

Low-Temperature Reaction Zones and Alpine Ultramafic Rocks of California, Oregon and Washington

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By ROBERT G. COLEMAN

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LOW-TEMPERATURE REACTION ZONES AND ALPINE ULTRAMAFIC ROCKS OF CALIFORNIA OREGON, AND WASHINGTON

By ROBERT G. COLEMAN

ABSTRACT

Metasomatism of varied rock types associated with alpine-type serpentinites is widespread in the Pacific coast area. This metasomatism is related to the process of serpentinization and the tectonic history of the ultramafic emplacement. Such diverse rock types as graywacke, gabbro, dacite, and basalt have been involved in the metasomatism. Originally, such metasomatized mafic rocks were named "rodingites," but a more general term such as "reaction zones" should be used, and such terms as "rodingite," "garnetized gabbro," "granat-vesuvian fels," "skarn," and "ophisperite" should be categorized as phases of a single process.

The reaction zones are developed along the serpentinite-country rock contacts and in tectonic inclusions and dikes contained within serpentinite. Hydrogarnet is the predominant mineral, but idocrase, diopside, prehnite, xonoflite, chlorite, and nephrite also are characteristic minerals produced during the metasomatic alteration of igneous rocks. In altered sedimentary rocks and silicic igneous rocks, albite, potassium feldspar, and a fibrous actinolite are often associated with prehnite. Chemical analyses and mineralogical data of serpentinites and calcium metasomatites are presented for 42 specimens from ultramafic bodies in Oregon, California, and Washington. The metasomatic alteration is produced by a loss of silica to the serpentinite and a concomitant enrichment of calcium and magnesium within the reaction zone. Increase in density, addition of water, and frequent association with the blueschist facies metamorphism indicate that the alteration occurred under conditions of elevated pressure and high activity of water. The pressure-temperature conditions during metasomatism are estimated from the known experimental stability fields of those minerals formed during the alteration, the maximum temperature being approximately 500°C and the minimum about 250°C, with pressures probably in excess of 4,000 bars. Such a pressure-temperature environment requires an unusual geologic environment as the combination of relatively low temperature and high pressure is not characteristic of igneous intrusions or load metamorphism. This report suggests that the reaction zones develop at the time when large portions of ultramafic mantle are tectonically emplaced into the base of the crust or are moved tectonically higher into the crust. Serpentinization of the ultramafic material is contemporaneous with alteration and tectonism. Thus, the alteration represents a tectonic contact metamorphism and is not related to igneous activity.

INTRODUCTION

Studies concerning the origin of alpine serpentinites have led to the observation that metasomatic reaction zones are related to the emplacement and formation of these serpentinites. The purpose of this paper is to point out the widespread metasomatism in the alpine

serpentinites that form elongate belts along the Pacific coast of the United States and to explain its origin. The geologic setting and petrologic character of the metasomatism appear to be related to the tectonic history of these serpentinites, and a tentative theory on their formation will be advanced. The author first became interested in this problem while studying the jadeite deposits within the New Idria serpentinite mass in the central part of the Diablo Range of California (Coleman, 1961). Here the association of calcium-rich rocks with jadeite and albite presented an unusual mineral assemblage. Several field seasons were spent reconnoitering California, Oregon, and Washington serpentinites to ascertain the distribution and relationships of these peculiar reaction zones. In 1962, a year was spent in New Zealand studying similar reaction zones from the Great Ultramafic Belt (Coleman, 1966). Additional fieldwork on this same problem has been carried out on the alpine serpentinites of Australia and New Caledonia. The field evidence and petrologic information accumulated from these studies, together with a survey of the literature, clearly suggest that metasomatism is nearly ubiquitous as a contact reaction of ultramafic bodies with the country rock and provide important information relating the formation of serpentinites to the tectonic history.

Rocks from these reaction zones have been given various names, depending upon their composition and textures. "Rodingite" was introduced to describe altered gabbros in the Dun Mountain serpentinites of New Zealand (Bell and others, 1911; Grange, 1927). The name is taken from the Roding River that drains much of the Dun Mountain ultramafic belt. Over the years the term "rodingite" has been employed to describe similar rocks from other serpentinites: Benson (1913, 1915, 1917, 1918), Australia; Turner (1930), South Westland, New Zealand; Wells, Hotz, and Cater (1949), southwestern Oregon; Cater and Wells (1953), northern California; Leech (1953), southwest British Columbia; Suzuki (1953), Japan; Bloxam (1954), Scotland; Baker (1959), Tasmania; Bilgrami and Howie (1960), Pakistan; Majer (1960), northwest Syria; Schlocker (1960), central California; Chesterman (1960), northern California; Seki and Kuriyagawa (1962), Japan.

The rodingites described by these authors are made up predominantly of calcium-rich silicates such as hydrogarnet, idocrase, and diopside and are probably derived from altered gabbros or basalts associated with the ultramafics. Other authors have called these rocks garnetized gabbros (Miles, 1950), granat-vesuvian fels (Murigoci, 1900), skarns (Korzshinskii, 1958), ophispherites (Jaffé, 1955), and kalksilikatfels (Müller, 1963). Related to the rodingites, and contained within or in

contact with alpine ultramafics, are masses consisting predominantly of sodium-aluminum silicates and having only thin borders of calcium-rich silicates. The jadeite deposits of Japan (Iwao, 1953), Burma (Lacroix, 1930; Bleek, 1907), and California (Coleman, 1961) are albite-jadeite masses contained within serpentinites and showing calcium-rich borders. Reed (1959) has described metasomatized argillites from the Dun Mountain serpentinites, and further work in New Zealand has brought to light metasomatized graywackes and limestones (Coleman, 1966). Chesterman (1960) has described calcium metasomatism of graywackes in contact with serpentinites. Various kinds of rocks showing metasomatism in contact with or contained within serpentinites are neither uncommon nor surprising.

Metasomatism as used in this paper refers to a change in the bulk composition of the rocks in the reaction zone between serpentinite and country rock or associated mafic rocks. This bulk-composition change is reflected by the appearance of a different mineral assemblage (Thompson, 1959).

All the metasomatic rocks associated with the serpentinites described in the literature referred to above and in this paper have similar characteristics, which may be summarized as follows:

1. The metasomatic reaction zones are within or in contact with serpentinite and have not been observed in unserpentinized ultramafic rocks or in the high-temperature aureoles of such rocks. The reaction zones are developed in diverse rock types in contact with the serpentinite.
2. The reaction zones develop at the contact between tectonic inclusions, dikes and layers of mafic rocks, and surrounding country rock and the serpentinite. Most of these reaction zones have been involved in those tectonic movements that have acted on the serpentinite. Some of the original reaction zones and associated rock have been broken and transported tectonically during and after serpentinization. Synkinematic brecciation and mylonitization in the reaction zones indicates that metasomatism accompanies deformation.
3. The chemical changes of the metasomatized rocks in the reaction zones trend toward a similar chemical composition. In the country rock, all the zones are undersaturated with respect to silica and show increases in calcium and, to a lesser extent, magnesium. In metasomatized gabbros and basalts where the chemical changes are well known, the reaction zone contains SiO_2 , Al_2O_3 , CaO , and H_2O in approximately the molecular proportions $3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 \cdot \text{H}_2\text{O}$. Those reaction zones derived from more silicic rocks, such as sandstone and granitic rocks, often

- contain a feldspar-rich zone or core and have a calcium-rich zone at the serpentinite contact. The serpentinite at the contact is also metasomatized and may consist of chlorite or nephritic actinolite.
4. The reaction zones are localized and cannot be considered as related to any metasomatism on a regional scale. There is no direct relationship between the size of the ultramafic mass and the intensity or amount of metasomatic alteration. Local alteration zones with these particular calcium-rich mineral assemblages have not been reported from other geologic environments..

ALPINE SERPENTINITES OF THE PACIFIC COAST, REGIONAL SETTING

The distribution of the ultramafic rocks in California, Oregon, and Washington is shown in figure 1. Certain faults and some of the ultramafics obviously are spatially related. Clark (1960) has shown that the locations of serpentinites are directly related to the fault systems of the foothills area of California and that the shape of the serpentinite masses are usually narrow and elongate parallel to the strike of the fault. Irwin (1964) postulated that certain California and Oregon ultramafics represent large overthrust sheets. Careful documentation of thrusting involving serpentinites has also been given by Brown (1964) for the northern Coast Ranges of California. Other areas of ultramafic rocks, notably in northern California and southwestern Oregon, that have irregular outlines and crosscutting relationships with the enclosing rocks may have preserved intrusive contacts. Serpentinites associated with normal faults have not been recorded in the Pacific coast region. Several large diapiric serpentinite emplacements along the crests of anticlinal ridges in the Diablo Range of central California are well documented. Although some serpentinites are associated with strike-slip faulting, serpentinite masses along the continental edge of the Pacific coast apparently are more commonly related to thrusting or diapiric piercements.

The ultramafic masses in northern Washington, although less elongate than those in California, are mostly related to major faults. Thayer (1963) has stated that the eastern Oregon ultramafics are igneous intrusions but that postemplacement movement and serpentinitization have affected their original position and shape. The degree of serpentinitization of ultramafic rocks in the Western United States is related directly to the tectonic history of each individual mass. Certain ultramafic masses having a complex tectonic history, such as the New Idria, Calif., serpentinite, are completely serpentinitized. Geologic evidence suggests that the New Idria mass has moved dia-

pirically upward, in successive tectonic steps, from middle Cretaceous to the present (Coleman, 1961; Eckel and Myers, 1946).

In contrast, certain ultramafics of the Klamath Mountains appear to have been emplaced as igneous intrusions during the Late Jurassic and show only partially serpentinized borders (Lipman, 1964). The Twin Sisters mass of intrusive "Tertiary?" (Ragan, 1963) dunite in northern Washington consists almost entirely of unaltered dunite with only a very thin skin of serpentinite (100 yd thick) developed at its contact with the country rock; this mass appears to have undergone diapiric movement. The primary igneous age¹ of the Pacific coast ultramafics therefore remains in doubt, as tectonism has allowed many of these intrusions to move after their original emplacement within the crust of the earth.

The presence of detrital serpentine debris within Mesozoic and Tertiary sedimentary rocks of California attests to the long exposure of ultramafic rocks at the surface. Abundant ultramafic debris in the basal member of the Swauk Formation of Late Cretaceous and Paleocene age in the Mount Stuart area of Washington indicates a Paleocene or earlier age for some of the Washington ultramafics. In eastern Oregon, Thayer (1963) has given a Triassic age to the ultramafics of the Strawberry Mountains; but 20 miles to the west along the South Fork of the John Day River, highly sheared serpentinites appear to diapirically invade upper Miocene basalts of the Columbia River Group. The occurrences suggest that the Pacific coast ultramafic rocks are probably emplaced during the deformational events which initiated metamorphism and folding of their surrounding eugeosynclinal sediments. This concept is not new, and was advocated by Hess (1955) to explain the distribution of alpine ultramafics throughout the world. Ultramafics showing only minor serpentinization and crosscutting relationships, such as the central core of the Klamath Mountains, probably represent conditions of emplacement in the initial and early stages of tectonism. Those more highly serpentinized and elongated ultramafics associated with major faults have undergone more than one period of deformation. Each successive period of orogeny has further serpentinized these ultramafics, allowing further diapiric movement to take place as a result of expansion and decrease of density at several times during the process (Milovanovic and Karamata, 1960; Ducloz and Vuagnat, 1962).

A careful search for high-temperature aureoles (1100°–1130°C; see Jackson, 1961) produced by magmatic emplacement along many contacts of Pacific coast ultramafic masses was not successful. That

¹ Primary igneous age as used here refers to the period of time when a melt of ultramafic composition crystallized.

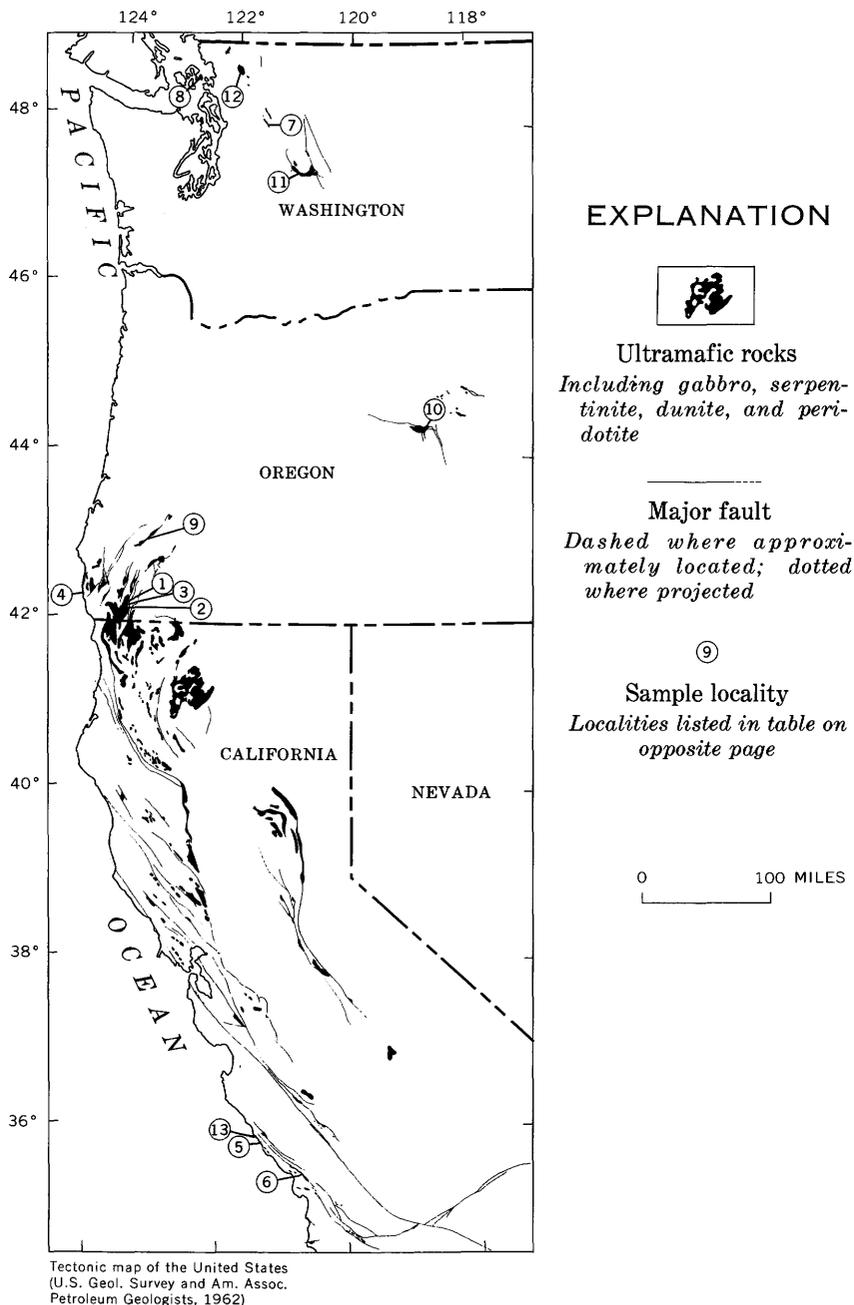


FIGURE 1.—Distribution of ultramafic rocks and location of sample localities in California, Oregon, and Washington. Data from U.S. Geological Survey and American Association of Petroleum Geologists (1962).

such contact effects do exist elsewhere has been suggested by MacKenzie (1960), Green (1964), and Challis (1965). Yet even these authors find that the observed contact metamorphism is not commensurate with the concept of a completely molten peridotite or dunite magma. For example, Lipman (1964, p. 199) states of the Klamath Mountains: "* * * the evidence accumulated indicates that the ultramafic pluton initially had the form of a gently dipping sheet, was intruded at temperatures of 500° to 700°C by flowage and recrystallization of an essentially crystalline mass concurrently with metamorphism of adjacent country rock to assemblages of the almandine amphibolite facies." Thayer and Brown (1964) described mafic and ultramafic contact effects as follows: "The only contact-metamorphic effects were slight to moderate recrystallization, without development of foliation, along contacts of gabbro and diorite with country rock. Continued strong deformation after intrusion is shown by widespread brecciation and albitization of gabbro, quartz diorite, and Paleozoic rocks, and by diapiric movement of serpentine that engulfed blocks of albite granite."

Contacts of the highly sheared Pacific coast serpentinites usually show no evidence of high-temperature thermal metamorphism; however, in some areas well-developed reaction zones are formed within the country rock. These zones resemble narrow contact aureoles observed around igneous intrusions except that the mineral assemblages are characteristic of low temperatures and metasomatism is extensive. This same metasomatic alteration also affects various tectonic inclusions engulfed within the serpentinite and mafic dikes and layers within the ultramafic masses. The low-temperature metasomatic zones in country rock are localized and are not proportional to the size of the ultramafic masses. The irregular distribution of the metasomatic zones of any one mass or from mass to mass precludes analogies to high-temperature contact metamorphism. The low-temperature metasomatic zones may mask earlier high-temperature contact effects.

KEY TO SAMPLE LOCALITIES SHOWN IN FIGURE 1

Map No.	Sample	Location	Quadrangle	Long W.	Lat N.
1	7-RD-60-A	Eureka mine road.....	Pearsoll Peak, Oreg.....	123°45'	41°20'
2	18-RD-60	Chetco Pass road.....	Pearsoll Peak, Oreg.....	123°49'	42°17'
3	24-RD-60-C	Illinois River bed.....	Pearsoll Peak, Oreg.....	123°46'	42°18'
4	38-RD-60-5	Myers Creek.....	Gold Beach, Oreg.....	124°25'	42°18'
5	7-RD-61-A	Salmon Creek.....	Burro Mountain, Calif.....	121°21'	35°48'
6	8-RD-61-1	Morro Creek.....	Cayucos, Calif.....	120°46'	35°25'
7	51-RD-61-E	Sultan Basin.....	Index, Wash.....	121°32'	48°00'
8	52-RD-61-A	Cypress Island.....	Anacortes, Wash.....	122°40'	48°35'
9	32-RD-61-1	Myrtle Creek.....	Roseburg, Oreg.....	123°19'	43°02'
10	41-RD-61-A	Baldy Mountain.....	John Day, Oreg.....	118°47'	44°18'
11	48-RD-61	Ingalls Peak.....	Mount Stuart, Wash.....	120°59'	47°29'
12	53-RD-61-D	Twin Sisters.....	Hamilton, Wash.....	121°55'	48°37'
13	3-RD-61	Cape San Martin.....	Cape San Martin, Calif.....	121°28'	35°53'

Challis (1965) has described a "high" temperature aureole at Red Mountain in New Zealand, where a later metasomatism has been superposed. Such effects could be expected in the Pacific coast ultramafics, but they have not been discovered. The following sections describe the occurrence of selected calcium metasomatites and relate their petrologic nature to the tectonic period of serpentinization and emplacement of ultramafics.

PETROLOGY OF REACTION ZONES

Descriptions of calcium metasomatites from many locations (fig. 1) of ultramafic bodies unrelated to each other are given here to demonstrate a similarity in mineralogy, chemistry, and genesis. The discussion is divided into two sections; the first describes small individual rodingite masses, and the second describes the progressive nature of the reaction zones on various rock types.

RODINGITES

Included in this discussion are those dense white calc-silicate rocks that typically contain hydrogarnet, diopside, idocrase, and chlorite and that represent the metasomatism of gabbros or basalts. These rocks invariably occur as isolated masses within sheared serpentinites and are identical with the rodingites originally described by Bell, Clarke, and Marshall (1911) from the Dun Mountain serpentinites of New Zealand.

The diversity in shape and size of several typical rodingites is illustrated in figure 2. These masses were originally tabular bodies and may represent altered dikes of mafic rock cutting the ultramafics. Material from Cypress Island was originally a coarse-grained gabbro dike (fig. 2A) that had been broken and distended within a narrow serpentinized band of peridotite. In contrast, fine-grained Morro Creek rodingite, having an elliptical and rounded shape, is included in extremely sheared serpentine (fig. 2F') and could be a fragment of a former mafic dike or, more likely, a tectonic inclusion of basalt. The outer surfaces of the rodingites often are slickensided, which indicates movement within the serpentinite, so all these rodingites have undergone some tectonic transport and some distension or fragmentation. A typical rodingite may only be a foot or more in width and rarely is more than 10-15 feet long.

In serpentinites exhibiting alteration of mafic dikes to rodingites, a progressive change of shape of mafic dikes from tabular to isolated discoids accompanies the progressive alteration to rodingite and tectonic transport in the serpentinite. The outer portion of these rodingites usually consists of a nearly black rind of chlorite or,

in some places, nephrite (fig. 2*B, C, F*), which contrasts with the nearly white calc-silicate core. These rinds are similar to the "black-wall" described by Chidester (1962, p. 65). The small Morro Creek rodingite is exceptional in that chlorite is present all the way into its center. The calc-silicates forming the central portion of rodingites are extremely fine-grained mixtures, and only rarely can modal data or textures be ascertained. Metasomatized tectonic inclusions of the more silicic igneous rocks or sediments are similar in their textures and structures to rodingites, but their central parts are usually rich in feldspar (Coleman, 1961). The more silicic inclusions are more commonly present along the serpentinite borders, whereas rodingites derived from preexisting mafic dikes or layers are rather evenly distributed throughout the serpentinite masses.

Microscopic examination of rodingites commonly reveals an igneous texture characteristic of basalts or gabbros, and thus the original rock type can be ascertained; however, cataclastic deformation may completely obscure any evidence of the original textures.

Mineralogical composition of rodingites is very simple and is dominated by hydrogarnet, diopside, idocrase, and prehnite (table 1). Where original textures are preserved, brown isotropic hydrogarnet, idocrase, or prehnite is pseudomorphous after feldspar. Ferromagnesian minerals alter to chlorite and tremolite or, in some rocks such as the Sultan Basin and Cypress Island rodingites, the pyroxenes are only partially altered to chlorite. Diopside seems to replace feldspars as well as the ferromagnesians. The atypical more silicic Myers Creek material contains prehnite, pectolite, and barium-rich potassium feldspar. These rocks are so extremely fine grained and poorly crystallized that optical mineralogy is often not diagnostic. Identification of the mineral assemblages was determined by X-ray diffraction of the whole rock and of density fractions separated by heavy liquids.

The associated serpentinites exhibit no textural or mineralogical characteristics that distinguish them from other typical rocks within the surrounding ultramafic mass. Thin section and X-ray study of the associated serpentinites, however, does reveal the presence of diopside, andradite, and nephrite. These minerals are secondary and replace the host serpentine as veins or as porphyroblastic crystals. The chlorite rim surrounding the rodingites progressively replaces the serpentine and retains some of the original textures of the serpentine. Determination of the serpentine mineral species revealed no particular polymorph characteristic of the enclosing serpentinites (table 1). Hostetler, Coleman, Mumpton, and Evans (1966) have shown that clinochrysotile and lizardite are the common polymorphs of alpine-type serpentinites.

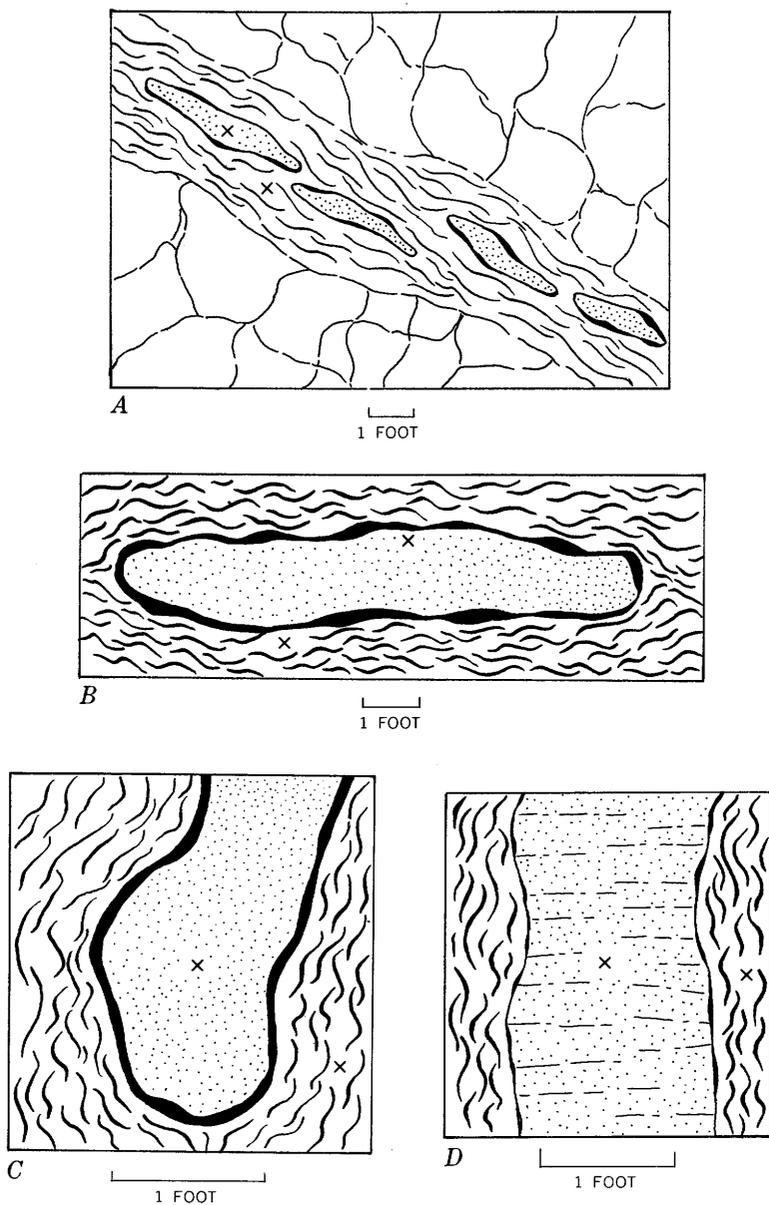
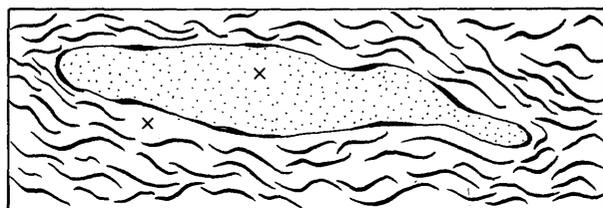


FIGURE 2.—Field sketches of rodingites from Oregon, Washington, and California, showing general shape and structure.

A, Cypress Island (vertical section) (52-RD-61-A).

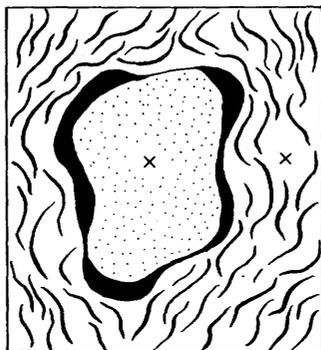
B, Illinois River bed (horizontal section) (2) 4-RD-60-C).

C, Chetco Pass road (vertical section) (1) 8-RD-60).



E

1 FOOT



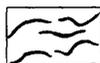
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1 FOOT

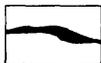
EXPLANATION



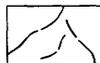
Rodingite or
Ca-metasomatite



Serpentinite



Chlorite or
nephrite borders



Ultramafic rocks

x

Approximate position of sample

D, Eureka mine road (vertical section) (7-RD-60-A).

E, Sultan Basin (horizontal section) (51-RD-61-E).

F, Morro Creek (horizontal section) (8-RD-61-1).

See fig. 1 for location, table 1 for mineral assemblages, and table 2 for chemical and spectrographic analysis.)

TABLE 1.—*Mineral assemblages and occurrences of rodingites*

Sample	Location	Mineral assemblage (in order of decreasing abundance)	Texture	Occurrence	Associated serpentinites
1	Eureka mine Road, Oreg.	Hydrogarnet, chlorite, diopside, sphene.	Original variolitic texture partially preserved.	Dikelike ellipsoid in sheared serpentinite. Width \approx 2 ft, length \approx 5 ft.	Clinochrysotile, lizardite, chromite, magnetite, garnet.
2	Chetco Pass Road, Oreg.	Diopside, hydrogarnet, chlorite.	Cataclastic.	Ellipsoidal inclusion in sheared serpentinite. Major diameter 3 ft, minor diameter 2 ft.	Clinochrysotile, orthochrysotile, brucite, magnetite.
3	Illinois River bed, Oreg.	Hydrogarnet, idocrase, diopside, chlorite.	Cataclastic.	Tabular dikelike mass within sheared serpentinite. Width 2 ft, length 8 ft.	Clinochrysotile, magnetite, orthochrysotile, brucite, garnet, pyroxene.
4	Myers Creek, Oreg.	Prehnite, pectolite, barium-rich orthoclase.	Cataclastic.	Rounded tectonic inclusion in sheared serpentinite. \approx 5 ft in diameter.	Clinochrysotile, orthochrysotile, magnetite.
5	Salmon Creek, Calif.	Hydrogarnet, chlorite, diopside, sphene.	Original ophitic basaltic texture preserved.	Small rounded mass within sheared serpentinite. \approx 1.5 ft in diameter.	Antigoritelike serpentine, brucite, magnetite.
6	Morro Creek, Calif.	Chlorite, prehnite, sphene.	Cataclastic.	Small rounded mass within sheared serpentinite. \approx 1 ft in diameter.	Clinochrysotile, lizardite, brucite, carbonate, magnetite.
7	Sultan Basin, Wash.	Hydrogarnet, chlorite, diopside, augite.	Gabbroic.	Flattened ellipsoid within sheared serpentinite. Width 2 ft, length 6 ft.	Clinochrysotile, amphibole, magnetite.
8	Cypress Island, Wash.	Albite, zoisite, pyroxene, natrolite, tobermorite, chlorite.	Gabbroic.	Dikelike tabular mass in partially sheared massive serpentinite. Width \approx 1 ft, length \approx 5 ft.	Lizardite, brucite, olivine, magnetite.

Chemical and spectrographic analyses of eight rodingites are given in table 2. The field sketches in figure 2 show the approximate position of the samples taken for analysis and mineralogical study. Low silica content and high calcium content characterize rodingites; this composition places the rodingites in a rather unusual chemical group as they also contain an unusual amount of water. The Morro Creek specimen is chemically distinct because it consists predominantly of chlorite. The presence of chlorite in nos. 2, 5, and 6 (table 2) also accounts for the higher magnesium content. In general, the silica content of the rodingites approaches that of the serpentinite when metasomatism is at its maximum. The serpentinites associated with the rodingites commonly show increases in both calcium and aluminum, indicating that these elements move out into the serpentinite during metasomatism. The chlorite and nephrite rims represent the complete reaction of serpentinite in the zone of alteration. In some places, however, postmetasomatic tectonic movement of rodingites has put them in contact with serpen-

TABLE 2.—Chemical and spectrographic analyses of rodingites and associated serpentinites

[Rapid rock analysis performed by methods similar to those described by Shapiro and Brannock (1956); analysts: Paul L. D. Elmore, S. D. Botts, Gillison Chloe. Quantitative spectrographic analysis by Robert Mays. Chlorine analysis by Joseph Budinsky and Irving May]

	1		2		3		4		5		6		7		8	
	7-RD-60-A Rodingite	7-RD-60-B Serpentine	18-RD-60 Rodingite	18-RD-60 Serpentine	24-RD-60-C Rodingite	24-RD-60-D Serpentine	38-RD-60-5 Rodingite	38-RD-60-A Serpentine	7-RD-61-1 Rodingite	7-RD-61-3 Serpentine	8-RD-61 Rodingite	8-RD-61-3 Serpentine	51-RD-61-B Rodingite	51-RD-61-B Serpentine	52-RD-61-A Rodingite	52-RD-61-B Serpentine
Chemical analyses (weight percent)																
SiO ₂	40.2	40.5	47.3	39.0	43.2	40.6	55.6	41.4	30.8	41.1	34.6	40.2	39.8	42.9	44.0	34.4
Al ₂ O ₃	10.5	1.6	3.7	5.4	8.6	1.8	9.8	1.5	18.5	1.1	15.5	8.9	20.8	7.5	27.5	3.30
Fe ₂ O ₃ ¹	12.2	6.8	6.4	5.5	11.8	6.6	2.0	6.7	13.4	6.5	8.6	7.4	3.9	11.2	.69	7.4
MgO.....	3.1	37.0	13.9	37.2	5.7	36.6	.78	36.8	14.4	38.1	22.7	37.3	5.8	23.5	1.0	41.1
CaO.....	32.7	1.1	26.8	.05	27.9	1.9	20.5	.21	13.2	.17	5.7	.23	25.7	7.3	13.8	.33
Na ₂ O.....	.07	.04	.07	.04	.21	.03	6.2	.05	.03	.12	.05	.14	.34	6.3	.08	.08
Cr ₂ O ₃.....	.01	.01	.01	.01	.03	.02	2.6	.02	.01	.01	.01	.22	.03	.18	.04	.04
H ₂ O+.....	.76	12.1	1.5	12.3	1.5	12.0	2.7	12.6	7.8	11.7	10.5	12.7	2.8	6.2	4.2	13.2
H ₂ O.....	.10	.88	.11	.87	.15	.83	.31	.92	.35	.79	.93	.84	.22	.43	.43	1.4
TiO ₂.....	.56	.03	.72	.03	.63	.03	.13	.02	.79	.03	.58	.02	.17	.31	.03	.02
MnO.....	.15	.12	.15	.11	.22	.09	.06	.08	1.2	.11	.23	.08	.14	.14	.02	.12
Total.....	100.35	100.18	100.66	100.51	99.94	100.50	100.68	100.30	100.50	99.66	99.47	99.72	99.69	99.85	98.15	98.39
Specific Gravity.....	3.59	2.70	3.29	2.83	3.44	2.75	2.81	2.87	3.07	2.70	2.81	2.76	3.25	2.98	2.78	2.62

Spectrographic analyses, minor elements (parts per million)

Co.....	19	90	33	80	30	90	6	100	40	70	34	75	17	90	<4	90
Ni.....	25	2000	140	2400	26	2000	29	2400	36	2200	46	2000	80	1000	16	2000
Cr.....	4	2000	200	2000	20	2200	32	4200	26	2800	20	2200	75	1800	20	3200
Sc.....	40	9	50	10	50	9	<4	75	10	44	8	14	20	<4	<4	
Zr.....	20	<10	90	<10	40	<10	80	<10	40	50	<10	<10	<10	<10	<10	
Sr.....	12	<4	<4	<4	120	<4	100	20	26	<4	50	<4	120	45	420	
Ba.....	<4	<4	<4	<4	<4	<4	1100	8	<4	90	4	130	10	190	4	
B.....	<20	50	<20	<20	<20	<20	30	<20	30	150	280	70	70	40	<20	
Cl.....	40	150	30	30	20	80	70	330	40	170	130	560	90	90	830	1500

¹ Total Fe given as Fe₂O₃.

1. Eureka mine Road, Ore.
2. Chetco Pass Road, Ore.
3. Illinois River bed, Ore.

4. Myers Creek, Ore.
5. Salmon Creek, Calif.
6. Morro Creek, Calif.
7. Sultan Basin, Wash.
8. Cypress Island, Wash.

tinite that shows no alteration. Rodingites have distinctly higher specific gravity than serpentinite or the protolith from which they are derived. A more complete discussion of the chemical and spectrographic analyses is given in the section on chemical petrology.

PROGRESSIVE METASOMATISM IN REACTION ZONES

To demonstrate that the metasomatism in the reaction zones was progressive and affected rocks other than basalts and gabbros, a series of samples were taken from reaction zones adjacent to the serpentinite contact out to apparently unaltered rock. Most of these samples are inclusions or dikes within serpentinites, but one represents the contact of serpentinite against country rock (Cape San Martin). These samples are isolated examples and cannot be, as yet, related to a comprehensive theory regarding reaction zones and history of alpine serpentinites. Nonetheless, the reaction zones are widespread and should offer some clues to the serpentinite problem.

MYRTLE CREEK, OREG. (loc. 9, fig. 1)

A large tabular mass of dacite within sheared serpentinite is exposed in a roadcut along U.S. Highway 101, 1 mile north of Myrtle Creek on the south bank of the Umpqua River. The serpentinite is an elongate mass that strikes northeast and appears to be in fault contact to the east with the Dothan Formation of Jurassic age. Diller (1898) considered the dacite to be intrusive into the Dothan but assigned no definite age to the dacite. A careful study of his map indicates that nearly all the dacite within the serpentinite of the Roseburg area can be interpreted as tectonic inclusions, whereas the other dacites are shown as intruding the Dothan Formation.

The altered porphyritic dacite mass at Myrtle Creek is tabular and is approximately 116 feet thick. The fact that this body is truncated by the serpentinite at the top and is associated with numerous smaller inclusions of the same rock type completely surrounded by serpentinite indicates that the dacite is a large transported inclusion, even though it may have originally been a dike that intruded the ultramafic rock.

The contact between the serpentinite and altered dacite is sharply delineated by a reaction zone of dense white rock which is about 3 feet thick on both borders (fig. 3). The outer 6 inches of the altered zone is a highly altered serpentinite whose original texture is retained but that now consists predominantly of diopside and calcite and minor amounts of serpentine and chromite (table 3, Nos. 6, 7). This altered serpentinite is sheared against the unaltered serpentinite (table 3, No. 8), indicating some postmetasomatic tectonic movement. A white

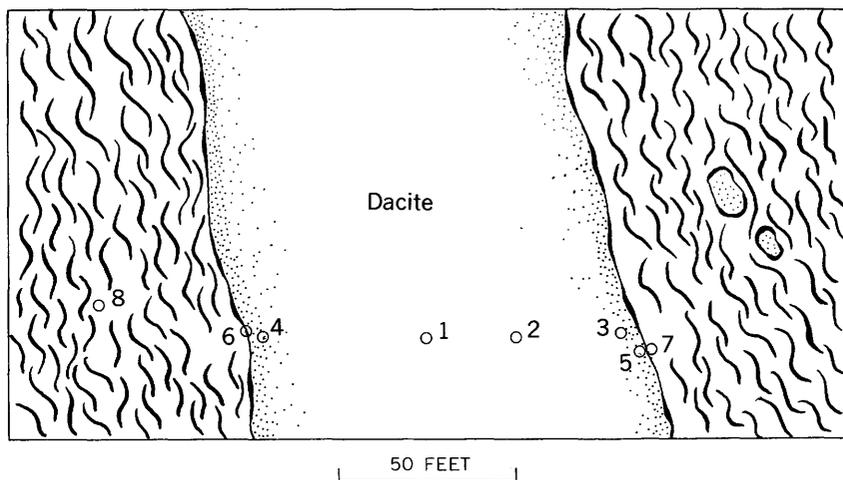


FIGURE 3.—Field sketch (vertical section) of locality at Myrtle Creek, Oreg., showing sampling locations and relationships between dacite and serpentinite. Explanation is the same as shown in figure 2. Numbers are those shown for samples in figure 4 and table 3.

dense rock with only faint porphyritic texture makes up the conspicuous metasomatic zone in the dacite (table 3, Nos. 4, 5). A specimen from the hanging-wall side (No. 5) is a fine-grained cataclastic mixture of hydrogarnet, xonotlite, calcite, and prehnite that is cut by 1 inch monomineralic veins of xonotlite, prehnite, and pectolite. Chemical and optical analyses of the pectolite were given earlier by Coleman (1961).

On the footwall side, alteration is less intense, and the altered dacite, consisting of albite, prehnite, amphibole, and calcite, retains its original porphyritic texture. Late 0.5-inch-thick prehnite veins are present in this zone. The texture of the rock is definitely porphyritic away from both altered zones, and a series of samples (table 3, Nos. 1, 2, 3) were taken to determine the nature of the alteration. In texture, Nos. 1 and 2 clearly represent partially altered dacite that consists of albite, chlorite, muscovite, quartz, hornblende, and calcite; in addition, No. 2 contains epidote and sphene. Original feldspar has altered to albite, muscovite, and calcite, and only minor amounts of igneous hornblende remain. The whole rock has undergone a low-grade metamorphism which may be part of the reaction zones seen at the borders or may be an earlier change. Intermediate to these slightly altered rocks of the dacite interior is sample 3, in table 3; this rock contains no quartz, and part of the groundmass feldspar is replaced and transected by small monomineralic veins of prehnite. The serial change within the inclu-

TABLE 3.—*Chemical and spectrographic analyses of samples from Myrtle Creek area, Oregon (loc. 9)*

[0, tested for but not found; -----, not tested for. Rapid rock analyses performed by methods similar to those described by Shapiro and Brannock (1956); analysts: Paul L. D. Elmore, S. D. Botts, Gillison Chloe, L. Artis, J. Glenn, D. Taylor, H. Smith. Quantitative spectrographic analysis by Robert Mays. Chlorine analysis by Joseph Budinsky and Irving May]

	Dacite		Metasomatites			Altered serpentinites		Serpentinite
	1 32-RD-61-3	2 32-RD-61-4	3 32-RD-61-5	4 32-RD-61-2	5 32-RD-61-6	6 32-RD-61-1	7 32-RD-61-7	8
Chemical analyses (weight percent)								
SiO ₂	62.5	67.2	56.1	53.7	39.4	41.0	41.3	39.7
Al ₂ O ₃	17.6	16.9	14.9	14.6	12.1	2.3	7.8	1.9
Fe ₂ O ₃.....	.77	.80	.39	.28	.88	1.6	.80	17.4
FeO.....	3.3	1.8	2.1	3.2	1.2	2.5	2.0	
MgO.....	1.6	.90	1.3	4.4	1.4	19.9	8.6	36.7
CaO.....	3.7	3.2	12.7	14.1	38.4	20.9	31.5	.05
N ₂ O.....	4.5	4.7	7.5	5.0	.11	0	0	.01
K ₂ O.....	1.2	1.4	.27	.07	0	0	0	12.5
H ₂ O+.....	2.2	1.3	2.3	2.1	3.3	4.6	3.2	1.1
H ₂ O.....	.21	.30	.24	.29	.45	.32	.28	.04
TiO ₂.....	.51	.31	.32	.41	.25	.02	.16	.02
P ₂ O ₅.....	.14	.09	.07	.14	.06	0	.02	-----
MnO.....	.16	.13	.17	.13	.18	.13	.15	.14
CO ₂	1.4	1.0	1.5	1.5	2.2	6.6	4.2	-----
Total.....	99.79	100.03	99.86	99.92	99.93	99.87	100.01	99.80
Specific gravity.....	2.72	2.73	2.77	2.87	3.01	3.00	3.06	2.72
Spectrographic analyses, minor elements (parts per million)								
Co.....	7	<4	<4	8	<4	28	34	100
Ni.....	<4	<4	<4	35	<4	1,500	1,600	2,000
Cr.....	6	6	6	32	10	1,100	1,400	2,800
Sc.....	4	<4	<4	10	<4	<4	4	11
Zr.....	140	140	90	110	90	<10	<10	<10
Sr.....	400	400	140	600	75	80	60	<4
Ba.....	800	650	90	380	<4	10	8	<4
B.....	<20	40	2,000	310	160	<20	210	180
Cl.....	40	50	40	50	40	50	30	40

¹Total iron as Fe₂O₃.

- Slightly altered dacite 50 ft from contact; consists of albite, chlorite, muscovite, quartz, hornblende, and calcite.
- Slightly altered dacite 41 ft from contact; consists of albite, quartz, chlorite, muscovite, hornblende, epidote, sphene, and calcite.
- Metasomatically altered dacite 6 in. from contact; consists of albite, prehnite, chlorite, muscovite, epidote, sphene.
- Calcium metasomatite near contact; consists of albite, prehnite, amphibole, calcite.
- Calcium metasomatite from contact; consists of hydrogarnet, xonotlite, calcite, prehnite.
- Altered serpentinite from contact; consists of diopside, serpentine, calcite, chromite.
- Altered serpentinite from contact; consists of diopside, serpentine, calcite.
- Serpentinite (unaltered) approximately 35 ft from altered dacite; consists of antigoritelike material, clinochrysoilite, magnetite.

sion demonstrates a progressive metasomatism. None of the described metasomatic minerals or textures of the dacite can be related to the igneous processes.

Chemical analyses of the alteration sequence, when plotted to show variation in the elements as related to the reaction zone, reveal systematic changes in bulk composition (table 3; figs. 3, 4). Samples 1 and 2 are assumed to represent the original bulk composition of the dacite;

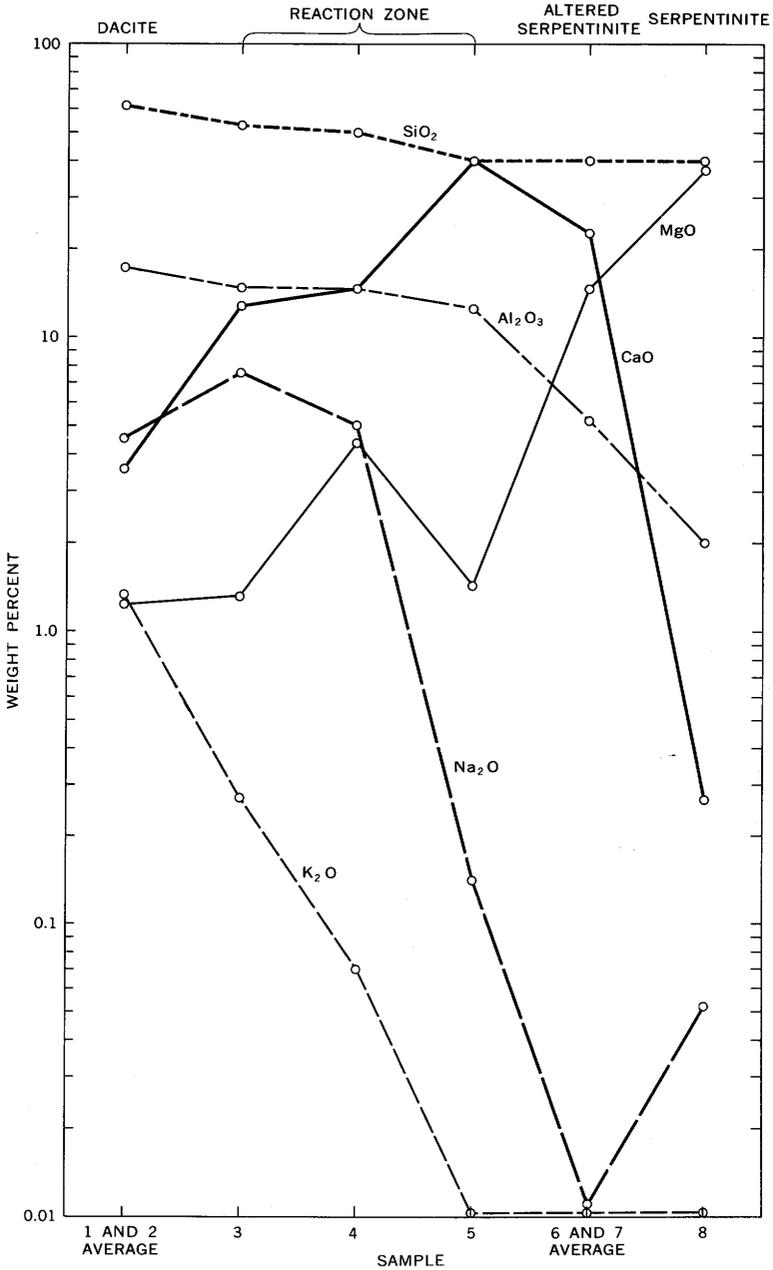


FIGURE 4.—Semilogarithmic plot of progressive chemical variation of samples from the Myrtle Creek area, Oregon. Sample numbers are those given in table 3 and figure 3. The abscissa does not represent horizontal distance between samples. Points are placed equidistant to exhibit chemical variations.

samples 3-5, progressively metasomatized dacite; sample 8, the original bulk composition of the serpentinite; and samples 6 and 7, metasomatized serpentinite. Calcium enrichment of calcium in the altered dacite and serpentinite indicates that this element was a mobile component during alteration and was fixed in the reaction zone. The magnesium is erratic and may have migrated from the serpentinite toward the reaction zone in the dacite. The alkalis, as plotted, indicate considerable mobility during metasomatism; potassium is progressively depleted, and sodium appears to concentrate in the reaction zone away from the serpentinite contact. The altered serpentinite is enriched in aluminium and the altered dacite depleted. Desilication of the altered dacite is obvious; however, there is some silica enrichment in the altered serpentinite. The increase in specific gravity and water content of sample 5, compared with the original dacite of 1 and 2 signifies high-water pressures during metamorphism.

BALDY MOUNTAIN, OREG. (loc. 10, fig. 1)

The hornblende gabbro from Baldy Mountain (SW $\frac{1}{4}$ NE $\frac{1}{4}$ sec. 31, T. 14 S., R. 33 E., John Day, Oreg., 15-minute quadrangle) is part of the Canyon Mountain ultramafic complex in eastern Oregon (Thayer, 1963). The hornblende gabbro dike intrudes and contains inclusions of partly serpentinitized pyroxene-rich peridotite. The dike is metasomatized and shows a marked asymmetric alteration, more intense on the footwall (fig. 5). This same peridotite generally forms a somewhat tabular zone between much larger areas of olivine-rich peridotite and gabbro-norite which Thayer (1963) considers to be Triassic in age.

The enclosing peridotite (table 4, No. 5) is only partially serpentinitized (10-15 percent by volume) and contains inclusions of plastically deformed mafic gabbro that is not related to the hornblende gabbro dike (table 4, No. 4). The peridotite consists of approximately 25 percent fresh and altered olivine and 75 percent pyroxene with the serpentinitized areas generally confined to the olivine grains. Minor amounts of amphibole were detected by X-ray diffraction of the whole rock but were not seen in a thin section.

The interior of the gabbro dike (table 4, No. 1; fig. 5, No. 1) consists of greenish-brown hornblende and calcic plagioclase (An₅₀), having a hypidiomorphic texture, and a minor amount of pyroxene. Magnetite is the dominant accessory mineral. Incipient replacement of the plagioclase by prehnite is the only indication of alteration. A sample near the footwall contact (fig. 5, No. 2) is altered (table 4, No. 2) and consists of hydrogarnet, prehnite, diopside, and minor amounts of sphene, chlorite, and primary amphibole. The original texture is retained but plagioclase is completely replaced by hydrogarnet and

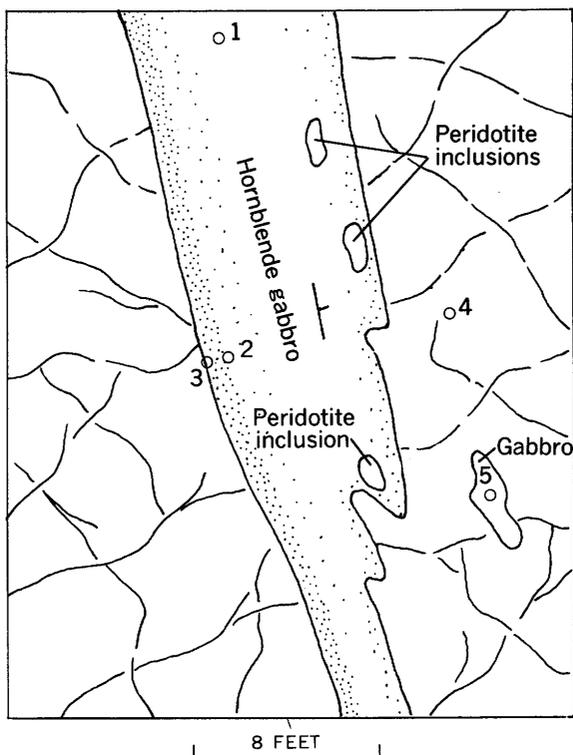


FIGURE 5.—Field sketch (horizontal section) of locality at Baldy Mountain, Oreg., showing locations of analyzed specimens and general relationships of specimens (table 4). Explanation is the same as shown in figure 2.

prehnite; the amphibole is replaced by diopside. Numerous monomineralic veins and patches of prehnite cut the gabbro. At the contact on the footwall side of the dike (fig. 5, No. 3), the hornblende gabbro has been metasomatized to a dense white fine-grained rock (table 4, No. 3) similar in appearance to the rodingites described earlier. Original igneous minerals of the hornblende gabbro have been completely replaced by hydrogarnet, diopside, prehnite, and chlorite, leaving only a faint trace of the preexisting textures. This petrographic evidence reveals a progressive metasomatism of the dike from the footwall side toward the center. This same alteration, but less intense, is developed on the hanging wall side of the dike. Replacement features and vein patterns indicate that the alteration followed the igneous emplacement, and there is no textural evidence relating metasomatism to the igneous event. From textural evidence, the source of the altering solutions appears to have been the peridotite, and the solutions probably

TABLE 4.—*Chemical and spectrographic analyses of samples from Baldy Mountain area, Oregon (loc. 10)*

[Rapid rock analysis performed by methods similar to those described by Shapiro and Brannock (1956); analysis: Paul L. D. Elmore, S. D. Botts, Gillison Chloe. Quantitative spectrographic analysis by Robert Mays. Chlorine analysis by Joseph Budinsky and Irving May]

	Altered gabbro 41-RD-61-C	Metasomatites		Peridotite 4- RD-61-E	Altered mafic gabbro 41- RD-61-D
	1	41-RD-61-B	41-RD-61-A	4	5
Chemical analyses (weight percent)					
SiO ₂ -----	47.8	39.4	43.6	48.5	40.8
Al ₂ O ₃ -----	14.5	15.4	10.8	2.9	16.3
Fe ₂ O ₃ ¹ -----	11.8	12.0	9.7	6.8	7.4
MgO-----	6.3	8.2	5.6	21.5	11.8
CaO-----	13.0	18.1	26.5	15.9	17.9
Na ₂ O-----	2.4	.30	.12	.13	.12
K ₂ O-----	.16	.03	.01	.02	.03
H ₂ O+-----	2.1	4.4	1.9	3.3	5.3
H ₂ O-----	.18	.25	.48	.36	.32
TiO ₂ -----	1.5	1.7	1.2	.14	.24
MnO-----	.20	.20	.16	.13	.15
Total-----	99.94	99.98	100.07	99.68	100.36
Specific Gravity-----	3.04	3.14	3.34	3.12	3.05
Spectrographic analyses, minor elements (parts per million)					
Co-----	37	44	30	36	40
Ni-----	70	85	70	240	90
Cr-----	20	16	12	1400	16
Sc-----	60	65	31	55	55
Zr-----	100	120	90	<10	<10
Sr-----	240	4	<4	<4	30
Ba-----	20	7	<4	<4	<4
B-----	180	150	220	180	160
Cl-----	270	110	40	90	10

¹ Total Fe given as Fe₂O₃.

- Slightly altered gabbro from the central portion of the dike; consists of hornblende, plagioclase, prehnite, magnetite.
 - Partially altered gabbro from the contact; consists of hydrogarnet, prehnite, diopside, amphibole, sphene, chlorite, plus primary amphibole.
 - Completely altered gabbro at the contact; consists of hydrogarnet, diopside, prehnite, chlorite.
 - Peridotite country rock enclosing gabbro; consists of clinopyroxene, olivine, orthopyroxene, serpentine. Sample taken about 3 ft from gabbro dike.
 - Small inclusion of altered mafic gabbro in peridotite; consists of prehnite, chlorite, pyroxene, idocrase, hydrogarnet.
- Spatial relationships of the samples are shown in figure 5.

were related to the incipient serpentinization. Increases in water content and density toward the altered zone suggest a high activity of water combined with fairly substantial total pressures.

A plot of the serial chemical changes illustrates the probable movements of certain major components (fig. 6). The alkalis are noticeably

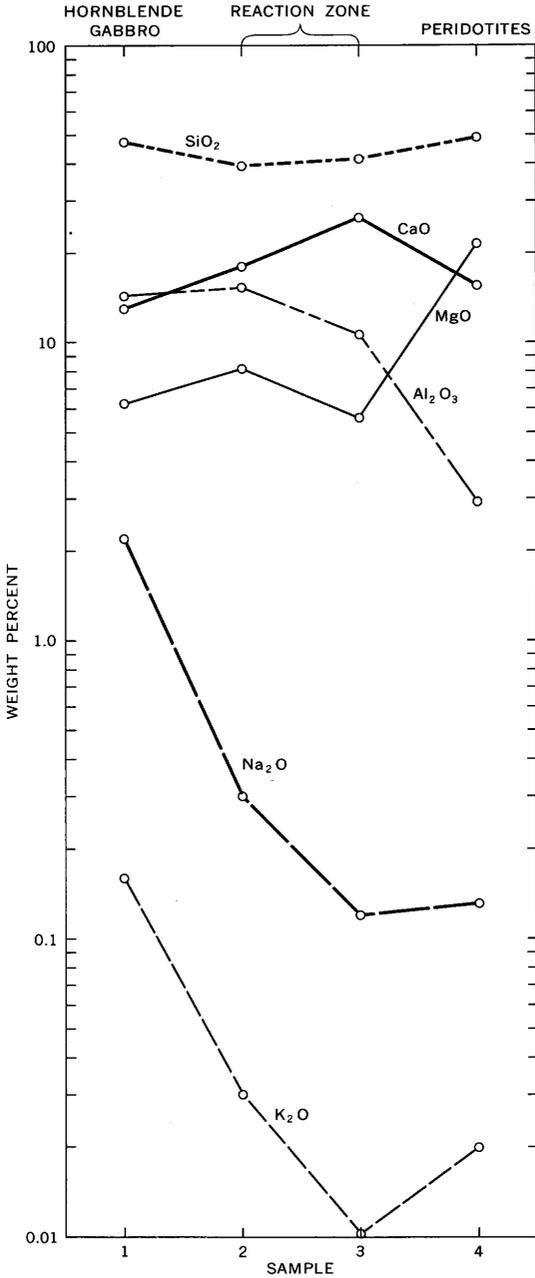


FIGURE 6.—Semilogarithmic plot of the progressive chemical variation of samples from the Baldy Mountain area, Oregon. Sample numbers are those given in table 4. The abscissa does not represent horizontal distance between samples. The points are placed equidistant to exhibit chemical variation.

depleted relative to the slightly altered hornblende gabbro (No. 1) in the most intensely altered zone, and they show more than a tenfold difference between the altered contact and the center of the dike. The lack of newly formed alkali-bearing minerals within the dike or peridotite leaves open the question of the direction of movement for the alkalis. Alumina is also depleted in the reaction zone (No. 3) and may follow the alkalis, but the abundance of new calcium-aluminum silicate indicates that alumina is partly fixed in the metasomatic zone. The enriched calcium in the altered zone is interpreted as being derived from the serpentized peridotite. Silica shows only moderate depletion during alteration and magnesium is erratic.

INGALLS PEAK, WASH. (loc. 11)

Smith (1904) described a large arcuate ultramafic mass surrounding Mount Stuart in the central part of the Cascade Mountains in Washington. Although the ultramafic intrusion is of uncertain age, it appears to invade upper Paleozoic metamorphic rocks, and a basal conglomerate consisting of ultramafic debris is present in the Swauk Formation of Late Cretaceous and Paleocene age resting unconformably on the ultramafics. Large areas of the ultramafic intrusion are partially serpentized and contain porphyritic granodiorite dikes in the vicinity of Ingalls Peak. Some of these dikes, particularly in the highly serpentized areas, have well-developed reaction zones at their contacts.

One of these dikes (fig. 7) was sampled to determine the nature of the alteration. This particular dike is approximately 5 feet in width and nearly vertical, forming a prominent exposure along a ridge crest. The contact between the dike and serpentinite is fairly sharp but is sheared. The partially altered granodiorite (table 5, No. 2) from the center of the dike has retained its porphyritic igneous texture. The feldspar is albite, and in some areas it is partially replaced by hydrogarnet and analcite. Secondary zoisite forms irregular patches throughout the rock. The small amount of pale-green amphibole present may be a primary igneous ferromagnesian mineral. For comparison of bulk composition, an analysis from Smith (1904) of an unaltered dike from this area is given (table 5, No. 1). At the contact of the altered dike, an intense reaction zone approximately 6 inches wide has developed (table 5, No. 3). The intensely altered rock has retained none of its original igneous textures and consists of a new mineral assemblage: hydrogarnet, albite, and analcite and minor amounts of prehnite, diopside, and tremolite.

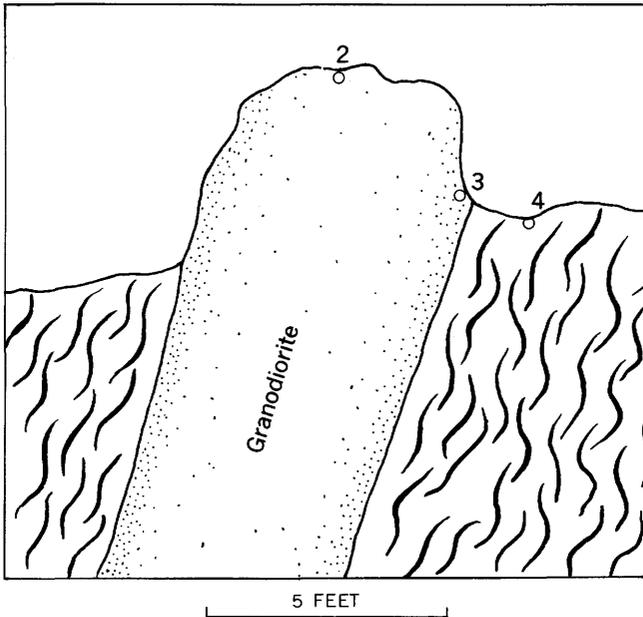


FIGURE 7.—Field sketch (vertical section) of locality at Ingalls Peak, Wash., showing locations of analyzed specimens and general relationships of dike and serpentinite. Explanation is the same as shown in figure 2. Numbers are the same as those given in figure 8 and table 5.

A plot of selected elements from the bulk analyses of the Ingalls Peak material illustrates a similarity to the trends recorded for the same elements in the Myrtle Creek and Baldy Mountain, Oreg., reaction zones (fig. 8, table 5). Calcium enrichment in the reaction zone of the granodiorite has resulted in a mineral assemblage dominated by calc-silicates. The concentration of silica, as well as that of potassium, decreases toward the serpentinite. The concentration of sodium increases toward the center of the dike but becomes depleted toward the contact. The aluminum remains nearly constant from the center of the dike to the reaction zone, but magnesium shows a slight depletion in the reaction zone. Although the reaction zone does not have consistently higher water content than the granodiorite, its specific gravity is higher than that of the granodiorite or the serpentinite.

TWIN SISTERS, WASH. (loc. 12, fig. 1)

The Twin Sisters ultramafic mass has only a narrow rim of serpentinite surrounding its nearly unaltered dunitic core (Ragan, 1963). Nonetheless, along the southern boundary, where the Nooksack River

TABLE 5.—*Chemical and spectrographic analyses of samples from Ingalls Peak and Twin Sisters area, Washington (loc. 11, 12)*

[Rapid rock analysis performed by methods similar to those described by Shapiro and Brannock (1956); analysts: Paul L. D. Elmore, S. D. Botts, Gillison Chloe. Quantitative spectrographic analysis by Robert Mays. Chlorine analysis by Joseph Budinsky and Irving May]

	INGALLS PEAK				TWIN SISTERS		
	Granodiorite 1	Altered granodiorite 48-RD-61-A 2	Reaction zone 48-RD-61-B 3	Serpentinite 48-RD-61-C 4	Altered gabbro 53-RD-61-D 1	Reaction zone 53-RD-61-D 2	Serpentinite 53-RD-61-F 3
Chemical analyses (weight percent)							
SiO ₂	63.78	57.6	48.8	40.9	49.6	38.6	38.6
Al ₂ O ₃	16.39	18.0	17.8	2.8	15.9	14.3	1.1
Fe ₂ O ₃ ¹	4.19	4.8	3.2	7.4	9.6	9.1	9.6
MgO.....	3.27	3.3	2.0	37.8	6.3	5.4	34.9
CaO.....	4.07	4.4	22.5	2.1	11.2	28.8	3.6
Na ₂ O.....	3.84	8.8	3.2	.08	4.3	.09	.04
K ₂ O.....	2.03	2.3	.04	.01	.31	.01	.02
H ₂ O+.....	1.82	2.3	1.6	8.0	.27	2.8	11.4
H ₂ O.....	.22	.21	.25	.40	.15	.12	1.0
TiO ₂.....	.44	.51	.35	.07	.64	.60	.05
MnO.....	.05	.07	.05	.14	.16	.13	.16
Total.....	100.10	100.32	99.79	99.70	98.43	99.95	100.11
Specific Gravity.....		2.70	3.13	2.86	3.06	3.42	2.73
Spectrographic analyses, minor elements (parts per million)							
Co.....		12	8	85	26	28	110
Ni.....		34	18	2000	60	50	800
Cr.....		34	12	3800	140	120	1000
Sc.....		18	12	13	44	48	17
Zr.....		110	70	<10	50	60	<10
Sr.....		500	120	<4	500	65	4
Ba.....		2400	65	<4	1400	<4	<4
B.....		30	200	130	140	130	90
Cl.....		100	50	130	200	70	460

¹Total Fe given as Fe₂O₃.

INGALLS PEAK

1. Unaltered porphyritic-granodiorite west of Mount Stuart area near Ingalls Peak, Smith (1904). Analyst: H. N. Stokes. Other elements given were P₂O₅ 0.11, SrO trace, BaO 0.08, LiO trace, S trace, Fe₂O₃ 1.12, FeO 2.76.
2. Partially altered porphyritic-granodiorite from center of dike; consists of albite, amphibole, zoisite, hydrogarnet, analcite.
3. Completely altered porphyritic-granodiorite from altered edge of dike; consists of hydrogarnet, albite, analcite, prehnite, diopside, tremolite.
4. Serpentinite 1½ ft from dike; consists of serpentine, brucite, olivine, orthopyroxene.

TWIN SISTERS

1. Partially altered gabbro from center of inclusion; consists of hornblende and blue-green actinolite, hydrogarnet, zoisite, albite, calcic plagioclase.
2. Completely altered gabbro from rim of inclusion; consists of hydrogarnet, pyroxene, idocrase, prehnite.
3. Serpentinite 5 ft from inclusion; consists of lizardite, clinochrysolite, brucite, pyroxene, magnetite.

has exposed the enclosing serpentinite, numerous metasomatized tectonic inclusions are present within the serpentinite and as house-size boulders in the river where it cuts the ultramafic mass. Ragan (1963) refers to these inclusions as "exotic" blocks and suggests that they may be related basement rocks of pre-Carboniferous age. An altered mafic inclusion in place was selected for study; its diameter is approximately 8 feet (fig. 9). A sample from the center of the mass (table 5,

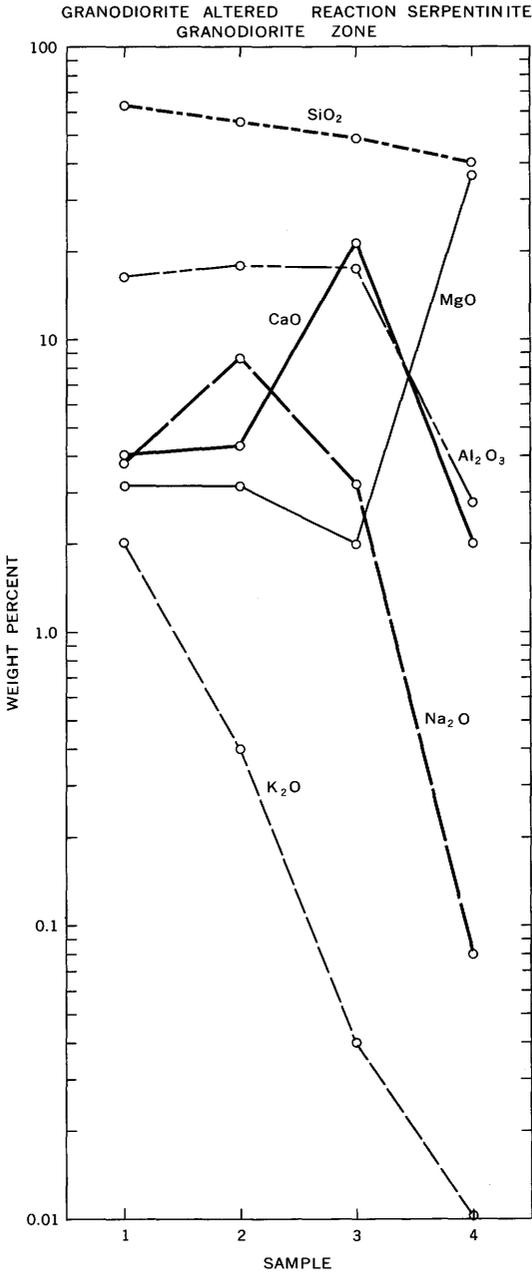


FIGURE 8.—Semilogarithmic plot of the progressive chemical variation of samples from the Ingalls Peak area, Washington. Sample numbers are those given in table 5 and figure 7. The abscissa does not represent horizontal distance between samples. Points are placed equidistant to exhibit variations.

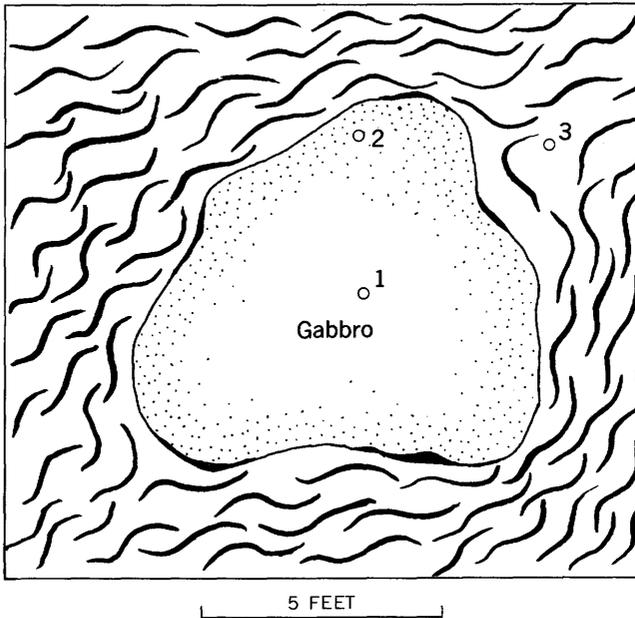


FIGURE 9.—Field sketch (horizontal section) of locality at Twin Sisters, Wash., showing locations of analyzed specimens and general relationships between altered gabbro and serpentinite. Explanation is the same as shown in figure 2. Numbers are those used in table 5 and figure 10.

No. 1) has a faintly recognizable gabbroic texture, but clear evidence of replacement is everywhere present in the mass. Original brown hornblende is retained, but its edges are being replaced by a feathery bluish-green actinolite. Original calcic plagioclase is being replaced by albite, and the albite and relict calcic plagioclase areas, in turn, are invaded by hydrogarnet and zoisite. A peripheral white dense zone (table 5, no. 2) approximately 6–8 inches thick surrounds the mafic mass. In the reaction zone, nearly all the original igneous textures have been obscured by intense alteration. Hydrogarnet, diopside, idocrase, and prehnite are the predominant minerals. This serial alteration can be seen in the inclusion by the change in color from a dark gabbro in the center to the nearly white gabbro at the outer boundary. The serpentinite contact is sharp and consists of highly sheared material. The serpentinite consists of lizardite and clinochrysolite and minor amounts of brucite. Original relict primary pyroxene is still present, but the olivine is completely serpentinized.

A semilogarithmic plot (fig. 10) shows that chemical changes in this sequence are nearly the same as those previously discussed. Smaller amounts of alkalis are in the outer zone than in the less altered core,

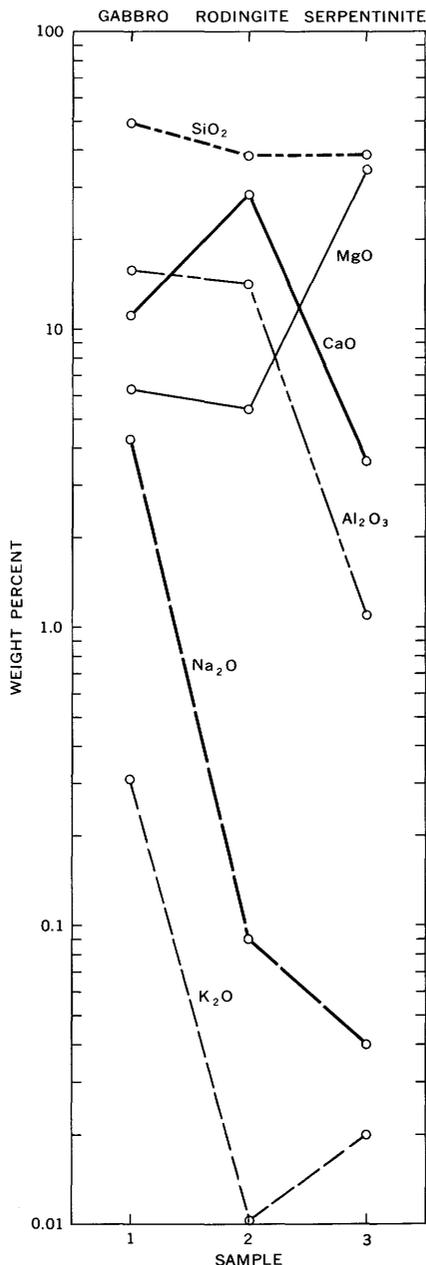


FIGURE 10.—Semilogarithmic plot of the progressive chemical variation of samples from the Twin Sisters area, Washington. Sample numbers are those given in table 5 and figure 9. The abscissa does not represent horizontal distance between samples; points are placed equidistant to exhibit chemical variations.

whereas in the central part, where some sodium enrichment may have taken place, albite is replacing the original calcic plagioclase. The reaction zone is strongly enriched in calcium; both magnesium and aluminum remain nearly the same, except for the abrupt change in the serpentinite. Silica shows a decrease of 11 weight percent from the center to the edge of altered gabbro. Again, the reaction zone contains more water than the parent gabbro and, yet, has a higher specific gravity than the rocks on either side.

CAPE SAN MARTIN, CALIF. (loc. 13, fig. 1)

A serpentinite body within a shear zone has reaction zones with numerous rock types in contact with and as inclusions within it. The well-known semiprecious nephrite jade found along the beaches of this area has been formed along these same serpentinite contacts (Crippin, 1951). Where California Highway 1 cuts through a small ridge near the Cape San Martin beacon, a large mass of Franciscan graywacke is contained within the serpentinite. At the contact, a 2-foot-thick dense fine-grained reaction zone formed within the graywacke (fig. 11). This type of alteration is nearly identical with that described

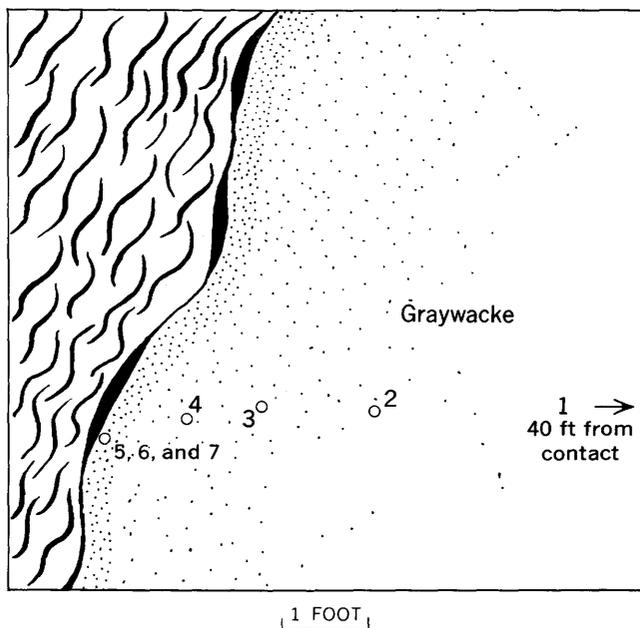


FIGURE 11.—Field sketch (vertical section) of locality at Cape San Martin, Calif., showing locations of analyzed specimens and general relationships of the graywacke and serpentinite. Explanation is the same as shown in figure 2. Numbers are the same as those shown in figure 12 and table 6.

by Chesterman (1960) at Leech Lake Mountain, Calif. To determine the mineralogical and chemical changes related to this occurrence, a series of samples were taken from the contact 40 feet out into nearly unaltered graywacke (table 6, Nos. 1-7).

TABLE 6.—*Partial chemical and spectrographic analyses of metasomatized graywacke from Cape San Martin, Calif. (loc. 13)*

[0, tested for but not found. Rapid rock analysis performed by methods similar to those described by Shapiro and Brannock (1956); analysts: Paul L. D. Elmore, S. D. Botts, Gillison Chloe, L. Artis, J. Glenn, D. Taylor; quantitative spectrographic analysis by Robert Mays]

	1 3-RD-61-5	2 3-RD-61-4	3 3-RD-61-3	4 3-RD-61-2	5 3-RD-61-1(3)	6 3-RD-61-1(2)	7 3-RD-61-1(1)
Chemical analyses (weight percent)							
SiO ₂ -----	67.3	62.6	59.1	47.3	46.3	46.7	47.7
Al ₂ O ₃ -----	13.9	15.2	14.1	16.8	14.8	13.2	10.8
Fe ₂ O ₃ -----	.89	.85	.74	.31	.25	.67	.58
FeO-----	4.1	4.5	4.6	3.9	4.5	4.3	5.2
MgO-----	2.6	3.0	3.3	3.0	4.7	5.6	11.6
CaO-----	2.4	4.6	7.9	23.1	24.9	25.3	19.4
Na ₂ O-----	4.1	4.6	4.3	.27	.05	.09	.13
K ₂ O-----	1.1	2.8	3.6	.61	.03	.00	.06
H ₂ O+-----	2.1	1.3	1.2	2.9	3.1	2.9	3.2
H ₂ O-----	.15	.11	.16	.20	.22	.14	.18
TiO ₂ -----	.72	.70	.76	.75	.63	.62	.79
P ₂ O ₅ -----	.13	.10	.10	.11	.09	.08	.12
MnO-----	.10	.08	.09	.09	.10	.12	.11
CO ₂ -----	.10	<.05	.05	.11	.28	.30	<.05
Total-----	99.69	99.89	100.00	99.45	99.95	100.02	99.92
Specific gravity--	2.66	2.72	2.78	2.94	3.02	3.03	3.03

Spectrographic analyses, minor elements (parts per million)

Co-----	11	14	12	12	14	11	20
Ni-----	40	30	30	30	20	30	210
Cr-----	180	160	210	310	410	190	440
Zr-----	130	120	150	100	90	90	10
Sr-----	260	480	700	280	330	180	220
Ba-----	220	1300	2300	300	20	<20	20

1. Slightly altered graywacke 40 ft from contact. Veins of potassium feldspar only evidence of metasomatism.
2. Partially altered graywacke ≈ 3 ft from contact. Amphibole, potassium feldspar, and chlorite metasomatic minerals.
3. Metasomatized graywacke 1.5 ft from contact. Prehnite, amphibole, potassium feldspar, chlorite (relict quartz, feldspar, epidote).
4. Metasomatized graywacke 1 ft from contact. Prehnite, diopside, calcite, potassium feldspar, chlorite.
5. Metasomatized graywacke 6 in. from contact. Prehnite, diopside.
6. Metasomatized graywacke 4 in. from contact. Prehnite, diopside, calcite, potassium feldspar.
7. Metasomatized graywacke at contact. Amphibole, diopside, prehnite, pumpellyite.

The nearly unaltered graywacke (table 6, No. 1) shows no evidence of widespread alteration and consists primarily of clastic grains of quartz, albite, and lithic fragments set in a pasty matrix consisting of chlorite and fine-grained detritus. Occasional detrital grains of epidote, apatite and zircon are present. Very small veins (less than one-fourth inch in diameter) consisting of quartz and potassium feldspar are the only indication of alteration; such potassium feldspar veins have not been found in graywackes unrelated to serpentinite contacts. The next sample, taken 3-5 feet from the serpentinite contact (table 6, No. 2) is grayish white and assumes a flinty appearance.

Even though the original clastic texture is clearly retained in this specimen, the thin section reveals finely fibrous actinolite, potassium feldspar, and chlorite replacing parts of the fine-grained groundmass and occurring as veins. Approximately 1.5 feet from the contact (table 6, No. 3) the original characteristics of the graywacke are gone, and at the contact the graywacke is a light-gray flinty rock. Staining of this rock for potassium feldspar by using the technique of Chayes (1952) revealed approximately 30 volume percent.

Thin-section study shows a detrital structure, but much of the rock is replaced by prehnite, potassium feldspar, fibrous amphibole, and minor amounts of chlorite. At 1 foot from the contact (table 6, No. 4) the rock is dense and white and appears to be completely altered; it consists predominantly of prehnite and diopside with only minor amounts of potassium feldspar, chlorite, and carbonate (fig. 12). In thin section, the clastic texture is still faintly visible, but none of the original detrital grains remain. The final sample, taken from right at the contact out to about 6 inches from the contact was sawed into three equal parts (table 6, Nos. 5-7) to determine any small-scale contact variations. These three specimens consist predominantly of prehnite and varying amounts of diopside and actinolite; aragonite and calcite form irregular patches. Pumpellyite is restricted to certain small areas of this contact rock. Generally, the clastic textures are completely eradicated, but occasional patches retain the original texture. Irregular pods and lenses of a fibrous tremolite-actinolite occupy zones between the serpentine and calcium metasomatite; none of these were of gem quality, but their presence at this point clearly suggests that much of the nephrite in this area may have formed in a manner similar to that suggested earlier for certain New Zealand nephrites (Coleman, 1966).

A plot of the chemical changes (fig. 13) shows the same trend as are shown in plots of the alteration of the mafic igneous rocks. The alkalis are definitely concentrated away from the reaction zone. Samples 2 and 3 may indicate the position of a potassium feldspar metasomatic front. The K_2O and Na_2O are undoubtedly derived from the breakdown of the preexisting detrital feldspars and mica, whereas the calcium must be from the ultramafic. The barium very clearly follows the potassium, and preliminary checks indicate that the barium is contained within the secondary potassium feldspar. Aluminum shows only minor variations in the altered graywacke and must not be mobile, whereas the silica gradient may indicate movement towards the ultramafic. The abundance of diopside in the contact rocks and increased magnesium in the reaction zone show that magnesium migrates from the serpentinite into the graywacke. Changes in

water content toward the contact are erratic, but specific gravity shows a remarkably consistent increase.

SUMMARY OF PETROLOGY

The foregoing discussion has detailed the metasomatism of rocks referred to as rodingites and of rocks whose original parentage ranges from graywacke to gabbro. By using chemical and textural evidence, the alteration and metasomatism of these rocks were shown to have occurred within or against serpentinites or partially serpentinitized ultramafics. The alteration appears to have produced a volume-for-volume replacement, and no evidence was found to relate this

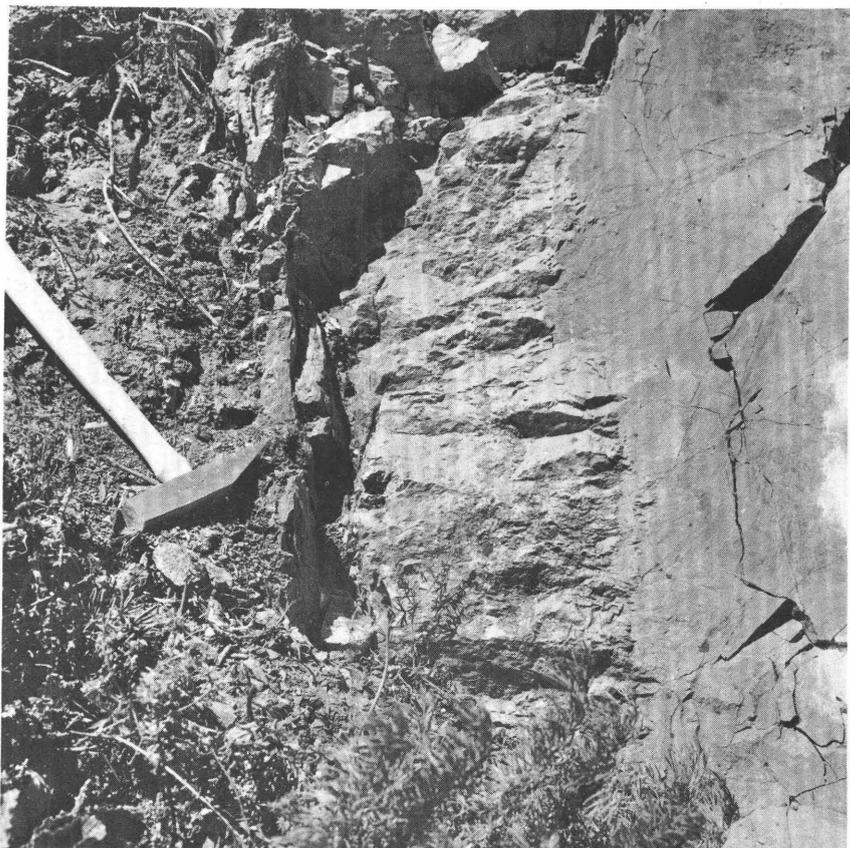


FIGURE 12.—Cape San Martin reaction zone against sheared serpentinite. Hammer is resting on serpentinite with point towards thin nephrite zone. Light-colored and jointed rock to right of hammer is equivalent to Nos. 5-7 in figures 11 and 13, and in table 6. Dense fine-grained rock on right margin of photograph is equivalent to No. 4. Photograph by Robert A. Loney.

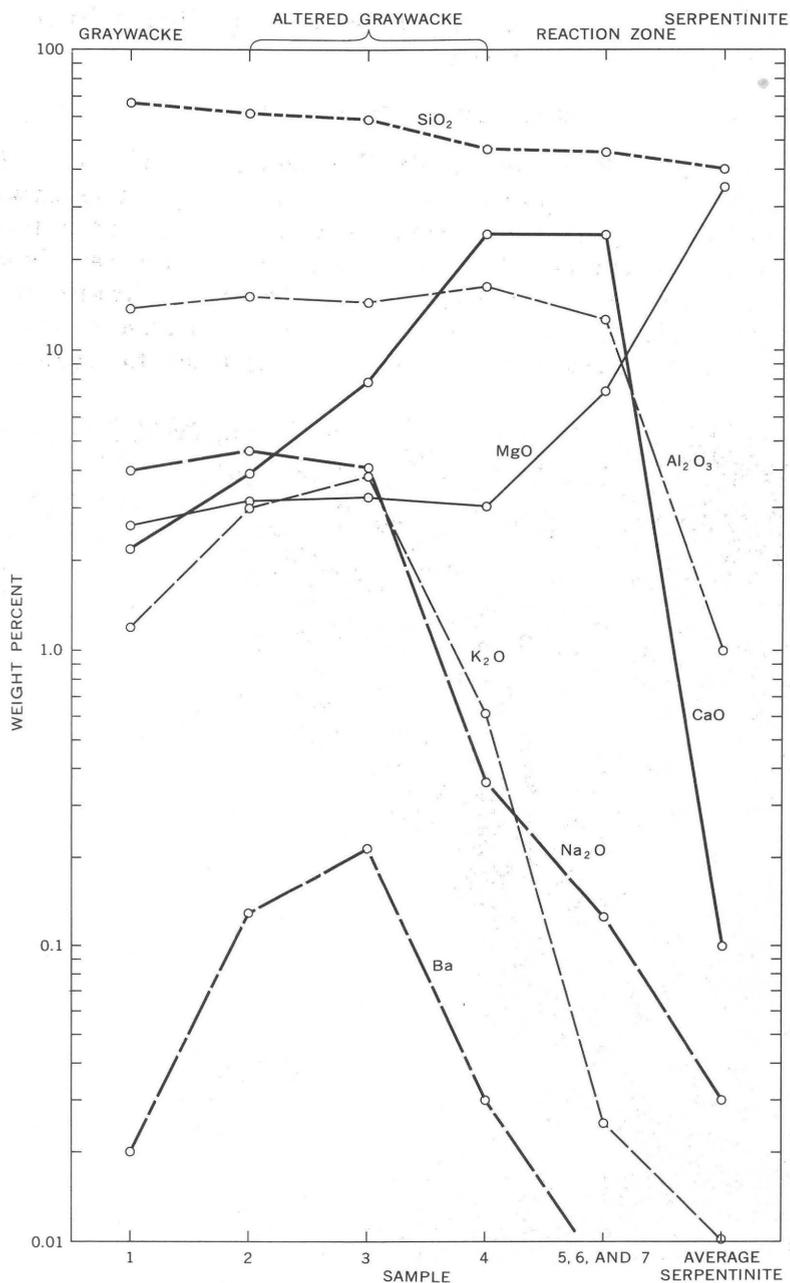


FIGURE 13.—Semilogarithmic plot of the progressive chemical variation of samples from Cape San Martin, Calif. Sample numbers are those given in table 6. The abscissa does not represent horizontal distance between samples; points are placed equidistant to exhibit chemical variations.

alteration to solutions resulting from igneous intrusion of the dike rocks or of the ultramafics. The fact that such metasomatism is always within or adjacent to serpentinitized rocks strongly indicates that the alteration is a result of this proximity rather than being related to some cryptic or obscure igneous body or to the late stages of cooling in the ultramafic bodies themselves.

The bulk chemistry, to be discussed further, reveals that this alteration process is metasomatic and is accomplished by solutions whose compositions are similar. Such solutions have repeatedly produced calcium metasomatism in the country rock of widely divergent ages and produced chlorite, amphibole, or diopside in the adjoining serpentinites.

The mineral assemblages are nearly identical in rocks of similar bulk composition, an indication that such metasomatism must have occurred at analogous pressures and temperatures. The following section will discuss the mineral assemblages and chemical relationships.

PETROGENESIS

As shown in the previous sections, mineralogical determinations and chemical analyses indicate analogous metasomatic alteration within both tectonic inclusions and country rock contacts associated with serpentinite. The highly sheared serpentinites of the Pacific coast often contain rodingites and metasomatized tectonic inclusions and contacts that could have formed only through a very complex history. The presence of cataclastic structures along many of the metasomatized serpentinite contacts indicates that tectonic movement has accompanied or followed the metasomatism. This tectonic movement is considered to be responsible, in part, for allowing the egress of fluids and for replenishing the supply of reactants. Thus the metasomatism is dependent on structure, fluids, and rock composition, a relationship considerably more complex than that at typical igneous contacts. It is not surprising, therefore, to find an erratic distribution of such metasomatism associated with serpentinitization. The tectonic instability of serpentinite bodies further complicates the history, as post-emplacement movements may displace serpentinites upwards in the earth's crust. Because this upward migration takes place under differing pressure and temperature conditions, the serpentinite may leave behind the original contacts, incorporate additional tectonic inclusions, and form additional new metasomatic contacts. Thus, metasomatic rocks formed as a result of several distinct tectonic periods may be closely associated within highly sheared serpentinite.

The metasomatic alteration of basalts, gabbros, and sediments, though involving only small areas of rocks, seems to be a process

characteristic of serpentization. The most common alteration product, rodingite—found mostly as inclusions or dikes within serpentinites—has been described from numerous ultramafic areas in the world, and the chemistry and mineralogy of these rocks are now fairly well known. In contrast to the widespread occurrence of rodingites, metasomatized sediments associated with ultramafics have only rarely been reported, perhaps because they have not been looked for (Lodochnikov, 1933; Chesterman, 1960; Coleman, 1961; and Reed, 1959).

The chemical changes during this metasomatism have a similar trend for all rock types, although the initial rock composition exerts a minor influence on the end product. Rocks initially containing considerable amounts of silica and alkalis, such as the sediments or silicic igneous rocks, may, after metasomatism, contain enriched areas of albite or potassium feldspar away from the reaction zone, in the cores of inclusions or less altered areas of country rock. Metasomatism in the reaction zone of both igneous and sedimentary rocks is characterized by enrichment in calcium and, in some rocks, magnesium, and by apparent movement of the alkalis away from the contact. Furthermore, the original unaltered rock always loses silica. The important point is that desilication and calcium metasomatism are universal in these altered rocks.

Intense metasomatism in rocks next to the serpentinites produces a zone of hydrated calcium-aluminum silicate that has various amounts of magnesium. In the serpentinite, this same metasomatism produces calcium-magnesium hydrates with various amounts of aluminum.

The rodingites analyzed in this paper and the minerals commonly found are plotted on an ACF diagram (fig. 14A). For comparison, a collection of rodingites and associated minerals from other parts of the world is plotted on a similar diagram (fig. 14B). These two diagrams closely overlap, and even though three-phase tielines are not drawn, most of the rocks can be enclosed within triangles by using diopside and chlorite as two phases and either zoisite, prehnite, grossular, or idocrase as the third phase, depending on the total calcium content. It must be emphasized that equilibrium is rarely attained in any of these rocks, and as metasomatism increases, their composition changes in the manner illustrated in figure 15. The mafic rocks describe fairly straight descent toward the calcium corner of the diagram (fig. 15A). The more siliceous rocks demonstrate a looping line of descent towards the calcium corner of the diagram (fig. 15B). The lower loop of the curve reflects the formation of alkali feldspars in the intermediate stages of alteration. Although local

equilibrium may be obtained during metasomatism, as long as reaction takes place, the trend of alteration is toward more calcic phases. Some insight can be had regarding the process of metasomatism if we consider mainly the calcium-bearing silicates.

Mineral stability diagrams can be constructed to relate these various phases, assuming, of course, that the mineral compositions and the other parameters remain constant. For this discussion, local equilibrium is assumed and pressure-temperatures are considered constant. It is also assumed that the original mineral affected by metasomatism is anorthite, that the activity of water is high and constant, and that the activity of aluminum and magnesium are constant. With these qualifications, it can be shown that a progression from anorthite to prehnite or zoisite to grossular (hydrogrossular) can take place with increasing activity of calcium (fig. 16A). At lower activities of silica, zoisite may appear instead of prehnite, but an increase in silica activity at certain fixed values of calcium activity could invert zoisite to prehnite. Such concentration variations may explain the presence or absence of zoisite and prehnite in the early stages of metasomatism, as these two minerals are not usually found in coexistence. If the same reasoning is used but silica activity is fixed and alumina is mobile, a mineral stability diagram of these same minerals demonstrates further relationships (fig. 16B). An increase of calcium activity apparently allows a change directly from prehnite or zoisite to hydrogrossular. If the alumina activity is lowered, prehnite could alter to xonotlite when the calcium activity increases. This reaction must reflect the progression at Myrtle Creek, Oreg., where prehnite has been replaced by hydrogarnet or xonotlite.

The metasomatic alteration of the serpentinite in these reaction zones is not fully demonstrated in this paper, but the progressive alteration of serpentinite shows the same dependence on the activities of silica and calcium. Again, if we make the same assumptions—the activity of water is high and constant and the activity of magnesium is constant—the dependence of calcium and magnesium minerals on the relative activities of calcium and silica can be diagrammed (fig. 16C). The formation of chlorite from serpentine depends on an increase of both silica and alumina, but this is not shown on the diagrams. If the silica and calcium activities are increased, serpentine and chlorite will react to form tremolite. Where the calcium activity is high relative to silica, diopside will form instead of tremolite; where silica activity exceeds that of calcium, talc forms from chlorite and serpentine.

The mineral assemblages present within the various reaction zones can be related to changes in the concentrations of calcium, silica, and

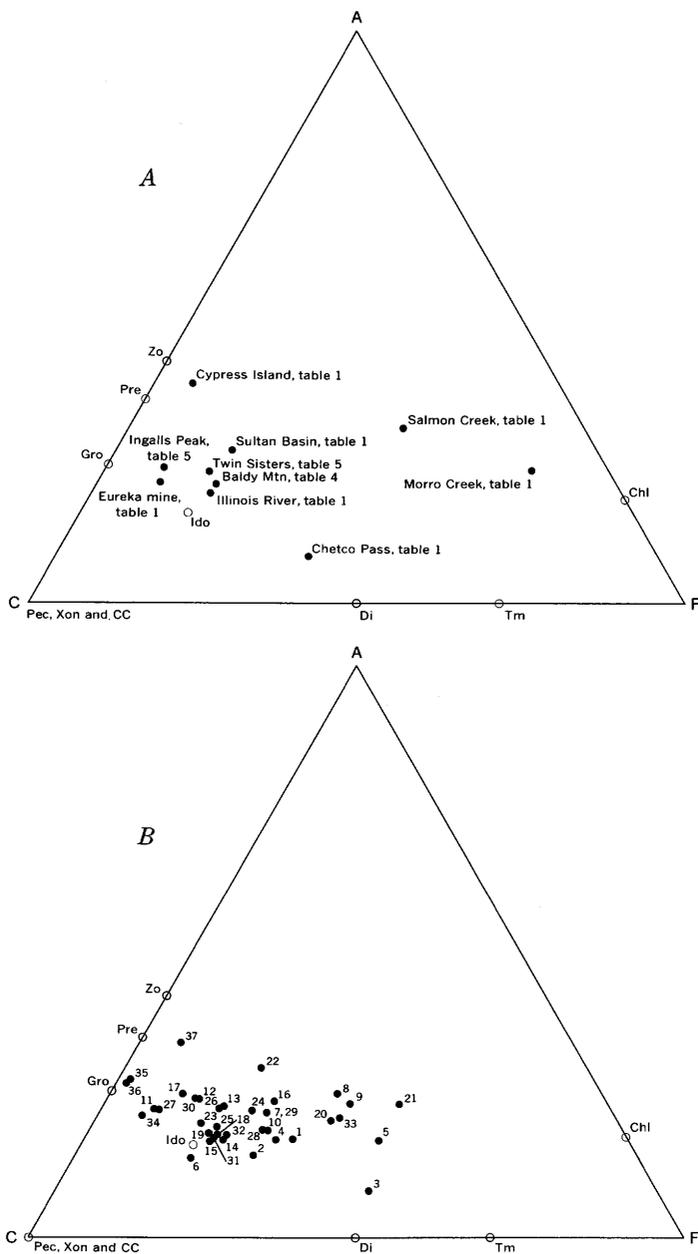


FIGURE 14.—ACF diagrams showing the common minerals associated with rodingites. *A*, Rodingites of Oregon, Washington, and California. *B*, Rodingites described in the literature. Zo, zoisite; Pre, prehnite; Gro, grossularite or hydrogarnet; Pec, pectolite; Xon, xonotlite; CC, calcite or aragonite; Ido, idocrase; Di, diopside; Tm, tremolite-actinolite; Chl, chlorite.

alumina as shown above. These chemical relationships are consistent with the observed mineral assemblages and reinforce the concept that the reaction zones result from metasomatic interchange of elements between serpentine and country rock.

KEY TO MINERAL ASSEMBLAGES AND LOCATIONS IN FIGURE 14B

1. Hydrogarnet-prehnite-zoisite rodingite; Girvan-Ballantrae complex, Ayrshire, Scotland (Bloxam, 1954).
2. Diopside (diallage)-hydrogarnet-vesuvianite rodingite; Eulamina, Mount Margaret goldfield, Western Australia (Miles, 1950).
3. Pyroxene-hydrogarnet-vesuvianite rodingite; Eulamina, Mount Margaret gold field, Western Australia (Miles, 1950).
4. Hydrogarnet-prehnite-xonotlite-diopside rodingite; Hindubagh, Pakistan (Bilgrami and Howie, 1960).
5. Hydrogarnet-prehnite-xonotlite-diopside rodingite; Hindubagh, Pakistan (Bilgrami and Howie, 1960).
6. Pectolite-hydrogarnet-thomsonite rodingite; Clear Creek, San Benito County, Calif. (Coleman, 1961).
7. Diopside (diallage)-hydrogarnet rodingite; Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
8. Prehnite rodingite; Valley of the Serpentine, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
9. Prehnite rodingite; Long Gully, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
10. Diopside (diallage)-hydrogarnet rodingite; Champion Mine, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
11. Diopside (diallage)-hydrogarnet rodingite; Code's Point, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
12. Diopside (diallage)-hydrogarnet rodingite; Lee Valley, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
13. Diopside (diallage)-hydrogarnet rodingite; Lee Valley, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
14. Diopside-hydrogarnet rodingite; Motueka River, Gordon Survey District, New Zealand (Grange, 1927).
15. Diopside-hydrogarnet rodingite; Motueka River, Gordon Survey District, New Zealand (Grange, 1927).
16. Idocrase-hydrogarnet-prehnite-zoisite rodingite; Anderson's Creek, Beaconsfield, County Devon, Northern Tasmania (Baker, 1959).
17. Hydrogarnet-diopside-idocrase rodingite; Ishikari Province, Hokkaido, Japan (Suzuki, 1953).
18. Hydrogarnet-diopside-idocrase rodingite; Ishikari Province, Hokkaido, Japan (Suzuki, 1953).
19. Prehnite-diopside-hydrogarnet rodingite; Cap Bassit, Northwest Syria (Majer, 1960).
20. Brown hornblende-prehnite rodingite; Hindubagh, Pakistan (Bilgrami and Howie, 1960).
21. Zoisite, brown hornblende, chlorite, sphene, center of ophispherite; Col'des Gets (Chablais, Haute Savoie), France (Jaffe, 1955).
22. Clinzoisite, prehnite, albite, chlorite, clinopyroxene, hornblende, central part of altered gabbro; Hayachime ultramafic complex, Kitakami Mountains, northern Japan (Onuki, 1963).
23. Idocrase, chlorite, diopside, so-called vesuvianels; Piz Lunghin, Maloja, Switzerland (Müller, 1963).
24. Diopside, grossular, rodingite; Piz Lunghin, Maloja, Switzerland (Müller, 1963).
25. Rodingite composition calculated from analyses of diallage and hydrogrossular (Bell, Clarke, and Marshall, 1911, p. 32).
26. Dense rodingite from near Trigonometrical Station, R. K. Lee Valley, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911, p. 33).
27. Fine-grained rodingite, Code's Point, Dun Mountain Tramway, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911).
28. Fine-grained rodingite, Champion Level, Champion Mine, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911, p. 33).
29. Fine-grained rodingite; near Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911, p. 33).
30. Fine-grained rodingite, Long Gully-Lee Valley, Dun Mountain, New Zealand (Bell, Clarke, and Marshall, 1911, p. 33).
31. Dense white grossularite-diopside rock; half a mile south-southeast of cairn at 2602 ft.; 1½ miles south of Mount Glennie, Motueka River Valley, Gordon Survey District, Red Hills, New Zealand (Grange, 1927, p. 165).
32. Dense white grossularite-diopside rock; near head of Motueka River, Gordon Survey District, Red Hills, New Zealand (Grange, 1927 p. 165).
33. Gabbro with prehnite-zoisite aggregate, Motueka Valley, 1¼ miles south-southeast of Mount Glennie, Gordon Survey District, Red Hills, New Zealand (Grange 1927, p. 165).
34. Hydrogrossular; Champion Creek, near old copper mine, Waimea Survey District, Dun Mountain area, New Zealand (Hutton, 1943, p. 174).
35. Hydrogrossular; Roding River, New Zealand (Bell, Clarke, and Marshall, 1911, p. 32).
36. Hydrogrossular; Roding River, New Zealand (Bell, Clarke, and Marshall, 1911, p. 32).
37. Prehnite-zoisite aggregate in altered gabbro; southwest branch of Wairoa River, Gordon Survey District, Red Hills, New Zealand (Grange 1927, p. 165).

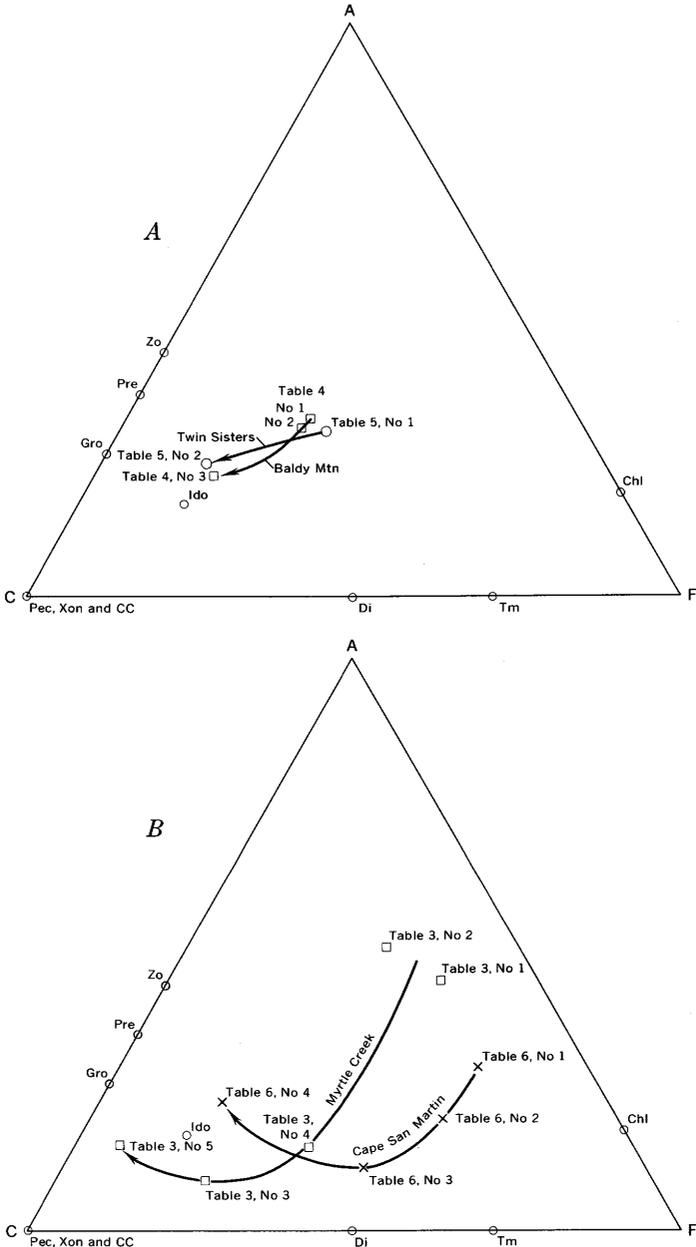


FIGURE 15.—Progressive changes in composition within reaction zones plotted on ACF diagrams. *A*, Gabbroic rocks reacting to form rodingites. *B*, High silica rocks (graywacke, San Martin and dacite, Myrtle Creek) reacting to form calcium-rich metasomatic borders. Zo, zoisite; Pre, prehnite; Gro, grossularite or hydrogarnet; Pec, pectolite; Xon, xonotlite; CC, calcite or aragonite; Ido, idocrase; Di, diopside; Tm, tremolite-actinolite; Chl, chlorite.

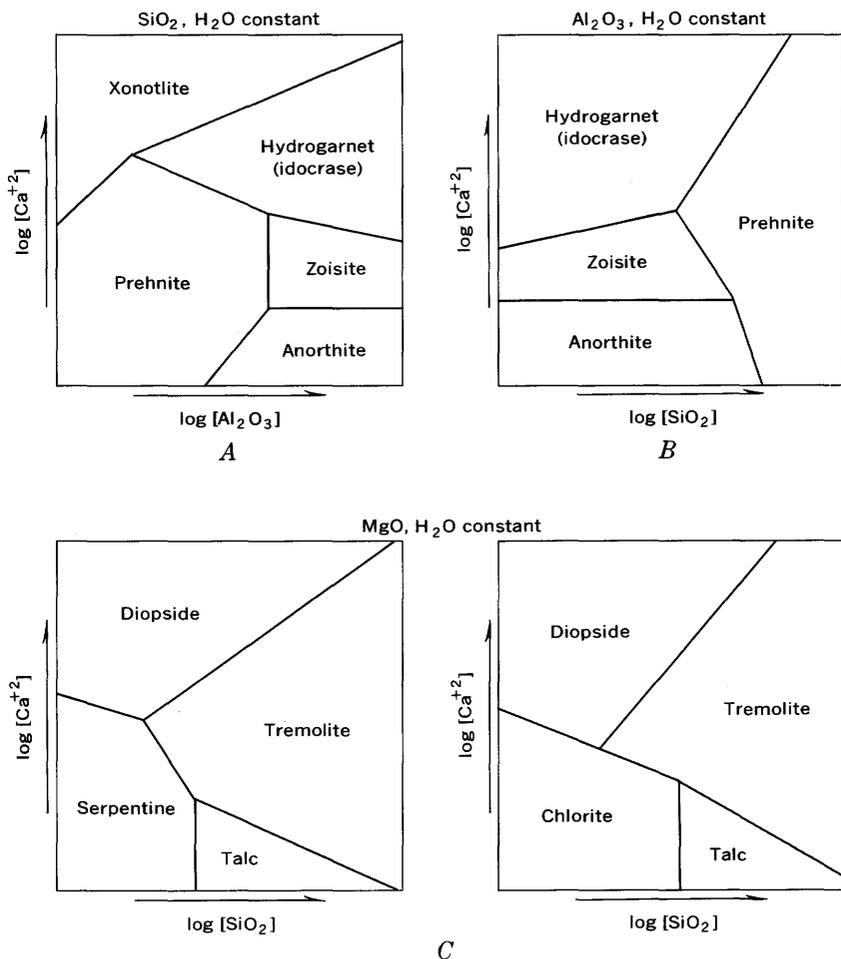


FIGURE 16.—Activity diagrams illustrating possible fields of stability for minerals present in reaction zones.

A, Ca (activity)–Al₂O₃ (activity) for hydrated calcium-aluminum silicates.

B, Ca (activity)–SiO₂ (activity) for hydrated calcium-aluminum silicates.

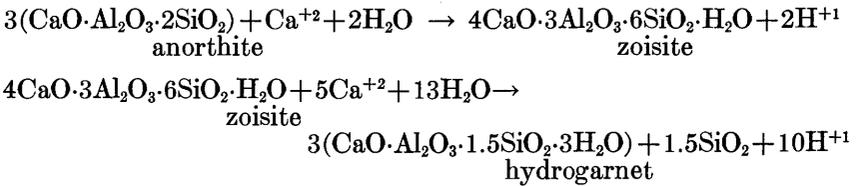
C, Ca (activity)–SiO₂ (activity) for calcium and magnesium silicates.

All compositions considered fixed with pressure and temperature constant but not specified.

The metasomatized mafic igneous rocks (rodingites) have very consistent mineral assemblages as listed below:

1. Hydrogarnet and chlorite.
2. Hydrogarnet, prehnite, and chlorite.
3. Hydrogarnet, diopside, and idocrase.
4. Hydrogarnet, idocrase, and chlorite.

Hydrogarnet is the dominant mineral in the rodingites. Assuming that hydrogarnet is related to the breakdown of the original calcic plagioclase and does not result from the breakdown of ferromagnesian, which alter to chlorite and actinolite, a series of reactions can be written that may represent the chemical nature of the metasomatism.

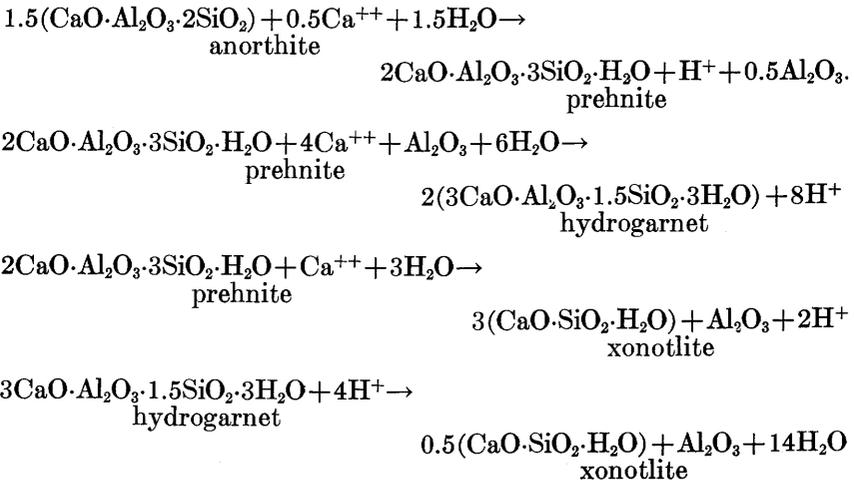


These reactions illustrate the nature of the metasomatism as being driven to completion by an increase in the activity of calcium and water. Other reactions can be written to include diopside, prehnite, and idocrase, but in general the same relations hold.

In the more siliceous altered sediments and igneous rocks from reaction zones, five different mineral assemblages develop in the most intensely altered zones, but in general there is an overall resemblance to the rodingites.

1. Albite, potassium feldspar, and tremolite-actinolite.
2. Tremolite-actinolite.
3. Diopside, tremolite-actinolite, prehnite, and chlorite.
4. Tremolite-actinolite, hydrogarnet, and diopside.
5. Hydrogarnet, prehnite, and xonotlite.

Again, using the calcium silicates common in these rocks, a series of reactions can be written to illustrate the trend of the metasomatism. Chlorite and actinolite-tremolite are assumed to not have any effect on these hypothetical reactions.



country rock. The ensuing sequence from the center of the ultramafic bodies outward is as follows:

antigorite→talc→actinolite→chlorite→biotite.

Coleman (1961) described a distinct zoning for those tectonic inclusions containing jadeite and enclosed within the serpentinite mass of New Idria, Calif. Francis (1955, 1956) found zoned bodies at Glen Urquhart, Scotland, that have reacted with the serpentinites and are depleted in silica and enriched in magnesium and calcium. Comparison of the mineral zonation formed at these widely separated occurrences and under different pressure-temperature conditions reveals strong similarities. Juxtaposition of serpentinite or ultramafic with other rocks of higher silica content in a pressure-temperature environment that would allow reactions to take place produces a distinctive suite of contact metasomatic minerals. These metasomatic minerals occur in distinct zones or produce monomineralic or bimineralic rocks. The suite of minerals formed depends on three factors: composition of rock in contact with the serpentinite; tectonic setting; and pressure-temperature conditions during reactions. Further work is needed before a classification can be established for reaction zones characterizing different environments, but the mineral assemblages probably could be used to establish the pressure-temperature conditions of formation.

PRESSURE AND TEMPERATURE CONDITIONS OF METASOMATISM

The metasomatic rocks are in direct contact with or completely surrounded by serpentinite, but direct contact of the metasomatites with unaltered dunite or peridotite was not observed by the author on the Pacific coast of the United States or in New Zealand, nor has it been reported in the literature. Thus, it is safe to predict that these metasomatic reactions must take place at temperatures below the breakdown of olivine and (or) pyroxene to serpentine. Bowen and Tuttle (1949) have said: "Serpentine cannot be present in any layer of the earth's crust whose temperature is normally above the decomposition temperature of serpentine under the pressure prevailing." The reaction

serpentine→forsterite + talc + vapour

fixes the serpentine breakdown at approximately 500°C at 1 kilobar; at higher total pressures, the breakdown temperature would increase only a few degrees. Additional work is needed to determine the stability of the various serpentine polymorphs, as Bowen and Tuttle were able to produce only one serpentine polymorph, chrysotile. The field relations of antigorite indicate that it may be more stable in a higher

pressure-temperature field than chrysotile. Recently Hostetler and others (1966) showed that brucite is commonly present in olivine-rich ultramafics and pointed out that its presence indicates that serpentinization may have taken place at temperatures 100°C lower than the generally accepted 500°C.

A nearly direct estimate of temperature can be obtained by consideration of the hydration state of the hydrogarnet in these metasomatic rocks. Yoder (1950) and Carlson (1956) showed that the silica and water content of hydrogarnet is related to its temperature of formation. The silica content of hydrogarnet increases with temperature up to 800°C, at which temperature grossularite is stable, whereas fully hydrated hydrogrossular is stable at 220°–226°C. These reactions are not pressure dependent; thus, if the hydration state of a hydrogarnet can be determined, its temperature of formation can be estimated. Hydrogarnets associated with jadeite and rodingite in the New Idria, Calif., serpentinite were found to indicate a possible temperature range from 240° to 360°C (Coleman, 1961). Later work by the author on hydrogarnets from New Zealand shows a temperature range of formation between 290° and 450°C. Caution is necessary in deducing temperature from relative hydration states as Zabinski (1964) has shown that idocrase is often present as cryptic intergrowth within hydrogarnet. Further mineralogical work on the Pacific coast hydrogarnets is needed before temperature estimates can be established for these, but on the basis of the New Idria and New Zealand estimates, we can probably say that the Pacific coast hydrogarnets formed within the temperature range of 240° to 490°C.

A third independent check on temperature of formation is afforded by the presence of xonotlite in the metasomatized rocks of the Pacific coast. The experimental work by Buckner, Roy, and Roy (1960) and by Flint, McMurdie, and Wells (1938) on the stability of xonotlite and wollastonite under hydrothermal conditions has shown that at 400°C and atmospheric pressure wollastonite will form from xonotlite by dehydration, or from a gel of appropriate composition, and that at elevated pressures 30,000 psi wollastonite will form at 430°C. The presence of xonotlite suggests, thus, that in some areas of metasomatism, the temperatures are probably within the same range indicated by the hydrogarnets, and both temperature estimates indicate that the metasomatism takes place in the temperature range where serpentine is stable.

Estimates of pressure during metasomatism are difficult to make and are necessarily approximate. In California, however, there is evidence that much of the calcium metasomatism develops contemporaneously with the glaucophane schist facies metamorphism (Chesterman, 1960; Coleman, 1961).

The presence of aragonite and jadeite in the New Idria reaction zones indicates that at temperature around 400°C the pressure would have to be about 9 kilobars. Of course, where these high-pressure minerals are not present, adequate estimates are difficult to make. Further temperature evidence can be obtained from the recent experimental work by Bell and England (1964) on the aragonite-calcite inversion. They have shown that aragonite is not quenchable at high temperatures, and if aragonite does form below 10 kilobars, the temperatures must be on the order of 200° to 300°C. The general increase of density of the rocks in the metasomatic reaction zones and the substantial water content indicate that the total pressure is high and that the water pressures are nearly equal to the total pressure. The pressure is estimated to be usually in excess of 4,000 bars.

The tectonic evidence for incremental upward diapiric movement of ultramafics indicate an environment wherein metasomatic reactions took place at various depths, and the inferred pressure range is therefore only approximate.

TECTONIC SETTING OF SERPENTINITE EMPLACEMENT AND ASSOCIATED METASOMATISM

There is very little convincing evidence that ultramafics in the Pacific coast region were emplaced as high-temperature igneous intrusions in the earth's crust. In many localities, large areas of ultramafics have no associated gabbros, and in these areas serpentinite is always in contact with the country rock rather than peridotite or dunite.

The tectonic nature of the contacts and the associated low-temperature-high-pressure reaction zones are rather strong evidence suggesting that emplacement of some ultramafics coincides with major tectonic events. The close association of the Pacific coast serpentinite belts with thrust faulting and other evidences of intense tectonism demonstrate that the ultramafics were emplaced in the upper crust as solid intrusions rather than as magmas (Bailey and others, 1964). The mechanical instability of sheared serpentinites is so great that repeated tectonic events following the initial emplacement promote their upward migration within the earth's crust. This still does not preclude the possibility that the peridotites and dunites crystallized from a magma within the mantle before being transported upward.

The concept of a solid intrusion of ultramafics is not new; Benson (1926) postulated this mechanism for the New Zealand ultramafics. More recently, Hess (1955) summarized various problems concerning serpentinites and island arcs and demonstrated that the latter may represent an early development of an alpine-type mountain system. Furthermore, he showed that the distribution of alpine-type ultramaf-

ics throughout the world follows an arcuate pattern and that, in the early stages, these rocks occupy continental margins. Thus, the favorable areas of ultramafic emplacement were along the continental margins, where the crust is thin and the M-discontinuity is only 10–20 kilometers below the ocean bottom.

If parts of the original peridotite mantle are contained within the ultramafics, the igneous formation of the ultramafics could have been much earlier than the tectonic event that emplaced them into the earth's crust. Textures of the primary ultramafics are igneous but are often overprinted by a deformational fabric. The low incidence of high-temperature contact metamorphism associated with many ultramafics in the crust is compelling evidence against a magmatic emplacement in their present setting. The universal serpentinization—partial along borders of large ultramafic masses or complete in the thinner masses—characterizing the tectonic belts demonstrates the chemical instability of dunite-peridotites within the crust. Bowen and Tuttle (1949) have given experimental evidence that precludes an ultramafic melt having a water content high enough to allow autometamorphism of the crystallized melt to serpentine.

Assuming that the Pacific coast ultramafics may have formed in the mantle as peridotite and later been transported upward along a major circum-Pacific fault, such peridotites would first intrude geosynclinal sediments at considerable depths (10–20 km) in an environment of high pressure and relatively low temperature (approximately 300°–400°C), depending on heat flow, composition of the sediments, and state of equilibrium between the sediments and peridotites. The invasion of water into the peridotite would cause serpentinization and resultant expansion. A local increase in pressure could be produced by expansion, assuming that the rocks had enough strength to sustain the local increase in pressure (Coleman and Lee, 1962). The alteration of peridotite to serpentine was shown to be exothermic by Bennington (1956); thus, temperatures would rise in the area of serpentinization. The preserved contacts of serpentine and metasomatized sedimentary rocks as described earlier show that metasomatism must take place after the major faulting of peridotite from the mantle up into the base of thick geosynclinal accumulations. Continued upward faulting would bring more water into contact with the ultramafic, and movement of the incompetent serpentinized parts would allow slabs of country rock to become included within the serpentine. During the dynamic emplacement, contact metasomatism would result because of the elevated temperatures (400°–500°C) and chemical activity of water, silica, and calcium at the contact.

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