distinctions in the field between the first and second stages of intrusion. The increase in volume of the lopolith by the second intrusive probably extended laterally in some places beyond the limits of the initial intrusion, and it is probable that less magnetiferous portions of the pyroxenite unit around the north and northeast periphery of the ultramafic represent crystallization from the second stage of intrusion.

The olivine-pyroxenite unit was probably mostly, but not entirely, crystalline at the time of the third stage of intrusion of peridotitic or dunitic material, and the arriving magma again must have found the hottest, still crystallizing, central portions of the olivine-pyroxenite the most accessible locus of intrusion. Some of the olivine-pyroxenite wall-rock must have been mobilized and assimilated by the dunitic magma. Therefore, due to assimilation of liquid portions of the olivine-pyroxenite magma, and remobilization and assimilation of some crystalline olivine-pyroxenite, portions of the dunitic magma, probably the earlier of a succession of dunitic intrusions, may have been locally contaminated to peridotitic composition. It is possible that the initial injections of the final, dunitic stage of intrusion were originally peridotitic in composition, but there are no criteria from which to determine the relative importance of this possibility versus effects of contamination of dunitic material by remobilization and assimilation of olivine-pyroxenite.

Dunitic rocks locally contain as much as 10% diopside, and rocks of the textural peridotite type vary from 10% diopside and 90% olivine to 60% diopside and 40% olivine (Table 3). According to the equilibrium diagram in Figure 41, melts with a composition to the right (forsterite side) of the eutectic point (12.5% forsterite and 87.5% diopside) would have precipitated only olivine until eutectic proportions were reached in the liquid, at which stage both diopside and olivine would have recrystallized in eutectic proportion. This requisite physico-chemical behavior explains such features as cross-cutting peridotite dikes and diopside-rich veins in dunite.

Evidence of local crystal settling in some peridotitic rocks implies rhythmic precipitation of eutectic proportions of diopside and forsterite in quiescent portions of the intrusive. These residual pockets of liquid must have been surrounded by more dunitic material which crystallized at a higher temperature. No diopside would have precipitated from the residual liquid until the composition and temperature of the eutectic point had been reached, at which point both diopside and forsterite crystallized together in eutectic proportion. It is proposed that diopside settled through the liquid faster than forsterite due to a higher density at that temperature and a more rapid rate of crystal growth.

The densities of pure diopside and pure forsterite at ordinary temperature are 3.275 and 3.216 respectively (4, p. 15). This difference is negligible, but the coefficient of thermal expansion is greater for olivine than for diopside. At 1000° the density of diopside is approximately 10°/o greater than olivine (4, pp. 32-33). Although no data are available for higher temperatures, the density of diopside at the eutectic temperature (1387°) must be more than 10°/o greater than the density of olivine.

The mechanism responsible for the rhythmic precipitation of the multiple layers is not clear. Similar mineral layering has been described in many less mafic igneous rocks such as the Bushveld (34), Stillwater (39), Duluth gabbro (19), and Skaergaard (45) intrusives and the Keweenawan lava flows (15). The most plausible explanation of this type of layering has been advanced by Wager and Deer, who attribute the banding in the Skaergaard intrusive to magmatic convection currents (45, p. 332):

> "It is believed that downward currents were formed along the walls of the intrusion due to the greater density of the cooled, and partly crystallized magma which occurred there. Compensating currents are considered to have swept across the floor of the intrusion; then to have to have risen at the centre to the top of the intrusion where cooling and concomitant increase in density again took place causing the circulation to continue....The minerals denser than the magma...would sink through the current and be deposited at the bottom of the liquid....The rhythmic layering must have been produced by a rhythmic variation in the conditions of deposition, and it is suggested that changes in velocity of the convection currents were responsible."

This type of mechanism may have been operative locally in the ultramafic intrusive at Union Bay, but it is very doubtful that rhythmic magmatic currents could have caused the extensive banding in the peridotitic rocks exposed on Duke Island, southeastern Alaska (Figures 37 to 40). The great continuity and planar character of the layers on Duke Island, plus the lack of features such as "trough banding" or channel cutting within the layered rock, are difficult to explain by a mechanism of convective currents. Although no satisfactory alternative explanation is proposed here, it is believed that the rhythmic precipitation of the multiple layers in both the Union Bay and the Duke Island ultramafic intrusives must be due to the fluctuation of a delicate physico-chemical balance between temperature, pressure, and composition.

ORIGIN OF THE MAGNETITE

All petrologic features of the magnetite in the ultramafic rocks at Union Bay clearly indicate that the magnetite is a primary crystalline product of the ultramafic magmas and is not material which has been added to, or which has replaced portions of, the already crystalline ultramafic rocks by secondary processes (excluding magnetite formed as a product of serpentinization).

In differentiated basic igneous bodies such as the Palisades sill (46) and the Skaergaard (45), magnetite has formed a major constituent of the rock during the later stages of crystallization in the intrusive. This relationship is reversed at Union Bay relative to the whole ultramafic complex. Most of the magnetite is concentrated in portions of the peripheral pyroxenite unit and has to be considered a product of an early stage of crystallization relative to the olivine-pyroxenite, peridotite, and dunite rocks in the more central portions of the complex.

In the pyroxenite unit, most of the magnetite is anhedral and interstitial to subhedral diopside crystals, and is evenly distributed throughout large portions of the rock. The distribution and textural relationships indicate that the magnetite crystallized in equilibrium with the diopside, probably at a eutectic point in the binary system magnetite-diopside. If this assumption is correct, the eutectic point must lie close to the magnetite portion of the system and the composition of the melt which precipitated the magnetiferous pyroxenite rock must have been close to the diopside side of the system, perhaps 80°/o to 85°/o diopside and 15°/o to 20°/o magnetite, because textures indicate that most of the diopside was crystalline before magnetite started to crystallize. The amount of magnetite precipitated must have been directly proportional to the amount of ferric iron in the melt.

Three possible explanations of the ferric iron in the melt, or the magnetite in the rock, may be considered: (1) assimilation of ferric iron-rich material by the initial ultramafic magma; (2) the oxidation of a portion of the ferrous iron in the magma to ferric iron by water derived from any source; and (3) proportional amounts of ferrous and ferric iron in excess of diopside and olivine contained in the original magma and derived at the source of the magma.

Residual portions of the gabbro intrusive which were still liquid, or least refractory portions remobilized and assimilated, at the time of the initial intrusion of ultramafic magma may have contained Fe_2O_3 and FeO, but probably not in excess of other molecules because there is no evidence that the gabbro intrusive had differentiated toward a ferro-gabbro in the manner of the Skaergaard intrusive. Furthermore, a mechanism of assimilation of iron-rich material by the ultramafic fails to explain the concentration of magnetite (20°/o of the pyroxenite rock) at contacts with schist containing approximately 5°/o total iron.

Therefore, it is doubtful that much, if any, iron was contributed to the formation of magnetite in the initial ultramafic magma by assimilation of foreign material. For reasons outlined below, it is proposed that all of the iron now present as magnetite was an original constituent of the initial ultramafic magma, but that the ratio of ferric to ferrous iron in the melt was increased to some extent by locally derived water.

Water diffusing into the relatively dry magma from the wall-rocks would have oxidized proportional amounts of ferrous iron in the melt as previously discussed. There is good evidence that some water did migrate into the intrusive from both schist and gabbroic wall-rocks, but it is not possible to explain the derivation of all, or most of, the magnetite concentrated in the pyroxenite unit in this way without assuming an unrealistic and complicated circulatory mechanism carrying water relatively great distances into the magma and circulating both water and ferric iron back to the periphery of the intrusive.

The chemical analysis of a representative specimen of magnetiferous pyroxenite from the ore zone shows 19% total iron (11.2% ferric, 7.8% ferrous), of which 14.5% (9.7% ferric, 4.8% ferrous) is in magnetite, and 4.5% (1.5% ferric, 3% ferrous) is in diopside (see analyses of specimen 32a and pyroxene mineral separate from specimen 32a in Table 1. Unless a concentrating mechanism is postulated for iron, the magma from which this rock crystallized must have contained 19% total iron. If all of the iron had been in the ferrous state, the magma, without any oxidation of the ferrous iron by water or other volatiles, would have precipitated a pyroxene containing approximately 70% of the hedenbergite molecule, or pyroxene and olivine containing approximately 70% of the hedenbergite and fayalite molecules respectively.

The diopside and olivine of the ultramafic complex range in composition only from 30% to 1% of the hedenbergite molecule for diopside, and from 22% to 7% of the fayalite molecule for olivine. Therefore, it is highly improbable that the original magma contained only ferrous iron, and equally improbable that oxidation ~~of~~

of ferrous iron by water or other volatile material could have been the controlling process responsible for the formation or concentration of magnetite.

If any process of concentration of iron, such as circulating volatile material in the magma, had been a dominant factor in the concentration of magnetite around the periphery of the ultramafic, there is no reason why magnetite should not have been locally concentrated to 90°/o or more, as commonly observed in contact metamorphic magnetite deposits. In a few places in the pyroxenite at Union Bay, the concentration of magnetite is as high as approximately 50°/o of the rock over small areas of outcrop of approximately 100 square feet or less. However, no block of ore on the order of 400 tons or more contains more than approximately 25°/o magnetite. This feature of the ore has been established by both extensive surface investigation and more than 9,000 feet of diamond drilling.

The most plausible explanation of the magnetite is that proportional amounts of ferric and ferrous iron were contained in the initial ultramafic magma. This assumption is the only satisfactory explanation of the even distribution of the magnetite throughout large volumes of pyroxenite, and requires no concentrating mechanism. However, there is good evidence that some water migrated from the wall-rocks into portions of the initial intrusive, and the state of oxidation of the iron in the melt and the amount of magnetite in the rock must have been increased accordingly.

It has been proposed that the composition of the initial ultramafic magma approximated 80°/o diopside ($D_{75}H_{25}$), 15°/o magnetite, and 5% olivine ($Fo_{80}Fa_{20}$). If this mixture (containing 19% total iron) had crystallized without further oxidation of the iron, the distribution of the iron should have been: 7.5% in diopside and olivine; 11.5% in magnetite. However, specimen 32a contains 20% magnetite (14.5% total iron) and the diopside ($D_{77}H_{23}$) contains only 4.5% total iron. Therefore, it is proposed that approximately 14% of the iron now present as magnetite in specimen 32a has been oxidized by water diffusing into the magma from the wall-rocks, either in the site of intrusion or en route, but most probably both.

Although they are much smaller features, the regular bands of magnetite found in a few places in the pyroxenite and olivine-pyroxenite units at Union Bay bear an interesting similarity to the oxide bands of the Bushveld (34). Bateman (3) has explained the oxide bands of the Bushveld complex by a mechanism of "gravitative liquid accumulation" whereby the heavy oxide liquid, under great hydraulic pressure, has accumulated on a floor and floated the silicates with such force that the adjacent silicate crystals have become strained, bent, and granulated. This explanation may be applicable to the magnetite bands at Union Bay, where, at a late stage in the crystallization of the rock, most of the diopside had crystallized and the residual, heavy, oxide-rich liquid locally settled into layers. However, an alternative explanation for the magnetite bands at Union Bay seems to be more tenable.

At a late stage in the crystallization of the pyroxenite, when most of the diopside, but little of the magnetite, had crystallized, the whole may have had enough rigidity to respond to stress as a solid. In this case, stress created by subsequent intrusion may have caused the almost wholly crystalline mass to fail along regular fractures. Following local pressure gradients created by the fracturing, the still-liquid portion of the magma (mostly magnetite) would then have accumulated along the fractures according to the principles of dilatency outlined by Mead (37). The bifurcation and close spacing of many magnetite bands and the granulation of adjacent diopside crystals are best explained by this type of mechanism.

THE PROBLEM OF METAMORPHISM

One of the principal objections to liquid ultramafic magmas has been the lack of high-grade metamorphic effects in the wall-rocks corresponding to the high temperatures which must be assumed for melts of ultramafic, especially dunitic, composition. Because there are no plausible mechanisms for reducing the temperature of the magmas, the problem at Union Bay is clearly one of accepting the necessary temperatures, and attempting to explain the lack of high-grade metamorphism.

At atmospheric pressure the melting points of pure diopside and magnetite are 1391° and 1590° respectively. The melting point of diopside containing 25°/o of the hedenbergite molecule must be approximately 1300°, and the eutectic temperature between diopside of this composition and magnetite must be below 1300°. The eutectic temperature of the system diopside-forsterite is 1387° (Figure 41), and the eutectic temperature between diopside and forsterite, each containing 25°/o of the ferriferous molecule, must be approximately 1290° (Figure 41).

According to Bowen's calculations, the change in volume from the solid to the liquid state is relatively small for forsterite (8, p. 208). Other data indicate that the change in volume from the solid to the liquid state is less for diopside than it is for the olivines (4, p. 15). Therefore, the effect of pressure upon the melting point is relatively small for both minerals ($\frac{dT}{d\rho} = \frac{\Delta V}{\Delta H} T$). Bowen calculated the increase in melting point of forsterite as 4.7° per 1,000 atmospheres, an increase of approximately 20° corresponding to a depth of 15 kilometers in the crust (8, p. 208). Therefore, the temperatures of the magmas during the first two stages of ultramafic intrusion at Union Bay, unless superheated, probably were between 1250° and 1350°.

The temperatures of the later stages of dunitic intrusion must have been approximately 1800°. However, the dunitic material intruded the central portions of the ultramafic complex, and no peridotite or dunite rocks are in contact with either schist or gabbro.

Temperature distributions, as a function of time, in and around cooling igneous bodies of simple geometric shapes, have been determined from Fourier's classical theories of heat conduction in solids, and have been presented by several authors, notably Lovering (35, 36), Larsen (32), and Taylor (41). This work incorporates simplifying assumptions concerning the uniformity of thermal properties in hot and cold rocks and neglects the effects of convection in the magma and dissipation of heat by radiation. Solution of problems for infinite, planar igneous bodies of finite thickness indicate: (1) that the temperature of the wall-rocks at the igneous contact rises rapidly to a maximum of approximately 60°/o of the original difference in temperature between the wall-rocks and the magma, and remains at this figure until the igneous body is completely crystalline; (2) that the maximum reached during the progressive rise and fall of temperature, for points in the wall-rocks beyond the igneous contact, travels outward from the contact with constantly decreasing value (41, p. 4).

The simplifying assumptions made in the course of the above work render its strict application to natural phenomena improbable. However, it is the best means available to guess at the order of magnitude of the temperatures in the wall-rocks at Union Bay.

If the regional temperature of the wall-rocks at the time of ultramafic intrusion was 200°, and if the temperatures of the first two stages of ultramafic intrusion were 1300°, the solution of the heat equation used by Taylor (41, p. 4) suggests a maximum temperature of 850° in the wall-rocks at the ultramafic contact. The final stages of intrusion of dunitic magma would have raised this temperature at least 100° locally. These temperatures, plus a lithostatic pressure of several thousand atmospheres, definitely satisfy the temperature-pressure conditions for the highest grade of contact metamorphism. However, it is improbable that the reactions involved in contact metamorphism proceed at a significant rate at any temperature without the catalytic effect of the presence of aqueous fluids.

The importance of water as an agent in processes of metamorphism has been particularly emphasized recently by Yoder (50, 51), but even classic theories of contact metamorphism attribute mineralogical changes within contact aureoles to relatively brief periods of accelerated chemical reaction controlled by the coincidence of high temperatures with the passage of catalyzing waves of aqueous fluids expelled from the crystallizing magmas (44, pp. 291 and 567).

At Union Bay there is no evidence associated with either the ultramafic or surrounding rocks that any volatile, fluid phases were expelled from the ultramafic magmas during cyrstallization. The occurrence of magnetite, probably the last mineral phase to crystallize in the peripheral portions of the ultramafic, is entirely confined to the ultramafic rocks, and is not transgressive into the wall-rocks, as in the case of contact metamorphic deposits. Even the minor concentrations of sulfide minerals, occurring around the periphery of the complex, are confined to ultramafic rocks. These features, plus the pattern of serpentinization and the peripheral disposition of the hornblende-pyroxenite unit, suggest that the ultramafic magmas, instead of emanating volatiles during crystallization, absorbed some aqueous fluids from the wall-rocks.

Because of the temperature gradient across the magma-wall-rock contacts, only non-equilibrium conditions could have prevailed. A quantitative solution of the problem of water distribution under these conditions has not yet been obtained. However, Kennedy has considered the case of a hot, dry magma intruding cool, wet sediments in a qualitative manner (31, p. 491), and has concluded:

> "The temperature of the sediments close to the magma will rise very rapidly, and in consequence the partial pressure of water in the sediments may increase at a rapid rate, provided the water is in pore spaces which do not communicate readily with the surface of the earth. Suppose the sediments are initially at 200° and have interstitial water at a partial pressure of 100 atmospheres. If the sediments are heated to 400° by the magma, and the water cannot escape, the partial pressure of the water will increase from 100 atmospheres to more than 3400 atmospheres. The water may then escape by diffusing into the magma. The marginal portions of the melt may thus become greatly enriched in water..."

Therefore, it is proposed that the lack of high-grade metamorphic effects in the wall-rocks around the ultramafic complex at Union Bay is not a reflection of low temperatures of intrusion, but rather is a result of the invasion of hot, but unusually dry, magmas, probably containing 0.3% or less water. Due to the anhydrous state of the magmas, they did not exude waves of volatile material during any stage of crystallization, but rather absorbed some aqueous fluid from the adjacent wall-rocks. The metasedimentary wall-rocks probably were not "wet" at the time of ultramafic intrusion, but must have contained approximately 3% water as a constituent of crystalline phases, as indicated by the chemical analysis of specimen 400 in Table 1. It is proposed that a portion of this water was mobilized through partial fusion by heat energy from the crystallizing magmas, and diffused from the wall-rocks into the anhydrous magmas as proposed by Kennedy (above).

These conditions, which must be the antithesis of contact phenomena adjacent to more hydrous magmas, must have inhibited high-grade metamorphism in the wall-rocks adjacent to both the gabbro and ultramafic intrusives at Union Bay, and may apply to the explanation of anomalously low grade metamorphic effects associated with some basic and ultrabasic intrusions in other regions.

THE SOURCE OF THE MAGMAS

The world-wide restriction of peridotite intrusive rocks, or their serpentinized equivalents, to orogenic belts indicates that mechanisms of generation and intrusion of ultramafic magmas are integrally related to the broader phenomenon of orogeny. The regional distribution of peridotitic intrusives in various parts of the world is summarized by Hess, who concludes that their emplacement occurs during the early stages of deformation in mountain belts (25).

The most probable source of ultramafic magmas is a ubiquitous peridotite layer, the upper boundary of which may constitute the Mohorovicic discontinuity. Many geologists accept the existence of this layer in the earth on the basis of geophysical evidence. The only geologic evidence suggesting a layer of this composition is the ultramafic intrusives themselves, and the occurrence, in some basaltic lavas, of blocks of ultramafic rock, which are plausibly explained by Ross as exotic inclusions derived from the peridotitic mantle (40). The mineralogy and chemical analyses of many of these inclusions, especially those collected from the Hawaiian volcanic province, are practically identical with ultramafic rocks at Union Bay (40, pp. 697-698).

The intimate space association of the gabbro intrusive and the ultramafic complex at Union Bay would be most simply explained by the derivation of both magma types by the same process at the same place in the mantle. Washington (48), Bowen (7), and, later, Buddington (11), have made the assumption that the peridotite shell of the earth is composed largely of olivine and pyroxene with approximately 20°/o to 30°/o feldspar, a composition approaching that of chondritic meteorites. Both Bowen and Buddington have emphasized that, if such material were subjected to fusion, there would be a stage at which the liquid, constituting approximately 40°/o of the mass, would be basaltic, or gabbroic, in composition (7, p. 316, and 11, p. 139).

However, the composition of any system similar to the composition proposed above for the peridotitic mantle is analogous to the ternary system diopside-anorthite-forsterite presented by Osborn and Tait (38, p. 419). The eutectic point in this system is 49°/o diopside, 44°/o anorthite, and 7°/o forsterite. Any liquid derived from this, or any similar, system should, upon crystallization, precipitate some olivine unless the composition of the melt was extraneously changed. The gabbro at Union Bay contains no olivine, and, therefore, it is improbable that the gabbro magma was generated from the same material as the ultramafic magmas.

Because none of the ultramafic rocks contain any feldspar at Union Bay, exclusive of some peripheral portions of the hornblende-pyroxenite unit, a further complication is imposed upon the hypothesis of a mutual source for both the gabbro and ultramafic rocks in that a mechanism is required for complete separation of the two magma types. No physico-chemical mechanism at the source, or gravity controlled mechanism en route to the site of emplacement, appears capable of such complete separation of the two liquids.

In all fairness to the hypothesis of a mutual source for both the gabbro and ultramafic magmas, it must be parenthetically noted that some ultramafic intrusions of size and association similar to the complex at Union Bay, notably the complex at Taberg, Sweden, studied by Hjelmqvist (26), seem to be quite amenable to explanation by this hypothesis. Most of the "olivinite" intrusive rock at Taberg contains some plagioclase (labradorite) identical in composition with the plagioclase of the associated gabbro. The gabbro also contains an unusual, pleochroic olivine identical with the olivine of the ultramafic rocks. These features of the rocks suggest a close genetic relationship between the gabbro and ultramafic rocks, which could be plausibly explained by fusion of material similar in composition to that proposed by Washington, Bowen, and Buddington for the peridotite shell of the earth (above).

However, the evidence at Union Bay indicates the more complex explanation that the gabbro and ultramafic magmas, although probably generated or tapped by the same process, were probably derived from different levels within the earth. In this case, the same orogenic process may have tapped or generated the gabbro magma at a high level in the mantle, or in the crust above the Mohorovicic discontinuity, and generated the ultramafic magmas at greater depth in the mantle.

Although the precise nature of the process has remained an unsolved problem, the generation of fluid magma from crystalline material at depth within the earth appears to depend upon a mechanism for either the focus of heat energy or the release of pressure, or, most probably, both. Such a mechanism, localized along a major fracture, or in a zone of weakness, which transected the Mohorovicic discontinuity, may have been responsible for the rise of the gabbro and ultramafic magmas along the same route and their close association in space at the site of emplacement.

If it is assumed that the gabbro and ultramafic magmas originated at different levels within the earth, as indicated by the evidence at Union Bay, explanations of their origins constitute two separate problems. The genesis of basaltic, or gabbroic, magmas has received a great deal of attention in the literature, and current thought is competently summarized by Turner and Verhoogen (44, pp. 194-200, 223). A recent and contributive discussion of the problem has been presented by Waters (49).

The simplest approach to the composition of the peridotite shell at the source of the ultramafic rocks at Union Bay is based upon the assumption that the mineralogy of the source material is directly reflected by the mineralogy of the ultramafic complex, exclusive of portions of the hornblende-pyroxenite unit which are, in part, composed of foreign material locally derived from the wall-rocks. On the basis of this assumption, the source material may have been composed largely of forsteritic olivine and diopside, with some magnetite, chromite, and other spinels. These minerals may have been, in part, randomly distributed throughout some portions of the source, constituting relatively homogeneous rock, and, in some places, may have been segregated into olivine-rich and diopside-rich bodies or layers.

If these assumptions are made concerning the composition of the source material, and if a local mechanism capable of focusing increasing amounts of heat energy is postulated, the following results are proposed, in chronological order:

1. From approximately 1250° to 1350°: rock composed of diopside, olivine, and magnetite produces a liquid of the composition of the eutectic point between magnetite and the most ferriferous diopside and olivine fractions. Concomitantly, rock composed of diopside and magnetite produces a liquid of the composition of the eutectic point between magnetite and the most ferriferous diopside fraction. These events would be accompanied and followed (overlapped in time) by fusion, in rocks composed only of diopside, first of the most ferriferous diopside fraction, followed by fusion of progressively more magnesian diopside. In rock containing less magnetite than eutectic proportions (probably the general case), the temperature would remain at the eutectic temperature between magnetite and diopside (or olivine, or both) until all of the magnetite had been melted.

2. From approximately 1350° to 1450°: continued fusion of progressively more magnesian diopside in rock composed of that mineral only, and, in rock composed of diopside and olivine, fusion of eutectic proportions of progressively more magnesian fractions of both minerals. At approximately 1450°, the probable eutectic temperature of the system diopside-forsterite at this depth, the

temperature would remain constant in rock composed of both minerals until all the diopside in rock at this temperature had been melted (assuming that, at this stage, the composition of the system lies to the right, or forsterite, side of the eutectic point).

3. From approximately 1450° to 1800°: Fusion of eutectic proportions of olivine and magnetite and olivine and chromite, where these minerals are in contact, until all the magnetite and chromite had been melted. Production of dunitic liquid by fusion of progressively more magnesian olivine.

This sequence of progressive fusion of the source material provides a tentative explanation of the sequence of ultramafic rocks in the complex at Union Bay. The evidence further indicates a periodicity of the processes responsible for the generation and migration of the magmas such that time gaps occurred between the three stages.

An important, and possibly the controlling, force responsible for the ascent of magma, once generated, must be the difference in density between the liquid and the surrounding rock, both being subject to lithostatic pressure. The densities of diopside and olivine glasses are 2.830 and 2.831 respectively (4, p. 15), and the density of liquid diopside at its temperature of crystallization (1391°) is 2.671 (4, p. 36). The densities of dry ultramafic magmas, devoid of a gaseous phase, and equivalent in composition to the ultramafic rocks at Union Bay, are probably less than crystalline basalt or gabbro (approximately 2.95) and greater than crystalline granite (approximately 2.65). Therefore, ultramafic magmas may have the ability to rise into, but not through the sialic portion of the crust, due to their relative density. This inference, that it may be physically impossible for ultramafic magma to rise to the surface of the earth, constitutes the most plausible explanation of the absence of effusive ultramafic rocks.

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