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ORIGIN OF DUNITES AND OF OLIVINE-RICH INCLUSIONS IN BASALTIC ROCKS¹

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ABSTRACT

Basaltic rocks characterized by nodulelike inclusions of olivine and related minerals are of world-wide occurrence and have long been known, especially in Germany. Everywhere the nodules show a remarkable uniformity of chemical and mineral composition and in this respect are similar to dunites—intrusive rocks of equally wide distribution. This similarity in the chemical and mineral composition of the two modes of occurrence and the wide distribution of both of these, suggest the value of a detailed study. This paper gives the results of a large number of chemical and spectrographic analyses of the minerals in the nodules and in dunites and discusses the mineralogic and geologic relationships. The authors conclude that dunites have been brought up from profound depth by orogenic processes, and olivine-rich nodules have been carried up from the same source by basaltic magmas.

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INTRODUCTION

Few igneous rocks present more interesting petrogenetic relationships or greater possibilities of significant conclusions based on those relationships than do the monomineralic rocks, and of these the peridotites, composed essentially of olivine, have been the most widely discussed. The geologist is interested in the distribution, mode of intrusion, and relations to tectonic processes; the mineralogist is interested in the minerals, their relationships, and the variations in their composition; and the geochemist is interested in the physical chemistry of their formation. Cosmogonists are interested in any information about the materials of the deeper portions of the earth's crust, which these rocks may reveal.

Peridotite rocks are found in two distinct modes of occurrence—as dunites and related rocks, and as olivine-rich nodules in basaltic rocks. These types, both of world-wide occurrence, are particularly significant in that they show chemical and mineralogic similarities that indicate a genetic relationship, which this paper will explore.

ACKNOWLEDGMENTS

The study of the minerals in olivine-rich nodule inclusions in basaltic rocks and of the same minerals in dunites was suggested by excellent samples submitted by Senor Carlos Sisniega from Camargo, Chihuahua, Mexico. The results of chemical analyses of the olivine, enstatite, chromian diopside, and chromian spinel from that locality indicated that a systematic study of similar materials would have geologic as well as mineralogic value.

The olivine nodules in the collections of the U. S. National Museum in Washington were made available for analysis by Dr. William F. Foshag, and represent materials from Kapfenstein, Austria; Dreiser Weiher, Germany; Peridot Cove, Arizona; and Salt Lake Crater, Oahu, Territory of Hawaii. Dr. Foshag's advice has been of great help in this study.

The writers wish to acknowledge the cooperation of Dr. Harry H. Hess of Princeton University, Dr. Hisashi Kuno of Tokyo University, Dr. Gordon A. Macdonald of the Hawaiian Volcanic Observatory, and Dr. Thomas P. Thayer of the U. S. Geological Survey. Monoclinic pyroxenes analyzed in the course of this investigation have been placed at the

disposal of Dr. Hess, and will thus contribute to his valuable studies of the pyroxene group of minerals. Through the courtesy of Dr. Kuno, samples which he collected from near Meng-Chian, east Manchuria, and from Ichinomegata, Oga Peninsula, Akita Prefecture, Japan, were made available. Dr. Kuno also provided the chemical analyses of the host rock of the nodule from Ichinomegata. Dr. Kuno is making an optical study of the orthorhombic pyroxenes analyzed in the course of this study.

Samples from several localities in Hawaii were contributed by Dr. Macdonald. The dunite and related websterite from Webster, North Carolina, were collected by the senior author, as were the dunite samples from Dun Mountain, New Zealand, and from a locality near Noumea, New Caledonia. The dunite from the Twin Sisters area of Washington was contributed by Dr. Thayer.

OCCURRENCES OF NODULELIKE INCLUSIONS IN BASALTIC ROCKS

The inclusions of olivine and related minerals in basaltic rocks, commonly called "knollen," have long been known in Germany and Austria, and many occurrences have been mentioned in the literature. Schadler (1914) has compiled a list of localities and papers that have been helpful in this study. These papers indicate that a zone of basaltic rocks, characterized by "knollen" reaches from western Poland across central Germany, in an arc beginning just west of Breslau and extending through Saxony, with a marked concentration in Hesse and the region immediately north, and seemingly ending on the west, at Luxembourg. Another zone seems to extend from the region of Graz west to the Black Forest and Kaiserstuhl regions along the north flank of the Alps.

Nodule inclusions in basaltic rocks have been reported from localities in Hungary, Bulgaria, Sweden, France, Portugal, and Sardinia. They are also known to occur in Jan Mayen—an island northeast of Iceland—Japan, Manchuria, Morocco and Nigeria in Africa, the Hawaiian Islands, New Zealand, Alaska, Mexico, and the western United States.

The type locality for dunite is South Island, New Zealand, where, together with its alteration product serpentine, dunite occurs in a zone in the rugged Southern Alps of that island. In the western Pacific, dunite and serpentine occur in great arcs and are recognized in New Caledonia, Australia, the Celebes, and the Philippines. In eastern North America a zone extends from Newfoundland to Alabama, and in western North America another zone extends from Alaska south through California. In the West Indies a belt extends from Cuba toward Guatemala. Other occurrences are known in Sweden, Norway, Italy, and Scotland. Dunite and serpentine occur in a belt in Asia Minor that extends eastward. Hess (1939) has discussed the relation of such belts to mountain-building

forces, and his paper is an excellent source of information on the relation of the distribution of dunite and serpentine to major tectonic zones.

Localities of Analyzed Materials

Hawaiian Islands: The largest group of specimens from any one locality is that from the Hawaiian Islands, contributed by Dr. Macdonald. The collection of samples from the 1801 Kaupulehu lava flow of Hualalai is especially complete, and shows a marked range in size and character of nodular inclusions. Stearns and Macdonald (1946, p. 147) describe the occurrence of these nodules as follows: "Several rivers [of lava] flowed seaward from this vent to form the Kaupulehu flow. This flow contains many thousands of angular and subangular xenoliths of dunite and gabbro mostly under a foot in diameter. . . . Apparently the magma stopped away a large precooled mass of dunite and gabbro before eruption."

Some nodules from Hawaii are nearly pure olivine with only a trace of diopside and chromian spinel. Other nodules are almost pure diopside, but many are made up of nearly equal proportions of olivine and diopside. The chromian spinel is sparse in most nodules but may comprise as much as 2 per cent. One specimen contains about equal proportions of plagioclase (An 75) and olivine, and another about the same proportion of diopside and plagioclase. The diopside is, for the most part, dark gray or gray green in the hand specimen but nearly colorless in thin section. Bright-green diopside, which is characteristic of the inclusions in other occurrences, was observed in only one specimen. The grains of olivine may be as large as 8 mm. in diameter, and the diopside grains, 12 mm. One specimen—representing a part of a single diopside crystal—is about 8 by 10 cm. in diameter.

The Kauai samples are part of the late Koloa volcanic series and came from the Grove Farm quarry near the road southwest of Lihue. The nodules are closely spaced in these samples, are subangular, and reach 5 cm. in diameter. The inclusions are dominantly olivine (Table 4, No. 9) and estatite (Table 5, No. 9). No diopside was observed, but a fraction of 1 per cent of chromian spinel (Table 7, No. 9) was noted.

An unusually interesting specimen submitted by Dr. Macdonald was collected by Rev. Walter Schilling of Hilo from a small cinder cone west of Hale Pohaku on the south side of Mauna Kea. This sample contains the four minerals that so widely characterize nodule inclusions—olivine, estatite, chromian diopside, and chromian spinel. An analysis of the chromian diopside is presented in Table 6, No. 10, and of the chromian spinel in Table 7, No. 10

The material from Salt Lake Crater, Oahu, is represented by U.S.N.M. Specimen No. 53948. The nodules reach a diameter of 4 cm. and are sub-

angular. The minerals present are dominantly olivine (Table 4, No. 8), enstatite (Table 5, No. 8), chromian diopside (Table 6, No. 8), and chromian spinel (Table 7, No. 8).

Another group of nodules is from stream boulders, from Kapohakukilomanu stream on the south slope of Kauai. These nodules are abundant but small—not larger than 1 to 3 cm. in diameter in the specimens observed. Many of them are subangular. Some of the nodules are almost pure olivine, but others contain pale-green chromian diopside. Enstatite is sparse in all the specimens; in fact the group is unusual in that chromian diopside is more abundant than enstatite.

Another group of samples is from the Ohia Lodge flow of 1950. The largest nodule in these specimens is 2 cm. in diameter. It is dominantly olivine but contains enstatite, chromian diopside, and chromian spinel. A slightly smaller nodule from the same source is composed of olivine, bytownite, enstatite, chromian diopside, and sparse chromian spinel.

Peridot Cove, Arizona: The locality locally known as the Peridot Cinder Cove, and described as Rice Station by Lawsen, lies in Gila County, Arizona, on the San Carlos Apache Indian Reservation, about 20 miles southeast of Globe, Arizona, and about 8 miles north of the Coolidge Dam. Subsequent to the study of the National Museum material, Ralph S. Cannon and N. P. Peterson of the U. S. Geological Survey visited the locality and collected additional specimens from about 1 mile west of the village of Peridot. Mr. Cannon reports that the material collected by them was from a scoraceous basalt layer underlying the cinder cone, and which contains abundant olivine nodules. The geologic age of the cinder cone is probably Late Pleistocene or Recent. For years the Apache Indians have collected and sold gem peridote from the area and guard it jealously. In describing the bombs, Lausen says, "The olivine bombs in the tuffs are usually ellipsoidal in shape and quite variable in size. The one shown in Fig. 1, p. 294 [of Lausen's paper], is fifteen inches in length. One was noted near the base of the cinder cone nearly thirty inches long and half as wide. . . . Invariably they are surrounded by a thin shell of vesicular basalt. . . . The surface of the bombs is rather smooth and suggests that there may have been some resorption of the olivine before it was thrown out by the explosions that gave rise to the tuffs.

"On a freshly broken surface the interiors of these bombs were found to consist of a granular mass of interlocking and glittering grains of olivine."

In a description of the diopside, Lausen states, "This material is relatively scarce. One large crystal found in the vesicular basalt was two inches in length. Usually the fragments are less than one-half inch."

Lausen describes the associated basalt flow as follows (1927, p. 295):

"In close proximity to the cone the basalt flow is ten feet thick; the lower six feet of which is thickly crowded with nodules of granular olivines . . . many of these nodules are quite angular, while others are rounded . . . and many of the nodules are so closely crowded together as to touch. At one place along the present edge of the flow it was estimated that olivine nodules constituted fully 60 per cent of the lower six feet of the flow, while the remaining 40 per cent was vesicular basalt." The analysis of the olivine from Peridot Cove is presented in Table 4, No. 3; of the enstatite, in Table 5, No. 3; of the chromian diopside, in Table 6, No. 3; and of the chromian spinel, in Table 7, No. 3. Many of the olivine grains are perfectly clear, reach a diameter of 1 cm., and have been used as gem peridot.

Lausen mentions the possibility that the olivine nodules are detached blocks of a mass of dunite occurring in this region, but, he rejects this mode of origin and concludes that the olivine masses were formed as segregations in a volcanic pipe.

In the summer of 1952, Dr. Ralph S. Cannon of the U. S. Geological Survey collected additional specimens from the Peridot Cove locality. One of these specimens is a volcanic bomb that is subangular in shape, and measures about 10 by 14 cm. An outer shell of basaltic material is only a few millimeters in thickness. The mineral composition is the same as that of samples previously studied. Some of the olivines which have weathered from the bombs range up to 1 cm. in diameter and constitute a source of gem quality peridot. Another bomb fragment is composed dominantly of clinopyroxene but it is dark colored in the hand specimen, rather than green. With this is a small proportion of chromian spinel and olivine.

Meng-Chian, Manchuria: The material from the town of Meng-Chian was described by Dr. Kuno as an olivine-enstatite-diopside nodule in an olivine basalt. The material is completely unaltered and contains chromian spinel in addition to the materials mentioned. The nodules are reported to reach 20 cm. in diameter. Dr. Kuno had no opportunity to collect more than a very small specimen at the time, and although he very generously sent us all the material available, there was not enough to supply the entire group of minerals in amounts adequate for chemical analyses. An analysis of the olivine is given in Table 4, No. 6 and of the enstatite in Table 5, No. 6.

Camargo, Mexico: The material from Camargo, Chihuahua, is broken into small fragments but evidently occurs as rather large cores in volcanic bombs. The minerals are very fresh, and all four minerals characteristic of nodule inclusions are abundant. The chromian diopside (Table 6,

No. 1) and chromian spinel (Table 7, No. 1) are unusually abundant and occur as crystals up to 4 mm. in diameter. The olivine (Table 4, No. 1) is in grains as much as 20 mm. in diameter, and the enstatite (Table 5, No. 1) reaches dimensions of 8 mm.

Ludlow, California: The material from Ludlow, San Bernardino County, California, was collected by Dr. Foshag of the National Museum (U.S.N.M. Specimen No. 94430). The specimen available for study is a rounded nodule about 8 cm. in diameter in an olivine basalt. The mineral grains are more uniform in size than in most materials of this type. The olivine (Table 4, No. 2) and enstatite grains (Table 5, No. 2) reach a maximum diameter of 4 mm. The green chromian diopside grains (Table 6, No. 2) are slightly smaller. Chromian spinel (Table 7, No. 2) in millimeter-sized grains is unusually abundant.

Dreiser Weiher, Eifel, Germany: Several geologists have discussed the olivine nodules that occur as cores in volcanic bombs at Dreiser Weiher in the Eifel. The latest and most detailed study of these nodules is by Frechen (1948).

The bombs, as described by Frechen (1948, p. 327) vary greatly in mineral content, as illustrated in the following table compiled from data given by him.

TABLE 1. MINERAL COMPOSITION OF NODULES FROM DREISER WEIHER

	1	2	3	4	5	6
Olivine	99	90	84	57	68	43
Enstatite	—	4	15	8	30	48
Chromian-diopside	—	2	1	30	2	4
Picotite	1	4	—	5	—	5

Frechen quotes several analyses of these minerals from various localities made by earlier workers but adds no complete new analyses of the Dreiser Weiher minerals.

Kapfenstein, Austria: In the southeastern part of Styria and adjoining parts of Hungary, along the eastern border of the Alps, a number of basaltic centers characterized by olivine nodules form part of the zone of centers. They have been described by Schadler (1914), and material from one of these centers is represented by the material from Kapfenstein, east of Gleichen. The basaltic tuff of Kapfenstein has long been known to contain typical olivine bombs. However, at other Styrian localities, like Kuruzzenkohl, south of Fehring and in Unterweissenbach, west of Feldbach, the basaltic tuff deposits are revealed through quarry-

ing operations. The nodules are wanting in the nepheline basalt of the region. Olivine nodules have also been observed in limburgite from Loipersdorf near Furstenfeld.

In describing the olivine bombs, Schadler (1914, p. 486) says, "Besides rounded and irregular fragment-like forms, the Styrian olivine bombs also commonly show a regular parallel arrangement as Heritsch (1908) has already observed. The size of the bombs is variable, and ranges through all dimensions up to a diameter of half a meter. . . . Mineralogically the olivine bombs of Styrian occurrences throughout are an aggregate of olivine, bronzite, chrome-diopside, and picotite."

Alaska: David M. Hopkins of the U. S. Geological Survey has brought to our attention basaltic rocks that contain abundant olivine-rich nodules. These nodules are described by Mr. Hopkins (personal communication) who states, "The olivine nodules occur in the Imuruk Lake region, Seward Peninsula, Alaska, in a region of basaltic rocks, which range from early Pleistocene to Recent in age. The flows from a few of the numerous vents contain abundant inclusions. These are commonly angular and range up to 3 inches in greatest dimension. The flows which contain mafic inclusions are exceptionally olivine rich; I assume that much of the olivine is derived from disintegrated inclusions." The material available for study was inadequate for complete chemical analysis of the chromian spinel, but it was found to contain about 15 per cent Cr_2O_3 .

In the course of studies of the rocks of the Aleutian Islands of Alaska, George D. Fraser of the U. S. Geological Survey collected olivine-rich nodules that occur in basaltic rocks from near the northwest coast on Kanaga Island, Andreanof Group.

Mr. Fraser (personal communication) states, "The host rock forms an isolated outcrop about 10 ft. by 50 ft. in an area devoid of other outcrops, so that the nature of the igneous body is in doubt. The rock is a dense, black altered basalt? with abundant, conspicuous, brown, olivine-rich inclusions up to a foot in diameter, both rounded and tabular. The age of the rock is unknown." Microscopic examination indicates that this is a fragmental rock in which limburgite is dominant.

The nodules are dominantly olivine with lesser amounts of bright-green chromian diopside, enstatite, and chromian spinel. Thus, the mineralogy of the Kanaga Island specimens is similar to all the others that have been studied. A sample of the chromian spinel was separated by heavy solutions, and chemical analysis shows the presence of 28.6 per cent of Cr_2O_3 .

Africa: A group of specimens with nodular inclusions in basalt from an area near Azrou Morocco in the Middle Atlas region were secured from Abbe Gaudefroy, curator of the mineralogical museum of Rabat, Moroc-

co. Some of these nodules were 2 to 3 cm. in diameter, but a fragment of a large nodule was 7 cm. long. The dominant mineral is very fresh olivine in grains that may be as large as 1 cm. in diameter. Enstatite grains reach 2 mm. and sparse chromian diopside and chromian spinel occur as millimeter-sized grains.

An olivine-rich nodular inclusion in basaltic rock from Rapp Hills, Durumi, Nigeria, is represented by U.S.N.M. Specimen No. 96584. This specimen is part of a rounded nodule about 8 cm. in diameter. The dominant olivine and less abundant enstatite grains reach 4 mm. in diameter. Sparse chromian diopside and spinel occur as millimeter-sized grains.

Localities of Earlier Studies

Many papers, some of which date back 100 years, have been published on the olivine-rich nodules in basaltic rocks. A few of the papers that give significant analyses or that contain significant discussions will be cited and briefly outlined.

Turner (1942, p. 299) has made valuable studies of olivine-rich nodules from basaltic rocks of New Zealand and has described them as follows: "Mineralogically the olivine nodules from New Zealand Tertiary and Pleistocene basalts are identical with lherzolites and harzburgites of plutonic origin. The constituent minerals include enstatite, chrome-diopside, picotite and chromite, none of which has been recognized in the enclosing basalt."

Olivine nodules have been reported by Lauro (1940) from Conca de Janas (Orosei), eastern Sardinia. He gives chemical analyses of carefully separated samples of olivine, green monoclinic pyroxene, bronzite, and picotite, which are cited in Tables 13 to 16, No. 11. Lauro concludes that the minerals of the nodules were concentrated by crystal settling and then dragged up by the basalt.

Schultz (1903) has described olivine nodules from numerous volcanic centers in the vicinity of Homberg, south of Kassel, Germany, where they occur both in flow rocks and as bombs in volcanic tuffs. The rocks enclosing the nodules are described as nepheline basalts, nepheline basanites, feldspar basalts, dolerites, and limburgites and are an excellent example of identical nodules occurring in very different rock types.

Ernst (1936) in a paper on the nodules derived from a melilitite basalt of Westberges, near Hofgeismar has thoroughly discussed their origin. Quotations from parts of this paper are included in the section on the origin of nodule inclusions (p. 729). He says that in mineral composition the nodules range from almost pure olivine, with less than 10 per cent of pyroxene and chromian-spinel, to a bronzite rock in which olivine is only an accessory mineral. The nodules are fresh, and serpentinization

is almost never observed. An analysis of the Westberges rock is given in Table 20, No. 2.

A complete chemical analysis of the monoclinic pyroxene made by Ernst (1936, p. 652) is given in Table 15, No. 9. A complete analysis of the other minerals is not given, but the picotite was found to contain 23 per cent Cr_2O_3 . Ernst also mentions a host rock characterized by olivine nodules from the locality of Hochbol, in the Swabian Alps (Ernst, 1936, p. 659), in which he calculates the presence of 44 per cent melilite.

Frechen (1948) includes a description of the occurrence of nodules in the basalt at Finkenbergr in the Siebengebirge region, near Bonn. The mineral content in the Finkenbergr occurrence varies widely, as shown by some of the proportions listed by Frechen (1948 p. 353).

TABLE 2. MINERAL COMPOSITION OF NODULES FROM FINKENBERG, NEAR BONN

	1	2	3	4	5	6
Olivine	95	67	70	65	—	—
Enstatite	—	20	30	30	75	100
Augite	5	10	—	2	25	—
Picotite	—	3	—	3	—	—

Many of the nodules carry the secondary minerals hornblende and biotite. The biotite shows distortion due to mechanical pressure, a relationship that led Frechen to conclude that this is the same force that produced the structures observed in the olivine.

Farsky (1876) describes "olivine nodules" in basalts from Kisakov, in Czechoslovakia, and gives analyses of the olivine, enstatite, diopside, and picotite, which occur in these rocks (see Tables 13 to 16, No. 1).

Knop (1877, p. 698) also gives analyses of olivine, orthorhombic pyroxene, clino-pyroxene, and chrome "eisenstein" (see Tables 13 to 16, No. 5) from Lutzelberges near Sasbach in the Kaiserstuhl.

Schuster (1878) describes olivine nodules in bombs from Repts, Siebenbürgen, Rumania, and describes olivine, augite, bronzite, and spinel from them. The same group of minerals from that locality has also been described by Bleibtreu (1883).

Bauer (1891, pp. 182-191) lists olivine, bronzite, chromian-diopside, and picotite, which occur at Stempel near Marburg Heisse, and gives chemical analyses reproduced in Tables 13-16, No. 9.

Zirkel (1904) discusses olivine nodules in the Rheinland region, mentioning olivine, bronzite, chrome-diopside, and picotite, and concludes that the nodules represent segregation from basalt.

OCCURRENCES OF DUNITE

Localities of Analyzed Materials

The minerals from several outstanding localities for dunite have been studied. These localities include Dun Mountain, South Island, New Zealand; Webster, North Carolina; New Caledonia; and Twin Sisters, Washington. A few descriptions of other localities are cited from the literature.

Dun Mountain, New Zealand: The Dun Mountain locality, near the city of Nelson in the northern part of South Island, New Zealand, is the type locality for the nearly pure olivine rock first called dunite by Hochstetter in 1859 (see also 1864). The dunite from the Nelson district has been briefly described by James Mackintosh Bell, and his coauthors Patrick Marshall and E. de C. Clarke (1911, p. 29-40). The dominant rocks of the area are dunite and its alteration product serpentine. The crystal fabric of this dunite has been studied by Turner (1942), and its serpentinization by Benson (1918).

Bell and associates (1911, p. 30) in discussing the dunite say, "Dunites have their most conspicuous exposure in the neighborhood of Dun Mountain. They consist almost entirely of olivine, but in all cases there are grains of a spinellid mineral which appears to vary between chromite and picotite. . . . There are occasional crystals of diopside in the dunite."

Harzburgite is described as composed of olivine, enstatite, and picotite; and in general it is strongly serpentinized. Another type of rock is composed of diallage, enstatite, and picotite and occurs in dikes that cut the dunite and harzburgite. Material of this type, collected by Ross, seems to represent partly serpentinized harzburgite or a phase intermediate between dunite and harzburgite. This rock contains olivine, bronzite or enstatite, chromian diopside, and the chromian spinel.

The nearly pure dunite mass resists erosion more effectively than the serpentinized phases, and forms bold outcrops of rocks which are red brown on the surface, thus giving the name to Dun Mountain and later the name dunite to the rock. Below a thin, outer oxidized film the dunite is remarkably fresh, and excellent material was obtained by Ross.

The most typical dunite at Dun Mountain is more than 90 per cent olivine (Table 4, No. 15), a few per cent chromian spinel (represented in Table 7, No. 15), and mere traces of the green chromian diopside. The chromian diopside was too sparse for separation in amounts adequate for chemical analysis, but the results of spectrographic study are given in Table 10, No. 15. Another type of rock from Dun Mountain is dominantly olivine but contains 10 to 15 per cent enstatite, which is represented in Table 5, No. 15. Like all specimens from Dun Mountain it contains traces of chromian diopside, whose green color contrasts so strongly with the pale color of the olivine that the merest traces are recognizable.

Webster, North Carolina: The dunite at Webster, North Carolina, is only locally serpentized, and much of it and the associated websterite are remarkably fresh. This is the type locality for websterite, a rock composed of enstatite, chromian diopside, and sparse, disseminated chromite. This rock was the source of the minerals used in this study, of which chemical analyses are given in Tables 4 to 7, No. 13.

The geologic relations in the region are given in the section on the origin of dunites.

New Caledonia: The New Caledonia material was part of the country rock associated with a chrome ore mine near Noumea. The peridotite of this part of New Caledonia is in general thoroughly serpentized, but a few specimens were collected by Ross that contained essential amounts of olivine and enstatite. The alteration complicated the separation of fresh minerals, but nearly pure olivine and enstatite were obtained. The alteration also obscured mineral relations, and the presence or absence of small amounts of monoclinic pyroxene could not be established. The analysis of the olivine is presented in Table 4, No. 14, and of the enstatite in Table 5, No. 14.

Lacroix (1942, p. 13–18), discussing the typical dunites of New Caledonia, says that they may be composed of olivine with or without “bronzite” and with spinel or chromite. Other phases of the peridotites are harzburgite composed of olivine, bronzite, picotite, and a mineral Lacroix calls clino-bronzite; bronzitite, a rock composed essentially of bronzite; and websterite, composed of bronzite and diopside.

Twin Sisters, Washington: One of the large dunite bodies of the world is that in the Twin Sisters area, about 20 miles east of Bellingham, Washington. It has been described by Thayer (personal communication) as follows: “The Twin Sisters dunite and olivine-rich saxonite form an oval pluton about 10 miles long by 4 miles wide. This rock is free from serpentine except around the margin and along throughgoing fracture zones. A large proportion of the rock is a pyroxene-free dunite, characterized by ragged, green olivine grains up to 5 cm. long, in a matrix of fine-grained olivine [Table 4, No. 12]. Saxonite containing 10 to 20 per cent enstatite probably forms two-thirds to three-fourths of the pluton, and pyroxene-rich peridotite probably constitutes 5 per cent or less. The chromite deposits range from small massive pods or lenses to elongate schlieren of disseminated chromite. Clinopyroxene of bright green color occurs along a well-defined fracture zone (Table 6, No. 12).”

Methods of Separation and Chemical Analysis

Chemical analyses of four minerals—olivine, orthorhombic pyroxene (enstatite), monoclinic pyroxene (chromian diopside), and chromian spinel—characteristically present in dunites and in nodules in basaltic

rocks made in the course of this study are presented in Tables 4 to 7, spectrographic determinations of minor elements in the same samples are shown in Tables 8 to 11, and the localities from which the specimens were obtained are shown in Table 3. Analyses by earlier workers of the minerals in nodules are given in Tables 13 to 16, and the localities represented by these analyses are given in Table 12. It should be noted that the results of the spectrographic determinations are reported in terms of the element, whereas the results of chemical analysis are reported in terms of the oxides.

TABLE 3. LOCALITIES OF SAMPLES ANALYZED IN TABLES 4 TO 11

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1. Camargo, Chihuahua, Mexico.
 2. Ludlow, California.
 3. Peridot Cove near Globe, Arizona (Lausen, 1927).
 4. Dreiser Weiher, Eifel, Germany (Frechen, 1948).
 5. Kapfenstein, Styria, Austria (Heritsch, 1908).
 6. Near Meng-Chian, Tun-hua State, east Manchuria.
 7. Ichinomegata, Akita Prefecture, Japan.
 8. Salt Lake Crater, Oahu, Hawaiian Islands.
 9. Kauai, Hawaii, Grove Farm Quarry, southwest of Librue.
 10. Hale Pohaku, south flank of Mauna Kea, Hawaii (Stearns and Macdonald, 1946, p. 163).
 11. 1801 Kaupulehu flow, Hualalai, Hawaii (Stearns and Macdonald, 1946, p. 147).
 12. Twin Sisters, northern Whatcom County, Washington.
 13. Webster, North Carolina.
 14. Noumea, New Caledonia, 10 miles southeast of.
 15. Dun Mountain, New Zealand (Turner, 1942).
-

The separation of essentially pure material for chemical analysis involved much tedious work and the adaptation of methods suitable to the different minerals. Olivine was so abundant and occurred in such large grains in all the samples—except in those from New Caledonia—that it was possible to inspect and hand-pick each grain individually. The New Caledonia olivine was concentrated from a partly serpentinized rock by means of heavy solutions. Enstatite could be hand-picked in several of the samples; but, in some, selected fragments were crushed and further concentrated by means of heavy solutions. The chromian diopside was least abundant of the silicate minerals and occurred as the smallest grains. Fragments of rock in which it was most abundant were selected by hand-picking, then crushed and further concentrated by means of the Frantz isodynamic separator, and finally hand-picked. The mineral was much more magnetic than the other silicate minerals, and high concentrations could commonly be obtained. The chromian spinel was obtained by selecting rock fragments rich in that mineral and partly con-

TABLE 4. ANALYSES OF OLIVINES
[M. D. Foster, analyst]

	From inclusions in basaltic rocks															From dunites				
	1	2	3	4	5	6	7	8	9	12	13	14	15							
SiO ₂	40.80	40.91	40.81	40.65	40.61	40.93	40.30	40.87	41.16	40.55	40.88	41.32	40.96							
Al ₂ O ₃	0.00	0.13	0.10	0.24	0.00	0.19	0.25	0.07	0.00	0.05	0.11	0.00	0.21							
Fe ₂ O ₃	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.00							
FeO	8.61	8.96	9.46	9.30	8.96	8.86	10.26	8.72	8.89	7.99	8.28	7.49	7.86							
TiO ₂	0.040	0.010	0.035	0.010	0.010	0.15	0.15	0.020	0.015	0.14	0.015	0.010	0.010							
Cr ₂ O ₃	0.04	0.03	0.03	0.04	0.04	0.05	0.03	0.02	0.02	0.06	0.02	0.04	0.02							
CaO	0.20	0.17	0.07	0.13	0.11	0.08	0.07	0.07	0.07	0.06	0.03	0.29	0.15							
MgO	49.77	48.95	49.12	49.55	49.88	49.52	48.60	49.78	49.56	50.57	50.10	49.56	50.45							
Na ₂ O ¹	0.00	0.02	0.01	0.02	0.01	0.03	0.04	0.01	0.03	0.06	0.02	0.01	0.01							
K ₂ O ¹	0.00	0.00	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.04	0.00	0.00	0.00							
MnO	0.13	0.15	0.15	0.13	0.12	0.11	0.09	0.15	0.15	0.12	0.15	0.15	0.13							
CoO	0.02	0.01	0.013	0.013	0.012	—	—	0.013	0.010	—	0.013	0.011	0.010							
NiO	0.38	0.34	0.28	0.28	0.32	0.30	0.41	0.34	0.30	0.28	0.32	0.31	0.25							
V ₂ O ₅	—	—	—	—	—	—	—	—	—	—	—	—	—							
H ₂ O	0.29	0.20	0.11	0.07	0.05	—	0.33	0.05	0.10	0.13	0.23	0.60	0.29							
Total	100.28	99.88	100.19	100.43	100.12	100.25	100.56	100.11	100.30	100.05	100.17	100.09	100.35							
Specific gravity at 4°C	3.338	3.337	3.349	3.347	3.324	3.342	3.349	3.333	3.334	3.321	3.331	3.293	3.313							

¹ Alkalies determined with flame photometer by S. M. Berthold.

TABLE 5. ANALYSES OF ENSTATHITES
[M. D. Foster, analyst]

	From inclusions in basaltic rocks															From dunites				
	1	2	3	4	5	6	7	8	9	13	14	15	13	14	15					
SiO ₂	55.04	54.40	53.84	53.92	55.70	54.86	54.78	55.38	54.85	56.33	54.82	51.56	56.33	54.82	51.56					
Al ₂ O ₃	3.91	4.10	4.80	5.32	2.56	2.66	3.50	2.97	2.18	1.28	1.00	1.60	1.28	1.00	1.60					
Fe ₂ O ₃	0.00	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00					
FeO	5.93	6.83	6.21	6.10	5.77	6.32	6.86	5.66	5.99	7.75	5.28	6.72	7.75	5.28	6.72					
TiO ₂	0.10	0.003	0.03	0.007	0.02	0.28	0.15	0.05	0.033	0.58	0.020	0.16	0.58	0.020	0.16					
Cr ₂ O ₃	0.34	0.76	0.90	0.94	0.73	0.80	0.55	0.80	0.80	0.58	0.80	0.63	0.58	0.80	0.63					
CaO	1.02	0.82	1.00	1.36	0.75	0.60	0.62	0.74	1.72	1.03	0.60	0.93	1.03	0.60	0.93					
MgO	33.56	32.84	32.48	32.45	33.86	34.14	33.28	34.19	33.72	32.74	35.62	37.88	32.74	35.62	37.88					
Na ₂ O ²	0.00	0.04	0.15	0.08	0.11	—	0.07	0.06	0.08	0.02	—	—	0.02	—	—					
K ₂ O ²	0.00	0.00	0.00	0.00	0.00	—	0.03	0.00	0.07	0.00	—	—	0.00	—	—					
MnO	0.15	0.13	0.12	0.12	0.10	0.12	0.13	0.12	0.09	0.12	0.09	0.12	0.12	0.09	0.12					
CoO	—	0.005	—	0.005	—	—	—	0.005	—	0.005	—	—	0.005	—	—					
NiO	0.07	0.07	0.07	0.07	0.10	—	0.09	0.07	0.08	0.04	0.05	0.15	0.04	0.05	0.15					
V ₂ O ₅	0.02	—	—	—	—	0.01	0.01	—	—	—	—	—	—	—	—					
H ₂ O	0.20	0.15	—	0.08	0.10	—	0.13	0.14	0.18	0.19	—	—	0.19	—	—					
Total	100.34	100.14	99.76	100.44	99.80	99.79	100.07	100.18	99.79	100.10	98.29 ¹	99.75	100.10	98.29 ¹	99.75					
Specific gravity at 4° C	3.304	3.305	3.279	3.312	3.297	3.298	3.304	3.278	3.291	3.302	3.211	3.302	3.302	3.211	3.302					

¹ May be partly serpentinized.

² Alkalies determined with flame photometer by S. M. Berthold.

TABLE 6. ANALYSES OF CHROMIAN DIOPSIDES
[M. D. Foster, analyst]

	From inclusions in basaltic rocks													From dunites	
	1	2	3	4	5	7	8	9	11	12	13				
SiO ₂	51.78	51.42	50.36	51.17	52.48	51.41	52.12	51.87	50.24	53.88	53.89				
Al ₂ O ₃	5.14	5.97	6.58	6.46	3.56	4.69	4.08	1.72	4.57	0.68	0.72				
Fe ₂ O ₃	1.75	1.43	1.53	0.85	1.13	0.69	0.82	1.61	2.53	0.16	0.00				
FeO	2.14	2.57	2.66	2.87	2.52	2.64	2.24	3.66	4.04	2.11	2.42				
TiO ₂	0.38	0.24	0.79	0.28	0.62	0.33	0.80	0.65	0.72	0.14	0.13				
Cr ₂ O ₃	0.95	0.80	0.92	1.20	2.12	1.03	1.44	1.07	1.22	0.87	0.69				
CaO	20.32	19.95	18.78	18.27	19.00	21.63	19.34	20.92	19.96	22.38	23.56				
MgO	16.04	16.17	16.59	17.65	17.03	16.32	16.48	17.94	16.53	18.84	17.84				
Na ₂ O ¹	1.06	1.36	1.41	1.20	—	0.72	2.14	0.33	0.58	0.78	0.52				
K ₂ O ¹	0.08	0.10	0.08	0.08	—	0.04	0.08	0.02	0.04	0.04	0.10				
MnO	0.12	0.15	0.09	0.16	0.15	0.11	0.09	0.06	0.13	0.07	0.12				
CoO	—	—	—	—	—	—	—	—	—	—	—				
NiO	0.041	0.045	0.037	0.036	0.034	0.040	0.041	0.040	—	0.039	0.028				
V ₂ O ₅	0.04	0.03	0.03	0.03	0.04	0.05	0.03	—	—	0.02	0.01				
H ₂ O	—	—	—	0.14	—	0.11	—	0.08	—	0.14	0.10				
Total	99.84	100.24	99.86	100.40	98.53	99.81	99.70	99.97	100.39	100.15	100.13				
Specific gravity at 4° C	3.322	3.329	3.323	3.311	3.332	3.311	3.312	3.320	3.305	3.271	3.303				

¹ Alkalies determined with flame photometer by S. M. Berthold.

TABLE 7. ANALYSES OF CHROMIAN SPINELS AND CHROMITES
[M. D. Foster, analyst]

	From inclusions in basaltic rocks										From dunites				
	1	2	3	4	5	7	7a ¹	8	9	10	11	12	15		
SiO ₂	0.46	0.44	—	0.43	—	4.10	—	—	0.22	0.18	0.50	0.86	0.40		
Al ₂ O ₃	47.63	41.68	—	27.81	—	48.06	53.43	—	19.29	24.06	26.93	8.81	13.37		
Fe ₂ O ₃	2.67	7.96	27.86 ²	7.84	29.81 ²	14.29 ²	0.00	20.62 ²	15.62	18.22	16.48	5.72	8.51		
FeO	9.86 ³	8.64 ³	—	6.81 ³	—	—	13.15 ³	—	16.68 ³	15.65 ³	15.37	17.96	13.90 ³		
TiO ₂	0.44	2.71	—	2.11	8.50	1.25	1.39	4.80	1.60	1.40	2.20	1.40	1.65		
Cr ₂ O ₃	19.24	18.34	11.47	14.05	32.87	11.00	12.23	28.29	34.87	27.30	24.54	55.17	48.48		
CaO	0.20	0.00	—	0.04	—	0.55	0.60	—	0.08	0.12	0.00	0.20	0.04		
MgO	19.22	19.71	—	20.69	—	21.30	18.29	—	12.14	12.92	13.66	10.02	13.23		
Na ₂ O	0.00	—	—	—	—	—	—	—	—	—	—	—	—		
K ₂ O	0.00	—	—	—	—	—	—	—	—	—	—	—	—		
MnO	0.15	0.13	—	0.12	—	0.11	0.11	—	0.18	0.15	0.15	0.16	0.07		
CoO	—	—	—	—	—	—	—	—	—	—	—	0.002	—		
NiO	—	—	—	—	—	—	—	—	—	—	0.07	—	—		
V ₂ O ₅	0.04	—	—	—	—	—	—	—	—	—	—	—	—		
H ₂ O	—	—	—	—	—	—	—	—	—	—	—	—	—		
Total	99.91	99.61	—	99.90	—	100.66	99.20	—	100.68	99.98	99.90	100.30	99.65		
Specific gravity at 4° C	3.850	3.905	—	3.913	—	3.886	—	—	4.395	4.293	—	4.289	4.396		

¹ Recalculated from 7, high SiO₂ of which indicates contamination by olivine.

² Total iron as Fe₂O₃.

³ Calculated to give 1:1 ratio of RO:R₂O₃.

TABLE 8. SPECTROGRAPHIC DETERMINATION OF MINOR ELEMENTS IN OLIVINES

[A. T. Myers, analyst]

	From dunites														
	1	2	3	4	5	6	7	8	9	12	13	14	15		
Mn	0.14	0.12	0.12	0.12	0.10	0.10	0.12	0.11	0.13	0.14	0.11	0.12	0.11		
Ni	0.44	0.25	0.25	0.30	0.30	0.30	0.35	0.35	0.35	0.25	0.30	0.25	0.25		
Cr	0.028	0.015	0.015	0.025	0.020	0.040	0.010	0.010	0.015	0.035	0.010	0.035	0.015		
Co	0.016	0.016	0.016	0.018	0.015	0.016	0.016	0.016	0.018	0.02	0.015	0.015	0.017		
Ti	0.004	0.001	0.008	0.006	0.003	0.004	0.003	0.003	0.002	—	0.0008	0.004	0.002		
V	—	—	—	—	—	—	—	—	—	—	—	0.003	0.001		
Ca	0.075	0.07	0.05	0.07	0.04	0.0X	0.0X	0.05	0.05	0.02	0.02	0.2	0.07		
Al	—	0.036	0.032	0.048	0.027	—	—	0.032	0.024	—	0.024	0.032	0.018		

Looked for but not found: Ag, As, B, Ba, Be, Bi, Cd, Ga, Ge, In, La, Li,¹ Mo, P,² Pb, Sb, Sr, Y, Zn, and Zr.

¹ Li present at about the 0.000X order.

² Not present at 0.5 per cent or more.

TABLE 9. SPECTROGRAPHIC DETERMINATION OF MINOR ELEMENTS IN ENSTATITES
[A. T. Myers, analyst]

	From inclusions in basaltic rocks															From dunites				
	1	2	3	4	5	6	7	8	9	13	14	15	13	14	15					
Mn	0.16	0.12	0.10	0.09	0.10	0.08	0.10	0.08	0.08	0.08	0.10	0.06	0.11	0.06	0.11					
Ni	0.080	0.070	0.065	0.070	0.070	0.065	0.060	0.065	0.050	0.065	0.060	0.050	0.040	0.050	0.060					
Cr	0.36	0.25	0.30	0.40	0.45	0.30	0.25	0.45	0.35	0.45	0.30	0.40	0.25	0.30	0.40					
Co	0.006	0.005	0.005	0.005	0.006	0.008	0.008	0.006	0.005	0.006	0.008	0.004	0.007	0.004	0.005					
Ti	0.09	0.04	0.20	0.07	0.06	0.04	0.12	0.03	0.02	0.03	0.02	0.02	0.02	0.002	0.01					
V	0.010	0.007	0.007	0.008	0.006	0.008	0.007	0.008	0.008	0.008	0.007	0.008	0.004	0.003	0.010					
Y	—	—	0.001	—	—	—	—	—	—	—	—	—	—	—	—					
Ca	—	0.6	0.8	0.9	0.8	0.5	0.6	0.5	1.2	0.5	0.6	0.5	0.9	0.5	0.9					

Looked for but not found: Ag, As, B, Ba, Be, Bi, Cd, Ga, Ge, In, La, Li, Mo, P,¹ Pb, Sb, Sr, Y, Zn, and Zr.

¹ Not present at 0.5 per cent or more.

TABLE 10. SPECTROGRAPHIC DETERMINATION OF MINOR ELEMENTS IN CHROMIAN DIOPSIDES

[A. T. Myers, analyst]

	From inclusions in basaltic rocks															From dunites				
	1	2	3	4	5	6	7	8	9	12	13	14	15							
Mn	0.11	0.12	0.08	0.12	0.12	0.10	0.09	0.08	0.08	0.10	0.10	0.05	0.10	0.10						
Ni	0.038	0.030	0.030	0.035	0.030	0.040	0.030	0.030	0.030	0.035	0.040	0.035	0.025	0.050						
Cr	1.24	0.65	0.70	0.80	1.5	0.85	0.70	1.0	0.75	0.8	0.45	0.75	0.45	0.65						
Co	0.005	0.004	0.005	0.005	0.004	0.004	0.004	0.004	0.005	0.004	0.005	0.005	0.005	0.005						
Ti	0.30	0.2	0.6	0.2	0.2	0.15	0.45	0.1	0.1	0.02	0.01	0.08	0.01	0.01						
V	0.044	0.02	0.02	0.02	0.02	0.02	0.04	0.02	0.02	0.02	0.02	0.008	0.008	0.02						
Y	—	0.004	0.005	0.004	0.001	0.002	0.004	0.002	0.002	—	—	—	—	—						
Sr	—	0.002	0.01	0.002	0.008	0.002	Tr.	0.02	0.0007	0.003	0.001	0.0004	0.0004	0.002						
Ba	—	—	—	—	—	0.000X	0.000X	—	—	—	—	—	—	—						
Zr	—	—	0.00X	—	0.00X	—	—	0.00X	0.X	—	—	—	—	—						

Looked for but not found: As, Ag, B, Be, Bi, Cd, Ga, In, La, Li, Mo, P, ¹Pb, Sb, and Zn.

¹ Not present at 0.5 per cent or more.

TABLE 11. SPECTROGRAPHIC DETERMINATION OF MINOR ELEMENTS IN CHROMIAN SPINELS AND CHROMITES

[A. T. Myers, analyst]

	From inclusions in basaltic rocks															From dunites		
	1	2	3	4	5	7	8	9	12	14	15							
Mn	0.10	0.07	0.07	0.06	0.12	0.08	0.09	0.15	0.14	0.09	0.14	0.14	0.09	0.14				
Ni	0.20	0.10	0.15	0.10	0.10	0.10	0.10	0.10	0.025	0.08	0.06	0.025	0.08	0.06				
Co	0.010	0.010	0.009	0.008	0.010	0.010	0.010	0.020	0.02	0.02	0.020	0.02	0.02	0.020				
Ti	0.1	0.02	0.3	0.1	0.4	0.04	0.1	0.4	0.06	0.02	0.2	0.06	0.02	0.2				
V	0.03	0.01	0.01	0.01	0.03	0.005	0.02	0.04	0.02	0.02	0.02	0.02	0.02	0.02				
Ga	—	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.001	0.002	0.002	0.001	0.002	0.002				
Ca	—	0.05	0.05	0.05	—	0.0X	0.04	0.07	0.4	0.2	0.04	0.4	0.2	0.04				
Zr	—	—	—	—	—	—	—	0.0X	—	—	—	—	—	—				

Looked for but not found: Ag, As, B, Ba, Bi, Cd, Ge, In, La, Li, Mo, P¹, Pb, Sb, Sr, Y, and Zn.¹ Not present at 0.5 per cent or more.

TABLE 12. LOCALITIES OF SAMPLES FOR ANALYSES QUOTED IN TABLES 13 TO 16

Locality	Author
1. Kosakov, Czechoslovakia	Farsky, 1876, pp. 207-208.
2. Buchberg, near Klein-Iser, Czechoslovakia	Braun, 1922, p. 278.
3. Unterweissenbach, Styria, Austria	Schadler, 1914, p. 491.
4. Kapfenstein, Styria, Austria	Schiller, 1905, p. 316.
5. Lutzelberges, near Sasbach, Kaiserstuhl, Germany	Knop, 1877, pp. 697, 698, 699.
6. Finkenberg, Siebengebirge, near Bonn, Germany	Bleibtreu, 1883, p. 520.
7. Kreuzberg, Rohn, Hesse, Germany	H. Link, 1887, p. 100.
8. Westberges, north of Kassel, W. Germany	Ernst, 1936, p. 652.
9. Stempel, near Marburg, W. Germany	Bauer, 1891, pp. 182, 186.
10. Reichenweiler, Alsace, France	G. Link, 1891, p. 663.
11. Conca de Janas (Orosei), eastern Sardinia	Lauro, 1940, pp. 186, 187, 190, 292.
12. Jan Mayen, an island northeast of Iceland	Scharizer, 1884, p. 708.
13. Vuoka Ruopsok, Sweden	Du Rietz, 1935, pp. 143, 144.
14. Pupuke Lake, Takopuna, New Zealand	Turner and Bartrum, 1928, p. 900

TABLE 13. ANALYSES OF OLIVINES

	1	2	3	5	9	10	11	13	14
SiO ₂	41.22	41.30	40.72	41.19	40.68	41.53	40.99	41.55	41.53
Al ₂ O ₃	0.15	0.17	—	—	—	2.33	—	0.01	0.42
Fe ₂ O ₃	—	0.55	—	—	—	0.58	0.38	7.34	0.10
FeO	9.0	9.81	9.47	8.54	9.19	10.27	8.58	—	8.51
TiO ₂	—	—	—	—	—	—	Trace	—	0.08
Cr ₂ O ₃	0.05	—	—	—	—	—	Trace	—	0.20
CaO	—	0.02	—	—	—	—	0.11	0.03	0.31
MgO	49.42	47.96	49.88	50.27	49.58	43.60	50.00	50.83	47.33
Na ₂ O	—	—	—	—	—	—	—	—	0.11
K ₂ O	—	—	—	—	—	1.69	—	—	None
MnO	0.18	—	—	—	—	—	0.20	—	0.15
CoO	—	—	—	—	0.02	—	—	—	None
NiO	0.29	0.38	—	—	0.50	—	Trace	—	0.44
CuO	—	—	—	—	0.08	—	—	—	—
H ₂ O	—	—	—	—	—	—	—	0.24	+0.24 -0.21
Total	100.31	100.19	100.07	100.00	100.05	100.00	100.16	100.00 ¹	99.70 ²

¹ Calculated after allowing for 6 per cent of enstatite.² Includes 0.02 S, tr. P₂O₅, NoSrO, no BaO, no V₂O₅.

TABLE 14. ANALYSES OF ENSTATITES

	1	3	4	5	6	9	10	11	13	
SiO ₂	56.23	53.29	53.40	54.39	52.50	54.16	55.45	52.67	53.79	55.80
Al ₂ O ₃	2.62	2.77	3.66	1.89	2.29	4.51	4.66	4.84	2.19	4.02
Fe ₂ O ₃	—	—	4.66	2.49	—	—	—	2.07	2.50	0.76
FeO	6.67	15.43	4.04	4.52	6.07	7.63	6.47	5.11	5.99	4.85
TiO ₂	—	—	—	0.12	—	—	—	0.60	Trace	None
Cr ₂ O ₃	0.34	—	0.34	—	0.00	0.48	Trace	—	0.26	0.20
CaO	0.96	1.79	0.75	0.05	4.35	1.97	1.07	1.55	2.08	None
MgO	32.27	27.01	33.16	34.88	32.23	32.46	32.97	32.82	32.20	34.70
Na ₂ O	—	—	—	—	—	—	—	—	—	—
							0.94			
K ₂ O	—	—	—	—	—	—	—	—	—	—
MnO	0.23	—	—	0.21	—	—	—	—	—	—
CoO	—	—	—	—	—	—	—	—	—	—
NiO	—	—	—	—	—	—	—	—	—	—
CuO	—	—	—	—	—	—	—	—	—	—
H ₂ O	0.95	0.35	0.26	1.71	—	0.28	—	—	0.20	0.23
Total	100.28	100.64	100.27 ¹	100.26		101.49	100.62		100.21	100.56

¹ Includes 2.00 per cent residue.

TABLE 15. ANALYSES OF DIOPSIDES

	1	3	5	7	8	9	11	12
SiO ₂	53.44	49.87	51.89	54.50	52.43	52.50	52.37	51.86
Al ₂ O ₃	3.74	5.44	4.76	6.47	4.16	5.19	6.11	1.56
Fe ₂ O ₃	—	2.75	—	—	2.66	—	1.44	2.44
FeO	4.70	2.50	4.40	4.00	3.53	2.31	2.01	3.46
TiO ₂	—	—	—	—	0.37	—	0.29	—
Cr ₂ O ₃	0.75	1.76	1.09	1.98	1.06	2.43	0.05	0.73
CaO	19.90	20.74	19.73	17.87	16.56	19.52	20.88	22.15
MgO	16.19	16.26	15.47	14.58	18.19	18.01	16.72	17.40
Na ₂ O	—	—	—	—	0.90	—	—	—
K ₂ O	—	—	—	—	0.07	—	—	—
MnO	0.31	—	0.54	0.70	0.12	—	0.10	Trace
CoO	—	—	—	—	—	—	—	—
NiO	—	—	—	—	0.08	—	—	—
CuO	—	—	—	—	—	—	—	—
H ₂ O	—	0.55	—	—	—	—	0.09	0.12
Total	99.03	99.87	100.18 ²	100.33 ³	100.37 ⁴	99.96	100.06	99.72

¹ H₂O—, 0.11; H₂O+, 0.09.

² Includes 2.30 per cent residue.

³ Includes 0.23 per cent BaO, 0.01 per cent V₂O₅.

⁴ Includes 0.03 per cent BaO and 0.01 per cent V₂O₅.

TABLE 16. ANALYSES OF PICOTITES

	1	5	9	11	11a ¹
SiO ₂	1.25	—	—	4.30	—
Al ₂ O ₃	52.47	20.06	39.91	31.43	34.92
Fe ₂ O ₃	21.42	—	—	22.60	15.38
FeO	—	12.98	26.64		10.27
TiO ₂	—	—	—	—	—
Cr ₂ O ₃	7.01	46.87	30.33	19.50	21.67
CaO	Trace	—	—	—	—
MgO	18.23	20.55	3.26	21.33	17.76
Na ₂ O	—	—	—	—	—
K ₂ O	—	—	—	—	—
MnO	—	—	—	—	—
CoO	—	—	—	—	—
NiO	—	—	—	—	—
H ₂ O	—	—	—	—	—
Total	100.38	100.46	100.14	99.06	—

¹ High SiO₂ content in sample 11 indicates contamination (olivine); sample recalculated in 11a.

centrating it with the Frantz isodynamic separator. This fraction was then crushed to a very fine size and briefly treated with sulfuric acid. The spinel was completely unattacked, but the surface alteration of the admixed olivine made it possible to float off the chromian spinel in methylene iodide.

Previous writers have commonly referred to the orthopyroxene as bronzite, and that name appears in most of the quotations cited. However, magnesium is strongly dominant over ferrous iron (about 33 per cent MgO to 6 per cent FeO) and enstatite is the better name. The chromian spinel has commonly been called picotite, but chromian spinel seems the best name where Cr₂O₃ is a dominant constituent.

The analyses were made according to the usual methods of rock analysis as described by Hillebrand and Lundell (1929) except for sodium and potassium, which were determined with the flame photometer by S. M. Berthold. Because of the small amount of material available for analysis on some of the samples, it was not always possible to determine Na₂O, K₂O, and H₂O, and for all the samples it was necessary to adopt a scheme of analysis that would permit the determination of as many constituents as possible on a single fraction. Thus, in the analysis of the olivines and pyroxenes, Cr₂O₃, V₂O₅, and CoO, as well as TiO₂, were determined on the SiO₂/R₂O₃ fraction (see Foster 1946, p. 15–18). After titration of total iron, subsequent to reduction in the Jones reductor, R₂O₃ was again precipitated. Separation of Fe₂O₃, TiO₂, and CoO from Cr₂O₃

and V_2O_5 was effected by fusion of this second R_2O_3 precipitate, after drying, in a porcelain crucible with Na_2O_2 followed by a water leach and filtration.

Because spectrographic determinations showed TiO_2 to be very low, iron was removed by ether extraction before determination of TiO_2 with H_2O_2 . After removal of H_2O_2 , CoO was determined on the same solution, using NH_4CNS and acetone. CaO and MnO were separated and determined on the magnesium precipitate after ignition and weighing, and NiO was determined on the fraction used for determination of ferrous iron, subsequent to titration of ferrous iron and removal of HF and H_2SO_4 .

As sodium carbonate, used to break down the olivines and pyroxenes, is not effective for the breakdown of chromian spinels and chromites, a different method of attack was required. The scheme of analysis used for these minerals is shown in Table 17.

TABLE 17. CHEMICAL PROCEDURE FOR CHROMIAN SPINELS AND CHROMITES

Fuse 0.5 sample with $NaHSO_4$, dissolve fusion in 1:5 H_2SO_4 , evaporate to fumes, dilute, digest, and filter

<i>Precipitate:</i> SiO_2 —ignite and weigh.	<i>Filtrate:</i> Sulfates of R_2O_3 group, Ca, Mg and Mn. Make double NH_4OH precipitation; filter.	
	<i>Precipitate:</i> Hydroxides of Al, Fe, Ti, Cr. Ignite and weigh, fuse in porcelain crucible with Na_2O_2 , leach, digest, filter.	<i>Filtrate:</i> Sulfates of Ca, Mg, and Mn. Precipitate and weigh as pyrophosphates, dissolve in dilute H_2SO_4 and determine CaO and MnO, obtain MgO by difference.
	<i>Precipitate:</i> Oxides of Fe and Ti. Dissolve in H_2SO_4 , dilute, reduce in Jones reductor and titrate to obtain total iron, add H_2O_2 , determine TiO_2 colorimetrically.	<i>Filtrate:</i> Na_2CrO_4 —Boil to eliminate H_2O_2 , acidify with H_2SO_4 , titrate with $FeSO_4$ and $KMnO_4$. Al_2O_3 by difference: Total weight R_2O_3 minus Fe_2O_3 , TiO_2 , Cr_2O_3 .

On those chromian spinel samples for which less than 0.2 was available for analysis, only Fe_2O_3 , TiO_2 , and Cr_2O_3 were determined.

The chemical and spectrographic results were in good agreement for all the minor elements except titanium. The tendency for discrepancies in the determination of titanium has been recognized previously, and the causes are to be the subject of further study.

Discussion of Chemical and Mineralogical Studies

The distribution of the major constituents in the four minerals—olivine, enstatite, chromian diopside, and chromian spinel—from olivine inclusions in basaltic rocks and from dunites is shown in Fig. 1. The high, low, and average values obtained for each constituent are shown enclosed in brackets, except those values that are so nearly the same that they are represented by two points, or only one. Both ferrous and ferric iron are included in the value shown as Fe_2O_3 , although in the olivines and enstatites iron was present as ferrous iron only.

The small range in the values for the different constituents in the silicate minerals from inclusions and from dunites—olivine, enstatite, and chromian diopside—is striking. This is particularly true of the olivines, in which, for all the specimens analyzed regardless of source, there is a range of not more than 1 per cent in the silica content, not more than 2 per cent in the magnesia content, and not more than 3 per cent in FeO content. With regard to the FeO content, however, a slight differentiation may be made between the olivines from inclusions and those from dunites, in that the FeO content of the dunite olivines falls in the lower part of the range, and the FeO content of olivines from inclusions falls in the upper part. All the iron in the olivines is present as ferrous iron. The average aluminum content of the olivines is 0.10 per cent.

In the enstatites from dunite the range between high and low values for silica and magnesia is about 5 per cent, but in the enstatites from inclusions the range for these constituents is not more than 2 per cent. All the values for silica in enstatites from inclusions lie in the upper part of the range of values for silica in enstatites from dunites. On the other hand, the values for MgO in enstatites from inclusions lie in the lower part of the range of values for MgO in enstatites from dunites. The range between high and low values for FeO in all the enstatites is not more than 3 per cent, with the values for FeO in enstatites from dunites falling in the median part of the range. One enstatite contains 0.16 per cent of Fe_2O_3 ; in the others, all the iron is present as ferrous iron. Al_2O_3 in the enstatites from inclusions averages 3.55 per cent and ranges from 2.18 per cent to 5.32 per cent; in the enstatites from dunites, it averages only 1.30 per cent and ranges from 1.00 per cent to 1.60 per cent.

The chromian diopsides from dunites are slightly higher in SiO_2 and CaO content and slightly lower in total iron content—as Fe_2O_3 —than the chromian diopsides from inclusions. The range between high and low values for these constituents in all the chromian diopsides, however, is less than 4.50 per cent. For MgO the range is less than 3 per cent. The greatest divergence in average content between diopsides from inclusions

and diopsides from dunites appears in the Al_2O_3 ; in the inclusions the average Al_2O_3 content is 4.80 per cent; in the dunites it is only 0.70 per cent.

Much greater differences were found in the composition of the chromite and chromian spinels than in the composition of the three silicate minerals. The disseminated type of chromite was obtained in sufficient amounts for analysis in only two of the dunite samples. These two samples were similar in composition and were much higher in Cr_2O_3 content than any of the chromian spinels from the inclusions. In fact they may be classified as true chromites, whereas none of the spinels from the nodules could be so classified. The nodules differ greatly among themselves in Fe_2O_3 , Cr_2O_3 , and especially Al_2O_3 content, ranging from 14.29 to 29.81 per cent in iron as Fe_2O_3 , from 11.00 to 32.87 per cent in Cr_2O_3 content, and from 19.29 to 53.43 per cent in Al_2O_3 content. On the other hand, in the chromite from dunite the Al_2O_3 ranges from 8.81 to 13.37 per cent, Cr_2O_3 from 48.48 to 55.17 per cent, and MgO from 10.02 to 13.23 per cent.

The distribution of the minor constituents— NiO , MnO , and Cr_2O_3 —is shown in Fig. 2, plotted on a scale 25 times that used in Fig. 1. The amounts of the minor constituents in the olivines from the nodules are almost identical with the amounts of the same constituents in the olivines from dunites, and the range of values is very small. This is also true of the MnO and NiO content in the enstatites and chromian spinels. The Cr_2O_3 content of the enstatites and chromian diopsides on the other hand, is much more variable, particularly in the minerals from the nodules. The average content of Cr_2O_3 in the enstatites from the nodules is very close to the average content of Cr_2O_3 in enstatites from dunites. However, the average content of Cr_2O_3 in chromian diopsides from the nodules is about 0.4 per cent higher than the average content of Cr_2O_3 in diopsides from dunites. The Cr_2O_3 content of most of the chromian diopsides from the nodules, however, was in the lower part of the range indicated in Fig. 2; in fact, only one specimen contained more than 1.5 per cent Cr_2O_3 .

The relationship of NiO to the major elements should be noted. A comparison shows that the average ratio of NiO to MgO is 0.663 in olivine, 0.023 in enstatite, and 0.002 in diopside. On the other hand, the ratio of NiO to FeO is about 0.036 in olivine, 0.02 in enstatite, and 0.015 in diopside. Therefore, the NiO does not follow the MgO but maintains roughly the same proportion to FeO in the three silicate minerals.

There is a progressive decrease in NiO content from the olivine through the enstatite to the chromian diopside. There is a marked increase in the Cr_2O_3 content in this series of minerals but the MnO content is remarkably constant throughout the whole suite of minerals.

DISTRIBUTION OF MAJOR CONSTITUENTS IN MINERALS IN OLIVINE INCLUSIONS FROM BASALTIC ROCKS AND IN DUNITES

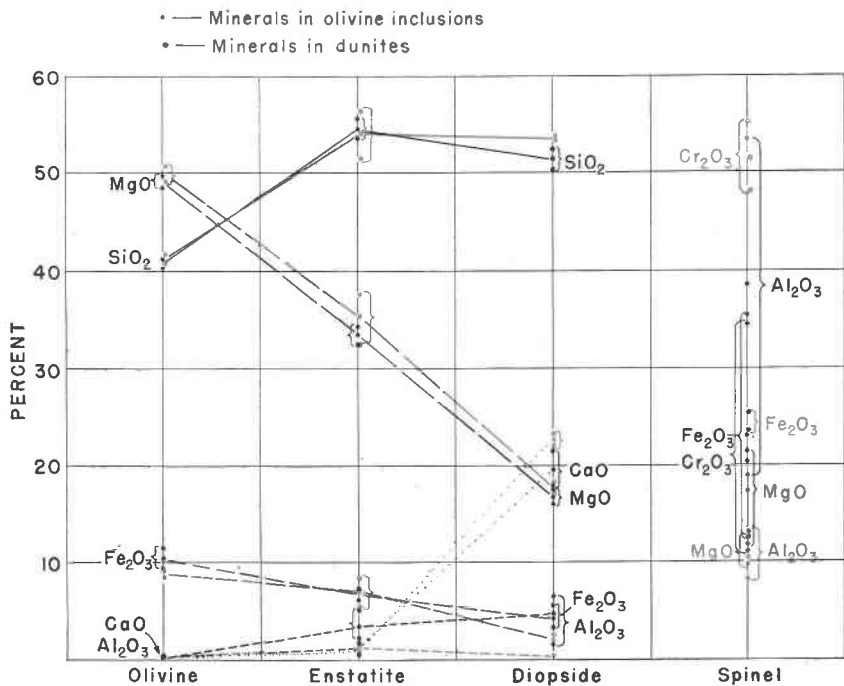


Figure 1

DISTRIBUTION OF MINOR CONSTITUENTS IN MINERALS IN OLIVINE INCLUSIONS FROM BASALTIC ROCKS AND IN DUNITES

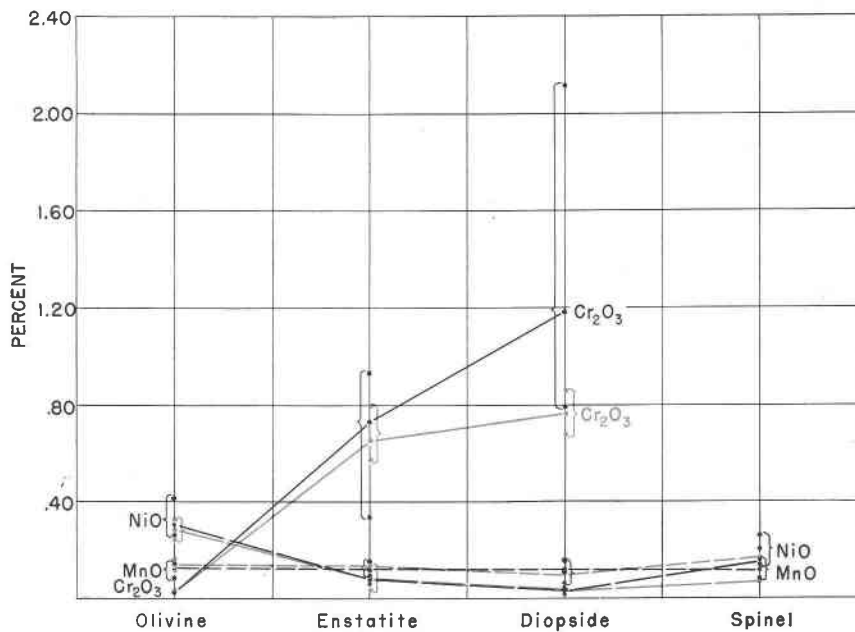


Figure 2

The CoO content is very low, amounting, in general, to only 5 to 10 per cent of the NiO content.

Relation to Host Rocks

Several workers, including Ernst (1936), Frechen (1948), and Turner and Bartrum (1928, p. 899), have made important contributions to an understanding of the relationship between the nodular inclusions, and the rocks in which they occur. Chemical analyses of five of these rocks are given in Table 20. The mode of No. 2 is given in Table 18 and of No. 4 in Table 19. The norms of the five rocks are given in Table 21.

- No. 1. Olivine basalt, 1801 Kaupulehu flow of Hualalai, Hawaii. Host rock of minerals listed as No. 11 in Tables 4 to 7, collected by Dr. Macdonald, analyzed by H. M. Hyman, U. S. Geological Survey. The minor elements determined by A. A. Chodos, U. S. Geological Survey, as follows:
 Ni 0.03, Co 0.006, Cr 0.04, Cu 0.02, V 0.03, Ga 0.001, Sc 0.002, Ba 0.06, Sr 0.1, Y 0.004, Yb 0.0003, Zr 0.02. Looked for but not found: Pb, Be, Ag, Au, Pt, Mo, W, Ge, Sn, As, Sb, Bi, Zn, Cd, Tl, In, La, Nb, Ta, Th, U, B.
- No. 2. Olivine melilitite forming matrix around olivine inclusion from Westberges near Hofgeismar, north of Kassel, Germany, analyzed by Theodor Ernst (1936, p. 647). The mode determined by Ernst as follows:

TABLE 18. MODE OF OLIVINE MELILITITE FROM WESTBERGES

Olivine	30	Apatite	3
Augite	34	Magnetite	} 7
Melilitite	7	Chromite	
Perovskite	2	Nepheline	} 14
Hauyne	1	(interstitial)	

- No. 3. Olivine basalt from Finkenbergl, Siebengebirge, near Bonn, Germany, described by Frechen (1948, p. 321). Dr. M. Hartwig-Bendig, analyst.
- No. 4. Olivine melilitite forming host rock for olivine inclusions from Hochbol Swabia, Germany. Cited by Ernst (1936, p. 659), analyzed by Wohlmann, described by Tröger (1934, p. 153).
- No. 5. Basalt from Ichinomegata, Akita Prefecture, Japan. T. Katura, analyst. Analysis received through the courtesy of Dr. Kuno.

TABLE 19. MODE OF OLIVINE MELILITITE FROM HOCHBOL

Olivine	23	Biotite	} 4
Augite	19	Perovskite	
Melilitite	44	Apatite	
Nepheline	6	Calcite	
Ores	4	Chromite	

TABLE 20. CHEMICAL ANALYSES OF NODULE-BEARING ROCKS

	1	2	3	4	5
SiO ₂	46.64	37.09	41.72	36.64	51.24
Al ₂ O ₃	14.45	8.49	13.04	7.96	17.98
Fe ₂ O ₃	3.18	5.65	2.68	6.19	3.30
FeO	9.77	6.53	10.00	5.59	6.61
TiO ₂	2.35	2.43	2.73	2.50	1.51
Cr ₂ O ₃	—	0.13	0.06	—	—
CaO	9.86	14.09	10.82	15.11	6.98
MgO	9.33	17.36	9.00	18.15	4.62
Na ₂ O	2.84	2.85	3.74	2.85	5.39
K ₂ O	0.97	1.56	0.88	1.44	2.10
MnO	0.19	0.19	0.18	0.17	—
NiO	—	0.11	—	—	—
BaO	—	—	0.07	0.05	—
ZrO ₂	—	—	0.03	0.03	—
CO ₂	0.01	—	3.19	0.53	—
P ₂ O ₅	0.34	0.99	0.58	0.91	—
H ₂ O—	0.00	0.45	0.27	0.03	—
H ₂ O+	0.06	2.16	0.92	1.56	0.35
Total	99.99	100.23 ¹	100.02 ²	99.71	100.08

¹ Includes 0.15 per cent SO₃.² Includes 0.11 per cent Cl.

TABLE 21. NORMS OF NODULE-BEARING ROCKS

	1	2	3	4	5
or					
ab	8.91		7.86		30.41
an	23.92	5.56	16.97	4.73	18.64
lc	4.36	7.42	3.93	6.55	9.60
ne	8.24	13.07	12.21	13.07	8.24
wo	9.64	19.28	5.34	19.51	6.74
en	23.19		22.38		11.54
fs	11.89		12.00		6.86
fo		30.39		31.56	
fa		3.06		1.02	
cs		3.63		4.48	
mt	4.63	8.10	3.94	9.03	4.86
il	4.40	4.55	5.16	4.70	2.88
ap	0.67	2.35	1.34	2.02	
hl			0.12		
cc			7.31	1.20	
	99.85	97.41	98.56	97.87	99.77

The modes and norms show that the nodules occur in rare rock types as well as in more normal olivine basalts. In four of the six rock analyses, Cr_2O_3 was determined and ranges from 0.06 to 0.19 per cent. However, even this Cr_2O_3 content is higher than that found in average basalts. Ten basaltic rocks from the Hawaiian Islands have been tested by spectrographic methods by K. J. Murata of the U. S. Geological Survey. Chromium was determined as Cr but has been recalculated to Cr_2O_3 for purposes of comparison; these rocks contain about 0.025 to 0.077 per cent Cr_2O_3 . A group of rocks from the Paricutin Volcano in Mexico contain from 0.025 to 0.034 per cent Cr_2O_3 . It thus seems improbable that basaltic rocks are normally high enough in chromium to produce silicate minerals and spinels that contain unusually high percentages of that element.

ORIGIN OF DUNITE

The senior author is acquainted with the dunite bodies of Pennsylvania, Maryland, and Georgia. He has also visited but not studied in detail those of Cuba, the South Island of New Zealand and New Caledonia. He has long been familiar with several dunite bodies of North Carolina, and it is on these that he bases his discussion of the bearing of the geologic relationships, upon the origin of dunites and related peridotites, particularly those of the Webster area. These bodies are the basis of comparisons with other dunite areas visited, and with the studies of other geologists.

North Carolina

The serpentinization in the dunite bodies of western North Carolina is very local, and large parts of these bodies are almost completely unaltered. Fresh and nearly pure olivine rocks are well exposed at such localities as Webster, Balsam Gap, Addy, Dark Ridge, and Democrat. In many places the contacts with the country rocks are well exposed. Much of the dunite contains 90 per cent or more of olivine, and locally disseminated chromite, rare single grains of enstatite, and conspicuous but rare grains of green chromian diopside may be present. The dunite itself in general is rather evenly granular, but in some places, notably at Addy, there is a great range in the size of the olivine grains. Crystals up to 4 cm. in diameter are commonly enclosed in a matrix of crushed grains, so that parts of the rock resemble a crush breccia. A part of a crystal unit 10 cm. in length has been observed that probably represents about half of the original crystal.

Webster is also the type locality for websterite, the orthopyroxene-diopside rock with accessory olivine. This rock forms an elongated mass parallel to the dunite with which it is associated, and of which it is evi-

dently a phase. The pyroxene (chromian diopside) is bright yellowish green (29.GG-Yi, Ridgeway color standards) and so makes a conspicuous outcrop.

Inclusions: Lenses of chromite large enough to have been mined occur within the Webster dunite and also occur in thin stringers. Most significant, however, are rounded masses shaped like a large teardrop, which are abundant at the Dark Ridge locality. The masses are evidently blocks that have been brought up from the depths by the intrusive force of the mushlike olivine, and the tail-like ends represent partly disintegrated and dragged-out portions of the chromite blocks.

In the vicinity of Webster, blocks of almost pure enstatite up to half a meter in diameter have been observed. They form rare but large, conspicuous inclusions in the dunite and smaller inclusions in the websterite. In these masses the individual crystals may reach 30 mm. in length. Millimeter-sized olivine grains make up a small part of the rock and occupy angular spaces between the large enstatite grains; chromite and chromian diopside grains are sparse. Zones of olivine in the enclosing dunite, characterized by variable grain size, form a flow structure that sweeps around some of the enstatite blocks, indicating that at the time of emplacement these blocks were rigid masses, and the olivine was a mushlike crystalline mass that flowed into place around them.

Structure: A marked parallelism of structure is a conspicuous characteristic of the Webster mass. Parallelism is so noticeable that it led early observers to assume that the mass was sedimentary in origin. In the dunite this is caused by persistent shear zones in which the olivine grains are crushed. The shearing has exerted a close control over the degree of serpentinization, so that sheared and serpentinized zones alternate with little-sheared and unserpentinized zones.

The websterite mass is parallel to the border of the dunite, and to the structure within it. The websterite itself shows marked lineation, resulting from parallel alignment of the pyroxene grains. It is also marked by long parallel lenses of nearly pure olivine oriented with the lineation. The websterite with its marked lineation seems to have flowed into position, as did the olivine enclosing the enstatite blocks.

Border Relationships: Between dunite and the enclosing quartz schist there is a zone of hydrothermal minerals (talc, anthophyllite, and vermiculite) that ranges from a few centimeters to a meter or so in width. This zone is composed of the same minerals and shows the same zonal relations as the minerals that have formed on the borders of pegmatite lenses where the pegmatites have locally intruded the dunite at a much later geologic age. Thus, the hydrothermal borders on the dunite are evidently the result of pegmatitic solutions that penetrated along the contacts.

The dunite was intruded at a temperature and in a condition that precluded any marked reaction with the enclosing quartz schist. This condition is significant because of the marked disequilibrium that must have existed between the quartz schist and the subsilicic dunite. Any reaction between dunite and quartz schist must have been so minor that it has been entirely concealed by later hydrothermal action. This same absence of contact reactions is characteristic of the Twin Sisters body in Washington.

Serpentinization: The local character of serpentinization and its relation to shear zones in the Webster dunite have been mentioned, and a general discussion of serpentinization need not be undertaken here. However, an interesting relation between olivine and serpentinization has been observed in the vicinity of the Woods chromite mine in Pennsylvania, where olivine crystals up to 15 cm. in length have been replaced by serpentine along crystal directions in the olivine. Two distinct types of serpentine are represented—one the usual reticulate type, and the other a distinctly later one that resembles chlorite. In the Buck Creek area of North Carolina there has also been serpentinization of olivine crystals along crystal directions. In both these areas, serpentinization was controlled by the crystal structure of the olivine.

The relationships in the Webster dunite and the associated websterite and similar bodies that seem most significant are (a) the marked parallelism in the lineation, shear zones, parallel zones of chromite, and zones of serpentinization; (b) the lack of any essential reactions between dunite and country rock; (c) the presence of blocks of enstatite and chromite, with flow lines in the dunite that sweep around blocks; and (d) the remarkable size range of the olivine grains in some of the dunite masses.

New Zealand

Turner and Verhoogen (1951, p. 240) have described the New Zealand occurrences of dunite and serpentine as follows: “. . . in southern New Zealand vertical sheets of peridotite and serpentine, believed to be of late Paleozoic age, include at least three individual masses whose continuous outcrops, dissected to a relief of 5,000 to 7,000 ft.; each exceed 40 miles in length, and locally attain a width (thickness) of 3 to 5 miles.” Turner states (personal communication): “Contact effects are limited or almost lacking, at least over most of the peridotite margins so far investigated. There is no indication of high-temperature metamorphism. All this fits in perfectly with Bowen’s theory.” In describing serpentinization, Turner says, “Most partly serpentinized peridotites that I have seen show clear evidence that serpentinization proceeds metasomatically from cracks that often are continuous through several crystals.”

Sweden

Du Rietz (1935, p. 138), in discussing the origin of the dunites of Sweden, concludes that the rock was probably formed as "an intrusion of an almost crystalline phase, with a complete lack of mineralizers. . . . The author has nowhere seen any convincing trace of contact metamorphism of the peridotite on the surrounding rocks." He reports the four characteristic minerals—olivine, diopside, enstatite, and chromite, or chrome picotite. In discussing serpentinization, Du Rietz (1935, p. 233) says, "In the region described by the writer no facts supporting the derivation of the serpentinizing solutions from the peridotite magma were observed." Du Rietz describes in detail the very widespread alteration of the original dunitic rocks and concludes (p. 257) "Hydrothermal waters originating from acid intrusions have produced the transformation." An analysis of the olivine from Sweden by R. Blix is given in Table 13, No. 13, and an analysis of enstatite from the same region by I. Suckdorff in Table 14, no. 13.

Physical and Chemical Relations

The high temperature of fusion of olivine (see Bowen and Schairer, 1935, p. 204, also 1936, p. 391–396) and the previously described absence of notable contact reactions between dunite and invaded rock, are the chief reasons why geologists have in general agreed that the olivine must have been introduced at moderate temperature only. However, there is no such general agreement as to the cause of this moderate temperature. Vogt (1926, p. 232) appears to be the only one who has postulated a melt with a temperature of 1,500° to 1,600° C., but he gave no consideration to contact relationships.

Hess believes that the olivine magma contained an essential amount of H₂O at the time of introduction. Bowen (1928, p. 166) quotes Harker as also postulating an essential amount of H₂O. Bowen (1928, p. 167) in his "general consideration of ultrabasic rocks" says, "These difficulties [the problem of temperatures of formation of dunite] disappear entirely if the rocks are accepted as the result of crystal accumulation without melting." Bowen and Tuttle (1949, p. 455) made a detailed study of the system MgO-SiO₂-H₂O and reached the following conclusions: "Under certain conditions of crustal deformation, apparently involving strong overthrusting, dunitic and related materials, coming at times perhaps from a peridotite shell of the earth, at other times from a peridotite mass that has formed as a differentiate of gabbroid magma, can be intruded in a completely crystalline state into accessible levels of the earth. . . . There is no reason to suppose that the crystalline mass initially has more than a trace of water."

Orogenic Relations

The relationship of ultrabasic rocks to the profound orogenic processes in the earth's crust was pointed out by Suess (1909), has since been noted by many geologists, and is carefully reviewed by Benson (1926). Hess gives detailed consideration to the relation between belts of dunite and orogeny. Hess (1939, p. 270), says: "The strong light upper crust [about 25 km. thick] is downbuckled into the peridotite substratum which lies perhaps 60 km. below the surface. The intermediate layer [between 25 and 60 km.] of basaltic material, being considerably hotter, is not quite so strong as the upper crust so that it deforms by flowing laterally, thus allowing the upper crust at the bottom of the downbuckle to come in contact with the peridotite substratum. The differential pressures developed in the region of the bottom of the downbuckle during deformation permit the squeezing off of a product of partial fusion of the peridotite substratum."

Hess (1939 p. 263) also states that "the typical serpentinized peridotites, which occur as narrow belts paralleling island arcs, mountain systems, or eroded roots of former mountain systems, were intruded as magmas of ultramafic composition, and are not magmatic differentiates of a gabbroic [mafic] magma. This type of ultramafic is limited entirely to such strongly deformed belts, and does not occur elsewhere."

Structures

Turner (1942, p. 281) made a careful study of the structures in the dunites of New Zealand and compared them with similar material from other occurrences. In commenting on the structures in dunite he says: "Certainly of deformational origin, however, are closely spaced, discontinuous, but sharply-defined lamellae parallel to (100) that may be observed in sections of many New Zealand dunites when viewed between crossed nicols . . . translation gliding remains the most probable mode of origin for lamellar structure sub-parallel to (100) in olivine. . . . There are strong objections to any hypothesis of origin of banded structures in the un-serpentinized dunites of New Zealand and the Hebridean province other than that of laminar flow in a partially, perhaps almost completely crystallized magma." Turner then gives the results of fabric studies of various types of dunites from several localities. Oriented fabric patterns were observed in all of these, and of one type, Turner (1942, p. 291) says, "The grains range from 0.5 mm. to 2 mm. in diameter, and commonly show distinct undulose extinction accompanied by translation lamellae parallel to (100) when observed between crossed nicols. No preferred dimensional orientation of grains could be detected."

The writers find translation structures in all the dunites and also in the

olivine-rich inclusions in all the materials examined in the course of this study. We have made no studies similar to those of Turner of the crystal orientation in dunites. However, the lineation in the websterite phase at Webster, North Carolina, is very noticeable.

Summary

There are four distinct lines of approach to the problem of the origin of dunite and related rocks. Bowen (1928) and Bowen and Tuttle (1949) have studied the geophysical problem presented by dunites and come to the conclusion that these rocks were intruded as a largely crystalline, mushlike material. Ross, Turner (1942), Thayer, and Du Rietz (1935) are representative of those who have made field studies of the geologic relationships and conclude that the intrusion of a mushlike mass is the mechanism that best accords with the field relations. Hess (1939) has considered the relationship of dunite bodies the world over with the profound orogenic processes and concludes that the material from which dunites formed "was a water-rich product of the partial fusion of the peridotite substratum." Turner (1942) has studied the structure of dunites of New Zealand and compared them with those of Skye and believes that both these dunites must have formed by the "laminar flow of a partially, perhaps almost completely, crystalline magma." These diverse approaches to the problem of the origin of dunite and related rocks seem to present convincing evidence that the rocks were formed by the intrusion of a largely crystalline mushlike material, and that this material was made up essentially of olivine. The relations also indicate that the peridotite substratum is the most probable source of so unusual a material.

Some dunites and related rocks show relationships with basaltic rocks and evidently have had a different genetic history with those previously discussed. Hess (1938, p. 334) mentions such rocks, which are part of the Stillwater complex. The rocks of the Hebrides (Bowen 1928, p. 166, and Harker 1904) are believed to be differentiates of basaltic rocks.

ORIGIN OF NODULELIKE INCLUSIONS IN BASALTIC ROCKS

Geologists who have discussed the origin of nodular inclusions in basaltic rocks have commonly concluded that the nodules are genetically related to the host rock, but some believe that they are derived from the peridotite shell of the earth's crust. Among those who believe in a derivation from the host rock are Lacroix (1894), Rinne (1893), Bauer (1891), Zirkel (1940) and Schwantke (1923). The most recent advocate of this origin is Frechen (1948). Heritsch (1908) postulated the derivation of the nodular inclusions from lherzolite (a peridotite composed of olivine, orthorhombic pyroxene, and monoclinic pyroxene) and Ernst (1936) has

made the most thorough presentation of the theory of a derivation from the peridotite shell.

Chemical and Mineral Relations

The study of 12 olivine nodules and the data from earlier studies show that material from many widely distributed regions is characterized by the same four minerals. Some nodules contain olivine crystals that range from 1 to 3 mm. in diameter, but commonly the range is much greater. Among the specimens from Hawaii, augite grains commonly range from 1 to 12 mm. in diameter, but one individual has a cleavage surface 10 cm. across. Olivine grains are at least 15 mm. in diameter in some of the inclusions. Bauer (1891, p. 182) has described olivine crystals in nodules from Stempel, near Marburg, up to 5 cm. in diameter and "bronzite" crystals equally large. The olivine grains in specimens from Camargo, Mexico; Rice Station, Arizona; Meng-Chian, Manchuria; and Dreiser Weiher, Germany, commonly range from 1 to 10 mm. in diameter, but some are even larger. Lausen (1927, p. 298) mentions a chromian diopside crystal at Rice Station (Peridot Cove) 2 in. in length.

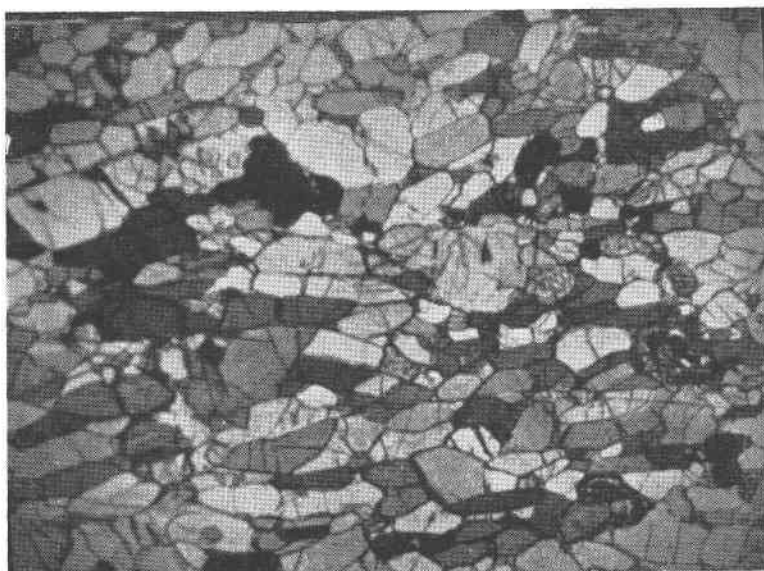


FIG. 3. Reproduction of an illustration by Ernst (1936, p. 638, Fig. 2) showing "grain deformation and elongation in the plane of foliated structure" of the olivine.

Structures

Ernst presents an excellent illustration (1936, p. 638, Fig. 2) reproduced in Fig. 3 showing "grain deformation and elongation in the plane

of foliated structure" of the olivine. He also illustrates (1936, p. 640, Fig. 4) translation lamellae in olivine. He concludes (p. 640) that they show "an outstanding structural arrangement in the olivine and present strong proof that the olivine had suffered dynamic stress, in contrast with the enclosing effusives." Foliated structures in olivine-rich nodules have been described from Germany, by Schulz (1903, p. 270); from Klein-Iser, Czechoslovakia, by Braun (1922); and from Italy by Andreatta (1934, p. 241). Heritsch (1908, p. 300) discussed these structures in the olivine nodules from Kapfenstein, Austria, and concluded that they indicated that they were derived from a peridotite zone of the earth's crust.

The great range in the proportions of the characteristic minerals of the olivine-rich nodules is shown by representative occurrences in Tables 1 and 2. The range is from almost pure olivine to almost pure enstatite, and as much as 30 per cent of chromian diopside may be present. Similar relations are shown in Hawaiian material, where some nodules are pure olivine, others are pure clinopyroxene, but chromian spinel is sparse, ranging from almost none to about 2 per cent.

A careful study of the relationships in olivine inclusions of a melilite basalt from Westberges was made by Ernst (1936, p. 637), who says, "I base the evidence of the foreign nature of the olivine nodules on the following summary. There is a similarity of the nodules with lherzolitic rocks [olivine-enstatite-monoclinic pyroxene] that must seem the more remarkable if one considers the limited variability of the nodules, with the very great difference in the rocks in which the olivine nodules occur, as in the phonolites, feldspar basalts, melilite basalts and limburgites."

Turner studied several nodules derived from basaltic rocks of New Zealand in connection with his work on the structures of dunites. In describing these rocks, Turner (1942, p. 294) says, "It is therefore suggested that all three nodules are fragments torn from masses of solid peridotite, which have formed under plutonic conditions, but have never flowed in in the form of injected bodies of largely crystallized peridotite magma." And (p. 299) "The petrofabric evidence, taken in conjunction with the widespread occurrence of olivine-rich nodules, in basalts in many parts of the world, points to deep-seated solid accumulations of olivine crystals and in some cases perhaps intrusions of peridotites as the source of the nodules in question." The foregoing observations by Turner seem to summarize very effectively the evidence of a close genetic relationship between the olivine-rich inclusions in basaltic rocks and dunites.

Source and Emplacement

A definite mechanism for the intrusion of dunite has been postulated, which indicates that this material was derived directly from the peridotite

zone. On the other hand, various mechanisms by which olivine-rich inclusions reached the surface have been suggested, and the problem arises as to their history after their departure from the peridotite layer. The olivine inclusions, or at least part of them, may not have come directly from the peridotite zone.

The nodules derived from basaltic rocks of New Zealand discussed by Turner had the same relation to basalts as those in other regions, but they occur in close proximity to one of the outstanding dunite areas of the world. They could thus be interpreted as having been torn from the buried dunite mass by the basalt as it made its way to the surface. The zone of nodule inclusions in basaltic rocks that extends across Germany could be related to a buried dunite zone associated with Alpine structures. That is, in these regions the inclusions might have arrived at the surface by a two-stage process. However, the profound downwarps that are believed to actuate dunite intrusion, even as buried masses, seem improbable in many of the areas where inclusions have been recognized. The Arizona and Mexico materials are from a plateau region where such downwarps are unknown, and according to Dr. Kuno (personal communication) the same is true for the Manchurian occurrence. The inclusions from the Hawaiian Islands are probably also unrelated to such profound downwarps. These facts, therefore, strongly suggest that in general the inclusions were not derived from dunite that had come part of the way from the peridotite zone.

Summary

The mineral, chemical, and physical relationships bearing on the origin of the nodulelike inclusions in basaltic rocks may be summarized as follows:

- (a) Olivine nodules occur throughout the world and everywhere contain the same four mineral groups—olivine, enstatite, chromian diopside, and chromian spinel.
- (b) The minerals of the nodules are the same in all occurrences; while the host rocks differ greatly in composition.
- (c) Essentially pure olivine nodules, pure enstatite nodules, and nodules dominantly chromian diopside are improbable as simultaneously formed, direct differentiates from basaltic magmas.
- (d) The great size of many of the individual mineral grains of the nodules does not indicate direct crystallizations from a basaltic magma.
- (e) The high chromian content of the spinels and of the pyroxenes seem to be an improbable concentration from a basaltic magma with a few hundredths of 1 per cent of Cr_2O_3 .

- (f) The nodules show structure typical of materials that have been subjected to orogenic stress.

The most probable origin of nodulelike inclusions seems to be that they are derived from the peridotite zone of the earth's crust and that most of them at least came directly from that zone.

ORIGIN OF DUNITE AND NODULELIKE INCLUSIONS CONTRASTED

The foregoing study has brought together paragenetic, mineralogic, and chemical data on two groups of rocks—dunites and nodulelike inclusions in basaltic rocks—which superficially seem to have quite different modes of occurrence. The significant characteristics of the two groups have been summarized, and we may now review the common relationships.

A comparative summary of the significant relationships shows that dunites and nodules have the following characteristics in common:

- (a) Similar mineralogy.
- (b) Remarkable chemical similarity.
- (c) World-wide occurrence.
- (d) Great range in size of crystals.
- (e) Similar range in variation of mineral proportions.

A few geologists have postulated a deep-seated origin for dunite, and others a deep-seated source for olivine-rich nodules in basaltic rock. However, Turner and Ernst seem to have been the only ones who have considered the origin of both these modes of occurrence.

The foregoing discussion indicates that olivine-rich nodules and dunite and related rock show a remarkable similarity in all essential relationships. Such parallelism in so varied and widely occurring a group of characteristics cannot be the result of a series of geologic accidents, and the origin of olivine inclusions in basaltic rocks and the origin of dunites must be considered together, notwithstanding the different modes of occurrence.

The most probable common genetic relationship that can be evoked seems to be derivation from the earth's peridotite shell. The dunites are believed to have been brought up from this shell by profound orogenic processes and the inclusions by eruptive processes that tapped the same profound depths.

Among the nodules of the 1801 Kaupulehu flow of Hualalai Island of Hawaii, are those composed of calcic plagioclase and olivine, or of calcic plagioclase and diopside. These nodules differ greatly in mineral composition from typical nodules, and so must have had a slightly different history. However, rocks composed only of plagioclase and olivine or of plagioclase and diopside do not present a relationship suggestive of direct crystallization from a basaltic magma. The most probable explanation

seems to be that of H.H. Hess (personal communication), that they are derived from a zone in the earth's crust somewhat higher than that of the olivine-rich nodules.

In the past, many geologists believed that the olivine-rich nodules were crystal segregations from their basaltic host rock, and some believe that the common genetic relationship that must be considered is that both the dunites and the nodulelike inclusions are related to basaltic rock. This relationship would postulate that great dunite bodies as well as the "secondary" ones of Hess (1938) were related to basaltic rocks.

In view of the foregoing relationships, a direct derivation of both dunites (excluding secondary dunites) and the nodules from basaltic rocks is improbable. The dunites here considered do not show any relation to basalts and in general occur in regions quite free from other igneous activity. Rather they do show a close relationship to profound orogenic processes.

The relationship between this indicated source of the material composing dunites and inclusions and current theories about the deep zones of the earth may be considered. There is general agreement that the peridotite zone lies unusually close to the surface in the central Pacific, and Gutenberg (1951) has given reasons for believing that this zone is even shallower than previously assumed. He says (p. 434), "In this case the Mohorovicic discontinuity would be at a depth of a few kilometers. . . . Again, "Summarizing the data, there is some indication that, in an area in the eastern Pacific Basin, the ultrabasic material with a velocity of about 8 km./sec. begins at a depth of only a few kilometers. . . ."

Hess and Maxwell (1953, p.3) state "The refraction seismic work of R. Raitt in the Pacific and the work of Ewing, Hamilton, Hersey, Officer, Press, Worzel, and Wuenschel in the Atlantic shows material probably of peridotitic composition at a depth of 15 km. below the sea floor possibly overlain by basalt and a thin veneer of sediments. Study by Ewing and Press of surface waves from earthquakes also indicates a predominantly peridotitic oceanic crust. . . . Samples of the oceanic peridotite crust are probably available for study for examples . . . and the olivine bombs [xenoliths] found in many basaltic volcanoes. . . ."

If these are the relations in the Pacific and the Atlantic, they would impose no improbable mechanism for bringing dunitelike materials to the surface as inclusions in basalts.

The depths to the Mohorovicic discontinuity in plateau regions is much greater, as indicated by the following statement by Gutenberg (1951, p. 438), "In the continents the crust is formed by a layer of sialic rock of a thickness varying from place to place, with an average of 10 km. Below it, down to the Mohorovicic discontinuity at a depth between

30 and 40 km., but deeper in some mountain areas, are simatic rocks." Under plateau regions the depth to ultrabasic rocks would probably be of order of 50 km. and so would impose a long distance of travel if basaltic material brought olivine-rich inclusions directly from the region of the Mohorovicic discontinuity. However, some recent studies of the heat flow and chemical segregation of the mantle by Hurley (1951, p. 328) lead to the following conclusion:

"Measurements on the Oregon basalts give values too high to permit the basalt to exist as a part of a permanent extensive layer below the discontinuity, and at the same time there is difficulty in achieving the temperature of 1,100° C. or so for the molten basalt if it occurred above the discontinuity. This argument is even more pressing in the case of oceanic volcanic islands. It is therefore suggested that at least some basalts are concentrates or extracts from partial fusion at depths of at least several hundred kilometers within the mantle, brought to the surface by convection, and representing a continuing source of alumina, alkalies, and other elements of continental growth."

Verhoogen (1953, p. 329) has discussed the petrological evidence on the temperature distribution in the mantle of the earth and says, "From the maximum observed temperature of lavas and their composition it is inferred that basaltic magmas are formed by partial melting of mantle material at a depth of less than 150 km. and at an initial temperature less than 1,400° C. This suggests that the temperature at the core boundary normally does not exceed 2,400° C. Rising material at this initial temperature would have at 150 km. depth a temperature sufficiently greater than the melting point at that depth to allow partial fusion."

CONCLUSIONS

Geologic, mineralogic, and chemical studies of peridotitic material from two distinct physical modes of occurrence but of almost identical composition provide additional information about the peridotite zone of the earth's crust, a zone inaccessible for direct observation. It is a zone whose composition has fundamental bearings on the tectonics of island arcs and the great ocean deeps, its upper surface is believed to represent the Mohorovicic discontinuity, and the rate of transmission of earthquake waves within the layer has contributed to an understanding of the internal structure of the earth. The mineral composition of this zone, and its relation to the mineral composition of meteorites also concerns those investigating the composition of heavenly bodies. For these reasons, information about the peridotite zone has significance for all the earth sciences. This paper is therefore offered as a contribution to the broader aspects of earth science.

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