Primary Textures and Mineral Associations in the Ultramafic Zone of the Stillwater Complex Montana

GEOLOGICAL SURVEY PROFESSIONAL PAPER 358

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By EVERETT D. JACKSON

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The petrographic features and origin of the layered chromitites, bronzitites, and harzburgites in the lower part of the Stillwater complex

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PRIMARY TEXTURES AND MINERAL ASSOCIATIONS IN THE ULTRAMAFIC ZONE OF THE STILLWATER COMPLEX, MONTANA

By Everett D. Jackson

ABSTRACT

The Stillwater complex can be divided into several major stratiform zones. The Ultramafic zone, with which this paper is concerned, lies near the lower margin of the complex along its entire exposure and has an average stratigraphic thickness of about 3,500 feet. The Ultramafic zone can be further subdivided into two members: the Peridotite member, which forms the stratigraphically lower two-thirds of the zone, and which is composed of conformably interlayered harzburgite, chromitite, bronzitite, and dunite; and the Bronzitite member, which forms the upper one-third of the zone and which is composed of a single thick layer of bronzitite.

The constituent grains of the layered rocks of the Ultramafic zone can be divided into two groups on the basis of texture: those that are commonly euhedral and occur in the rocks as uniform-sized individual crystals; and those that are molded on these individual crystals. Minerals of the first group represent the primary precipitate, which crystallized in the magma column, settled, and accumulated on the floor of the magma chamber. Minerals of the second group represent the interprecipitate material, which crystallized in place in the pore spaces surrounding the primary precipitate.

The three primary precipitate minerals of the Ultramafic zone—olivine, bronzite, and chromite—make up about two-thirds by volume of the rocks. These settled crystals are euhedral and closely packed, and they would be self-supporting if the interprecipitate material were removed. The grain size ranges of any one settled mineral in any given layer are remarkably small, and size distributions are virtually lognormal. In layers containing two settled minerals, each mineral tends to have lognormal size distributions, but the two minerals are not necessarily in hydraulic equivalence. Planar structures are formed in the rocks wherever settled minerals are elongate or flattened; however, lineation is weak or absent. Changes in grain size, relative proportions, and presence or absence of the three settled minerals define layering planes. Of these factors, presence or absence of the settled phases is most important, and the Peridotite member is made up of repetitive layers caused by the cyclic appearance and disappearance of olivine, chromite, and bronzite in regular sequence.

Euhedral shapes of the settled crystals and simple relations between the primary precipitate and interprecipitate material have been obscured in many rocks by reaction replacement and secondary enlargement. Three reaction pairs are recognized: olivine-bronzite, olivine-augite, and bronzite-augite. Secondary enlargement has occurred where settled crystals continue to grow after deposition, and the extent to which this process operated appears to be inversely related to the rate of crystal accumulation. Making allowance for these processes, the initial porosity of the crystal mush appears to have ranged between 20 and 50 percent and to have averaged about 35 percent.

The interprecipitate material makes up about one-third of the volume of the rocks. It can be divided into three types: (1) secondarily enlarged, optically continuous rims on settled crystals; (2) material that has partially replaced settled crystals by postdepositional reaction replacement; and (3) material that simply fills interstitial cuspate cavities between euhedral or secondarily enlarged settled crystals. New phases, which occur as interstitial but not as settled constituents, include plagioclase, chromian augite, and (in some rocks) minor amounts of biotite, quartz, and grossularite-pyrope. The presence or absence, proportions, and order of crystallization of these minerals are largely dependent on the settled phases present in the rocks and on the amount of secondary enlargement. Interstitial minerals have strong tendencies to be poikilitic, and the average size of oikocrysts appears to be related to the grain size of settled minerals in the rocks. Oikocrysts are randomly distributed and oriented; they bear no relation to the layering plane.

The textures of the rocks of the Ultramafic zone show every gradation between automorphic-poikilitic and xenomorphic, and this textural variation is largely dependent on the amount of secondary enlargement that has occurred. Rocks with little enlargement have interposition fabrics with euhedral settled crystals and contain relatively large amounts of predominantly poikilitic interstitial material; rocks with much enlargement have mosaic fabrics and contain little or no interstitial material.

The three settled minerals have a strong tendency to occur singly rather than in combination with one another. Settled olivine and bronzite occur together in about 12 percent of the rocks of the Ultramafic zone; they are mutually exclusive in the remaining 88 percent. Although quantitatively less important, chromite commonly occurs as the only settled mineral in chromitites. Settled chromite and bronzite are generally antipathetic, but chromite and olivine occur together in all proportions. In contrast to the wide proportional variation of the settled minerals in the various layers, the bulk composition of the interstitial minerals is relatively constant. In a general way, the composition of the interstitial material approaches that of the chilled gabbro at the base of the complex.

The layered rocks of the Ultramafic zone are believed to have formed during crystallization of a single saturated basalt magma by accumulation of early crystal precipitates that fell, layer on layer, to the floor of the magma chamber and after deposition were enlarged or cemented by the magma from which they had crystallized. The textures and structures of the rocks suggest that the magma near the floor of the intrusion was essentially stagnant throughout the accumulation of the Ultramafic zone. Other relations indicate that crystallization of the primary precipitate took place near the bottom of the magma chamber, and that the cyclical compositional layers directly reflect changing crystallization products of the magma with time. It is proposed that the textures, mineral associations, and cyclical rock distributions in the Ultramafic zone can best be explained by a mechanism involving continuous but variable-depth convection, which caused periodic refreshment of the stagnant magma undergoing crystallization in the lower part of the intrusion. Each set of cyclic compositional layers is therefore believed to be the product of a period of stability in the lower magma, preceded and succeeded by overturn.

INTRODUCTION

FIELDWORK, ACKNOWLEDGMENTS, AND SCOPE OF REPORT

This paper presents some results of work done between 1951 and 1955 as a part of a comprehensive investigation of the stratigraphy, geochemistry, and petrography of the Ultramafic zone of the Stillwater complex by the U.S. Geological Survey. Detailed mapping of the chromite deposits of the complex was done between 1939 and 1943, under the supervision of J. W. Peoples. Reports of this work, and geologic maps of most of the complex, have been published: Peoples and Howland (1940); Wimmler (1948); Howland, Garrels, and Jones (1949); Peoples, Howland, Jones, and Flint (1954); Jackson, Howland, Peoples, and Jones (1954); Howland (1955); Jones, Peoples, and Howland (1960). The present investigation has called for additional mapping and study of many problems which had to be bypassed because of the pressure of wartime urgency. I spent about 15 months in the field during the summers of 1951 through 1955; P. R. Vail assisted in the field work in 1952 and 1953; and R. L. Christiansen assisted in 1954.

Two members of the Geological Survey have been especially helpful to the conduct of this investigation. Arthur L. Howland introduced me to the Stillwater complex and worked closely with me during the first three summers of fieldwork. The critical advice and ideas of Arthur H. Lachenbruch on the subject of heat relations have contributed substantially to the conclusions on the origin of the Stillwater complex outlined in this report.

GENERAL GEOLOGY OF THE COMPLEX

The Stillwater complex is a differentiated "gravity-stratified" igneous sheet, which strikes northwest across the northern margin of the Beartooth Mountains, in Stillwater, Sweetgrass, and Park Counties, Mont. (fig. 1). The exposed strike length of the complex is about 30 miles, but it is terminated at both ends by faults. The maximum exposed stratigraphic thickness is 18,000 feet; Hess (1940, p. 377) estimates that the original thickness was 25–45 percent greater.

In general, the rocks of the complex are unaltered and well exposed. Locally, the more mafic rocks have been serpentinized, but preservation of primary textures generally permits mapping of the original rock types. Five deeply glaciated canyons cut the complex nearly at right angles to its strike, thus exposing it continuously through a vertical distance of 5,000 feet.

The general structural and age relations between the complex and adjoining formations have been described in a paper by Jones, Peoples, and Howland (1960). In Precambrian time the parent magma of the complex was intruded as a horizontal sill into pelitic sedimentary rocks of unknown age, which were metamorphosed to cordierite-hypersthere-biotite-quartz hornfels (Howland, 1954, p. 1264–1265). After it crystallized, the complex was locally intruded by granite, tilted about 25 degrees in the eastern part, beveled by erosion, and buried by sediments ranging from Middle Cambrian through Mesozoic in age. All these rocks were later deformed during the Laramide orogeny, and the complex now stands nearly vertical. Much faulting accompanied the rotation of the complex to its present position.

Internally, the complex consists of a series of conformably layered subsilicic rocks that range in composition from dunite to norite and anorthosite. Peoples (1936, p. 358) has divided these rocks into four major stratiform units: the Basal chilled zone, Ultrabasic zone, Banded zone, and Upper zone. According to Jones, Peoples, and Howland (1960), Hess has abandoned the terms Banded zone and Upper zone and has proposed a five-unit stratigraphic section for the rocks above the Ultramafic zone.

Peoples' terminology is the basis for the informal stratigraphic nomenclature used in this report. The terms Basal zone, Ultramafic zone, and Banded zone correspond to Peoples' Basal chilled zone, Ultrabasic zone and Banded zone, respectively. In addition, the Ultramafic zone has been divided in this report into two members: the stratigraphically lower Peridotite member and the stratigraphically higher Bronzitite member.

In the usage of this paper, the Basal zone includes those rocks that underlie the stratigraphically lowest harzburgite layer and is composed of pyroxene gabbros, norites, and feldspathic bronzitites. This zone is irregularly developed along the south margin of the complex. Locally it is absent, but at its maximum measured exposure it is 700 feet thick. Where well developed, the lower part of the Basal zone is composed of fine-grained ophitic gabbro containing many

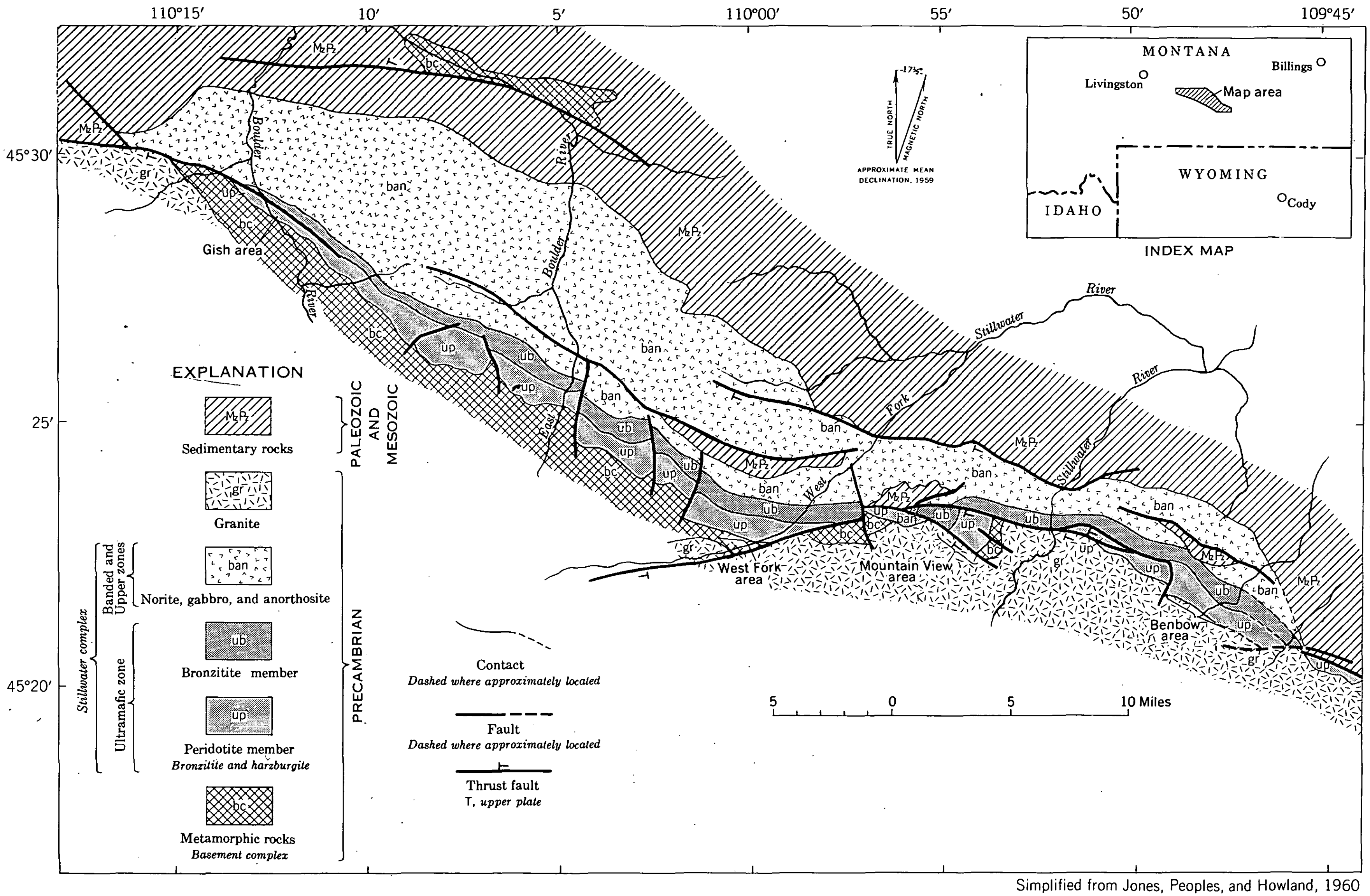


Figure 1.—Geologic index map of the Stillwater complex.

inclusions of hornfels. Upward the rock is coarser grained, has fewer inclusions, and contains less clinopyroxene and plagioclase. The upper rocks of the zone are, for the most part, fine- to medium-grained layered bronzitites with automorphic-granular textures; but in several areas a few lenticular layers of norite occur within the bronzitite.

The Ultramafic zone, with which this paper is largely concerned, contains dunites, chromitites, harzburgites, and bronzitites, and it overlies comformably the Basal zone, where present, or lies directly on basement. The Ultramafic zone averages about 3,500 feet in thickness, including the rocks between the base of the stratigraphically lowest harzburgite in the complex and the base of the stratigraphically lowest norite in the Banded zone; both the upper and lower contacts are sharp and can be traced the entire length of the complex. The lower two-thirds of the Ultramafic zone, here called the Peridotite member, is composed of alternating, conformable layers of dunite, chromitite, harzburgite, and bronzitite; the upper one-third of the zone, here called the Bronzitite member, is composed of a single thick unit of bronzitite. Most of these rocks have medium- to coarse-grained automorphic- to hypautomorphic-granular or poikilitic textures, but some have a xenomorphic-granular texture.

The layered rocks lying stratigraphically above the Ultramafic zone have a maximum exposed thickness of about 14,000 feet and are composed of alternating layers of norite, gabbro, and anorthosite. Norite and gabbro are most abundant in the lower part of the section; anorthosite and olivine gabbro are more common in the upper part. The rocks are medium to coarse grained, and most have hypautomorphic-granular or poikilitic textures.

The most striking feature of the complex is the regular and persistent layered character of its rocks. Hess (1940, p. 377) has shown that the compositions of the mineral phases in the complex change in a systematic fashion upward from the base. Superimposed on this gradual mineral compositional change are the remarkably continuous zones formed by abrupt changes in mineralogic associations. Within the zones are many alternating compositional layers defined by the presence and absence of individual minerals. Superimposed on the compositional layers are concordant layers defined by change in proportions, grain size, or habit of minerals. The layering is remarkably similar to sedimentary bedding and is recognized and mapped by the same criteria, such as change in mineralogic composition, proportion of minerals, texture, grain size, and orientation of constituent grains. Although certain similarities between these layered rocks and detrital sediments exist, and although textural comparisons between the two are made in the text of this report, the writer proposes that the origin of the Stillwater rocks more nearly resembles that of chemical sediments.

The complex is believed to be a product of the fractional crystallization of a basaltic magma, formed by the settling of crystals, layer on layer, to the nearly horizontal floor of the magma chamber. The constituent grains of the layered rocks can be divided into two categories: well-sorted individual crystals, which make up about 65 percent of the layered rocks; and anhedral, commonly poikilitic grains, which are molded on the well-formed individual crystals, and which make up the remaining 35 percent of the rocks. The individual crystals define the layering plane by upward changes in proportions or size; the interstitial material has no direct relation to the layering plane. Hess (1938a, p. 264–268) deduced from these and other textural considerations that the well-formed individual grains represent primary precipitates from the main magma, successively accumulated on the floor of the magma chamber, and that the interstitial grains represent material crystallized from the magma surrounding these settled crystals. I believe this to be the only tenable theory to explain the textures and structures of the layered rocks of the complex.

The purpose of this paper is threefold: to describe the distribution and interrelations of the primary minerals of the Ultramafic zone of the complex; to point out the dominantly sedimentary nature of the texture of the rocks within the zone; and to discuss some of the genetic implications of these distributions and textures. Subsequent publications will describe the primary structures, stratigraphy, and geochemistry of the ultramafic rocks of the complex.

COMPOSITION OF THE ROCKS

MINERALOGY

The rocks of the Stillwater complex are composed essentially of only five primary solid solution minerals: olivine, orthopyroxene, clinopyroxene, plagioclase, and chromite. In addition, very minor amounts of primary biotite, sulfide minerals, and quartz occur in some rocks. The compositions of the essential minerals and their overall isomorphous variations within the complex have been described in a series of papers by Hess (1939, p. 431; 1940, p. 377).

All five of the essential solid solution minerals occur in the Ultramafic zone of the complex. Detailed compositional studies within the zone have not yet been completed, but the general range of composition is: bronzite, En_{75-90}; olivine, Fo_{80-95}; plagioclase, An_{65-85};

and chromite, in Thayer's (1946, p. 205) terminology, $Cr_{52}Al_{39}(Mg_{51})$–$Cr_{69}Al_{26}(Mg_{39.5})$. Two clinopyroxenes from the Ultramafic zone were determined by Hess (1949, p. 646 and 647) to be chromian augites with the compositions $Ca_{37}Mg_{56}Fe_7$ and $Ca_{40}Mg_{52}Fe_8$.

ROCK TYPES IN THE ULTRAMAFIC ZONE

In the field, the layered rocks of the Ultramafic zone have been divided into four major compositional types: bronzitite, harzburgite, dunite, and chromitite (Peoples and Howland, 1940, p. 378–380). Although these rock names, with appropriate mineralogic and textural modifiers, have been found convenient for field classification, many of the rocks do not conform strictly to the definitions given in standard texts. The local usage of the terms is described below. In addition to the four types of layered rocks, small irregular intrusive bodies of dunite and of noritic, gabbroic, and troctolitic pegmatite occur within the zone.

Bronzitite is used as a general term to designate the equigranular, medium- to coarse-grained rocks whose principal constituent mineral is bronzite (figs. 2, 60–62); these rocks, by definition, contain no olivine. An average mode for bronzitite is given in column 1 of table 1. Bronzite constitutes 50–99 percent of bronzitite, and occurs as individual equidimensional or broad prismatic grains or crystals, mostly between 1 and 4 mm in diameter. Chromite is absent from most bronzitite but occurs in some in amounts up to 3 percent as 1.1- to 0.4-mm octahedra (or clusters of octahedra), which are located between, rather than within, the bronzite crystals. All bronzitite contains some plagioclase and bright green chromian augite, invariably interstitial to, and molded on, bronzite crystals. Plagioclase makes up from less than 1 percent to 35 percent of the rocks; chromian augite, from less than 1 percent to 16 percent. Both these minerals are commonly poikilitic, enclosing large numbers of bronzite grains. Interstitial quartz, generally accompanied by minute amounts of grossularite-pyrope garnet, occurs in bronzitite in the Basal zone and in the top of the Bronzitite member of the Ultramafic zone. In the bronzitite of the Basal zone, quartz occurs in amounts up to 5 percent; in the Bronzitite member of the Ultramafic zone, it is present in amounts less than 0.1 percent. Biotite occurs in some bronzitite in amounts up to 2 percent.

TABLE 1.—*Average modes of principal rock types*

	Rock types						
	(1) Bronzitite	(2) Olivine bronzitite	(3) Granular harzburgite	(4) Poikilitic harzburgite	(5) Poikilitic chromite harzburgite	(6) Olivine chromitite	(7) Chromitite
Number of modes averaged	38	5	19	22	16	10	22
Bronzite	83.2	83.1	52.8	17.6	26.7	16.7	4.2
Olivine	--------	4.6	33.6	70.4	40.7	19.4	3.9
Chromite	.2	1.0	1.0	2.0	27.0	58.4	80.3
Plagioclase	12.3	8.5	9.1	7.0	1.9	2.5	6.2
Chromian augite	4.1	2.8	3.4	2.8	3.5	2.8	5.1
Biotite	.1	--------	.1	.2	.2	.2	.3
Quartz	.1	--------	--------	--------	--------	--------	--------
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Rocks which are texturally and mineralogically similar to bronzitite but which contain olivine in measurable amounts up to about 10 percent are termed olivine bronzitite, and the average mode for a rather limited number of specimens is listed in column 2 of table 1. Olivine occurs as single crystals 1–2 mm long, or as clusters of crystals almost always slightly smaller than the contiguous bronzite crystals. Olivine bronzitite grades into granular harzburgite on increase of olivine to amounts greater than 10 percent.

Harzburgite is used as a general term to designate the medium- to coarse-grained rocks composed principally of olivine and bronzite, both in amounts exceeding 10 percent by volume. Harzburgite has been divided into two types on the basis of texture: granular harzburgite and poikilitic harzburgite (figs. 3, 4); the average modes of each are given in columns 3 and 4, table 1. Granular harzburgite is texturally identical with bronzitite and differs from it compositionally only by the substitution of olivine for bronzite. The volumetric sum of these two minerals makes up 65–95 percent of the rock. Harzburgite with an olivine content of less than 10 percent grades into olivine bronzitite. Chromite is more commonly present in granular harzburgite than in bronzitite, but it does not occur in amounts greater than 4 percent in individual specimens. Plagioclase and chromian augite are ubiquitous interstitial constituents of granular harzburgite, in amounts up to 20 and 10 percent, respectively. Quartz or grossularite-pyrope has not been observed, although biotite occurs in minor amounts in many specimens of granular harzburgite. Poikilitic harzburgite is compositionally similar to granular harzburgite but differs texturally. In poikilitic harzburgite, bronzite occurs only in irregularly spherical oikocrysts, generally ¾–4 inches in diameter, which enclose large numbers of olivine grains. Olivine crystals, generally ranging from 1 to 4 mm in diameter, are scattered evenly throughout the rock, making up 50–90 percent of its volume. Chromite is considerably more abundant in poikilitic harzburgite than in bronzitite or granular harzburgite, and almost all the chromitite layers in the complex lie within poikilitic harzburgite layers. Chromite occurs in all proportions with olivine, as small

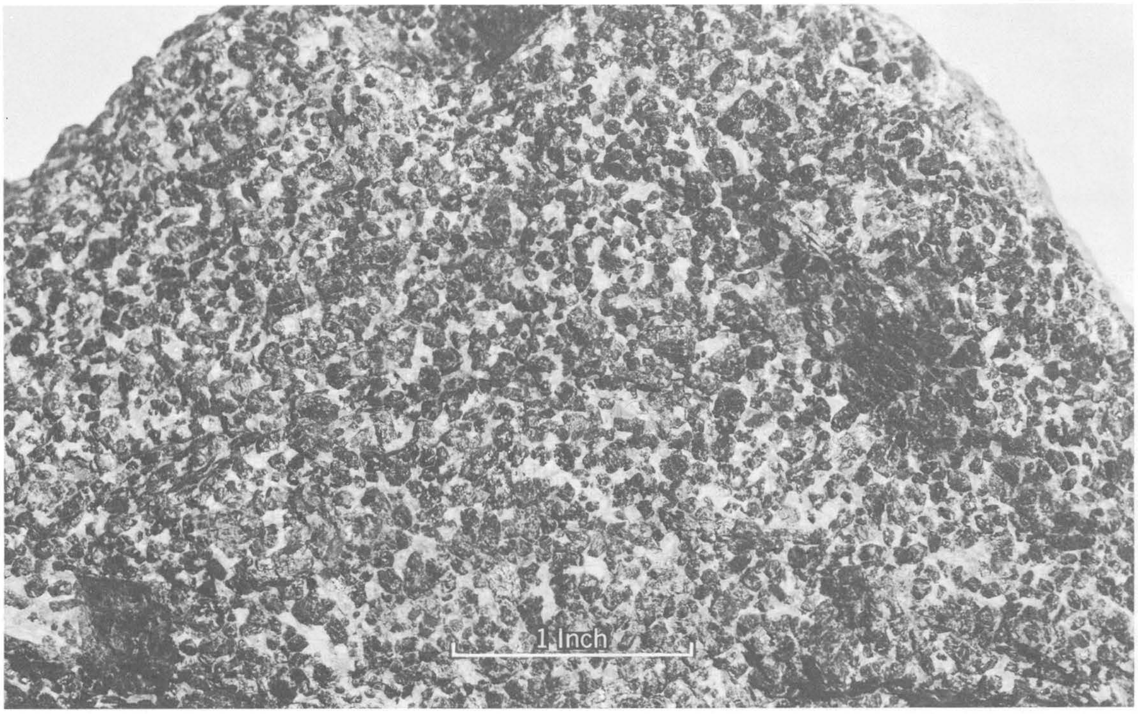


FIGURE 2.—Bronzitite hand specimen. Dark euhedral grains are bronzite; darker areas are augite oikocrysts; white interstitial material is plagioclase.

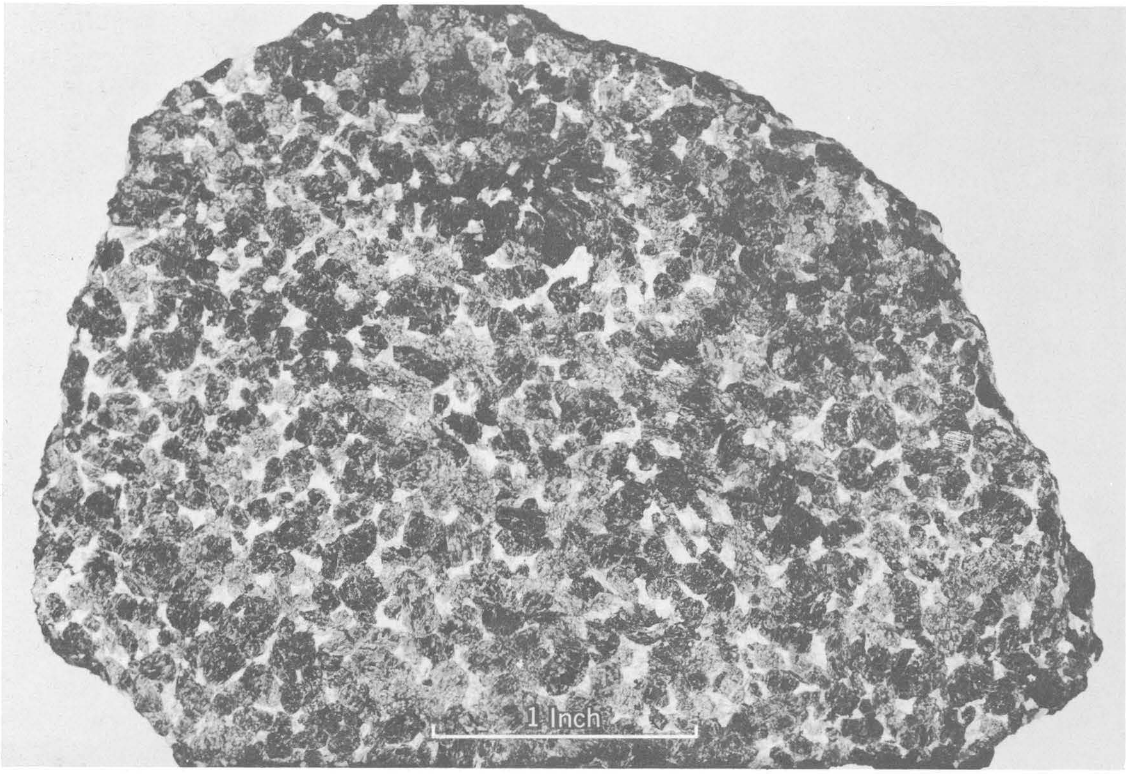


FIGURE 3.—Granular harzburgite hand specimen. Black euhedral grains are bronzite; gray euhedral grains are olivine; white interstitial material is plagioclase.

PHOTOGRAPHS OF BRONZITITE AND GRANULAR HARZBURGITE HAND SPECIMENS

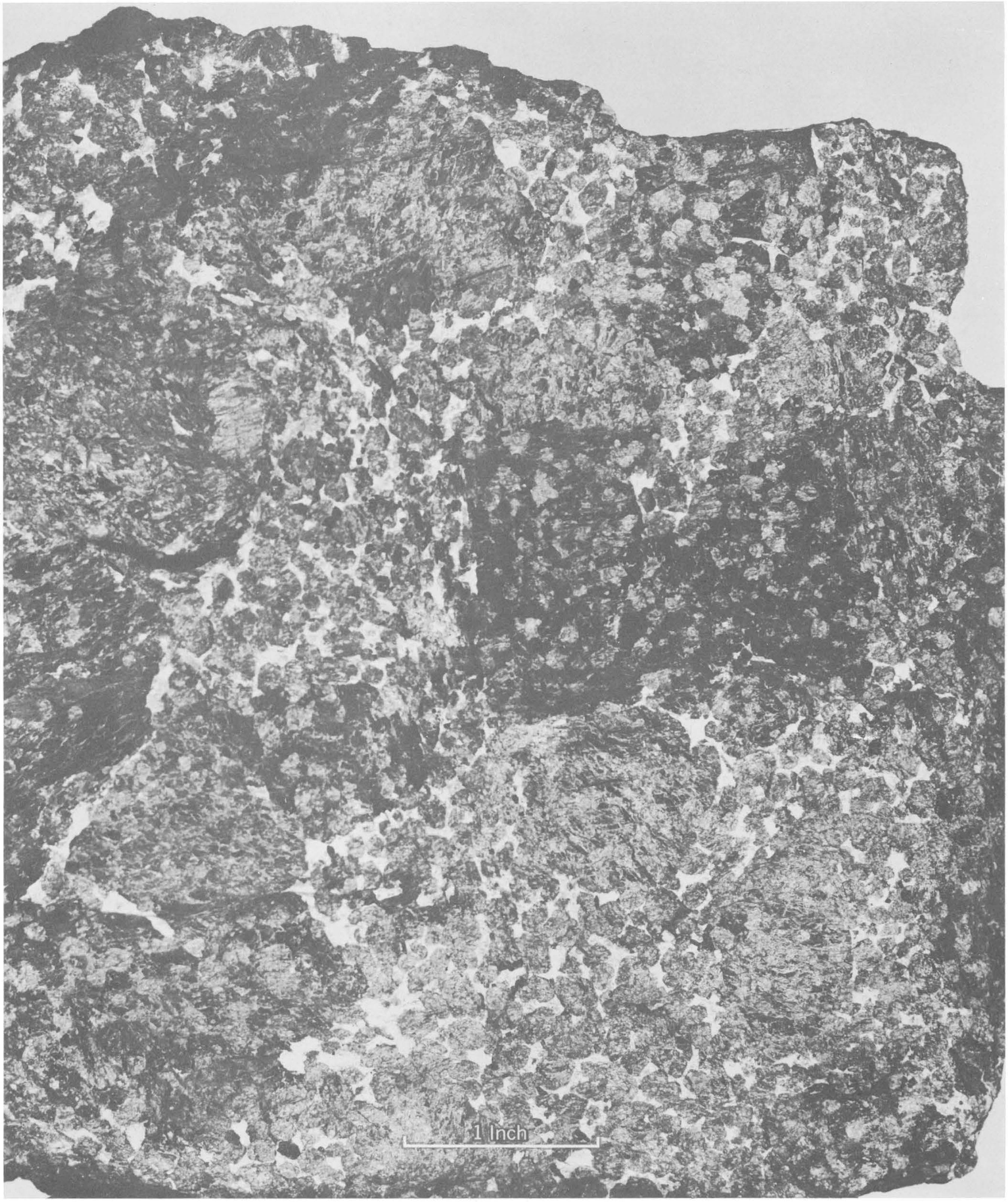


FIGURE 4.—Photograph of poikilitic harzburgite hand specimen. Gray euhedral grains evenly distributed through rock are olivine; 1- to 2-inch gray and black ovals are bronzite oikocrysts; white interstitial material is plagioclase.

octahedra evenly scattered between the olivine grains. Poikilitic harzburgite containing more than 5 percent chromite is termed poikilitic chromite harzburgite. Rocks in which chromite has displaced olivine as the principal constituent are termed olivine chromitite. Poikilitic harzburgite contains between 5 and 40 percent of poikilitic bronzite. Plagioclase is commonly interstitial to olivine between bronzite oikocrysts, making up as much as 20 percent of some rocks. Chromian augite is a less abundant constituent of poikilitic harzburgite than of the other rocks, but it does occur in a few rocks in amounts up to 12 percent. Minor amounts of biotite are present in all poikilitic harzburgite, but neither quartz nor grossularite-pyrope has been observed.

Dunite is used as a general term to designate rocks containing more than 95 percent olivine. Dunite is not abundant in the Stillwater complex, but it does occur locally, both as parts of primary layers and as secondary bodies cutting irregularly across the layering (fig. 5). The secondary dunites have been described by Hess (1938b, p. 334–339) and will be treated only incidentally in this paper. The layered dunites commonly contain accessory chromite and interstitial grains or small oikocrysts of bronzite. Dunite, on increase of interstitial bronzite, grades along the strike of the layering into poikilitic harzburgite. In some dunites, bronzite is absent and the rock consists of an interlocking mosaic of olivine grains (fig. 59). Some dunite contains a few percent of interstitial plagioclase.

Olivine chromitite is a term used to designate rocks whose principal constituent is chromite, but which contain lesser amounts of olivine as individual crystals scattered through the rock (fig. 9, central part). An average mode is given in column 6, table 1. Chromite occurs as individual octahedral crystals, generally 1–4 mm in diameter, which surround or are located between the olivine crystals. The olivine crystals are generally about 10 times the diameter of the chromite crystals, and on increase in olivine abundance the rocks grade into poikilitic chromite harzburgite (fig. 53). Bronzite is generally present as an interstitial mineral in amounts up to 35 percent, and interstitial plagioclase and chromian augite may be present in amounts up to 11 and 7 percent, respectively. Biotite is nearly always present in small amounts, but quartz has not been recognized.

Chromitite is a term designating those rocks whose principal constituent is chromite, but which contain less than 5 percent individual olivine crystals (fig. 10; upper part of fig. 53). An approximate average composition is given in column 7 table 1. Chromite makes up from about 55 to 90 percent of such rocks and, as in other rock types, generally occurs as 1- to 4-mm octahedra. Most chromitite contains no individual crystals of olivine, but olivine may occur as an interstitial constituent; as such, it appears in amounts up to 20 percent in individual specimens. Bronzite and plagioclase are common but not ubiquitous interstitial constituents, in some rocks occurring in amounts up to 15 and 17 percent, respectively. Chromian augite is slightly more abundant in chromitite than in other rocks, in amounts up to 27 percent. Biotite is nearly invariably present up to a maximum of 2 percent, but generally in amounts less than 0.5 percent. Quartz does not occur.

Norite, gabbro, and troctolite pegmatites occur within the Ultramafic zone, but not as layered rocks. Although not abundant, pegmatites occur as irregular bodies, with intrusive contacts, which locally cut the layering plane but generally are elongate parallel to it. Most commonly these bodies are irregularly developed along the base of massive chromitite layers; in general, the thicker the chromitite, the larger and coarser grained the pegmatite. Only those pegmatites associated with layered chromitite contain chromite, and these chromite crystals have identical sizes and size distributions with those of the layered chromitite invaded. Chromite crystals in pegmatite are therefore present as included and redistributed xenocrysts rather than as primary crystallization products. In the larger bodies, pyroxene and plagioclase crystals attain lengths in excess of a foot, but olivine crystals greater than 3 inches in diameter have not been observed. Good examples of both volume-for-volume replacement (fig. 7) and expansion during crystallization (fig. 8) have been observed.

LITHOLOGIC SIMILARITIES AND CONTRASTS

The various lithologic types of the layered rocks of the Ultramafic zone have a common compositional feature: all consist principally of individual crystals of bronzite, olivine, or chromite, or a mixture of these three constituents, set in a gabbroic mesostasis of plagioclase, bronzite, and augite. The volumetric sum of the bronzite, olivine, and chromite crystals ranges from 50 to 99 percent, regardless of the proportions in which they occur. Mixtures of olivine and chromite occur in all proportions; mixtures of olivine and bronzite occur through the range from 99–20 percent bronzite to 1–80 percent olivine, but chromite and bronzite are generally antipathetic. Although such mixtures do occur, there is an extreme tendency for these minerals to occur singly. Rocks composed only of bronzite and mesostasis constitute about 65 percent of the volume of

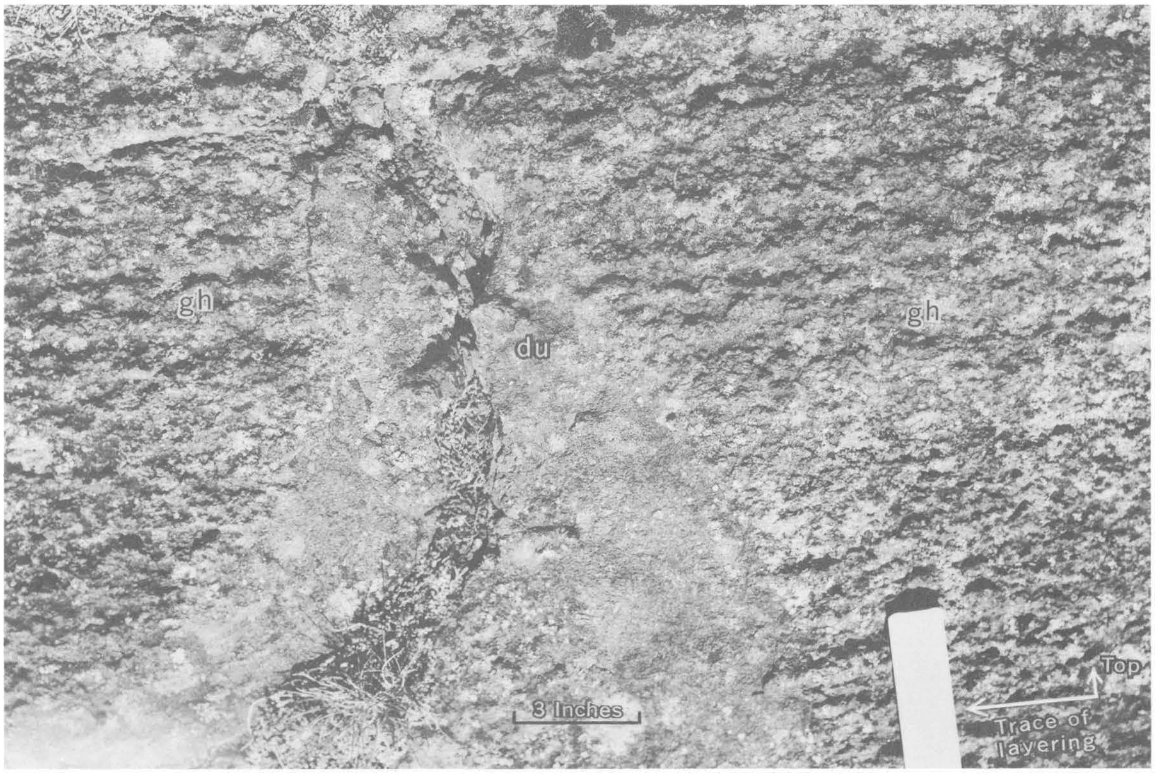


FIGURE 5.—Secondary dunite cutting layered granular harzburgite. du=dunite; gh=granular harzburgite.

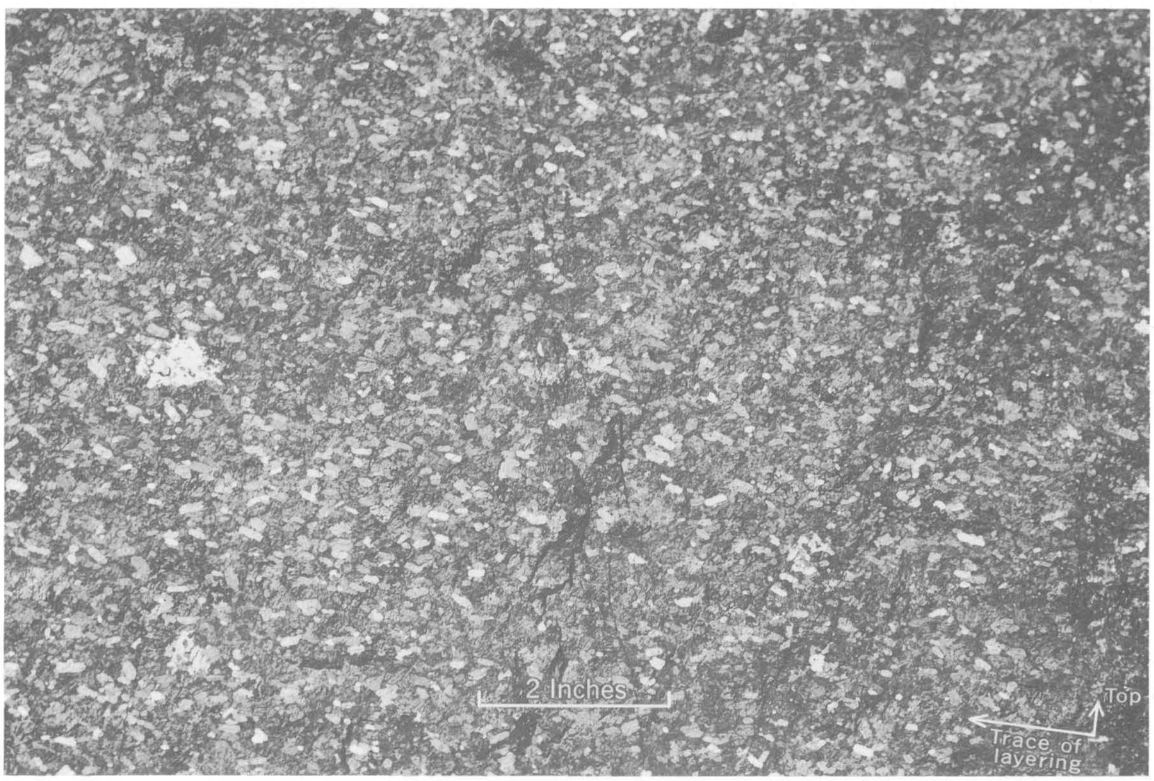


FIGURE 6.—Planar structure in bronzitite. Note that foliation of bronzite is not perfect but that many grains stand at high angles to the layering plane and others appear to be propped up by underlying grains. Highly reflecting area at left center is augite oikocryst.

FIELD PHOTOGRAPHS OF PRIMARY STRUCTURES IN THE ULTRAMAFIC ZONE

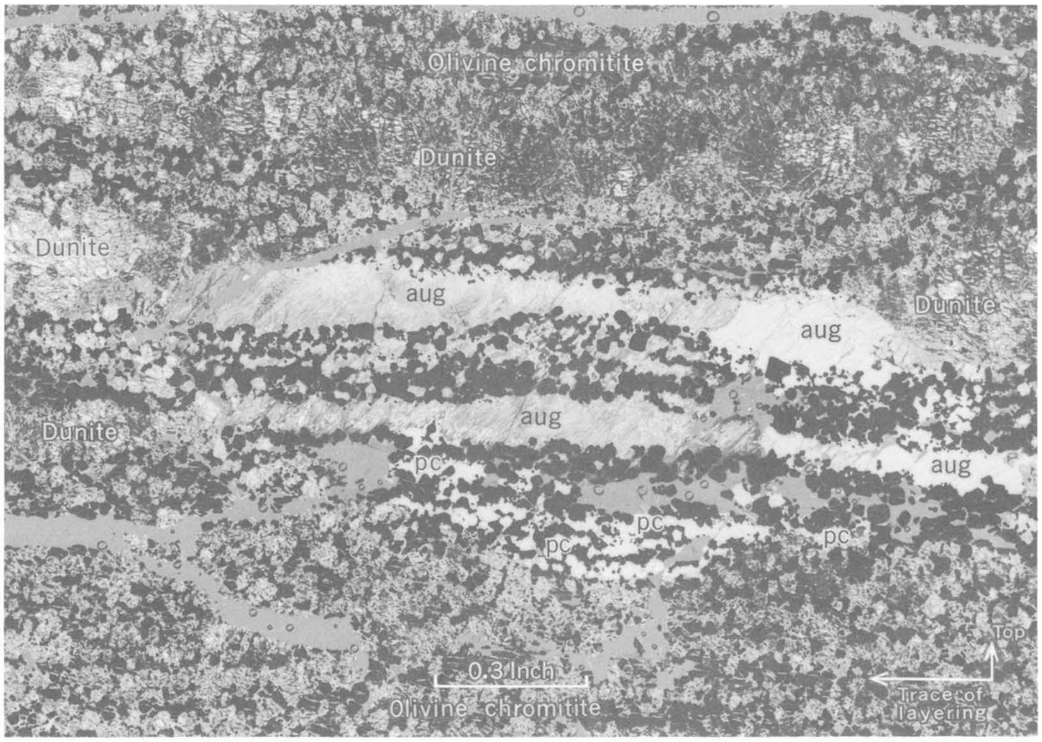


FIGURE 7.—Volume-for-volume replacement of olivine by gabbro pegmatite. Chromite grains are unaffected, and the delicate layering is not disturbed. aug=augite; pc=plagioclase. Crossed nicols.

FIGURE 8.—Volume increase during replacement of olivine by olivine gabbro pegmatite. Chromite grains are unaffected, but have been redistributed, destroying the layering within the area occupied by the pegmatite. Layers above the segregation have been bowed upwards. br=bronzite; ol=olivine; pc=plagioclase. Crossed nicols.

PHOTOMICROGRAPHS OF PEGMATITIC SEGREGATIONS IN LAYERED ULTRAMAFIC ROCKS the Ultramafic zone; rocks composed only of olivine and mesostasis constitute another 25 percent; rocks containing mixtures of olivine and bronzite make up only about 10 percent of the zone. Although rocks in which chromite is a major constituent make up only a small part of the volume of the Ultramafic zone, many of these rocks consist only of chromite and mesostasis.

The volumetric sum of the interstitial grains ranges from 1 to 50 percent, regardless of the volumetric proportions present. In contrast to the wide proportional variation of the peridotitic crystals in the various rocks, the composition of the mesostasis is relatively constant; plagioclase seldom if ever constitutes more than 35 percent of any rock in the zone, clinopyroxene seldom more than 25 percent, and interstitial bronzite seldom more than 50 percent. Plagioclase and clinopyroxene occur interstitial to all the peridotitic major constituents, but bronzite occurs interstitially only in rocks which contain few or no individual bronzite crystals. Olivine is not common as an interstitial constituent and when it does occur is confined to chromitites containing no individual olivine crystals.

TEXTURES OF THE ROCKS

The minerals of the Ultramafic rocks can be divided into two general groups on the basis of shape and mutual grain relations: those which are commonly euhedral and always occur as individual grains or crystals, and those which are invariably anhedral and molded around these individual crystals. Olivine and chromite belong to the first group, plagioclase, clinopyroxene, quartz, and biotite to the second. Bronzite is unique, being an important constituent of both groups in the Ultramafic zone, but bronzite of the two habits does not generally occur together. Minerals of the first group are considered to be the primary precipitate, which crystallized and settled from the molten magma and successively accumulated at its floor; minerals of the second group crystallized at a later stage, in the pore space surrounding the crystal accumulate. The distinction between the two groups in analogous to the distinction made in clastic sedimentary rocks between detrital grains and cement: thus, the former came into existence outside of, and prior to, the formation of the rock of which it now forms a part; the latter was formed in the places it now occupies in the rock.

In distinguishing between these two genetic groups in the Stillwater complex, Hess (1939, p. 430–432) used the term "settled crystals" to describe those grains that fell to form a crystal mush, and the term "interstitial mineral" to describe the material crystallized from the interstitial liquid between the settled crystals. Wager and Deer (1939, p. 127–132), who encountered similar textural relations in the layered rocks of the Skaergaard intrusion, used the terms "primary precipitate" and "interprecipitate material." They defined (p. 127) the primary precipitate as ". . . discrete crystals or small glomeroporphyritic groups which separated from the overlying magma . . ." and the interprecipitate material as ". . . crystallized from the magma surrounding the primary precipitate."

In this report the terms "settled crystals" and "primary precipitate" will be used synonymously to describe those crystals that grew in and were separated by settling from the overlying magma. The term "interprecipitate material" will be used to include all minerals that grew in place in the rocks. I prefer to reserve "interstitial" for a descriptive term without genetic connotation.

The primary precipitate of olivine, bronzite, and (or) chromite makes up about two-thirds of all the layered rocks of the Ultramafic zone. The remaining one-third is composed of (1) interprecipitate enlargements of settled crystals, and (2) interstitial plagioclase, bronzite, and clinopyroxene "cement." The settled crystals were self supporting prior to development of the interprecipitate material. Settled crystals that are not equidimensional tend to lie with their long axes in a plane parallel to the floor of the intrusion (fig. 6); however, lineation in the foliation plane is weak or absent. Changes in grain size or proportions of the three settled minerals upward in the section produced layering in the rocks (fig. 9), and such layers are remarkably continuous along the strike.

The interprecipitate material occurs as enlarged rims on settled crystals, in interstitial grains, and in large, sponge-shaped oikocrysts. The oikocrysts bear no relation to the layering plane and commonly cut across the delicate planar structures exhibited by the settled crystals (fig. 10).

The distinction between individual euhedral settled crystals and space-filling interprecipitate material is evident in many rocks by change in mineralogy. Two processes have, however, operated after crystal settling to obscure such clear-cut relations: secondary enlargement and reaction replacement. Where crystals continued to grow after deposition, interference boundaries developed, and the original euhedral shapes of the settled crystals were obscured by addition of optically continuous material. Where settled crystals were partially replaced by reaction with the interprecipitate magma, the originally euhedral crystals were rounded and embayed.

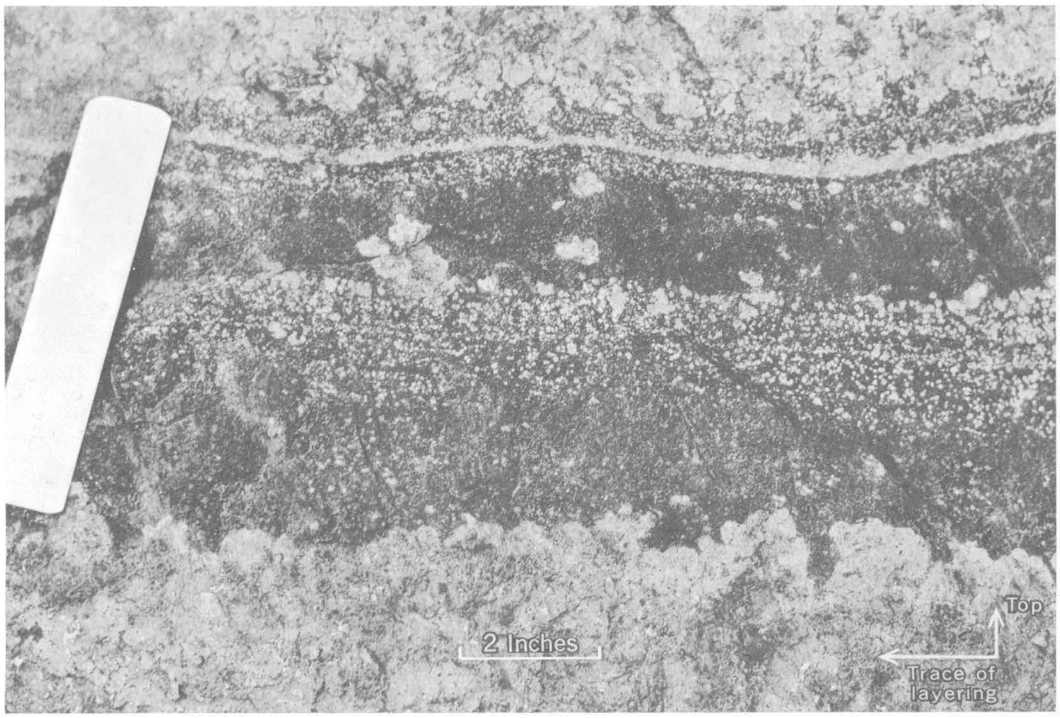


FIGURE 9.—Layering in chromitite and poikilitic harzburgite. The layering is defined by changes in grain size and mineralogy, and the unit of layering is one grain thick. Lower light gray layer is poikilitic harzburgite; central darker layer is chromitite and olivine chromitite; upper light gray layer is poikilitic chromite harzburgite. Note rhythmic layering with "dense" chromitite at base and "less dense" olivine chromitite at top, repeated twice in photograph.

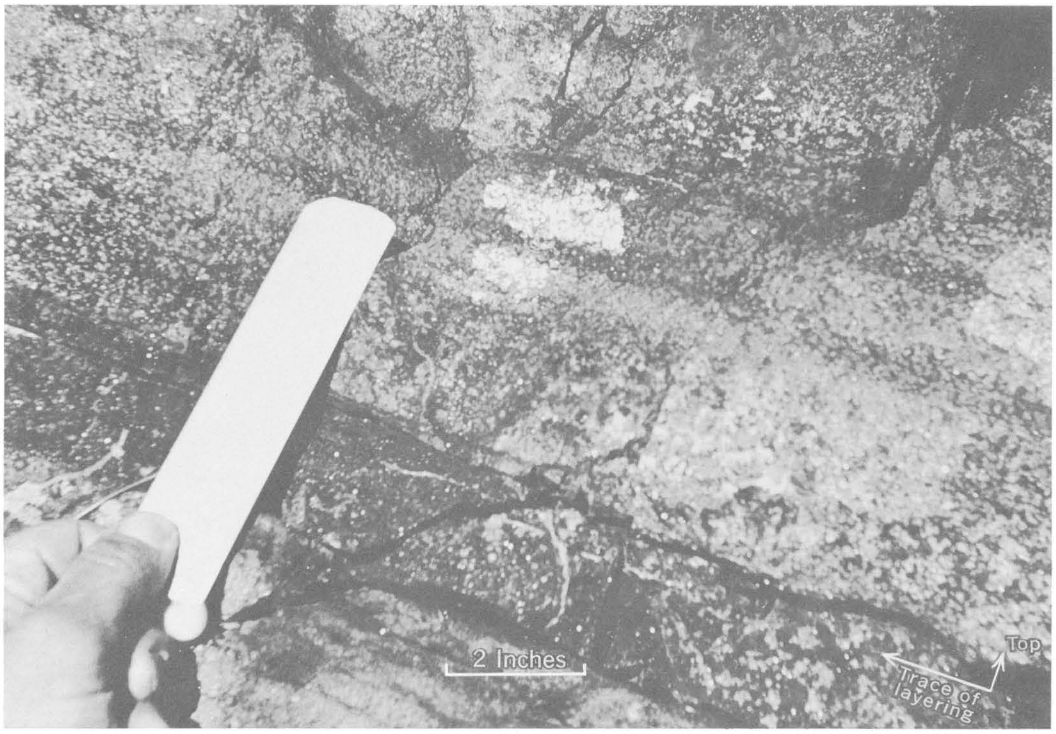


FIGURE 10.—Layering in chromitite and olivine chromitite. The layering is produced by the primary precipitate minerals olivine and chromite. The highly reflecting areas are bronzite oikocrysts cutting across layers. Lower black layer is chromitite; upper layers are olivine chromitite containing varied proportions of olivine and chromite.

FIELD PHOTOGRAPHS OF PRIMARY STRUCTURES IN THE ULTRAMAFIC ZONE

The layered rocks have some textures that can be described in ordinary igneous terminology, and others more accurately described in terms usually reserved for sedimentary rocks. In the following discussion, both igneous and sedimentary terminology will be used to describe appropriate textural features; but these terms will be used, in so far as possible, in their descriptive, rather than genetic, sense.

PRIMARY PRECIPITATE

SHAPE OF THE SETTLED CRYSTALS

In many rocks of the Ultramafic zone, the individual grains of chromite, olivine, and bronzite are completely bounded by crystal faces, but every gradation between euhedral and anhedral grains exists. Euhedral grains are associated with rocks that include relatively large amounts of interstitial material. With reduction in the amount of interstitial material due to enlargement of the settled constituents, these crystals develop generally polygonal interference boundaries. The degree of automorphism varies from layer to layer, but it is relatively constant in any given layer and can be predicted by knowledge of the amount of interstitial material within that layer. Independently of this effect, settled olivine and bronzite have rounded and embayed forms wherever they are in contact with interstitial pyroxene.

EUHEDRA

The euhedral crystals show only a limited number of preferred forms. The dominant form of chromite is the octahedron, although dodecahedral modifications occur in some rocks, particulary on the larger crystals. Strongly distorted crystals are uncommon, although in rocks where chromite crystals are clumped there is restricted development along join surfaces. In rocks where chromite is a minor constituent, the octahedral outlines as seen in thin section are generally sharp and angular; but in most chromitite, the edges of chromite crystals are rounded (fig. 72). The radius of rounding is generally less than one-tenth the long diameter of the octahedra. Olivine crystals are domatic and nearly equant, commonly slightly elongated parallel to the *c* axis, and slightly flattened on the (010) crystal face. Brachydomes are well developed and basal terminations uncommon. Many olivine crystals have slightly rounded terminations. Bronzite crystals are domatic, generally equant to broad prismatic, less commonly tabular. Crystals are simple, generally formed by eight nearly equally developed faces in the prism zone terminated by flat domes. Typical prismatic forms are elongate parallel to the *c* axis, and the short axis is *b* (using the orthopyroxene orientation preferred by Hess and Phillips [1940, p. 271–272]). Although most bronzites are stubby and nearly equidimensional, crystals with dimensions of 1:5:10 are not uncommon. Bronzite crystals in any one layer generally have the same habit (fig. 60). Terminations of bronzite crystals as seen in thin section are generally sharper than those of chromite and olivine.

SUBHEDRA AND ANHEDRA

The subhedral and anhedral grains may be divided into two types: those that share mutual interference boundaries with each other, and those that are anhedral against the interstitial material. Chromite, olivine, and bronzite may all have interference boundaries in rocks containing less than about 30 percent interstitial material. In rocks containing less than 10 percent gabbroic mesostasis, the peridotitic grains have polygonal outlines and equigranular mosaic textures (figs. 59, 62). Only olivine and bronzite have anhedral boundaries with interstitial material: olivine has irregular, embayed contacts where surrounded by interstitial bronzite; and bronzite is embayed where it is in contact with clinopyroxene.

DISCUSSION

Textural evidence, which will subsequently be discussed, indicates that all of the settled crystals were originally euhedral, and that those not currently euhedral were altered in shape after deposition, either by continued growth or by reaction with the interprecipitate magma.

The euhedral development and tendency toward equidimensional shapes are typical of crystals which have grown freely suspended in a saturated solution, and it is difficult to believe that rocks composed of 70 percent of perfectly formed olivine or chromite or bronzite could possibly have crystallized in place. The rounded corners of some olivine and chromite crystals were probably caused by partial resorption prior to deposition. According to Buckley (1951, p. 45, 257), such effects are not uncommon in artificially prepared crystals and can be caused by slight changes in temperature, pressure, viscosity, and other factors.

DISTRIBUTION OF THE SETTLED CRYSTALS

The distribution of the three settled minerals differs with stratigraphic height above the floor of the complex, and the repetitive occurrence and absence of these constituents give rise to the well-developed compositional layering. Along planes parallel to the layers, the kind and proportions of the settled minerals remain essentially unchanged. Description of distribution of the primary precipitate is therefore largely concerned with stratigraphy, a subject which will be outlined here, but which will be considered in more detail in a subsequent publication.

Distribution of settled minerals within the various rock types is reasonably simple. Poikilitic harzburgites and dunites essentially contain only settled olivine, although a small percentage of settled chromite is present in almost all of them. In many chromitites, chromite is the only settled constituent, although a small percentage of settled olivine is present in some. In most bronzitites, bronzite is the only settled constituent. Mixtures of settled olivine and bronzite are present in olivine bronzitites and granular harzburgites, as are mixtures of settled olivine and chromite in olivine chromitites. A characteristic feature of the settled mineral distribution throughout the entire section is that settled phases do not persist vertically across the layering but appear, disappear, and reappear.

BASAL ZONE

Along much of the base of the complex, where the chilled gabbro is separated from the Ultramafic zone by fine-grained bronzitite, settled bronzite is the first primary precipitate mineral of the Basal zone and of the complex. In several areas bronzite is joined by settled plagioclase in a few thin, lenticular layers within the bronzitite. In those areas where Basal zone bronzitite is not developed, the first precipitate is olivine of the Ultramafic zone.

ULTRAMAFIC ZONE, PERIDOTITE MEMBER

In the lower part of the Ultramafic zone, the settled phases not only appear but also disappear in a regular order. Detailed field mapping has shown that the rock sequence—poikilitic harzburgite, chromitite, olivine chromitite, poikilitic harzburgite, granular harzburgite, bronzitite—is repeated, with minor variations, some 15 times within the Peridotite member. Several examples of these rock sequences, or cyclic units[1], are illustrated in figure 19. A typical example of the variation within cyclic units, in terms of stratigraphic appearance and disappearance of settled minerals, is shown in figure 11. Olivine and chromite appear abruptly at the base of the unit, with olivine comprising about 99 percent of the settled material and chromite about 1 percent. No settled bronzite is present. About midway in the poikilitic harzburgite section, olivine abruptly disappears, succeeded by settled chromite alone. In this particular cyclic unit the accumulated chromite forms a layer 7 inches thick. At the top of the chromitite layer chromite is joined by olivine, and the two minerals appear together, with olivine gradually increasing in amount and chromite decreasing, to the top of the olivine chromitite layer. In many cyclic units, however, the decrease and disappearance of chromite and concomitant increase of olivine is not gradational but abrupt, with repeated alternations upward of chromite-rich and olivine-rich rock. At the base of the granular harzburgite layer, olivine and chromite are joined abruptly by relatively large quantities of settled bronzite (fig. 88), and throughout the remainder of the granular harzburgite layer, settled bronzite increases in amount at the expense of olivine. Chromite generally disappears completely within the granular harzburgite layer. At the top of the granular harzburgite layer, olivine abruptly ceases to be a settled constituent of the rock, and only settled bronzite crystals remain. In other cyclic units, however, the contact between granular harzburgite and bronzitite is smoothly gradational; in still others, the disappearance of olivine is oscillatory. At the top of the bronzitite layer, bronzite disappears abruptly, and the section is overlain by the poikilitic harzburgite layer of the succeeding cyclic unit.

Ignoring accessory chromite in poikilitic harzburgites, the order of appearance of settled minerals within each cycle is olivine, chromite, bronzite; the order of disappearance is chromite, olivine, bronzite. The appearance of each new phase is abrupt, but the disappearance may be abrupt or gradational.

ULTRAMAFIC ZONE, BRONZITITE MEMBER

Essentially, the only settled constituent of the thick Bronzitite member of the Ultramafic zone is bronzite. The section begins at the upper contact of a granular harzburgite layer, as do the thinner bronzitite layers of the Peridotite member, and differs from them only in thickness. About 100 stratigraphic feet below the top of the Bronzitite member, bronzite is joined by a few percent settled chromite, and this gradually diminishes in amount, disappearing before the bronzite is abruptly joined by large quantities of settled plagioclase at the base of the layered norites.

DISCUSSION

The direction of top and bottom in the complex can be demonstrated by slump structures, crystal sorting, and other gravity-controlled phenomena, so that the stratigraphic order of appearance and disappearance of the settled minerals can be said to be their order of accumulation. Further, relative ages of accumula-

[1] The term "cyclic unit," used here to describe repeated sequences of sharply defined layers, should be distinguished from the term "rhythmic unit," used by Brown (1956, p. 8) to describe layers characterized by gradually changing proportions of primary precipitate minerals.

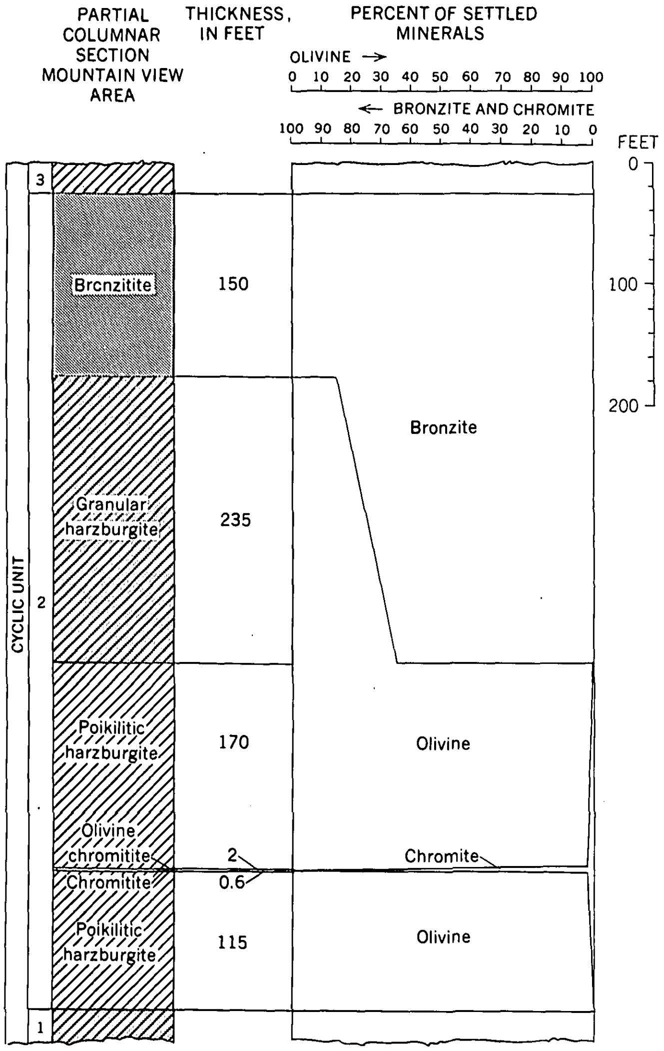


FIGURE 11.—Stratigraphic variation of settled minerals in a typical cyclic unit of the Peridotite member.

tion of the settled phases, based on the law of superposition, are from older at the base to younger at the top. In this sense, the oldest crystal accumulate along most of the base of the complex is bronzite, succeeded within a very short stratigraphic distance by olivine and chromite, and, much higher in the section, by settled plagioclase and augite. Within the cyclic units of the Peridotite member, the older settled minerals are olivine and chromite, followed by younger bronzite.

In order to demonstrate that the order of accumulation is identical with the order of crystallization of the Stillwater magma, it is necessary to show that the magma crystallized in a closed system, that crystal products did not accumulate except at the floor, and that long-term suspension or floating of crystallization products did not occur. These conditions are discussed elsewhere in this report.

INTERNAL CHARACTER OF THE SETTLED CRYSTALS

INCLUSIONS

Inclusions in settled olivine, bronzite, and chromite crystals are present but relatively uncommon. In all three minerals the distribution of inclusions is related to the layering plane, in that thin layers containing abundant inclusions are separated by much thicker sections in which inclusions are rare.

Inclusions in chromite can be divided into two types, both relatively uncommon: (1) those which are made up of the same material that surrounds the chromite grain, and which are commonly in optical continuity; and (2) those which are made up of individual crystals that have no relation to the surrounding material. Inclusions of the first type occur in large erratic chromite grains, very sparsely scattered among normal-sized chromite crystals, and seem to be made up of a shell of smaller chromite grains. The large, compound grains tend to have euhedral shapes (fig. 12) but are commonly embayed. These crystals are believed to have formed in the magma as clusters of chromite grains that continued to grow on their outer surfaces while suspended. After deposition, their open irregular cavities were filled by interprecipitate minerals. Inclusions of the second type have smooth margins, are centrally located within the chromite grain, and are composed of olivine, usually accompanied by small amounts of pleochroic brown mica. The inclusions bear no relation to the material surrounding the grains; in some rocks, the inclusions are unaltered where interstitial material is partly serpentinized. These inclusions do not occur in rocks where chromite is a minor constituent, and they are rare even in most chromitites. In a few chromitite layers, however, from 10 to 20 percent of the chromite grains contain these olivine inclusions. The distribution of this type of inclusion suggests that small olivine crystals acted as nucleation centers for chromite growth. The olivine crystals apparently did not continue to grow after chromite crystallization began, for such inclusions are confined to massive chromitite layers.

Olivine crystals, like those of chromite, rarely contain inclusions. Chromite is the only included mineral that was observed, and it occurs in three different distributions: (1) as single euhedra in the central part of olivine crystals; (2) as abundant small crystals around the periphery of olivine crystals; and (3) as abundant small crystals evenly distributed throughout the olivine crystals. Although chromite occurs mostly between olivine grains rather than within them, sparse inclusions of the first type occur in all rock types containing the two minerals. Where chromite crystals

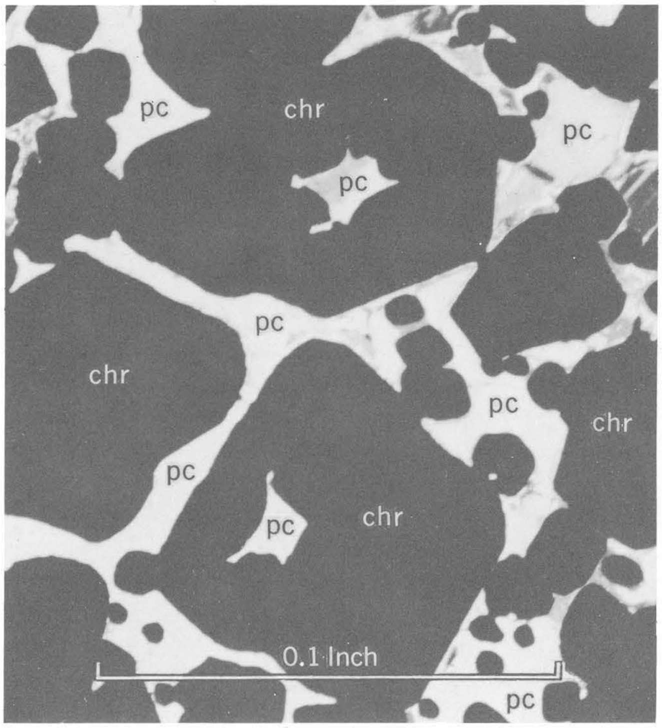


FIGURE 12.—Inclusions in chromite crystals. chr=chromite; pc=plagioclase. Crossed nicols.

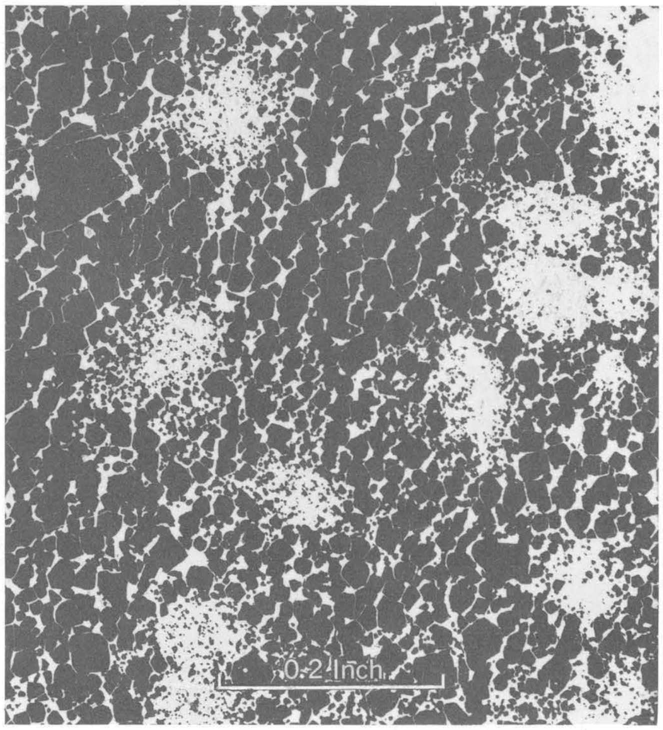


FIGURE 13.—Fine-grained chromite inclusions (black) in olivine (white ovals). Olivine chromitite. Plane polarized light.

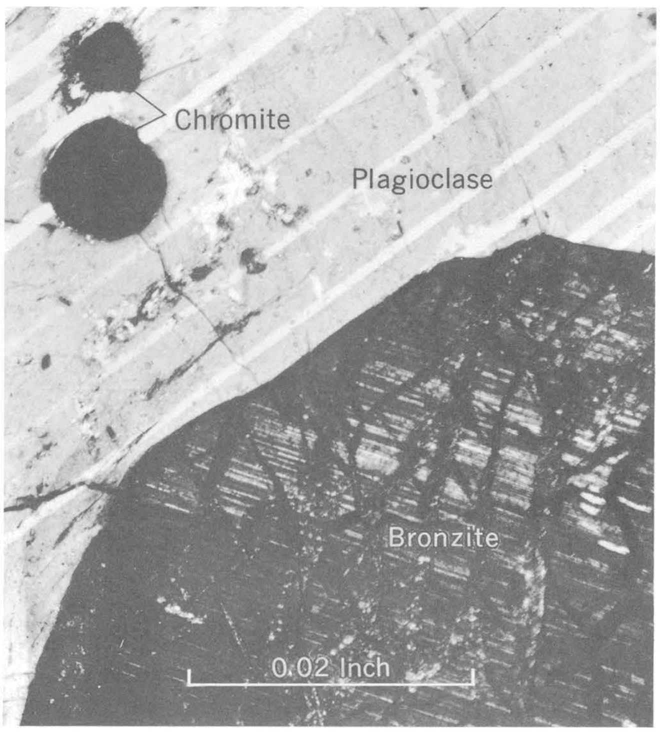


FIGURE 14.—Clinopyroxene lamellae in euhedral bronzite. Lamellae pinch out at margin. Crossed nicols.

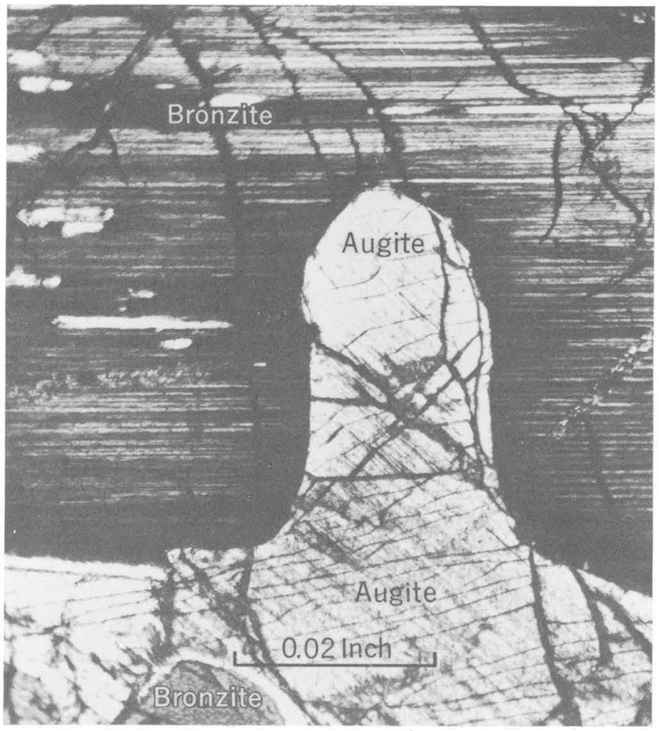


FIGURE 15.—Clinopyroxene lamellae in partially replaced bronzite. Lamellae pinch out adjacent to replacing augite. Crossed nicols.

PHOTOMICROGRAPHS SHOWING INTERNAL CHARACTERISTICS OF SETTLED MINERALS occur both within and between olivine crystals, the included chromite crystals are generally smaller. Olivine crystals with inclusions of the second and third type occur only in a few olivine chromitite layers, but where they occur, each one in the layer has the same internal character. In some of these layers, the olivine crystals have a clear core and marginal chromite inclusions; in others the olivine is crowded with chromite inclusions throughout, and these become slightly larger in size toward the margin (fig. 13). In both cases the size break between the included chromite crystals and those packed between the olivine crystals is sharp, the included crystals usually being about one-fourth as large. The included crystals tend also to have perfect terminations, whereas those between olivine crystals are slightly rounded. Inclusions of all three types are believed to represent envelopment of chromite by olivine during the growth and differential settling of the crystals through the magma column. The central location of many of the chromite crystals of the first type may indicate that some olivine formed around a nucleus of chromite. Inclusions of the second and third type occur only where chromite is an important constituent of the rock and probably indicate simultaneous crystallization of the two minerals. In the second type, olivine crystallization preceded that of chromite, and in the third, chromite apparently preceded olivine.

Rare inclusions of olivine, chromite, and plagioclase have been observed in bronzite crystals. Settled bronzite crystals with olivine inclusions are confined to rocks in which olivine also occurs as discrete crystals. Included olivine grains are rounded and embayed, suggesting partial replacement by bronzite; discrete olivine crystals in the same rocks are larger and euhedral. In keeping with the general antipathy of chromite and settled bronzite, chromite inclusions are extremely uncommon, being confined to rocks in which chromite also occurs between settled bronzite crystals In the few examples observed, crystals of chromite within and between those of bronzite appear to be about the same size. In one specimen cut from the Bronzitite member of the Ultramafic zone at its contact with the stratigraphically lowest norite layer, plagioclase inclusions in bronzite were observed, but other specimens from the same horizon do not contain them. In this specimen, the bronzite crystals average about 2 mm in diameter, and about one-half of them contain one or more prisms of plagioclase, 0.2 mm in length, near their margins. No individual settled plagioclase occurs in the rock, but that in the norite layer above is the same size as the bronzite. It would appear that in this specimen plagioclase and bronzite had crystallized in part simultaneously.

Certain inferences as to the paragenesis of settled minerals coexisting in the rocks can be drawn from the nature of their inclusions. It has been demonstrated that, in some cases, olivine and chromite crystallized simultaneously. The absence of inclusions in olivine and chromite in most rocks containing mixtures of these minerals can be explained in two ways: (1) olivine and chromite in all such rocks crystallized simultaneously, with widely spaced crystallization centers and with no tendency for one mineral to act as nuclei for the formation of the other; or, (2) olivine and chromite in most of these rocks crystallized at slightly different compositional horizons in the magma.

A somewhat different problem exists in rocks containing mixtures of settled olivine and bronzite. The well-known reaction relation between olivine and bronzite has been established in the Stillwater magma by the presence of embayed olivine grains in the centers of bronzite crystals. In most granular harzburgite and olivine bronzitite, however, olivine individuals are not rimmed by bronzite, but the two minerals occur side by side as euhedral crystals (fig. 34). These relations may have occurred in two ways: (1) the coexisting olivine and bronzite in the rocks represent the assemblage present at the reaction boundary between olivine and bronzite in a homogeneous magma; or, (2) the olivine and bronzite in the rocks crystallized alone at slightly different compositional horizons in the magma. In the first case, either reaction rims around olivine or rounded olivine grains would normally be expected, especially on those individual crystals located in the upper parts of the layers. In the second case, assuming that bronzite must fall through magma in equilibrium with olivine, some evidence of melting of bronzite crystals might be seen, unless the settling velocity was rapid compared to the distance of fall.

ORIENTED INTERGROWTHS

Regular intergrowths in unaltered chromite have not been observed. Many crystals of olivine, however, contain minute, opaque blades of metallic minerals uniquely oriented on (100) of the host. The blades are discontinuous, generally average about 0.05 mm in length, and presumably represent exsolution of an iron or titanium oxide.

Hypersthene in the chilled gabbro at the base of the Stillwater complex contains clinopyroxene of two types: (1) abundant coarse, discontinuous lamellae or blebs, 0.1 mm thick, oriented on irrational planes in the host; and (2) narrow, more regular lamellae oriented parallel to (100) of the hypersthene. Poldervaart and Hess (1951, p. 472–489) and Brown (1957, p. 529–534) consider lamellae of the first type to be indicative of primary crystallization of pigeonite, which, on cooling, exsolved augite—for the most part oriented on (001) of the pigeonite—and, on further cooling, inverted to hypersthene. The presence of relict pigeonite lamellae is considered to indicate that these pyroxenes crystallized above the orthopyroxene-clinopyroxene inversion temperature (Hess, 1941, p. 582–584).

Bronzite crystals in the layered rocks of the Basal zone and throughout the entire Ultramafic zone, on the other hand, contain only regular, well-developed clinopyroxene lamellae oriented parallel to (100) of the bronzite. These lamellae are commonly 0.001–0.002 mm thick and are generally spaced 0.005–0.01 mm apart. No relict pigeonite lamellae have been observed. Bronzite with simple (100) lamellae has been described by Hess and Phillips (1938, p. 450–456); Poldervaart and Hess interpret this as indicating primary crystallization of orthopyroxene and exsolution of clinopyroxene on slow cooling. Pyroxene crystallization temperatures throughout the upper part of the Basal zone and the entire Ultramafic zone were, according to Hess (1941, p. 582–584), below the orthopyroxene-clinopyroxene inversion temperature for their range in composition.

Some indication of the relative sequence of clinopyroxene exsolution in settled bronzite can be obtained by examination of the margins of the crystals. In a zone about 0.05 mm thick around the peripheries of euhedral crystals, the (100) lamellae pinch out (fig. 14). The tips of the narrowing lamellae extend to the terminating crystal face. Presumably, this is a primary border effect caused by the local reduction of unit volume from which Ca^{+2} can migrate during the exsolution. Similar pinching effects also occur around chromite inclusions in bronzite, and along a very few apparently pre-exsolution fractures. Lamellae in relict, partially resorbed bronzite surrounded by interstitial augite also pinch out at the bronzite-augite contact (fig. 15). This suggests that exsolution in settled bronzite occurred after crystallization of much of the interprecipitate magma.

In summary, the character of the lamellae indicates that all of the settled bronzite of the Basal and Ultramafic zones crystallized below its inversion temperature as primary orthopyroxene, cooled very slowly, and exsolved clinopyroxene lamellae at some time after at least the major part of the interstitial material had crystallized.

ZONING

Zoning has not been observed in euhedral settled crystals within the Ultramafic zone. In a few nearly monomineralic layers, however, anhedral olivine and bronzite grains have narrow, gradational selvages of slightly more iron-rich material, which are believed to be related to continued growth of these crystals after deposition. Zoned chromite has not been observed, although in a few highly altered rocks, rims of secondary magnetite around chromite grains can be seen in polished section.

FRACTURES

Almost all the minerals are intimately fractured on a microscopic scale, and many of these fractures are loci for whatever alteration the minerals exhibit. The great majority of fractures cut settled and interstitial material alike and are related to postconsolidation deformation. In a few rocks, however, tongues of interprecipitate material extend into fractures that cut settled crystals; equally uncommon, exsolution lamellae in bronzite grains pinch out on either side of prominent cracks. These relations suggest that, in a few places, settled crystals were fractured prior to the complete solidification of the interprecipitate magma, and prior to the exsolution of clinopyroxene from the bronzite.

UNDULATORY EXTINCTION

In several parts of the complex, near the base of the Ultramafic zone, the rocks are characterized by plastic deformation of layers, drag folds, and broken layers healed by dunite. Although the same compositional rock types present in the main part of the Ultramafic zone can be recognized in these areas, the rocks have xenomorphic textures, and the constituent grains show brecciated margins, patchy extinctions, bent pyroxene exsolution lamellae, rupture on cleavage planes, and other evidence of postdepositional deformation (fig. 16). It is in these areas that the crosscutting dunite segregations described by Hess (1938b, p. 334–340) occur, and these are also characterized by xenomorphic textures and deformed minerals. Although typical interstitial minerals are generally absent from these rocks, plagioclase and interstitial bronzite, where present, are highly strained, showing patchy extinctions and rupture surfaces on cleavage planes. Undulatory extinction is most highly developed in the olivine grains, all of which show repeated undulatory banding on planes near (100), or continuous extinction changes, or patchy strain shadows. Differences in extinction position in the same olivine exceed 30 degrees in many grains, but translation lamellae have not been observed. Chromite in some of these rocks is slightly anisotrophic.

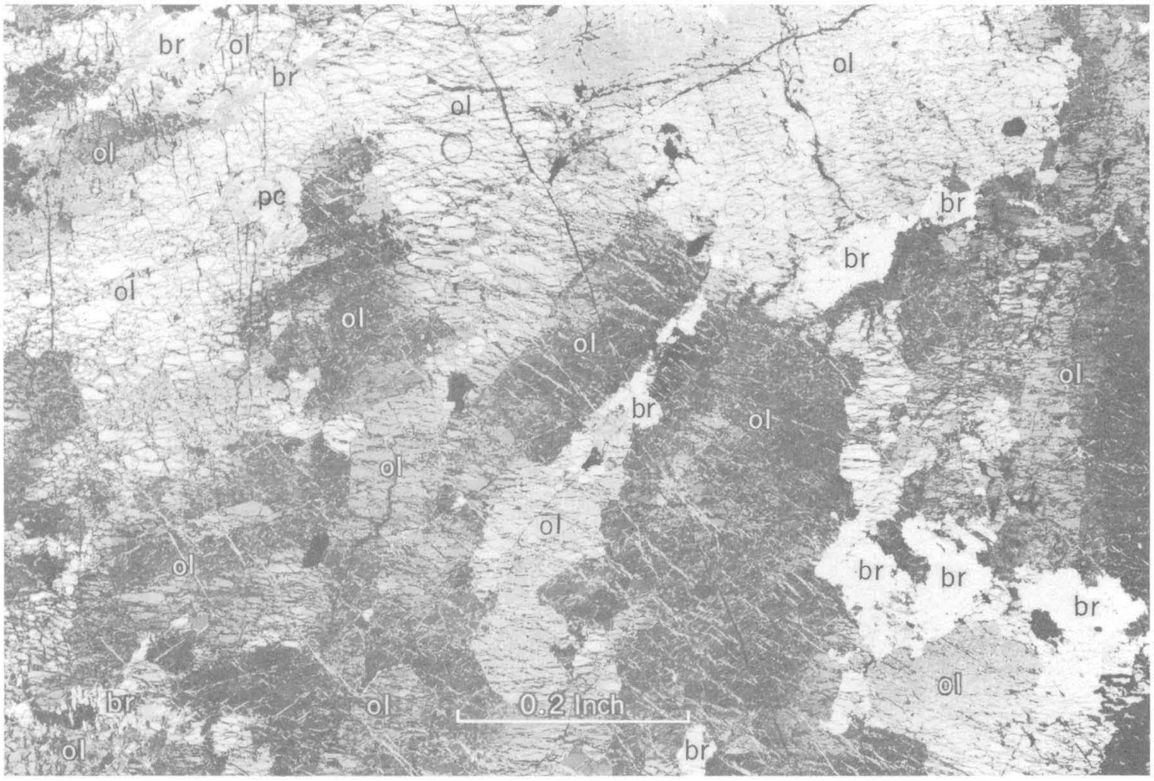


FIGURE 16.—Early deformation texture in poikilitic harzburgite. Grains are strongly undulatory with patchy extinctions and brecciated margins. ol=olivine; br=bronzite; pc=plagioclase. Crossed nicols.

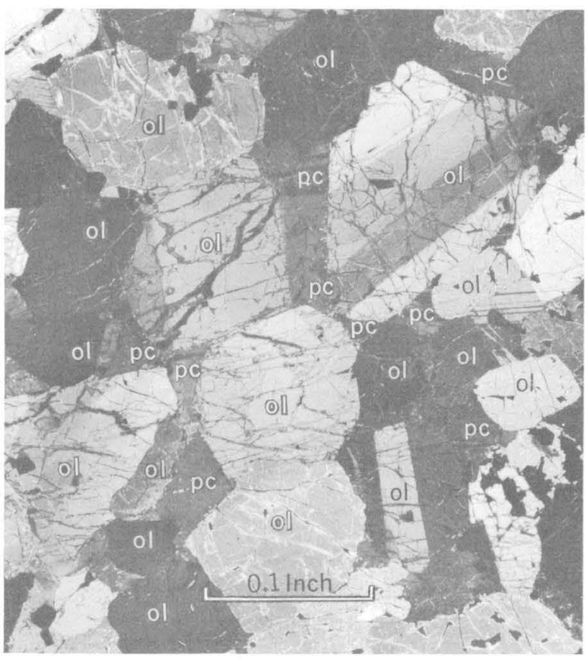


FIGURE 17.—Weak undulatory banding of olivine in poikilitic harzburgite. About one-third of the olivine in the specimen shows some banding. ol=olivine; pc=plagioclase. Crossed nicols.

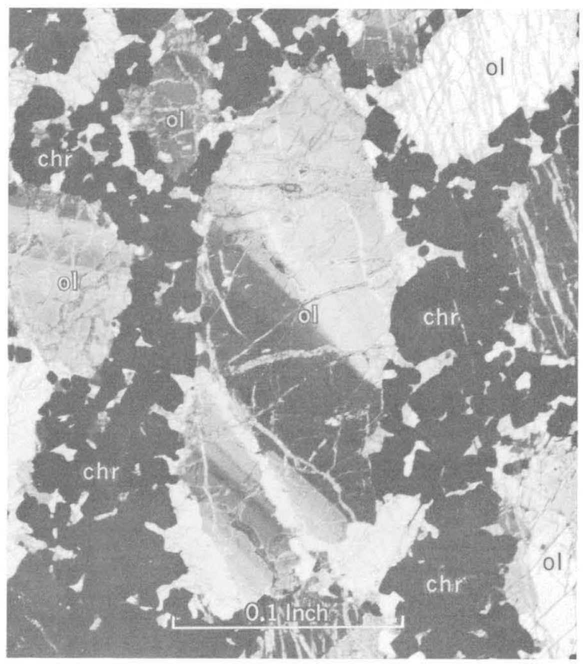


FIGURE 18.—Compound undulatory banding of olivine in olivine chromitite. All olivine grains are undulatory and in some grains banding is repeated on ruptures. ol=olivine; chr=chromite. Crossed nicols.

PHOTOMICROGRAPHS SHOWING UNDULATORY BANDING IN OLIVINE GRAINS

In contrast, the layered rocks that form the main bulk of the Ultramafic zone—stratigraphically above the deformed areas where present—are characterized by abundant interstitial plagioclase and pyroxene, undeformed layering, and absence of crosscutting ultramafic bodies. The plagioclase and pyroxene of these rocks show no evidence of intragranular strain, but olivine crystals in many of the layers show comparatively weak undulatory banding. The bands, which are 0.1–1.0 mm thick, are sharply defined along nonrational planes subparallel to (100). A complete range exists from rocks which contain no undulatory olivine to those in which all the olivine grains have extinction bands; however, the latter are rare. The number of bands per grain ranges from 2 or 3 in rocks in which only a small proportion of the olivine grains are undulatory, to 10 or 15 in rocks where all are undulatory. In olivine with 2 or 3 extinction bands, the crystallographic orientation of the subindividuals commonly differs by 1 to 3 degrees (fig. 17). In olivine with multiple extinction bands, the extinction positions in the subindividuals commonly change consistently in the same direction from one side of the grain to the other. In a few rocks where bands are highly developed, this consistent change may be interrupted by ruptures and repeated several times (fig. 18), so that a total extinction difference of 20 degrees may be produced. However, these ruptures—as well as patchy or continuous extinction changes and brecciation—are extremely uncommon in the main body of the Ultramafic zone. Within these rocks, undulatory extinction is best developed and most common in layers containing mixtures of olivine and chromite, and in adjacent poikilitic harzburgite. It is less common and more poorly developed in granular harzburgite and olivine bronzitite.

Turner (1942, p. 280–300) considers undulatory extinction in olivine to be an expression of combined flexure gliding and incipient rupture of the olivine space lattice, and he believes that the presence of undulatory olivine is evidence of intragranular deformation after the complete solidification of the rock which contains them. This is abundantly substantiated by field evidence in the locally deformed areas near the base of the Ultramafic zone, and it seems likely that such deformation took place above serpentine stability temperatures (Bowen and Tuttle, 1949, p. 455). In many of the rocks from the main part of the zone, however, undulatory olivine is the only evidence for internal deformation. The rocks are not sheared; they retain their depositional fabrics, and coexisting chromite and bronzite retain their euhedral shapes. Furthermore, undulatory and internally homogeneous olivine can be found in all proportions in the rocks, apparently without favored orientations for either type (fig. 46). It would thus appear that olivine is very sensitive to deformation.

A great deal more work would be necessary to account for the localization of undulatory minerals both areally and within samples, or to relate the preferred orientations to deformation mechanisms, or to the period of deformation. From field evidence, such as incompetent behavior of layers and healing of fractures, it seems reasonable to assign the major deformation of the local areas near the base of the Ultramafic zone to a period before complete solidification of the mush, and perhaps before the major part of the rocks of the zone were deposited. Very early deformation would also account for the general paucity of interstitial minerals in these rocks, for the trapped magma would have been squeezed out during deformation by filter press action. In the main part of the Ultramafic zone, it may be significant that undulatory olivine is more commonly developed in olivine chromitite than in other rock types. It seems possible that the relatively fine grain size of the chromitite makes it less competent than other rocks in the section. The single specimen investigated from the main part of the zone, which contained strongly undulatory olivine, proved to be a tectonite (fig. 47). Possibly this structure is related to the known Precambrian tilting, or to Laramide folding of the complex to its present position. If so, the effects are local only, for not only do many layers contain undeformed olivine, but interstitial quartz in the Basal zone and Bronzitite member shows no strain shadows or undulatory extinction.

GRAIN SIZE AND GRAIN-SIZE DISTRIBUTION

The superficial similarities of grain-size variation and distribution between settled crystals of the Ultramafic zone and clastic grains of sediments are striking. Layers formed by changes in grain size are parallel to the compositional layering, and in some layers change in grain size accompanies compositional change. Grain sizes are remarkably consistent along the layering plane. The distribution of grain sizes of settled olivine, bronzite, or chromite within almost all compositionally homogeneous layers shows a positive skewness that is largely eliminated by logarithmic transformation, and sorting characteristics most nearly resemble those of beach sands. More detailed study, however, reveals many features of size distribution distinctly different from those of clastic sediments. Many rocks, for instance, contain mixtures of settled olivine and either bronzite or chromite. Each of the settled minerals in such rocks has approximately lognormal size distributions with small sorting coefficients, but these settled minerals are most commonly not in hydraulic equivalence. Further, the sedimentary structures usually associated with coarse sands are not abundant. Scour and local unconformity occur but are extremely rare. Unequivocal crossbedding has never been observed in the Ultramafic zone. Small-scale size-graded bedding is rare and, in the few places where recognized, is just as commonly coarse-zone up as coarse-zone down. The origin of the rocks of the Ultramafic zone is believed to have been more similar to that of chemical than that of detrital sediments. In the following section, however, comparisons are largely with detrital rocks, for size and sorting in chemical sediments have not been investigated to the same extent.

In order to describe adequately the grain-size variation in the closely packed settled crystals of the Ultramafic zone, quantitative size measurements were made using standard sedimentary techniques. Because of the coherent nature of the rocks, all size measurements were made in the following manner: for the finer grained rocks, areas to be measured were blocked out on 2- by 2-inch thin sections, and the diameter of each grain within the area was measured by means of the micrometer ocular of a microscope; for the coarser grained rocks, measurements were made with a millimeter scale on etched rock slabs. For each specimen, the apparent diameter of each grain as seen in section was measured and separately tabulated. In specimens that contained nonequidimentional grains, the maximum and minimum diameters of the grains were read and averaged. Where more than one of the three settled minerals was present in a specimen, grain sizes of each mineral were measured separately. In rocks for which mean diameters only were desired, between 75 and 100 grains of each mineral species were measured. In rocks for which size-distribution curves were to be constructed, between 150 and 400 grains of each mineral species were counted and individually tabulated. In each case, grains were counted until cumulative arithmetic means of the measurements were nearly stabilized. In addition, the maximum 95 percent confidence limit of the mean was determined on one well-sorted and one more poorly sorted sample and was found to be 8 and 12 percent respectively. The tabulated measurements were assigned to ½ Udden size grades, number percentages for each interval were calculated and plotted as histograms and cumulative curves, and quartile measures were read graphically. It should be recognized that grains measured in section show not only their true diameters, but diameters less than the true ones. Corrections for sectioning have not been applied to these measurements, both because the results were to be used only for comparative purposes within a single study and because of doubt as to the applicability of sectioning corrections to grains not spherical or ellipsoidal in shape (Greenman, 1951a, p. 271–272). The general effect of an arithmetic mean correction such as that proposed by Krumbein (1935, p. 482–496) would be to increase the reported arithmetic mean diameters about 25 percent. If the cumulative size distribution curves were corrected by the method proposed by Greenman (1951b, p. 447–462), the quartile sorting coefficients would be lowered about 6 percent.

GRAIN SIZE

In the layered rocks of the Ultramafic zone, olivine crystals range in diameter from 0.5 mm to more than 40 mm, but the great majority of grains are 1–4 mm. Bronzite crystals range from 0.5 mm to 15 mm, but, like olivine, most commonly are 1–4 mm. Chromite crystals are always smaller than associated bronzite and olivine; in most rocks they are 0.1–0.4 mm in diameter, but they occur with observed extreme diameters of 0.02 mm and 5 mm.

The vertical distribution of grain sizes within the Ultramafic zone is complex, and study of the variation has been confined to stratigraphic sections in the eastern 15 miles of exposure. Within the Basal zone of the complex in this area, there is a gradual, but somewhat irregular, increase in grain size from the chilled lower margin up to the base of the Ultramafic zone. The average grain size of the chilled marginal gabbro itself is about 0.3 mm, and the bronzitite layers above it contain euhedral bronzite crystals ranging in average diameter from about 0.7 mm to 1.0 mm. Upward, with the appearance of the first settled olivine (the base of the Ultramafic zone) a sharp change in size was observed, and the lowest ultramafic layer has an average grain size of about 2 mm.

Within the Ultramafic zone, there are three types of sharp vertical size change: (1) A decrease in size invariably occurs from silicate to chromitite layers, because grains of chromite are always smaller than those of bronzite or olivine. (2) A size change occurs at the base of each poikilitic harzburgite layer, the overlying poikilitic harzburgite being coarser grained than the layer stratigraphically below it. (3) Sharp size changes occur within some layers of bronzitite, harzburgite, and chromitite without a change in mineral constitution of the rock. Each of these types of size variation is illustrated in figure 19. The chromite crystals in chromitite in the lower part of cyclic unit 2 have an average grain size about one-twelfth that of the olivine on either side, and the chromite crystals in the lower part of cyclic unit 15 have about the same

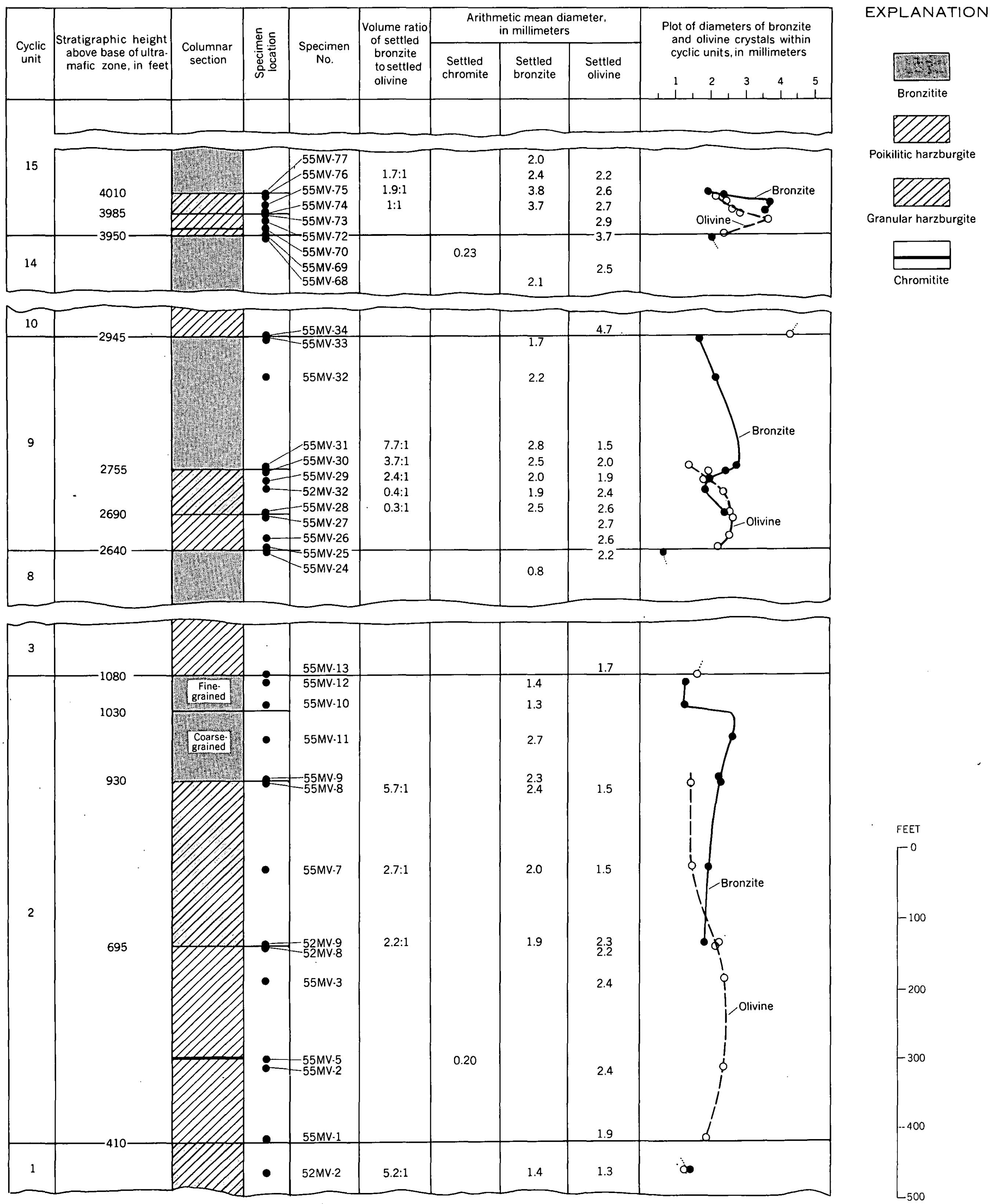


FIGURE 19.—Stratigraphic distribution of mean diameters of settled bronzite and olivine crystals in the Peridotite member in the Mountain View area.

size ratio. In detail, the boundary surfaces between silicate layers and layers of the finer chromitites are cuspate, analogous to conglomerate-sand contacts in sedimentary rocks (figs. 20, 21).[2] Five examples of sharp increases in size between the poikilitic harzburgites and the rocks underlying them can be seen in figure 19, and these size breaks coincide with the compositional layering contacts. In the same figure, an example of a sharp grain size change within a compositional layer is shown in the bronzitite of cyclic unit 2. Contacts at which such changes within compositional layers occur are parallel to the boundaries of the layer. Most such intralayer size changes observed are, like the example in cyclic unit 2, from coarse to fine upward in the section, and the grain size of the stratigraphically higher, finer grained upper portion typically increases gradationally away from the contact. Sharp grain size changes also occur in some chromitites (fig. 35), but in these, no grading above the contact has been observed.

In addition to the sharp variations in grain size, there are three types of gradual vertical grain-size changes within the Ultramafic zone: (1) small-scale size-graded bedding, both right side up and upside down; (2) gradual increases and decreases in grain size at intervals of 100 to 500 stratigraphic feet, which are related to the cycles; and (3) a gradual overall increase in grain size to near the center of the Ultramafic zone, followed by a decrease to the top.

Small-scale size-graded beds are rare features of the Ultramafic zone; only a few unequivocal graded beds have been seen in the field (fig. 22), and laboratory work has failed to turn up additional examples. The graded beds observed range from 1 to 3 inches in thickness, and in about one-half of the occurrences grain size diminished downward—that is, the graded beds were upside down. In the layered norites and gabbros above the Ultramafic zone, where small-scale graded beds are slightly more abundant, the ratio of upside down to right side up is about the same. Density-graded beds, or "rhythmic layering," which is a prominent feature of the entire complex, should not be confused with size-graded beds, even though the density-graded beds have been compared with size grading in sedimentary rocks by some authors (Wager and Deer, 1939, p. 271; Cooper, 1936, p. 32; Hess, 1938a, p. 265).

The second type of gradual grain-size variation occurs within the cyclic units of the Peridotite member, and the size behavior of settled olivine and bronzite in three of these cycles is shown in figure 19. Olivine crystals within the three cycles gradually increase in size stratigraphically upward to a point near the base of the granular harzburgite layers, then decrease. The abrupt appearance of bronzite as a settled crystal at the bases of the granular harzburgite layers has no pronounced effect on the gradual increase or decrease in size of the olivine. As the bronzite exceeds olivine in volume, the sizes of olivine grains decrease sharply. The earliest bronzite crystals in each cyclic unit, which are those near the bases of the granular harzburgite layers, are also relatively fine grained. Like the olivine, these gradually increase in size to a point in the lower part of the bronzitite layers, then decrease in size toward the upper parts of the sections. In the lower part of cyclic unit 9, however, this pattern is complicated by an initial diminution in grain size of the bronzite. The gradual variation in bronzite grain size shows no discontinuity as olivine ceases to be a constitutent of the rock. The maximum and minimum average size attained by olivine and bronzite in a given cycle are very nearly equal but occur at different positions in the cycle. Further, the maximum and minimum sizes attained by olivine and bronzite within a cycle are not related to the thickness of the cyclic unit. A major violation of this general pattern of size variation occurs at the base of a few cyclic units, including the one containing the main chromitite layer. In these, the basal poikilitic harzburgite is composed of extremely coarse olivine crystals up to the base of the chromitite, but above the chromitite the normal size-variation pattern of olivine obtains.

The grain-size variation of chromite in single massive chromitite layers is probably much like that of olivine and bronzite in harzburgite and bronzitite. The size variation of the chromite is so small, however, and the number of measurements necessary to sample adequately a particular horizon is so large, that such a vertical grain-size variation cannot be said to be general. About 2,000 measurements were made on one 7-inch-thick chromitite layer, and the results are summarized in table 2. Several other similar massive layers were more cursorily examined, and generally were slightly coarser grained near the center than at either margin. In some simple chromitite–olivine chromitite layers, where the amount of chromite in the chromitite decreases upwards, there is a gradual diminution of chromite grain size toward the top; but this variation again cannot be said to be general. It has been noted, however, that although the compositional break between chromitite and olivine chromitite in such rocks is generally extremely sharp, there is no size difference between the chromite grains at the top of the chromitite and the bottom of the olivine chromitite. The chromitite–olivine chromitite contacts are

[2] I am not acquainted with previous descriptions of this relation, and the term "cusp texture" is here coined to describe it.

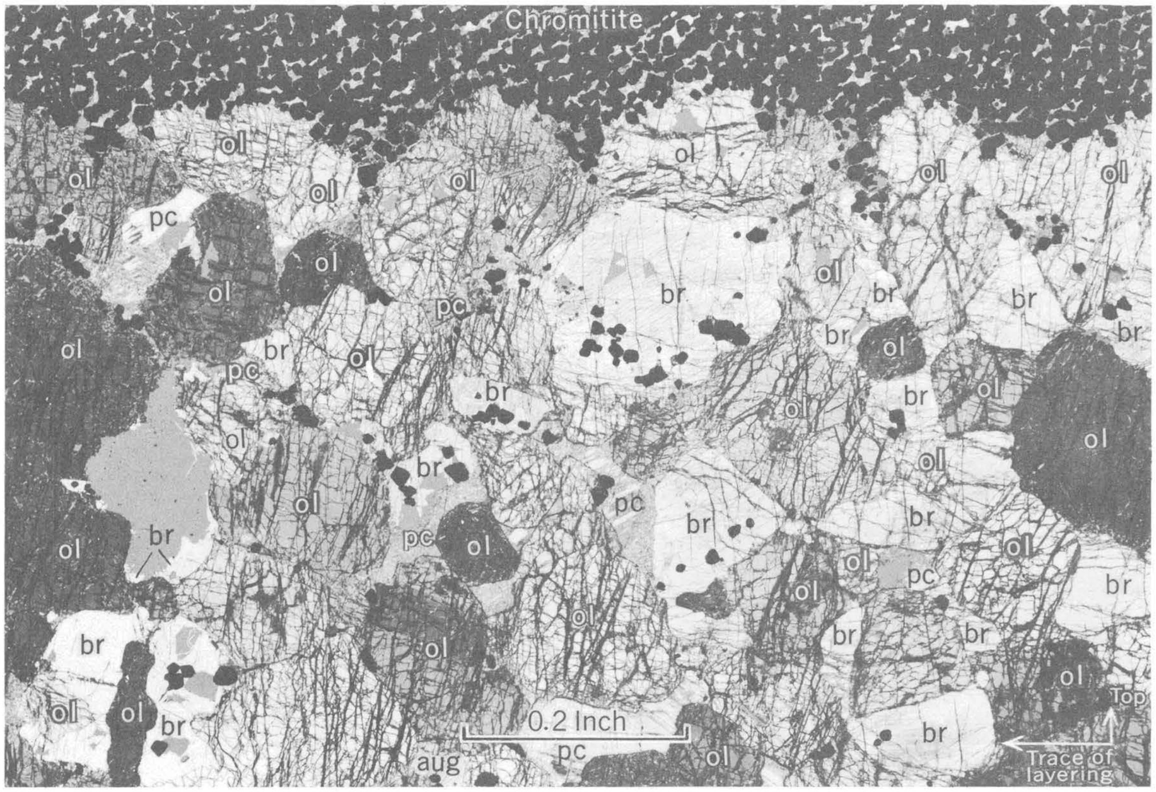


FIGURE 20.—Photomacrograph of cusp texture at chromitite-poikilitic harzburgite contact. The chromite crystals have sifted down between the larger olivine grains. ol=olivine; br=bronzite; pc=plagioclase; aug=augite. Crossed nicols.

FIGURE 21.—Field photograph of cusp texture. The poikilitic harzburgite above the chromitite (dark layer) is considerably finer grained than the poikilitic harzburgite below it. Light gray areas are lichen.

CUSP TEXTURE ILLUSTRATED

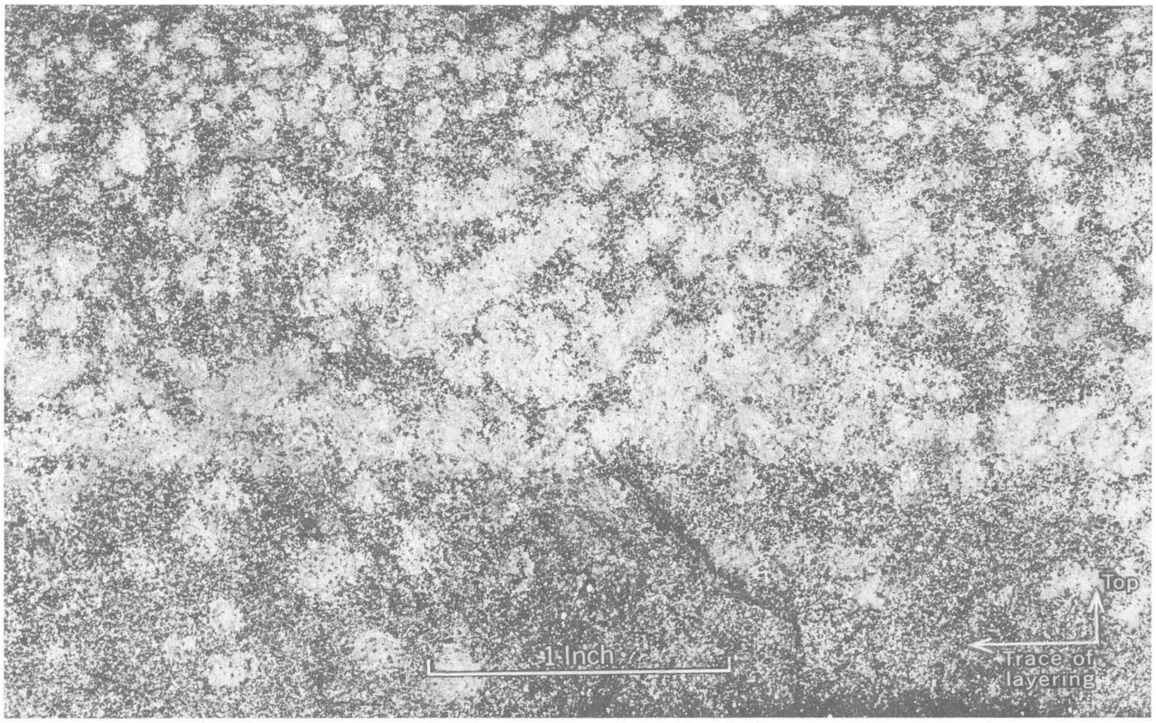


FIGURE 22.—Size-graded bedding in olivine chromitite. Lower layer is chromitite. Olivine grains decrease in size stratigraphically upward; chromitite grains are the same size throughout.

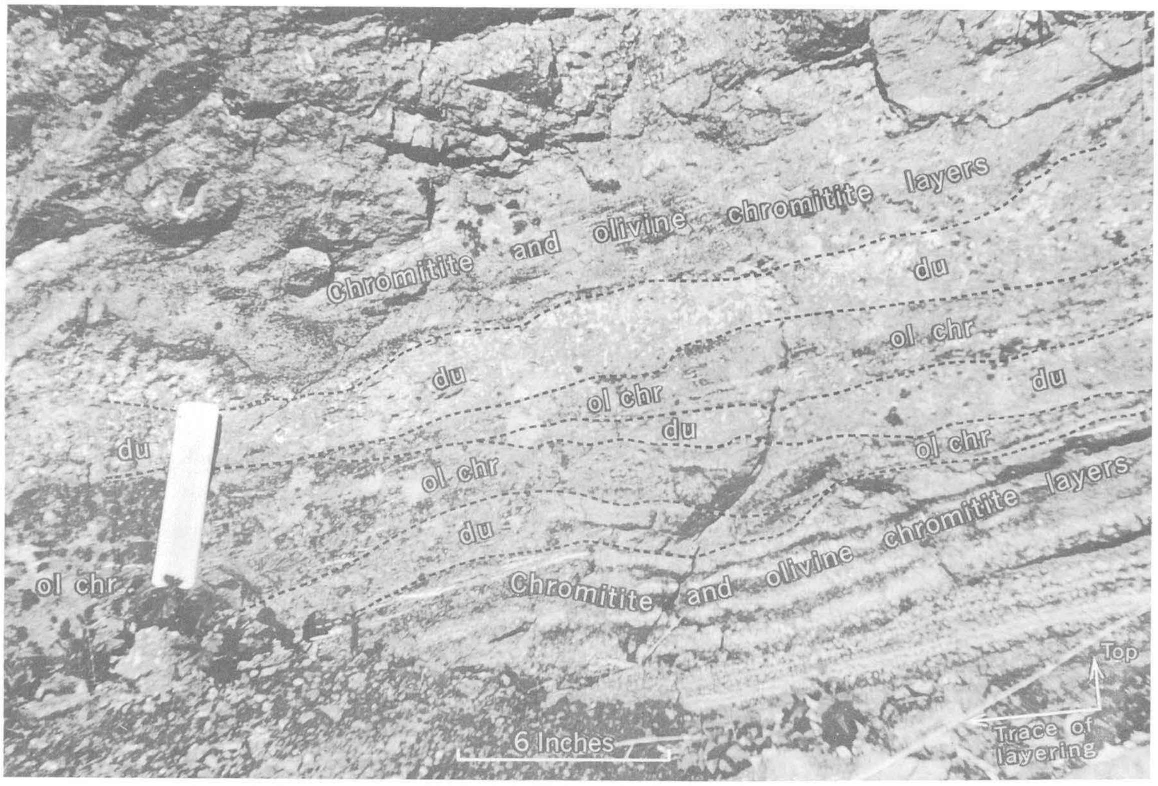


FIGURE 23.—Local unconformities in chromitite-dunite section. Lowest dunite is cut out to right of photograph; central dunite is cut out to left. du=dunite; ol chr=olivine chromitite.

FIELD PHOTOGRAPHS OF LAYERED STRUCTURES IN THE ULTRAMAFIC ZONE

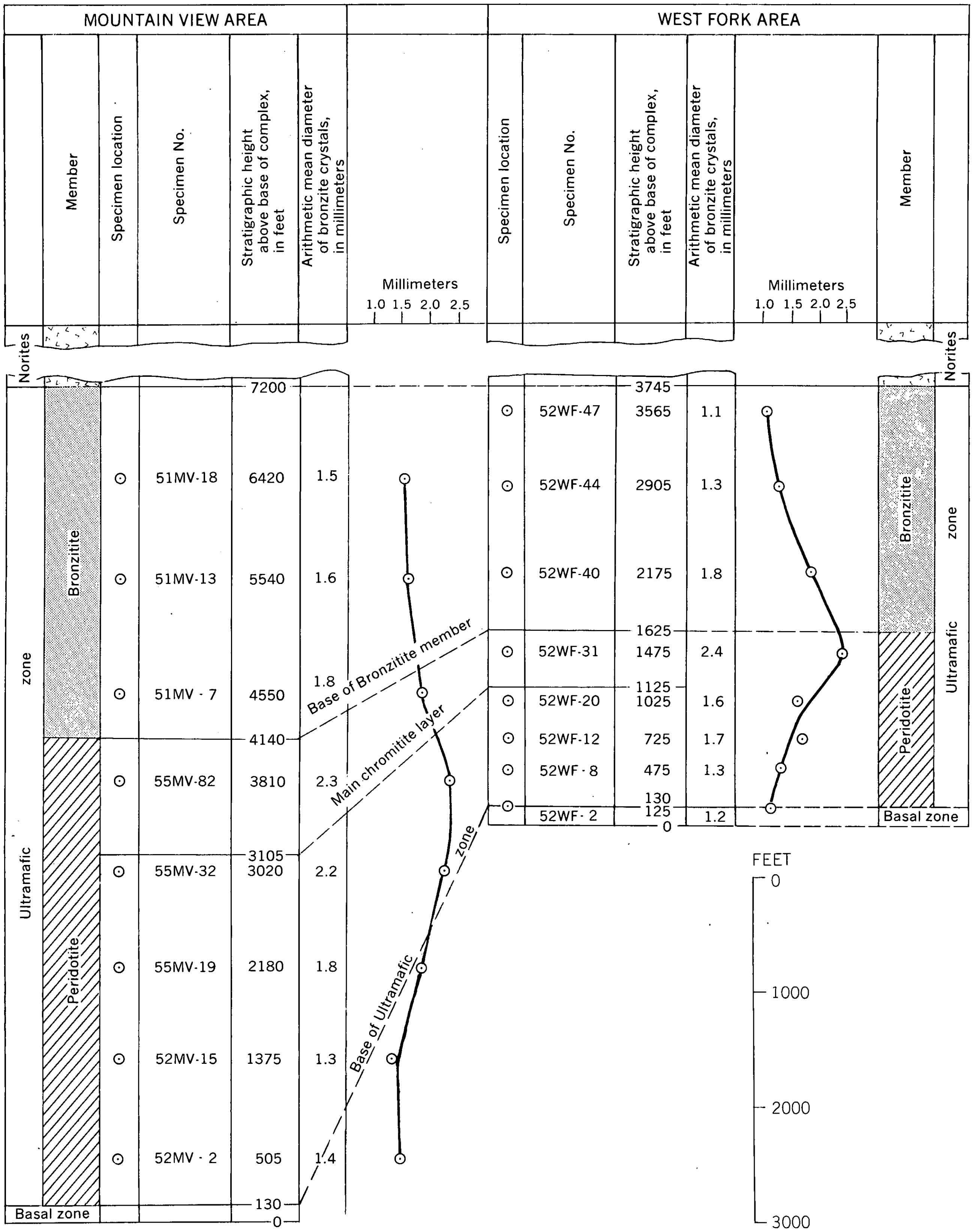


FIGURE 24.—Stratigraphic distribution of mean diameters of settled bronzite crystals in bronzitite in the Mountain View and West Fork areas.

thus analogous to the contacts between poikilitic harzburgite and granular harzburgite, in that the grain size of chromite or olivine is unaffected by the abrupt appearance of another phase, which is larger in the first type of contact and smaller in the second. In complex chromitite layers, where the section is composed of many alternating layers of massive and disseminated chromitite, no simple size variation has been found.

TABLE 2.—*Arithmetic mean diameters of chromite crystals in a 7-inch-thick massive chromitite layer*

Specimen No.	Height above base of chromitite (inches)	Arithmetic mean diameter of chromite crystals (mm)
7UU	6. 5	0. 143
7UL	5. 25	. 161
7MU	4	. 151
7ML	3	. 149
7LU	1. 25	. 146
7LL	0	. 137

The third type of gradual size variation in the Ultramafic zone is an overall change in average grain diameter superimposed on all the minor variations thus far discussed. This variation is not readily apparent unless some consistent horizon within any of the alternating compositional layers is compared throughout the Ultramafic zone. Figure 24 illustrates the stratigraphic variation in grain size in two sections about 5 miles apart. Sizes of bronzite crystals in bronzitite layers were chosen for comparison in each case so that the section could be extended through the Bronzitite member of the Ultramafic zone. Within the Peridotite member, specimens were chosen from near the centers of bronzitite layers, but in the Bronzitite member, specimens were chosen at nearly equal stratigraphic intervals. Grain size of the settled bronzite gradually increases nearly to the base of the Bronzitite member, then decreases to the top of the Ultramafic zone. One significant sharp size change within the Bronzitite member, not shown in figure 24, occurs about 100 feet below the top of the member wherever this section is exposed. Grain size of bronzite individuals at this horizon increases from 1.1–1.4 mm to 1.8–1.9 mm, and bronzite continues at this size into the lowest norite layer. Grain sizes of olivine in the Ultramafic zone have the same overall variation as bronzite, if olivine crystals from the same relative stratigraphic position within the cycles are compared. Olivine crystals attain their maximum size near the base of the Bronzitite member and above this horizon are, of course, no longer constituents of the rock.

The overall size distribution of chromite is slightly different. In figure 25 the average size of the settled chromite crystals at the footwall of the various chromitite layers in the Mountain View area is compared with the stratigraphic position of the chromitite. The maximum size is reached about a thousand feet below the base of the Bronzitite member and the grain size of the chromite gradually decreases from this point upwards. Although the maximum grain size is at the base of the thickest chromitite, the variation as a whole has no relation to thickness of layers. It should be emphasized that these samples were taken from a consistent stratigraphic horizon in each chromitite layer (the footwall). The overall variation would be concealed with random sampling because the internal vertical size variation within the main chromitite layer is as great as the overall size variation shown in figure 25.

No systematic study of lateral size variation has been made. On a small scale, grain sizes are remarkably

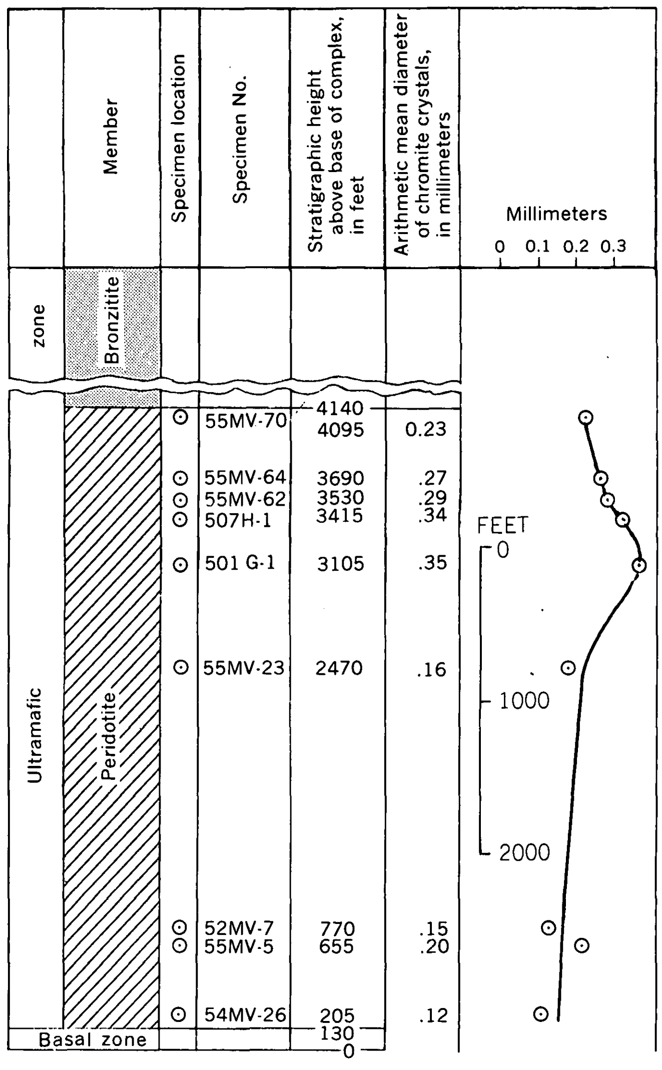


FIGURE 25.—Stratigraphic distribution of mean diameters of settled chromite crystals in chromitite in the Mountain View area.

constant along the layering plane. In the Benbow area, for example, an uncommonly coarse-grained chromitite layer, 2 inches thick, near the base of the Peridotite member was followed for 1½ miles along the strike. At its westernmost exposure the average grain size of its chromite crystals is 1.1 mm; 7,000 feet to the east their mean diameter is 1.2 mm. On a gross scale, Wager and Deer (1939, p. 263) were able to show that the average size of crystals in the layered rocks of the Skaergaard intrusion increased in size from the margins of the intrusion toward the center. No such gross lateral variation has been observed in the field in the Stillwater complex. The data given in figure 24 seem to indicate that, at any given stratigraphic position, the rocks in the thinner West Fork section are slightly finer grained than those of the thicker Mountain View section. The grain sizes of a third section, intermediate between these two in thickness but east of the Mountain View section in position, were determined, and the average bronzite diameters were found to be very close to those in the Mountain View section. A great many more measurements would be necessary to determine if this apparent lateral variation is related to stratigraphic thickness, to lateral position, or to neither.

SORTING

Size-frequency distributions of the settled crystals within compositionally homogeneous layers are symmetrically disposed when plotted on a logarithmic scale, and most distributions appear as straight-line curves when plotted on logarithmic probability paper. Such distributions are said to be lognormal and are typical of size distributions in many sedimentary rocks (Krumbein, 1938, p. 84–90). For comparison, the size distributions of sand grains in a well-sorted sandstone (the St. Peter) and chromite grains in a chromitite layer are plotted graphically in figure 26. The distribution curves for the St. Peter sandstone were constructed from measurements made in thin section by Krumbein (1935, p. 486). Neither set of measurements is corrected for sectioning effects; both are grouped into the same arithmetic intervals; and both are based on more than 300 measurements. The similarity between the distribution curves is obvious. The chromitite is slightly coarser grained, but both rocks have the same degree of sorting,[3] as shown by the equal slopes of their cumulative curves.

Sorting in most of the layered rocks that contain only one settled mineral is remarkably good, and sorting indices are nearly constant, regardless of grain size. For illustration, distribution curves and parameters of the three varieties of such rocks is given in figure 27. In each example, size-frequency distributions are plotted on a logarithmic base using one-half Udden scale class limits, and both histograms and cumulative curves are shown. Medians and sorting coefficients were obtained from quartile measures, but arithmetic means were calculated directly from the individual measurements. Quartile sorting coefficients range from 1.27 to 1.50 in most of the layered ultramafic rocks, and normally there are 3 or 3½ Udden classes that contain more than 1 percent of the total individuals. These sorting characteristics are remarkably like those of the marine beach sands described by Martens (1939, p. 207–218), although the average grain sizes of beach sands are considerably finer. No difference in average sorting has been found between poikilitic harz-

[3] The term sorting is used here in a statistical sense, without implication as to the agency responsible for the spread (Pettijohn, 1957, p. 37).

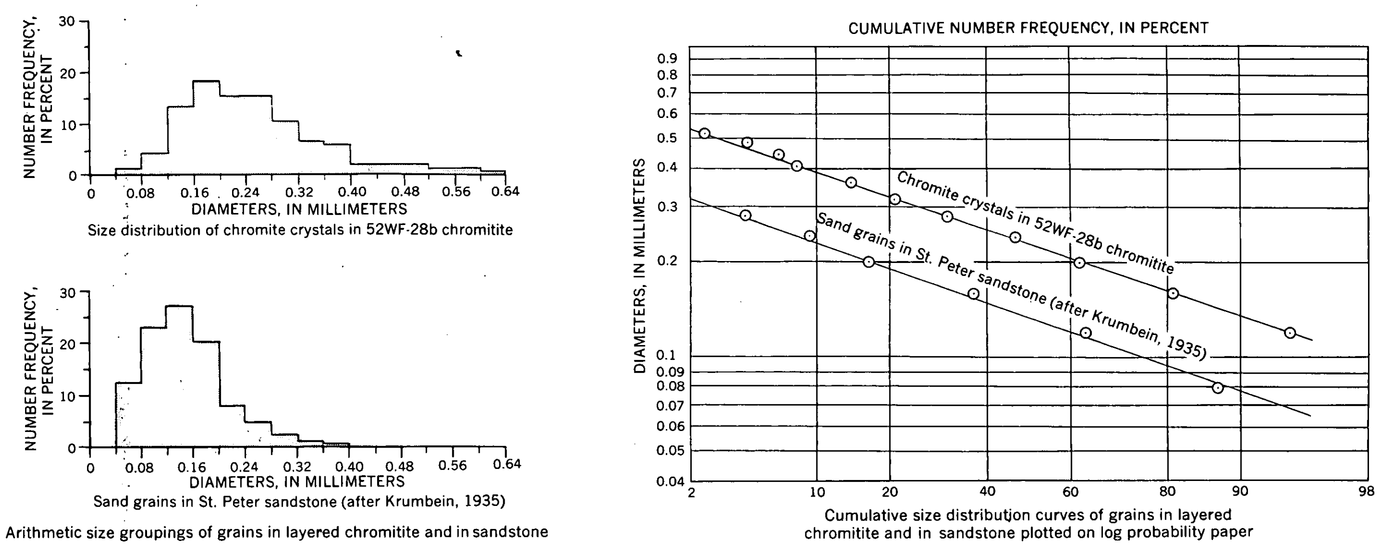
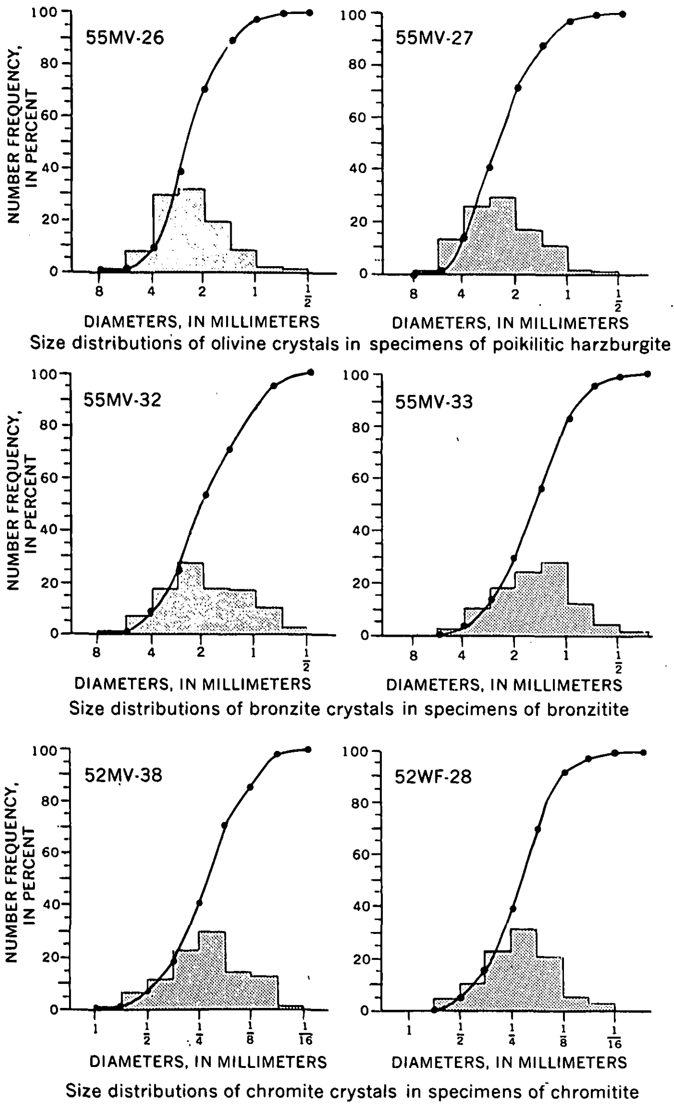


FIGURE 26.—Grain-size distribution curves of chromitite and sandstone.



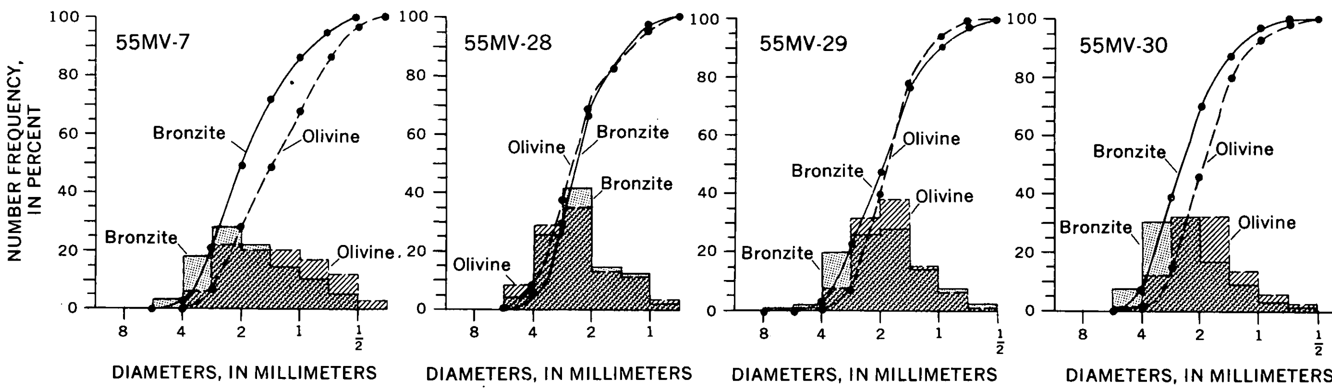
Specimen No.	Arithmetic mean diameters, in millimeters	Median diameters, in millimeters	Sorting coefficient $\sqrt{Q_3/Q_1}$
55MV-26	2.57	2.53	1.31
55MV-27	2.68	2.53	1.37
55MV-32	2.18	2.07	1.48
55MV-33	1.74	1.54	1.40
52MV-38	.25	.23	1.36
52WF-28	.24	.22	1.32

FIGURE 27.—Comparison of size-frequency distributions in layered rocks containing only one settled mineral.

burgite, bronzitite, and chromitite, nor has a consistent variation in sorting with change in grain size, stratigraphic position, or areal location been discovered.

In olivine chromitite, poikilitic chromite harzburgite, olivine bronzitite, and some granular harzburgite—the four principal rock types that consist of two varieties of settled crystals—sorting is poor or bimodal if, as is the common practice in sizing sediments, no distinction is made between mineral types. If, however, the two settled constituents are measured and tabulated separately, each is found to be well sorted, but generally different in average size. The size-frequency distribution curves in figure 28 illustrate the general range and type of sorting variations in four selected specimens of rocks containing both settled olivine and settled bronzite. As previously noted, the average diameter of the two constituent minerals can be roughly correlated with their relative abundance and stratigaphic position. No such correlations of degree of sorting can be made, nor is the sorting coefficient related to absolute or relative grain size. As illustrated in figure 28, the slopes of the distribution curves of the two minerals in the same rock tend to be similar, and in some rocks the sorting coefficients are identical. In rocks where slight differences in spread exist, either olivine or bronzite may have the steeper curve. The size-frequency relations between coexisting olivine and chromite in structureless olivine chromitite and poikilitic chromite harzburgite are similar to those of olivine and bronzite, with two exceptions: (1) the chromite is invariably much smaller than the olivine, never exceeding it in average diameter; and, (2) the distribution curves of coexisting olivine and chromite are generally more similar in both shape and slope than the distribution curves of coexisting olivine and bronzite. Figure 29 illustrates the size-distribution variations in four selected specimens containing both settled olivine and chromite. The distributions as a whole are strikingly bimodal, although each constituent has a narrow spread. The similarity in distribution-curve slopes of olivine and chromite in the same rock is very close compared to the range in slope between rocks. One specimen of coarse-grained poikilitic harzburgite containing accessory chromite has been included to illustrate the independence of sorting index with respect to average grain size and relative abundance of the chromite and olivine.

In a few places in the Ultramafic zone, current structures have been observed. These structures are most easily recognized in the chromitite layers because of the contrast in size and color of the constituents. Figure 23 illustrates scour and local unconformity in the upper part of the main chromitite layer. Typically, the grain size of the settled crystals is finer than average, and the rock consists of alternating laminae of dunite and olivine chromitite, which is in contrast to the relatively thick bedding of sections that show no current structures. The size distributions in a sequence of these layers were investigated and found to be considerably different from those of structureless olivine



Specimen No.	Mineral	Arithmetic mean diameters, in millimeters	Median diameters, in millimeters	Quartile sorting coefficient	Volume ratio of bronzite to olivine in rock
55MV-7	Olivine Bronzite	1.54 2.05	1.36 1.97	1.52 1.44	2.7
55MV-28	Olivine Bronzite	2.58 2.47	2.58 2.45	1.30 1.26	0.3
55MV-29	Olivine Bronzite	1.91 1.99	1.82 1.96	1.28 1.37	2.4
55MV-30	Olivine Bronzite	2.01 2.53	1.93 2.46	1.29 1.29	3.7

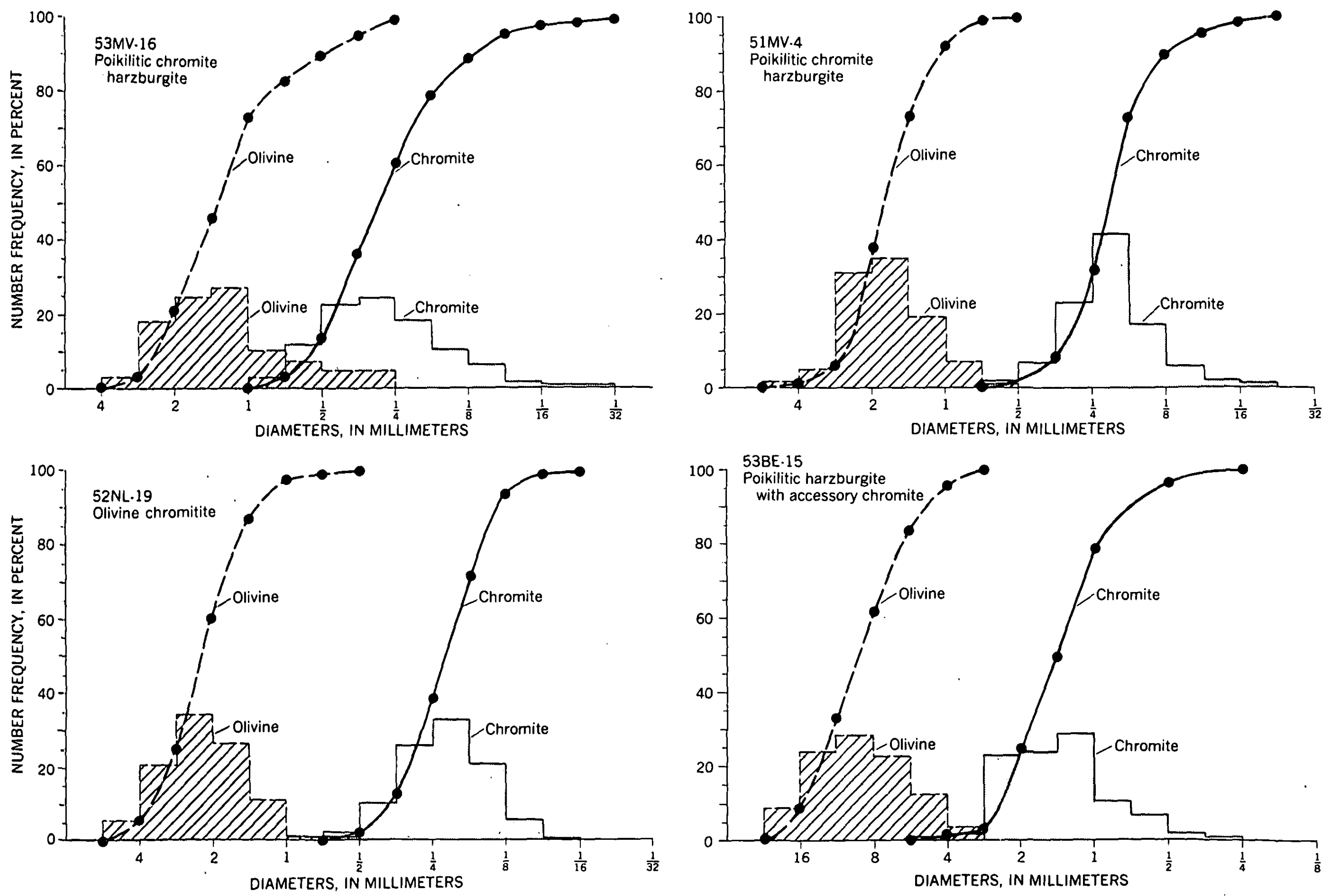
FIGURE 28.—Comparison of size-frequency distributions of coexisting olivine and bronzite crystals in layered granular harzburgites.

chromitite and granular harzburgite. The layered sequence investigated is illustrated in figure 30 and size-distribution data are given in figure 31.

The most obvious feature of the sequence is that the fine-grained olivine is associated in layers with the chromite, and that these layers are separated by coarse-grained dunite. The distribution curves of coexisting olivine and chromite (layers B, H, J, and L), in distinction to the distribution curves of these minerals in structureless olivine chromitite, are unlike, the chromite being considerably more poorly sorted than olivine. The olivine of these olivine chromitite layers has nearly symmetrical distribution, but the chromite is strongly skewed to the coarser size. The size distribution of olivine grains in the coarse dunite (layers C, K, and M) is similar to that of the chromite in the olivine chromitite layers. Despite the large variations in arithmetic mean diameters of olivine grains in the various layers, all their modes are the same, as are those of the chromite. If it is assumed that the modes of olivine and chromite in these layers represent the modes of lognormal distributions of available chromite and olivine before deposition, then current action has removed the fine fraction of olivine from the coarse dunites and the fine fraction of chromite from the olivine chromitites. The coarse dunite layers would have been deposited from the strongest currents, which suspended the finer olivine and all the chromite. The olivine chromitites would have been deposited by the weakest currents, which allowed deposition of all the olivine but which still suspended or carried off the finer chromite fractions. Regardless of interpretations as to mechanisms of origin, the most significant feature of the distribution is that where olivine chromitite or poikilitic chromite harzburgite appears internally structureless in the field, sorting indices of olivine and chromite in the rock are nearly equal, but, in the few localities where current structures can be observed in the field, chromite is much more poorly sorted than the associated olivine. This relation is shown graphically in figure 32.

SIZE-DENSITY RELATIONS

The common association of small, dense chromite crystals with larger, lighter olivine crystals suggests that these minerals may have had nearly equal settling velocities. Rittenhouse (1943, p. 1725–1780), who studied the size distributions of light and heavy minerals in fluvial sands, found the equivalent hydraulic size of two minerals to be closely related to their densities, the coarser light minerals being associated with the coarser heavies, and the finer light minerals with the finer heavies. As illustrated in figure 33, this relation does not obtain in either the internally structureless or the current-bedded olivine chromitites. On theoretical grounds, none of the coexisting olivine-



Specimen No.	Mineral	Arithmetic mean diameters, in millimeters	Median diameters, in millimeters	Quartile sorting coefficient	Volume ratio of chromite to olivine in rock
53MV-16	Olivine Chromite	1.42 .31	1.37 .29	1.43 1.43	0.60
51MV-4	Olivine Chromite	1.83 .23	1.79 .22	1.29 1.25	0.11
52NL-19	Olivine Chromite	2.32 .24	2.27 .23	1.31 1.30	1.00
53BE-15	Olivine Chromite	9.40 1.48	9.20 1.41	1.38 1.39	0.02

FIGURE 29.—Comparison of size-frequency distribution of coexisting olivine and chromite crystals in structureless olivine chromitites and poikilitic chromite harzburgites.

chromite associations would appear to be hydraulically equivalent. According to Christiansen (1935, p. 480), Stokes' law is valid where the Reynolds number $\left(\frac{2rv\rho}{\eta}\right)$ is less than 0.2. The Reynolds number of the largest olivine grains measured (9.4 mm average diameter) exceeds 0.2 only at viscosities of less than 20 poises, and grains of more normal diameter exceed 0.2 only at viscosities of less than 2 poises, so that Stokes' law should adequately express the settling rates of all the particles considered here. In table 3 the relative settling rates of coexisting olivine and chromite are tabulated, assuming a magma density of 2.7. It is apparent from the wide variation in values that the differences in size between olivine and chromite is not compensated by differences in density, and that the particles are not hydraulically equivalent. It should be noted, however, that, on the average, the current-bedded olivine chromitites approach hydraulic equivalence more closely than structureless rocks containing the two minerals. It is also obvious from inspection of figure 19 that coexisting olivine and bronzite in granular harzburgite and olivine bronzitite are not hydraulically equivalent. Olivine and bronzite have nearly the same density in the composition range existing in the Ultramafic zone and, theoretically, should have the

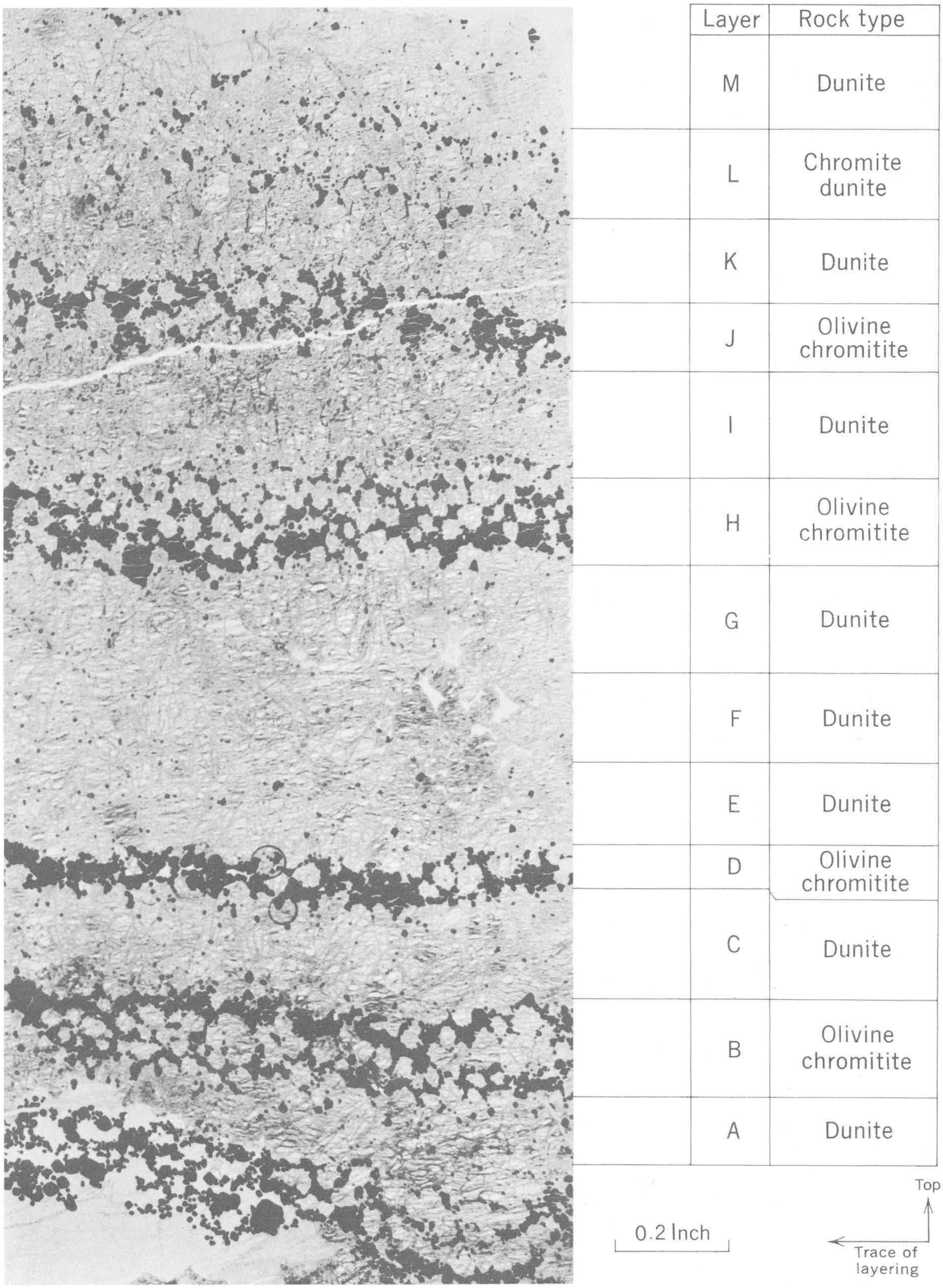
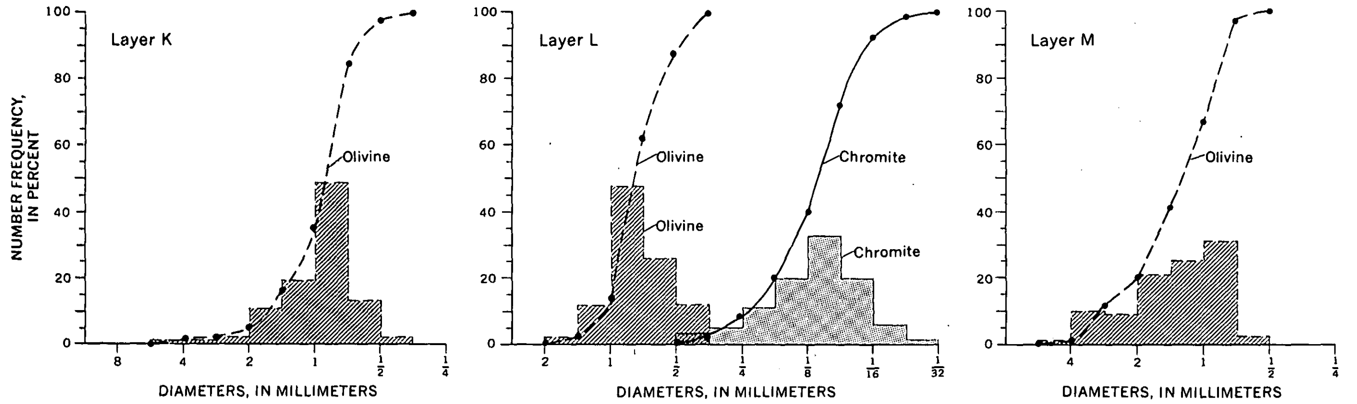
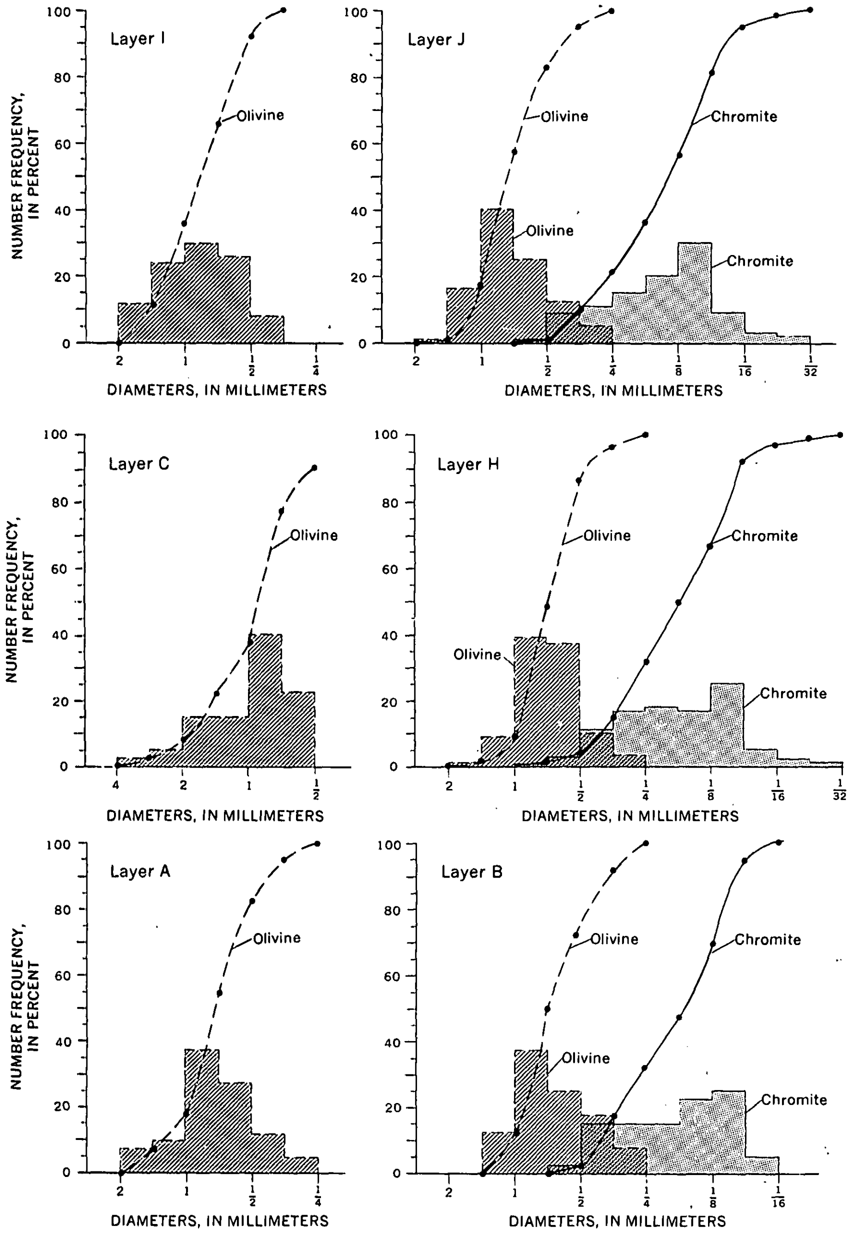


FIGURE 30.—Photomacrograph of layered olivine chromitite-dunite stratigraphic sequence A–M. Black grains are chromite, gray grains are olivine, light gray areas are plagioclase. Plane polarized light.





Thickness, in millimeters	Layer	Rock type	Mineral	Arithmetic mean diameter, in millimeters	Median diameter, in millimeters	Modal diameter, in millimeters	Sorting coefficient	Ratio of arithmetic mean sizes of olivine to chromite
1	N	Chromitite	Chromite	0.21				
8	M	Dunite	Olivine	1.53	1.28	0.84	1.38	
5	L	Chromite dunite	Olivine Chromite	0.75 .14	0.75 .12	0.84 .11	1.16 1.38	5.3
4	K	Dunite	Olivine	1.05	0.85	0.84	1.23	
3	J	Olivine chromitite	Olivine Chromite	0.75 .18	0.75 .13	0.84 .11	1.25 1.45	4.2
5	I	Dunite	Olivine	0.94	0.87	0.84	1.38	
4	H	Olivine chromitite	Olivine Chromite	0.72 .22	0.70 .18	0.84 .11	1.26 1.63	3.3
5	G	Dunite	Olivine	1.44				
4	F	Dunite	Olivine	1.09				
4	E	Dunite	Olivine	0.92				
2	D	Olivine chromitite	Olivine Chromite	0.84 .26				3.2
5	C	Dunite	Olivine	1.06	0.90	0.84	1.34	
2	B	Olivine chromitite	Olivine Chromite	0.73 .22	0.71 .17	0.84 .11	1.34 1.53	3.3
3	A	Dunite	Olivine	0.74	0.75	0.84	1.30	

SAMPLE 55DR-1

FIGURE 31.—Comparison of size-frequency distribution of olivine and coexisting olivine and chromite in current-bedded dunites and olivine chromitites.

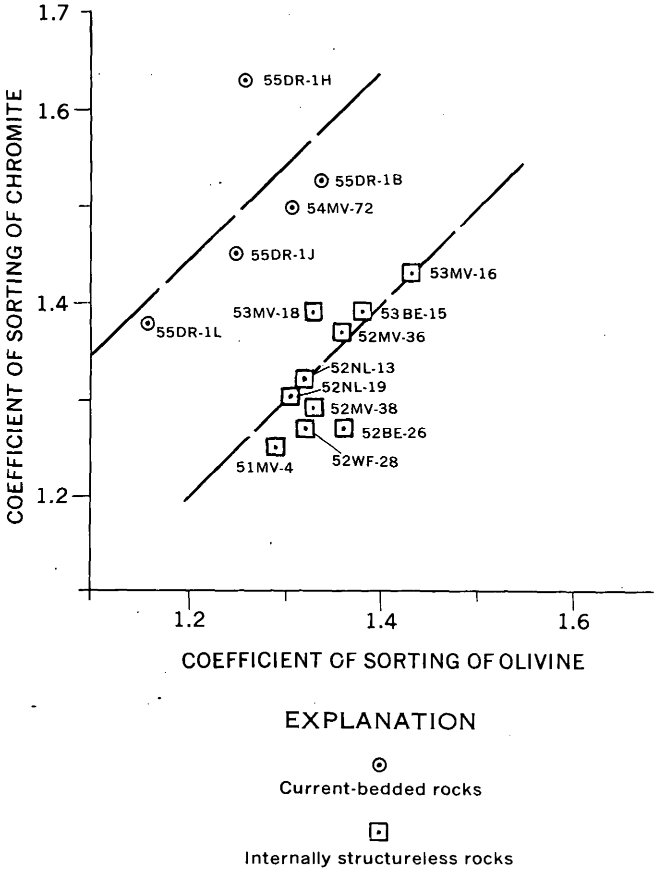


FIGURE 32.—Ratios of sorting coefficients of coexisting olivine and chromite in olivine chromitite and poikilitic chromite harzburgite.

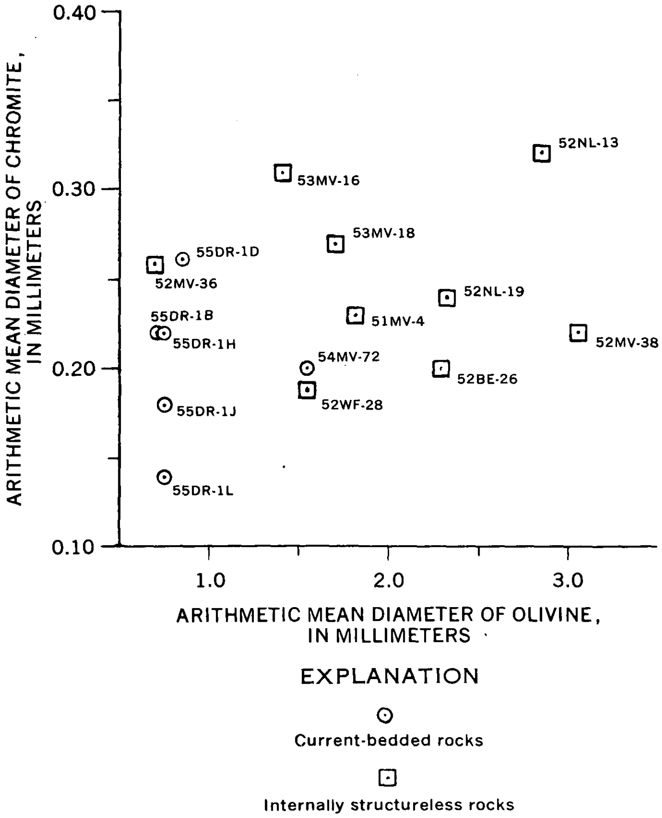


FIGURE 33.—Ratios of mean diameters of coexisting olivine and chromite in olivine chromitite and poikilitic chromite harzburgite.

same diameter in equivalent association, but coexisting olivine-bronzite diameter ratios range from 1.3:1 to 0.5:1. At the one extreme the Stokes settling rate for olivine would be 1.8 times that of bronzite, and at the other extreme bronzite would theoretically settle 3.5 times faster than olivine.

TABLE 3.—*Relative settling velocities of coexisting olivine and chromite*

Specimen No.	Arithmetic mean diameter (millimeters)		Settling velocity olivine: settling velocity chromite [1]
	Chromite	Olivine	
52MV-38	0.22	3.03	67
52BE-26	.21	2.38	45
52NL-19	.24	2.32	33
13	.32	2.87	28
52WF-28	.21	1.68	22
51MV-4	.23	1.83	22
54MV-72 [2]	.20	1.55	21
53BE-15	1.48	9.40	14
53MV-18	.27	1.62	13
55DR-1L [2]	.14	.75	10
53MV-16	.31	1.42	7.4
55DR-1J [2]	.18	.75	6.1
1B [2]	.22	.73	3.9
1H [2]	.22	.72	3.8
1D [2]	.26	.84	3.7
52MV-36	.26	.68	2.4

[1] Computed from Stokes' law assuming the density of the magma to be 2.7; olivine 3.3; chromite 4.4.
[2] Current-bedded olivine chromitite.

From textural evidence in the Ultramafic zone, it seems doubtful that the effective size, and therefore the settling rate, is modified to any extent by groups or clusters of crystals sinking together. Effects of clumping are most easily evaluated in rocks containing mixtures of two settled phases, and preaccumulation clustering apparently has occurred in a few olivine bronzitite layers, where groups of 4 or 5 olivine crystals welded at their contacts are irregularly distributed throughout the rock (fig. 36). In the great majority of olivine bronzitite and granular harzburgite specimens, however, individual crystals of bronzite and olivine are evenly distributed throughout the rocks (fig. 34). A few compound chromite grains formed by clusters of smaller crystals have been recognized, but these are easily separated from their individual associates and, where observed, have been measured in aggregate. Synneusis texture in chromite as described by Vogt (1921, p. 321) has not been observed in the Stillwater chromitite, although a superficially similar texture has been developed in olivine chromitite by close packing of large olivine and small chromite crystals (fig. 53). Chain texture, identical with that described by Sampson (1932, p. 126–127) from the Bushveld complex, occurs in some Stillwater chromitite.

The long, branching, generally curved "chains" seen in thin section consist of as many as 30 contiguous grains, and the elongation of these bears no relation to the layering plane (fig. 37). Bastin (1950, p. 7) suggests chain texture may be a variety of synneusis texture, but I doubt that they represent preaccumulation aggregations. The curved, branching groups of crystals seen in two dimensions are probably not chains, but complex three-dimensional structures. In the Ultramafic zone, chain texture occurs only where the interstitial material between chromite grains makes up about 25–30 percent of the rock; where interstitial material makes up more of the rock, most chromite grains do not touch; and where interstitial material is less abundant, all the grains mutually interfere. It seems most probable, therefore, that the chain effect is caused by fortuitous sectioning of tightly packed chromite octahedra.

DISCUSSION

The size-distribution data have important bearing on the problem of mechanism of crystal accumulation, particularly in respect to the effect of convection current as agents of transportation and deposition. Gravity sinking of crystals to the floor of a magma chamber seems to be generally accepted as an essential condition for the formation of layered intrusions of this type, and gravity settling in basaltic liquids has been abundantly demonstrated (MacDonald, 1944, p. 177–189; Fuller, 1939, p. 303–313) and experimentally verified by Bowen (1915, p. 175–191). Wager and Deer (1939, p. 262–289), in one of the best documented discussions of crystal accumulation, propose that, in addition to settling by gravity, the minerals of the Skaergaard intrusion were transported and deposited by convection currents sweeping across the floor of the magma chamber. The existence of currents was deduced from igneous lamination, lineations, and trough banding in certain parts of the intrusion (1939, p. 262–289), and, as evidence of their effectiveness, the authors found an enrichment of heavy melanocratic minerals near the margin of the intrusion (1939, p. 40, 263), and a gradual increase in the average size of plagioclase crystals away from the margin toward the center of the mass (1939, p. 71, 263). Pulsatory variation in the velocity of convection currents was considered responsible for variation in the proportion of light and heavy minerals deposited in any place, giving rise to rhythmic layering. In the Stillwater complex, the very local scour and unconformity effects indicate that currents were present at certain times and in certain parts of the magma chamber during the period of crystal accumulation.

It does not seem to me, however, that currents in the magma were important in either the transportation or deposition of the primary precipitate minerals in the Ultramafic zone for the following reasons: (1) no trough banding has been observed; (2) lineation of elongate minerals is weak or absent; (3) although a wide range of grain size of settled crystals is recognized in some rocks, size-graded bedding is almost nonexistent; (4) in nearly all rocks containing two coexisting settled phases, the two minerals are not in hydraulic equivalence; and (5) in the rocks in which current bedding can be observed, the size-distribution relations are markedly different from those of the structureless rocks. It should be noted that rhythmic layering or "gravity stratification" in the Ultramafic zone is developed in rocks containing two settled constituents of different density. In many olivine chromitites, for instance, "gravity stratification" is properly developed with denser chromites concentrated at the base, and these gradually give way to less dense olivines at the top (fig. 9). Because size affects settling velocity as the square and density only to a power of one, however, every one of the "gravity-stratified" layers so constructed is hydraulically upside down. I do not wish to imply that no convection currents existed in the Stillwater magma, and am aware of the problems of extremely slow settling rates in thick stagnant magmas, but I do wish to point out here that current transportation and deposition of the primary precipitates in the lower part of the Stillwater complex is incompatible with the textures of the rocks.

The lognormal distribution of grain sizes in many sedimentary rocks has suggested origin by some natural process concerned with grading by fluid movement, and Krumbein (1938, p. 89–90) has suggested that fluctuation in wind velocity is one process capable of producing such distributions. The effectiveness of such a mechanical sorting process is largely dependent on the viscosity of the fluid and on the density difference between the particles and the fluid, and Kuenen (1951, p. 25–26) has experimentally determined that the degree of sorting is greatly reduced in fluids of high viscosity and density. In a highly viscous magma, therefore, it seems doubtful that mechanical sorting of precipitates with a large size range could account for the narrow size spread in the rocks.

In a magmatic system, where the suspending fluid is also producing the particles by crystallization, it seems possible that logarithmic size distributions might be produced by crystal growth as well as by fluid movement. Loveland and Trivelli (1927, p. 193–217) found logarithmic size-frequency distributions of silver bromide crystals in photographic emulsions. They

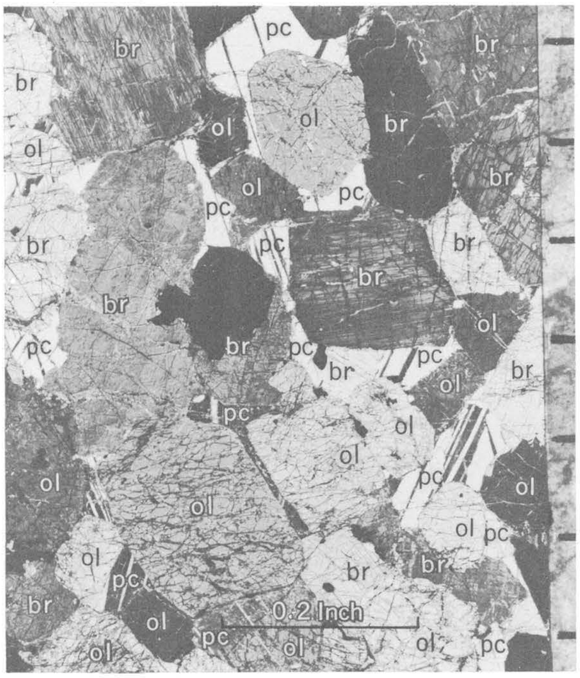


FIGURE 34.—Coexisting settled olivine and bronzite in granular harzburgite. The two minerals occur side by side as euhedral crystals, evenly distributed throughout the rock. ol=olivine; br=bronzite; pc=plagioclase. Crossed nicols.

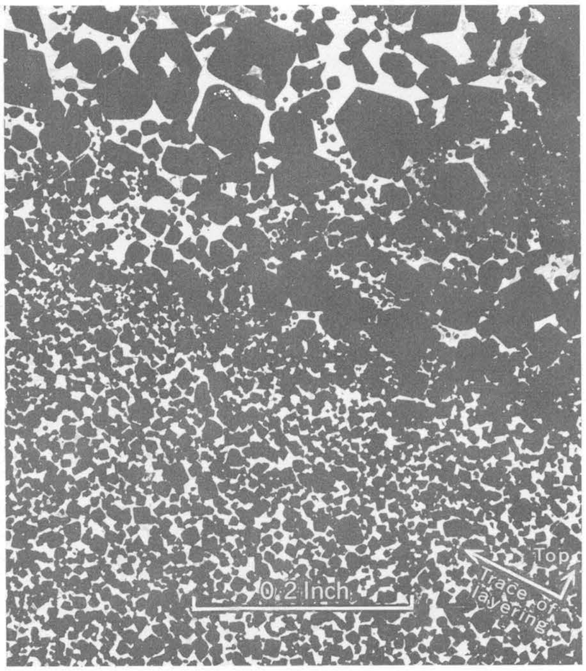


FIGURE 35.—Sharp change in grain size within a chromitite layer. Black grains are chromite; white mesostasis is plagioclase. Crossed nicols.

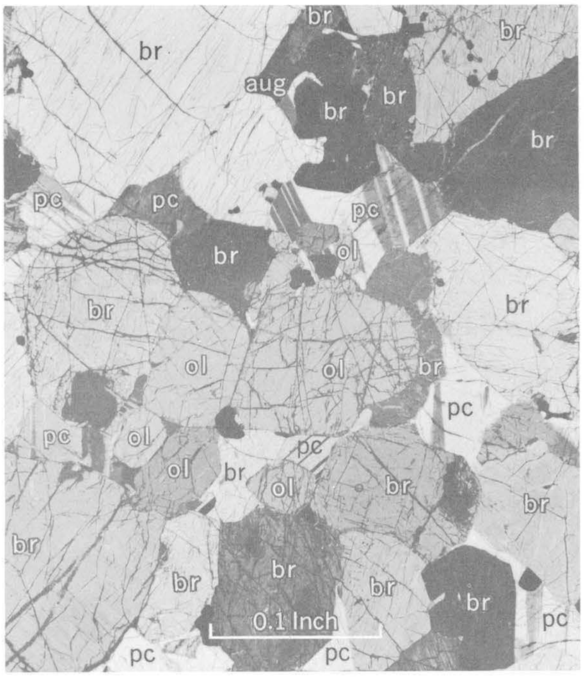


FIGURE 36.—Clustering of olivine crystals in olivine bronzitite. Contacts between most olivine crystals in cluster are welded. ol=olivine; br=bronzite; pc=plagioclase; aug=augite. Crossed nicols.

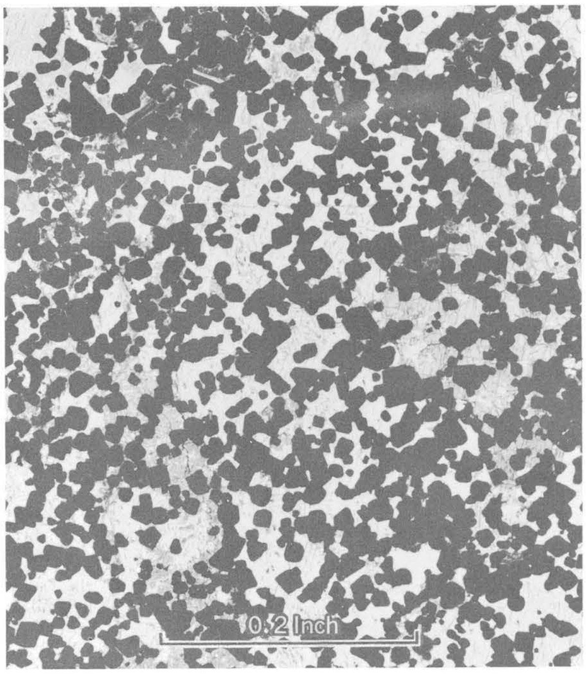


FIGURE 37.—Chain structure in chromitite. Many of the chromite crystals are connected into two-dimensional irregular "chains." Mesostasis is plagioclase, bronzite, and augite. Crossed nicols.

PHOTOMICROGRAPHS OF SETTLED MINERAL DISTRIBUTION IN THE ULTRAMAFIC ZONE reasoned that the distribution is a result of crystal growth proportional to the attained size of the crystals at any given instant, and predicted that the logarithmic form would be found to be uniquely involved in the case of precipitates.

I therefore propose that the close approach to lognormal distributions of the three primary precipitate minerals in the Ultramafic zone is a phenomenon produced by crystallization and supply, and that the sorting or spread is a direct measure of the range of size of the crystallization products of the magma immediately above the continually rising floor of the magma chamber. If two minerals were crystallizing simultaneously or at slightly different horizons in the melt, their relative average diameters would probably depend largely on their concentrations, solubilities, and relative distances of fall to the floor. Simple crystal sinking of two minerals which had inherently different sizes would explain the apparently anomalous observed relations of narrow, symmetrical size distributions of different minerals in the same rock, where these minerals are not in hydraulic equivalence and have no consistent size relation in different rocks. Any currents strong enough to cause suspension of hydraulically lighter particles would tend to skew or destroy the lognormality of the distribution and, at the same time, move the minerals closer to hydraulic equivalence. This is in accord with the field and laboratory observations.

A corollary of this argument is that crystallization, and therefore supply, must be continuous. Should crystallization suddenly cease while only one mineral was being supplied, the finer crystals of that constituent would fall at a slower rate than the coarser crystals, and a normal graded bed would occur. Should crystallization cease while two minerals were present in the supply then the hydraulically heavier mineral would be preferentially deposited at the base and gradually give way to the lighter constituent at the top. Should crystallization begin again after all the individuals of the previous cycle had settled, then the first of the new crystals to be deposited on the floor would be smaller than those higher up because they would have fallen a shorter distance through the magma, and a reverse graded bed would result. This has been illustrated by Bowen (1915, p. 175–191) and Bowen's figure 1*a* shows such reverse graded bedding of olivine crystals in an artificial melt.

The factors influencing the size of crystals collected on the floor of the magma chamber are many and complex; these include: (1) the rate of heat loss from the intrusion, (2) the viscosity, temperature, and composition of the magma, (3) the solubility of minerals crystallizing from it, and (4) the rate and distance of fall of crystals to the floor. Despite the abundance of variables, some speculations as to the origin of the various types of size changes described can be made. The relatively fine grain size of the chromite may be related to the relatively low concentration of chromium in the magma, and perhaps to the solubility of chromite in the magma. The sharp size breaks at the bases of the poikilitic harzburgite layers are believed to represent hiatuses in crystallization, and the relatively fine grain size of olivine crystals in the lower part of these units is believed due in part to slight supercooling probably necessary to inaugurate crystallization (Overbeek, 1952, p. 63). The gradual increase in grain size of these olivine crystals upward in the section is probably caused by the relatively longer growth times of crystals that began crystallizing farther from the floor, as described by Bowen (1915, p. 175–191). The large-scale size breaks within compositional layers, such as the one illustrated in cyclic unit 2, figure 19, where gradual increases in size occur upward in the overlying unit, would seem to be caused by the same processes. The gradually diminishing grain sizes of olivine in the granular harzburgite layers is not a result of resorption, for the olivine crystals retain their euhedral character even where present in very small amounts. It is possible that olivine crystallization is restricted to increasingly narrower zones above the floor, and that this is reflected in the gradually smaller proportion and grain size of the olivine crystals. A similar explanation might account for the decreasing size of bronzite crystals in the bronzitite layers. It seems likely that the overall increase in grain size upward in the Peridotite member is a function of the decrease in cooling rate from the walls of the magma chamber as the thermal gradients are gradually flattened, so that each cycle is repeated with a slightly coarser grain size throughout.

ORIENTATION OF THE SETTLED CRYSTALS

Planar orientation of platy or elongate minerals in the layering plane is sporadically developed throughout the complex, as has been described by Jones, Peoples, and Howland (1960); but lineation, or alinement of long axes within the layering plane, is poorly developed.

Dimensional orientation of settled crystals is not commonly observed in the Ultramafic zone in the field, because of the tendency for all three precipitate minerals to occur in nearly equidimensional habits. In some layers in the lower two-thirds of the zone, however, bronzite crystals assume a broad prismatic habit, and the broadest surfaces of the crystals tend to lie in the layering plane. Average attitudes obtained on the broad surfaces of such crystals are parallel to the compositional layering. Such orientations are never perfect, and in places crystals can be observed at high angles to the layering, giving the appearance of being propped up on underlying individuals (fig. 6). The perfection of the dimensional orientation seems to be related to the degree of elongation or flattening of the bronzite in the rock. This is best illustrated in the uncommon rocks that contain bronzite crystals of both equidimensional and tabular habits (fig. 54). The equidimensional crystals show no preferred orientation, but the layering plane is marked by the broad surfaces of the tabular crystals.

Because the settled crystals are commonly euhedral and because the habit and the ratio of crystal dimensions of any mineral type in a given layer is relatively constant, it is possible to investigate the degree of perfection of dimensional orientation by optical methods. Hambleton[4] studied the optical orientations of principal minerals in 6 specimens from the Ultramafic zone. In one specimen each of an anorthosite pod and a poikilitic harbzurgite layer the fabric diagram of plagioclase and olivine showed little significant preferred orientation. In the four bronzitite specimens investigated, one reported as being composed of equidimensional bronzite crystals showed no obvious preferred orientation. The other three bronzitite specimens are reported as having "lath"-shaped crystals with the flat (100)[5] crystal face parallel to the layering plane. In each of these three specimens, therefore, there is a strong concentration of X perpendicular to the layering, and Y and Z tend to lie in the layering plane. In one of Hambleton's specimens both Y and Z form girdles; in a second, the Y and Z diagrams are almost identical, showing two maxima about 90° apart; and in the third, Y and Z show mutually perpendicular maxima in the layering plane. Hambleton concludes that the coincidence of the flat face of the bronzite crystals with the layering plane is best explained by movement of rigid particles in a fluid magma, and that the observed lineation suggests flow of the magma during deposition of the crystals.

Because such marked lineation had never been observed in the field, and because planar structure is an intermittent phenomenon in the Ultramafic zone, the present investigation was directed toward three objectives: (1) to determine if crystal orientations were purely dimensional; (2) to determine the degree of perfection and, if possible, the relative abundance of lineated fabrics; and (3) to determine whether the layering plane could be found by petrofabric methods where it is not visible in the field. Optical orientations of bronzite in four specimens and olivine in three specimens were determined. In one of these specimens the optical orientation did not conform to the dimensional orientation and the rock is believed to be a tectonite. In the other six specimens the following relations were noted: (1) the perfection of the optical orientations are directly dependent on the habits of the crystals making up the rocks; (2) five of the specimens displayed concentrations of long axes in the layering plane; of these, one had a weak unimodal lineation of long axes, one had a weak bimodal lineation, and the remaining three had long axes evenly distributed in the girdle; and (3) three of the four megascopically structureless specimens studied showed significant planar structures.

In rocks where olivine or bronzite occur in elongate habits, the long axes form a girdle in the layering plane; where bronzite occurs in flattened habits, the pole to the broadest face is perpendicular to the layering plane. These patterns, characterized by crystals lying in positions of least potential energy with reference to the layering surface, are interpreted as apposition fabrics.

The seven specimens for which optical orientations were determined were collected in each case from near a compositional contact, so that the layering plane could be accurately located on the hand specimens, even within apparently massive layers. Three mutually perpendicular thin sections, including one in the layering plane, were cut from each specimen. Measurements of crystal dimensions of 30 to 50 individuals, oriented with a, b, or c perpendicular, were made for each specimen, using the three mutually perpendicular sections, and these were converted to ratios and averaged. The X, Y, Z axes of 80 crystals for each specimen was determined with a 4-axis Universal stage on thin sections cut in the layering plane, and axis positions were plotted on a Schmidt net. Petrofabric diagrams were constructed for each principal optic direction. In those specimens showing a concentration of long axes in the layering plane, points were replotted on polar coordinate paper and azimuthal distribution histograms constructed after the method described by Krumbein (1939, p. 681–685). Eighty measurements for each optic direction seem to provide sufficient information for recognition of the essential features of the orientation patterns encountered, but individual submaxima are probably not significant.

[4] Hambleton, W. W., 1947, A petrofabric study of layering in the Stillwater complex, Montana, unpublished Master of Science thesis, Northwestern University, 61 p.

[5] (010) of the orientation used in this report.

BRONZITE

As previously noted, bronzite crystals occur in a wider variety of habits than do olivines but generally occur in a particular habit within a single layer.

Specimen 54EDJ–71 was selected as typical of the bronzitites which contain stubby, anchiequidimensional bronzite crystals, and in which no macroscopic preferred crystal orientation can be detected. The average ratio of crystal dimensions of bronzite in the rocks was determined to be $a:b:c$ equals 0.92 : 0.77 : 1, using the orthopyroxene orientation preferred by Hess and Phillips (1940, p. 271) and equating c to unity. Diagrams of the distributions of the principal optic directions in 80 bronzite grains are shown in figure 38. Y axes appear to be randomly distributed, but a very weak preferred orientation of X and Z can be detected. About one-half of the bronzite crystals lie with Z near the layering plane, and of these about 40 percent are oriented with the short axis $X=b$ nearly perpendicular to the plane. The orientation is, nevertheless, too weak to permit unequivocal location of the layering plane.

Specimen 54EDJ–80, an olivine bronzitite, was selected to study the orientation of bronzite crystals with short prismatic habits. A preferred orientation was not detected in this specimen in the field, but a planar structure was observed on the hand specimen subsequent to slabbing. The average ratio of crystal dimensions $a:b:c$ was determined to be about 0.67 : 0.62 : 1. The fabric diagrams (fig. 39) show an excellent Z girdle in the layering plane, and little or no preferred distribution of X and Y, which correspond to the almost equally short a and b crystal axes. A histogram of azimuthal distribution of Z axes was prepared from polar coordinate plots as a check on preferred orientation with the girdle. Figure 42 shows a broad lineation over about 60° of the first and third quadrants, which was not apparent at the outcrop nor on etched slabs cut in the layering plane.

Two specimens of bronzitite composed largely of broad prismatic bronzite crystals were investigated. One of these, specimen 54EDJ–100, was collected from a normal compositional layer with an average grain size of 2.2 mm. The second, 54EDJ–74, was finer grained, averaging 1.3 mm, and was collected 2 inches below a thin chromitite layer showing scour structures and believed to be current bedded. Both specimens showed a strong planar structure parallel to the compositional layering in the field. The average ratio of crystal diameters in 54EDJ–100 was 0.79 : 0.51 : 1; in 54EDJ–74, 0.67 : 0.39 : 1. The optical orientations of these specimens are shown in figures 40 and 41. Both

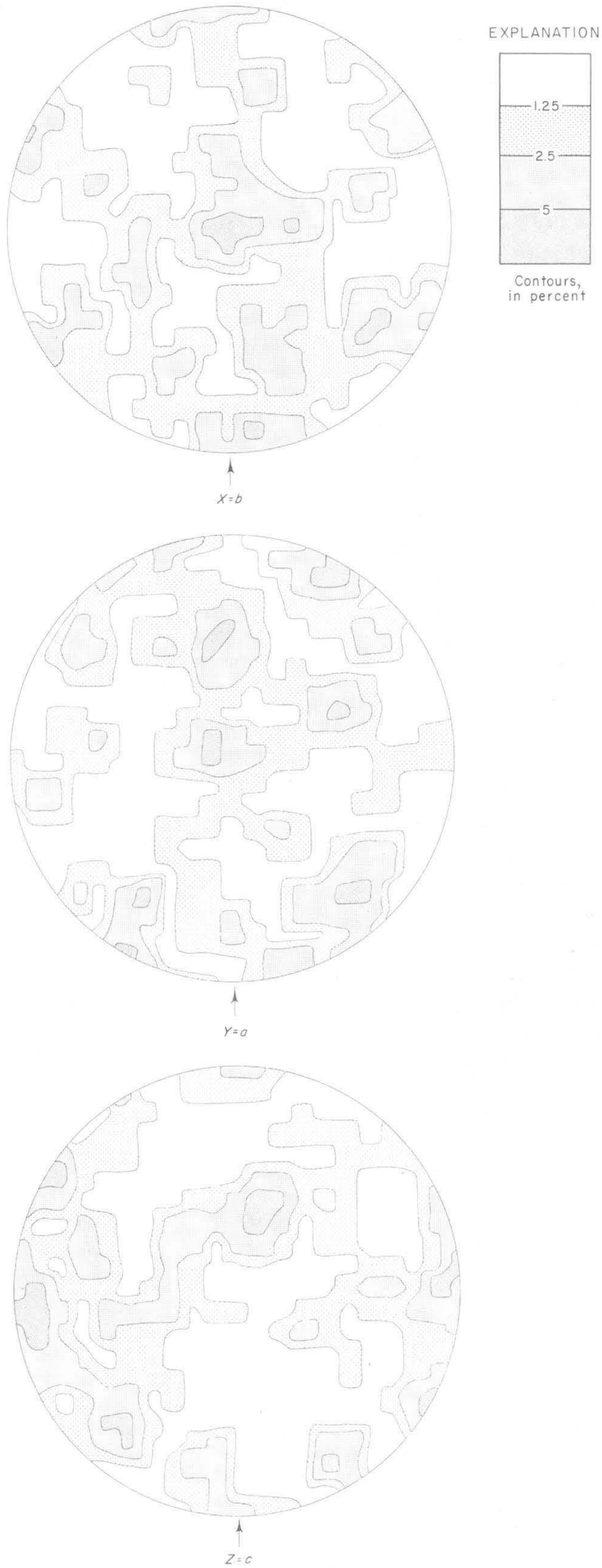


FIGURE 38.—Fabric diagrams of 80 anchiequidimensional bronzite grains in bronzitite specimen 54EDJ–71. Sections parallel to layering.

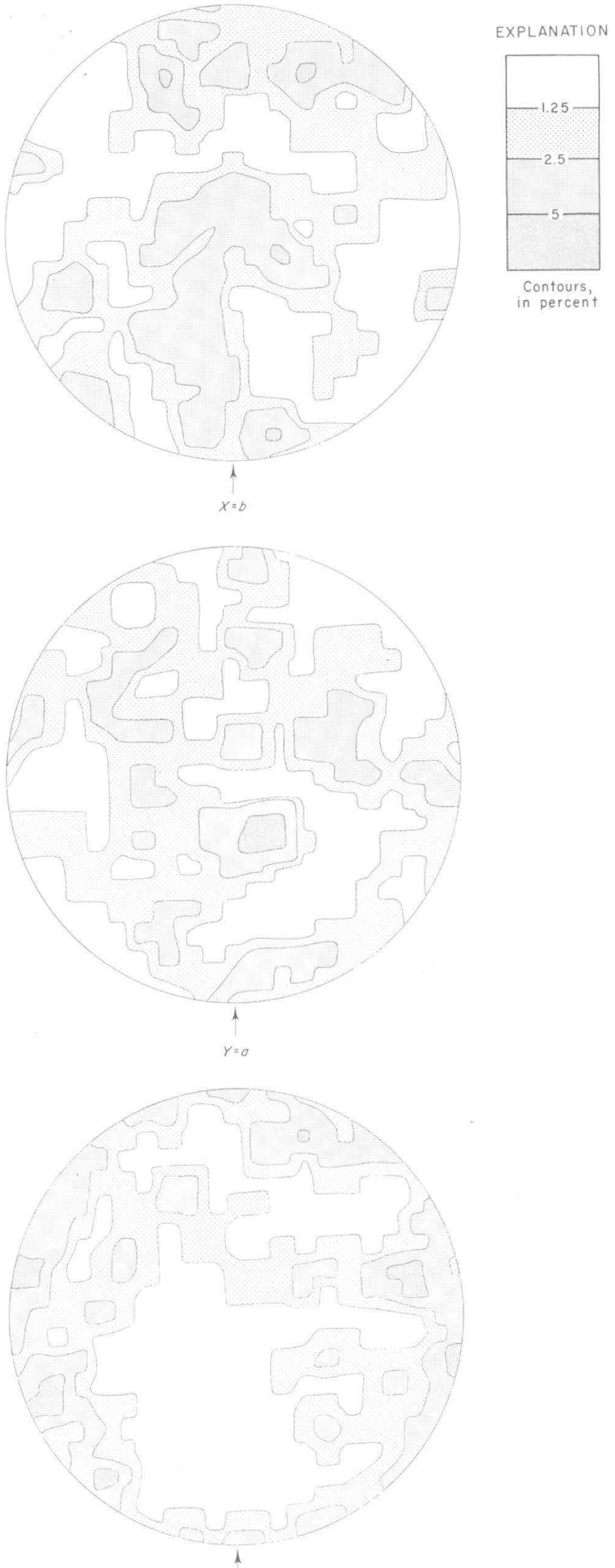


FIGURE 39.—Fabric diagrams of 80 prismatic bronzite grains in olivine bronzitite 54EDJ–80. Sections parallel to layering.

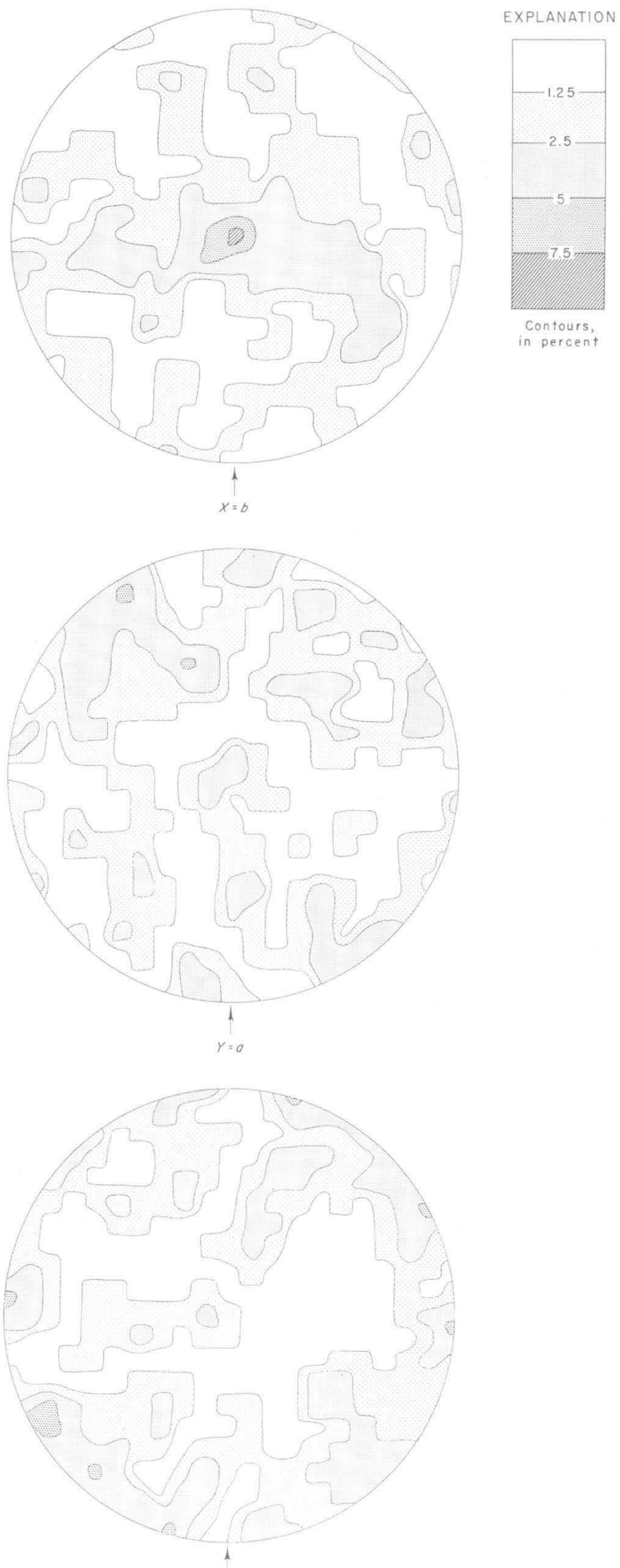


FIGURE 40.—Fabric diagrams of 80 broad prismatic bronzite grains in bronzitite 54EDJ–100. Sections parallel to layering.

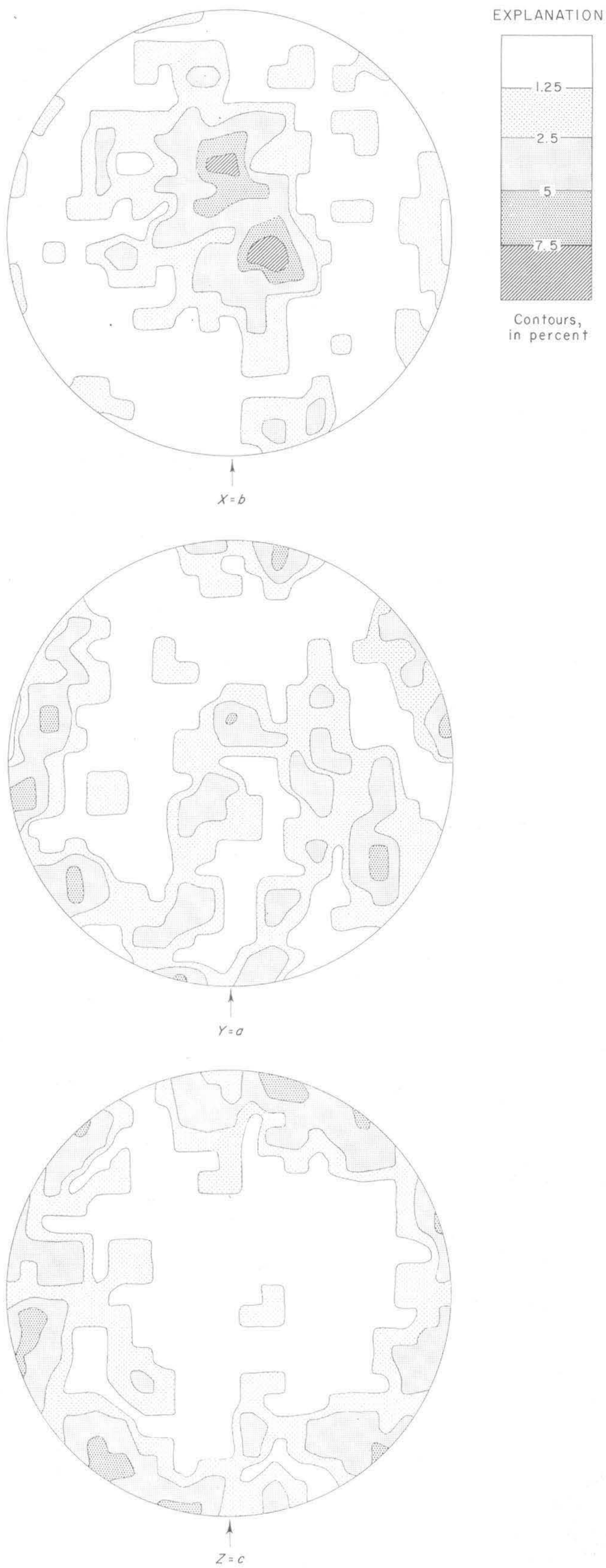


FIGURE 41.—Fabric diagrams of 80 broad prismatic bronzite grains in olivine bronzitite 54EDJ–74. Sections parallel to layering.

show a 7½ percent concentration of X axes perpendicular to the layering, well developed Z girdles perpendicular to the X maximum, and little or no preferred orientation of the intermediate Y axes. In both specimens there is a tendency for girdle development of X, and in 54EDJ–74 two X submaxima occur about equidistant from the pole to the layering plane. The significance of this is not apparent. Both the X maximum and the Z girdle are better developed in specimen 54EDJ–74, which has the more extreme difference in average $b:c$ dimensions. Azimuthal distribution plots of the bronzite Z axes in these two specimens (fig. 42) show little or no preferred direction of alinement.

The orientation of the investigated bronzite appears to conform to the following patterns: (1) where crystals are nearly equidimensional they have little or no preferred orientation; (2) where crystals have a broad flat surface, that surface tends to lie in the layering plane; and (3) where crystals are elongate, the long

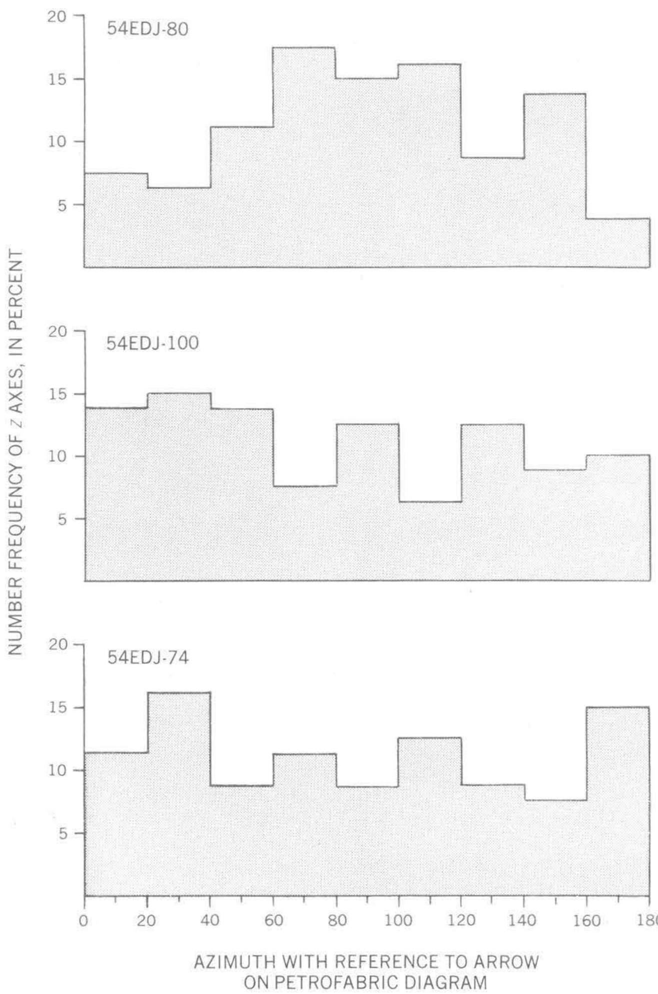


FIGURE 42.—Azimuthal distribution of bronzite $Z=c$ axes in specimens showing Z girdles.

axis tends to lie in the layering plane regardless of whether or not the crystal is flattened. A rude lineation was discovered in one specimen where it had not been suspected, but lineation was not detected in the other two specimens showing Z girdles.

OLIVINE

Of the three specimens studied, olivine crystals showed uniform extinction in one, were weakly undulatory in the second, and showed extreme undulatory banding in the third.

Specimen 52WF–28 was selected as being typical of internally structureless poikilitic chromite harzburgite, within which no preferred dimensional orientation of olivine crystals could be detected either at the outcrop or on etched slabs. The olivine crystals, whose originally euhedral boundaries are marked by surrounding chromite crystals, have narrow selvages of bronzite. None of the olivine is undulatory. The average ratio of original crystal dimensions $a:b:c$ was determined to be 0.76:0.63:1. The fabric diagrams illustrated in figure 43 show a fairly well developed Y girdle in the layering plane and almost no preferred orientation of X and Z, although there is a slightly greater concentration of the shorter X axis perpendicular to the section. An azimuthal plot of Y axes (fig. 45) shows little or no preferred orientation within the layering plane.

Specimen 54EDJ–79 was selected for study as a typical poikilitic harzburgite. The rock is composed of about 80 percent olivine in stubby anchiequidimensional crystals, and appears structureless in hand specimen. No dimensional orientation of crystals could be detected at the outcrop or on etched slabs. The average ratio of olivine intercepts was 0.78:0.64:1, nearly identical with the average intercepts of specimen 52WF–28. The fabric diagrams, figure 44, show a discontinuous Y girdle in the layering plane and little or no preferred orientation of X and Z. The Y fabric diagram and the azimuthal distribution of Y axes, plotted in figure 45, show two Y concentrations about 65° apart. In this specimen 37 of the 80 measured olivine crystals showed undulatory extinction. Most undulatory grains are composed of 2 or 3 extinction bands and the difference in orientation between the subindividuals ranges from 1° to 3°. Interstitial plagioclase and bronzite show no evidence of deformation, and, because of the similarity to specimen 52WF–28, it is concluded that the original fabric of the rock has not been significantly altered. Undulatory grains and grains with internally uniform extinction were plotted separately and their distribution is shown in

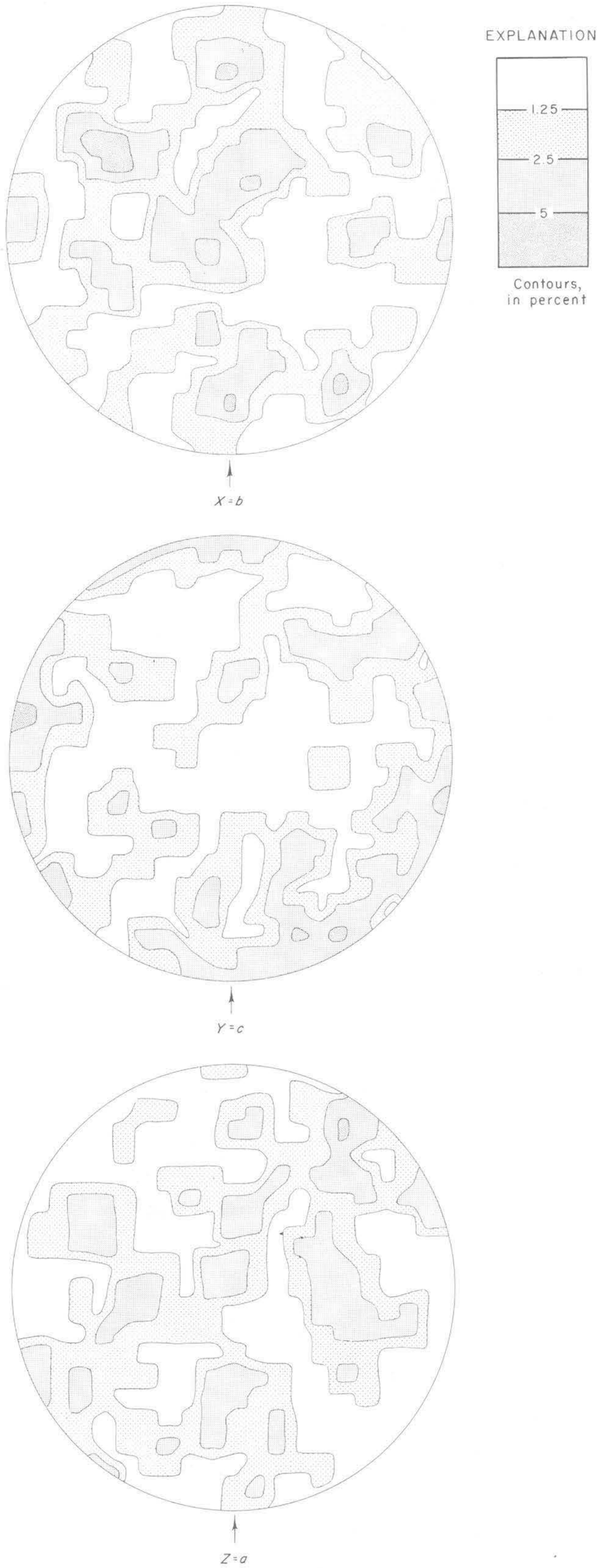


FIGURE 43.—Fabric diagrams of 80 anchiequidimensional olivine grains in poikilitic chromite harzburgite 52WF–28. Sections parallel to layering.

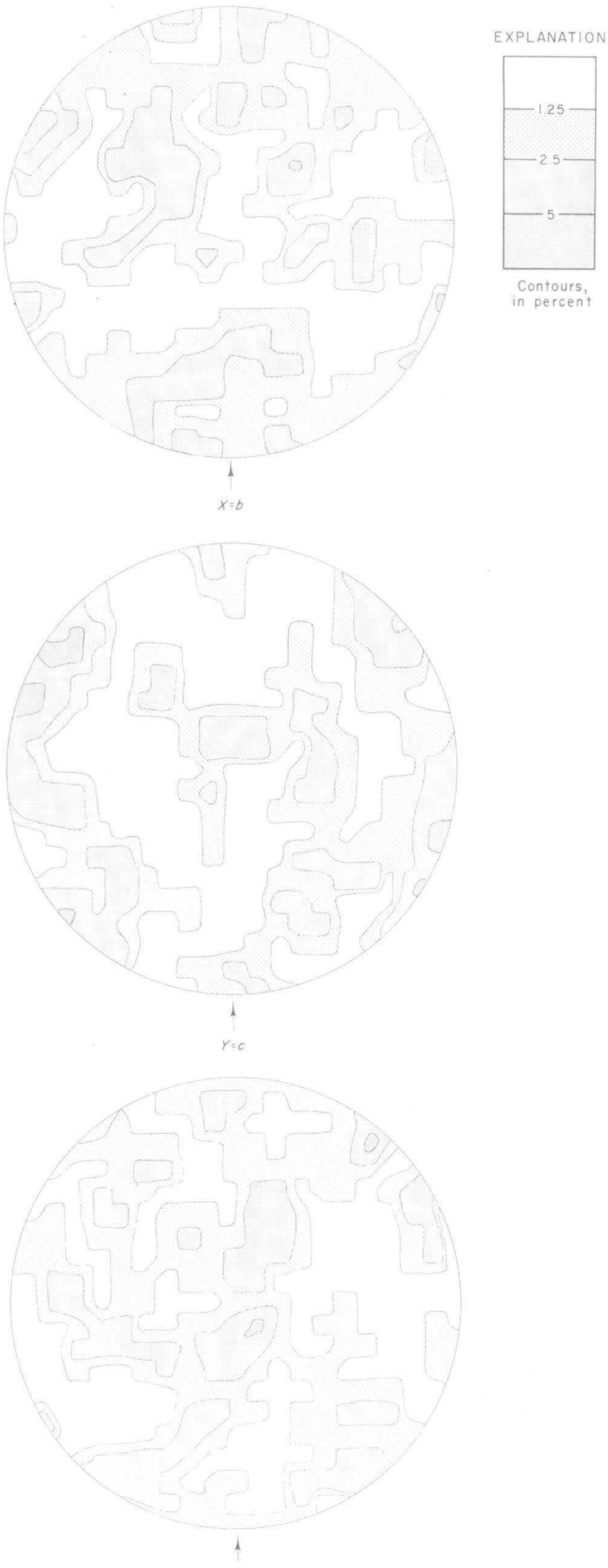


FIGURE 44.—Fabric diagrams of 80 anchiequidimensional olivine grains in poikilitic harzburgite 54EDJ–79. Sections parallel to layering.

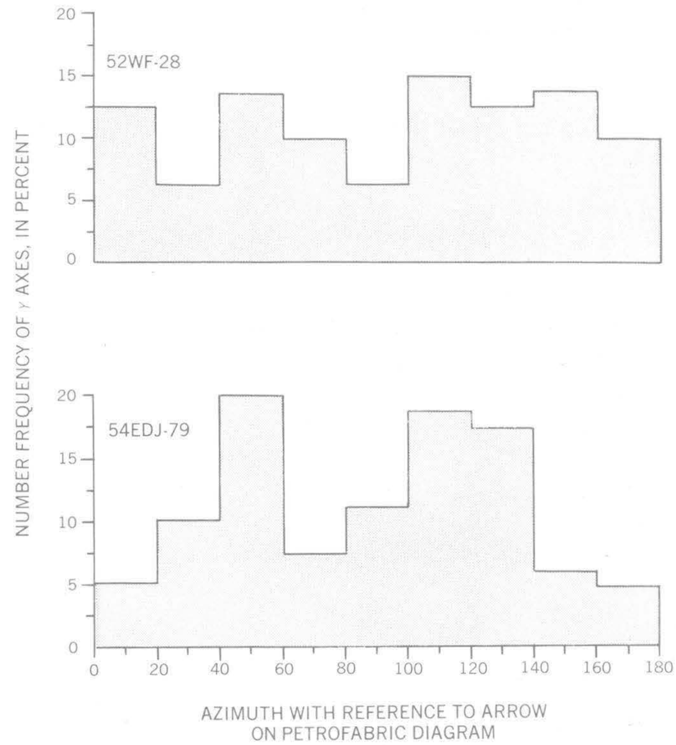


FIGURE 45.—Azimuthal distribution of olivine $Y=c$ axes in specimens showing Y girdles.

figure 46. No significant preferred position of either type can be established.

Specimen 52MV–41, a poikilitic chromite harzburgite, contained the most strongly undulatory olivine of any rock examined from the main part of the Ultramafic zone. Nearly every olivine grain consists of 5 to 15 subindividual bands. Some of the grains are brecciated at the margins. Chromite crystals between the olivine are euhedral and undeformed, but slightly anisotropic in polished section. The olivine grains are round and nearly equidimensional in the layering plane, but flattened parallel to it, giving the rock a foliated appearance. The fabric diagrams illustrated in figure 47 represent the average axis positions for 50 grains. The diagrams show a well-developed Y girdle at right angles to the layering, and a strong Z maximum in the layering plane nearly perpendicular to the girdle. Although the Z maximum is split in the fabric diagram, the azimuthal histogram illustrated in figure 48 shows only a single maximum, and a greater number of measurements would probably fill in the fabric diagram. X shows no obvious preferred orientation. In most of the 50 grains, the orientation of the subindividuals changes consistently from one side of the grain to the other. The most widely divergent subindividuals of each grain were measured and plotted separately, and in some grains, prominent intermediate bands were also determined. The positions of the

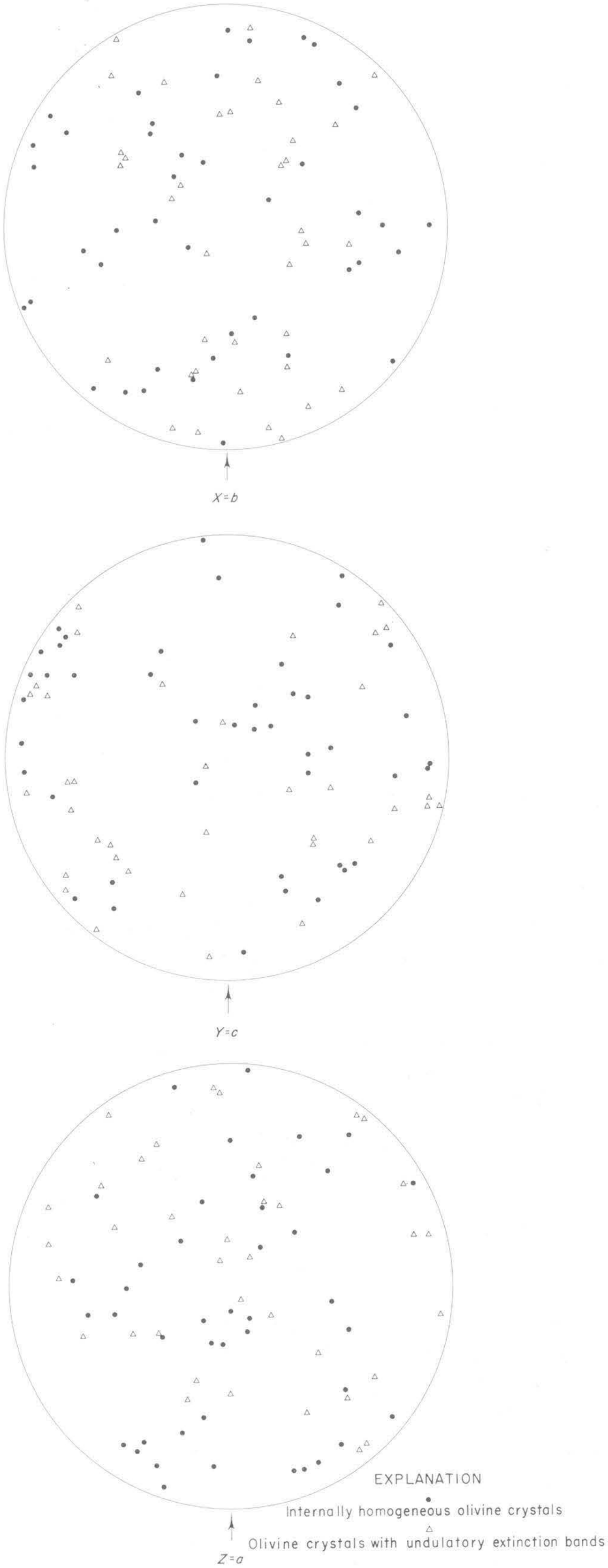


FIGURE 46.—Distribution of undulatory olivine grains in poikilitic harzburgite 54EDJ–79.

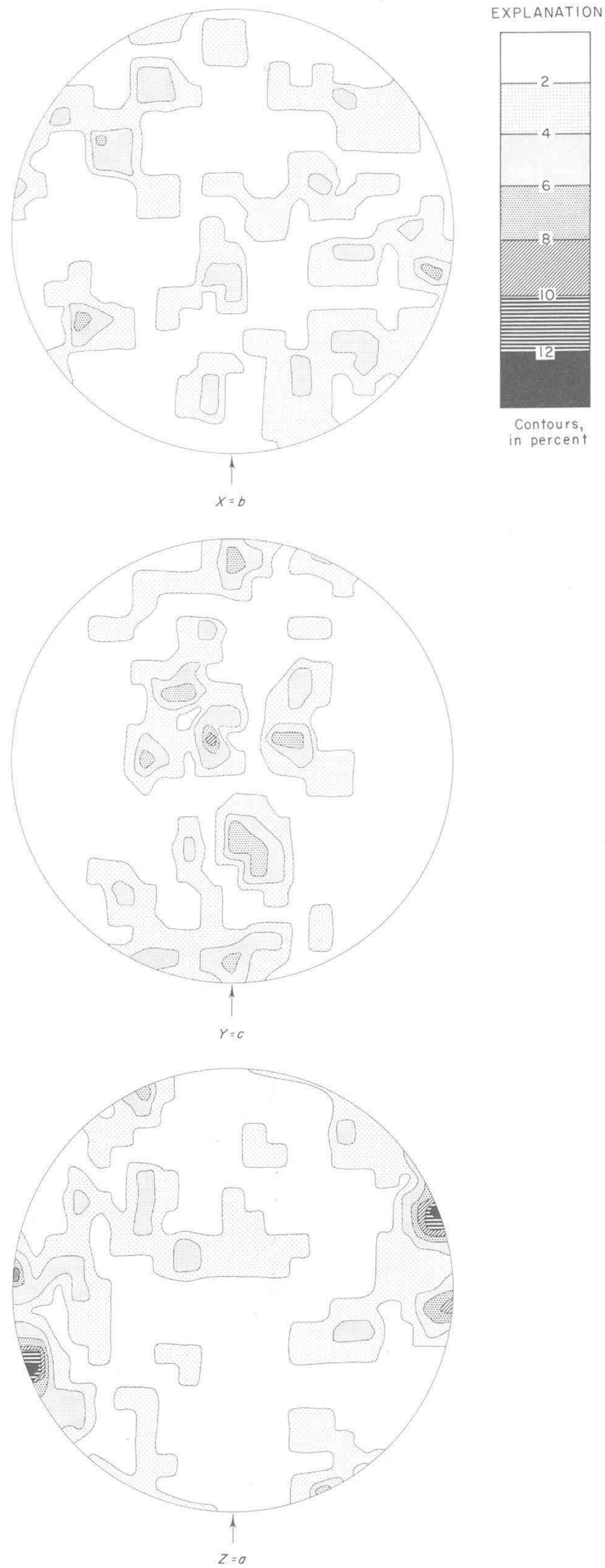


FIGURE 47.—Fabric diagrams of average positions of 50 flattened olivine grains in poikilitic chromite harzburgite 52MV–41. Sections parallel to layering.

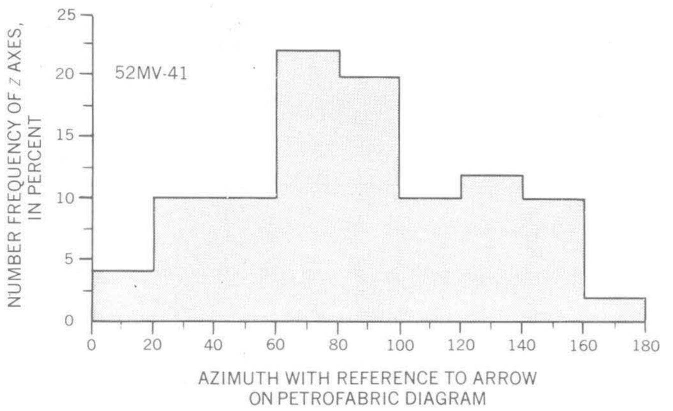


FIGURE 48.—Azimuthal distribution of olivine $Z=a$ axes in the layering plane.

measured undulatory bands for each of the 50 grains are shown in figure 49. In most grains Y shows the least divergence, and Z is generally more divergent than X. In all grains where more than two extinction bands were measured, the Z axis changes in a consistent direction from one side of the grain to the other, but both X and Y are observed to rotate in some grains (that is, 6, 22, 31, 39, 49 . . .). Some regularity in the direction of divergence of X and Y can be observed, but the trends of divergence do not appear to be so pronounced as those of the Z axes. If, as in the undeformed olivine fabrics investigated, the Y axes originally lay preferentially in the layering plane, then these axes have revolved up to 90°, at the same time turning to bring Z axes to a maximum at right angles to the Y girdle.

The orientation patterns of the two undeformed olivine-rich rocks are dimensional, and the slightly elongate Y axes are preferentially oriented in the layering plane. Olivine crystals are not sufficiently flattened on b to produce X maxima perpendicular to the layering. As previously noted, the shape of olivine crystals seems to change very little throughout the Ultramafic zone, and presumably these patterns are typical of all olivine-rich rocks throughout the zone. The relative abundance of Stillwater complex rocks whose primary fabrics have been altered by deformation is unknown, but such effects are thought to be minor because of the scarcity of rocks with strongly developed undulatory olivines. Although many rocks contain a few olivine grains with poorly developed undulatory bands, deformation has apparently not been severe enough to alter their fabrics.

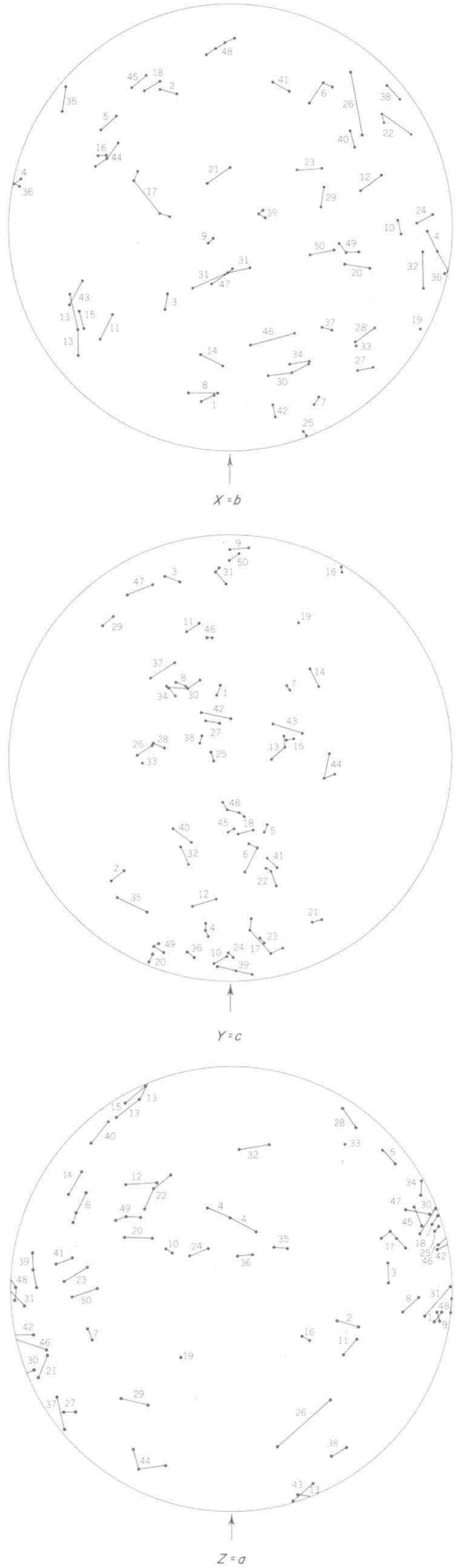


FIGURE 49.—Distribution of undulatory olivine in specimen 52MV–41. Dots connected by straight lines represent observed positions of indicatrix axes in subindividuals of the same crystal.

DISCUSSION

The fabrics of settled olivine and bronzite in the undeformed rocks of the Ultramafic zone are dimensional, and the degree of perfection of preferred grain orientation is dependent on the degree of anisotropism of grain shape. Fabrics of this type, which imply orientation prior to the solidification of the magma containing the crystals, might be accomplished by at least four mechanisms: laminar mush flow; magma currents; simple gravity settling; or postdepositional compaction.

Phillips (1938, p. 130–135) and Turner (1942, p. 280–300) have described certain peridotites and chromite-rich dunites in which the optical orientation of olivine is governed by its external shape and have proposed that the fabric of these rocks originated by laminar flow in a largely crystalline "magma" in the process of intrusion. Huang and Merritt (1952, p. 865–868) find a dimensional and consequent optical orientation in certain troctolites that they interpret as being flow banded. There are several strong objections to origin of layering in the Stillwater complex by laminar mush flow: (1) the extreme lateral continuity of layers only a few inches thick; (2) the prevalence of gradational layering and regular cyclical size changes throughout the layered sequence; and (3) the abundance of delicate textural features, such as layers one crystal thick and cusp textures. Furthermore, many of the fabrics assigned by these authors to origin by flow of a largely crystalline mass show a strong linear alinement of long axes in the layering plane, a feature very poorly developed in Stillwater rocks.

Magma flow has been proposed by several authors as a mechanism for obtaining dimensional fabrics in layered igneous rocks. Current-bedded sedimentary rocks have strongly lineated fabrics (Krumbein, 1942, p. 1355–1402; Nanz, 1955, p. 130), and preferred elongations are also produced where sand grains are deposited by flowing air and water in laboratory experiments (Dapples and Rominger, 1945, p. 246–261). It would seem probable, therefore, that magma currents, if capable of producing a dimensional orientation of grains, should also produce a strong lineation of long axes. In the Skaergaard intrusion, where evidence for magma currents has been abundantly demonstrated, Wager and Deer (1939, p. 271–275) found lineation of plagioclase crystals wherever such crystals had developed rectangular shapes. In the Merensky Reef, Schmidt (1952, p. 233–279) found long axes of orthopyroxenes and plagioclases alined parallel to the sides of circular depressions whose origin he ascribes to swirling magma currents, whereas the orthopyroxenes in the undisturbed Reef show no directional alinement in the layering plane. In the Ultramafic zone of the Stillwater complex, current structures have been observed locally but no systematic study of orientations within these areas has been made. By analogy, however, the two rudely lineated fabrics encountered in the present study, as well as those described by Hambleton (see footnote 4, p. 38), seem best assigned to current action.

It seems reasonable to expect that platy or elongate crystals sinking through quiet magma would tend to accumulate with their largest surfaces parallel to the floor of the magma chamber. The perfection of such orientation would depend on the size and habit of the crystals, their density difference from the magma, and the viscosity of the magma. The efficacy of this process has, however, been questioned by several authors. Turner (1942, p. 295) concluded, on the basis of his examination of a specimen from the differentiated sill of Lugar, Ayrshire, that settling of olivine crystals under the influence of gravity as they separate from a basic magma under static conditions fails to produce a preferred orientation of the olivine space lattice. Huang and Merritt (1952, p. 866) similarly failed to find preferred orientation in olivine from a troctolite in the Wichita Mountains, Oklahoma, which they believed from independent evidence to have been formed by gravity settling. Both authors, however, reported equant olivine in these specimens, and it would seem from the present investigation that random fabrics in gravitationally settled rocks may be caused simply by lack of dimensional anisotropism of the minerals involved. Wager and Deer (1939, p. 268) doubted that the platy parallelism of tabular plagioclase in the Skaergaard intrusion resulted from direct sinking of crystals, because of the feebleness of orienting forces acting in a viscous magma of nearly the same density as the crystals. Van den Berg (1946, p. 199), however, had no hesitation in assigning dimensional fabrics of plagioclase and bronzite in Bushveld gabbros to crystal settling, and, in the Ultramafic zone of the Stillwater complex, the olivine and bronzite grains must have had considerably greater densities than the magma through which they fell. The process of orientation by simple settling and toppling leads to nonlineated fabrics, which thus would explain the position of grains in those rocks, which contain elongate crystals randomly disposed in the layering plane.

The role of postdepositional compression in orienting grains is difficult to evaluate. Borg and Maxwell (1956, p. 71–81) have produced dimensional fabrics in loose quartz sands by compressional deformation under conditions simulating burial at depths of 16,000 to 35,000 feet, but the relative amount of orientation caused by initial packing of the sand into cylinders and the amount caused by the subsequent deformation were not determined. If, as seems likely, settled crystals were very loosely packed at the surface of the floor of the magma chamber, considerable compaction and consequent rotation of crystals could be accomplished by jarring or from compressive weight of burial, and such rotation should at least intensify any dimensional grain orientation already present.

Several inferences as to conditions of crystal deposition in the Ultramafic zone may be made from the observed fabrics. Rocks containing elongate settled crystals that tend to be evenly disposed in the layering plane were probably deposited in the absence of magma currents. The disposition of the crystals is probably a result of simple gravitational forces that caused grains to assume their most stable position on the floor of the magma chamber. This process was assisted to an unknown extent by postdepositional compaction. Rocks containing elongate settled minerals that tend to be concentrated in one or two directions in the layering plane were probably influenced by weak magma currents during deposition. Rocks with little or no preferred orientation of settled crystals are composed of nearly equidimensional grains, and these rocks give little information as to conditions during deposition.

RELATIONS OF THE PRIMARY PRECIPITATE TO THE INTERPRECIPITATE MATERIAL

The original relative volumes of settled crystals and of the interprecipitate magma between them can be measured directly in a few rocks, but in most the boundaries of the primary precipitate have been obscured either by reaction with the interprecipitate magma or by continued growth after deposition.

REACTION REPLACEMENT

Textural relations in the Ultramafic zone suggest that under the particular conditions of crystallization obtaining, reaction relations existed between olivine–bronzite, olivine–augite, and bronzite–augite. Resorption textures have only been observed between settled and interprecipitate minerals. It should be noted that settled bronzite coexists with settled olivine in the Ultramafic zone without resorption textures, and that settled orthopyroxenes similarly coexist with settled clinopyroxenes in parts of the Banded zone.

Textural evidence for the three reaction pairs mentioned above may be summarized as follows: (1) Wherever settled olivine is surrounded by interstitial or poikilitic bronzite or augite, and wherever settled bronzite is surrounded by interstitial or poikilitic augite, the normally euhedral settled crystals are rounded and embayed. (2) Where augite or bronzite occurs as poikilitic host crystals, the number of centers of included settled crystals within and between the oikocrysts is the same, but volume of settled crystals within the oikocrysts is much reduced. (3) Single settled crystals at the edges of pyroxene oikocrysts are embayed where in contact with pyroxene and euhedral at the emergent ends. The reaction relation between olivine and bronzite is well known, and the textural features between these minerals are explained as reaction replacement of settled olivine in contact with the interprecipitate magma to form bronzite. The similar textural relations where augite is the interstitial mineral suggest that olivine–augite and bronzite–augite are likewise reaction pairs, at least within the Ultramafic zone.

Reaction textures involving chromite have not been observed.

OLIVINE → BRONZITE

Replacement of olivine by interstitial bronzite is most highly developed in poikilitic harzburgites, which are composed of essentially equigranular olivine in a mesostasis of poikilitic bronzite and interstitial plagioclase. Olivine grains within the bronzite oikocrysts are, without observed exception, rounded, embayed, and in some cases separated into islands (fig. 50). Between the poikilitic bronzite crystals, on the other hand, where the interstitial material is plagioclase, olivine crystals are commonly euhedral and invariably larger in size than those included in bronzite in the same hand specimen (fig. 50). At the margins of bronzite oikocrysts, single olivine crystals can be observed which are euhedral at the ends that protrude into plagioclase, but which are embayed at the ends that are in contact with bronzite (fig. 51). In rocks where chromite is an essential constituent, the original shapes of the olivine crystals before resorption are outlined by rims of formerly contiguous chromite (fig. 53). Textural evidence that the replacement of olivine by bronzite was postdepositional is provided by thin chromite layers within the poikilitic harzburgites, which pass continuously through the rock without regard for the composition or orientation of the interstitial material (fig. 10). In most rocks the centers of the roughly spherical bronzite oikocrysts contain smaller olivine remnants than do the edges.

OLIVINE → CHROMIAN AUGITE

Chromian augite oikocrysts, about one-half inch in diameter, are rare rather than essential constituents of poikilitic harzburgite and, where present, are accompanied by interstitial bronzite. They are more commonly associated with olivine in granular harzburgite, where bronzite oikocrysts are not developed, and, in these rocks, augite oikocrysts contain embayed bronzite

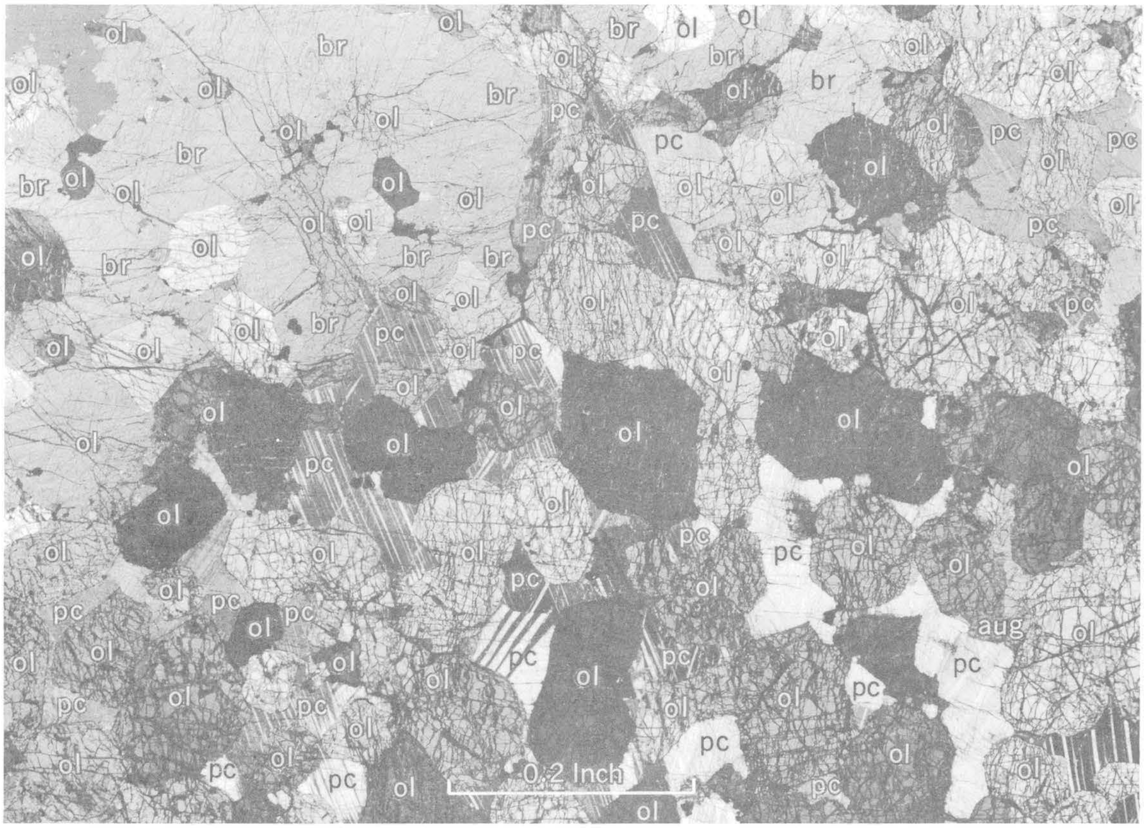


FIGURE 50.—Reaction replacement of settled olivine in poikilitic harzburgite. Olivine crystals surrounded by interstitial plagioclase (in lower part and at right of photograph) are euhedral; olivine grains within bronzite oikocrysts (upper left) are rounded, embayed, and islanded. ol=olivine; br=bronzite; pc=plagioclase; aug=augite. Crossed nicols.

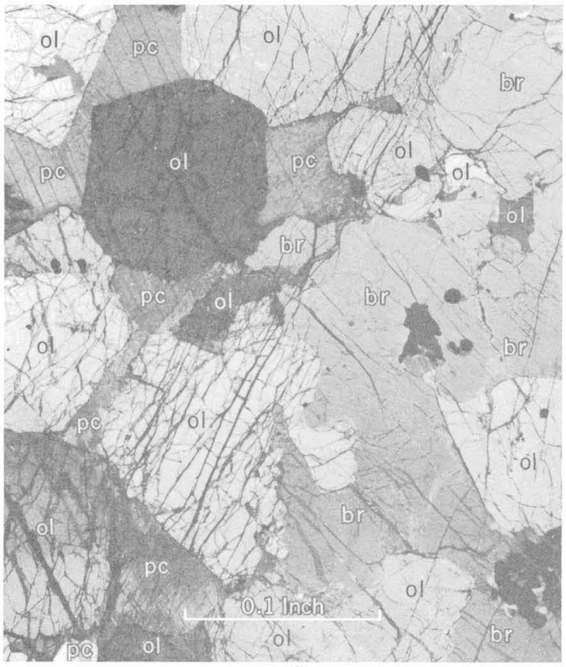


FIGURE 51.—Reaction replacement of settled olivine by bronzite. Single olivine crystal at lower left of photograph shows crystal faces against plagioclase, but is partially replaced where in contact with bronzite. ol=olivine; br=bronzite; pc=plagioclase. Crossed nicols.

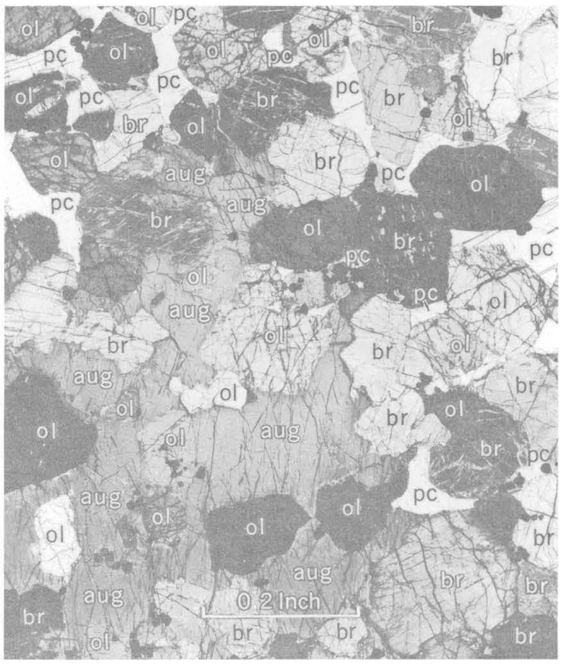


FIGURE 52.—Reaction replacement of settled olivine and bronzite in granular harzburgite. Settled minerals surrounded by interstitial plagioclase are euhedral; both olivine and bronzite within augite oikocryst are rounded and embayed. ol=olivine; br=bronzite; pc=plagioclase; aug=augite. Crossed nicols.

PHOTOMACROGRAPHS OF OLIVINE → BRONZITE AND OLIVINE → AUGITE REACTION TEXTURES

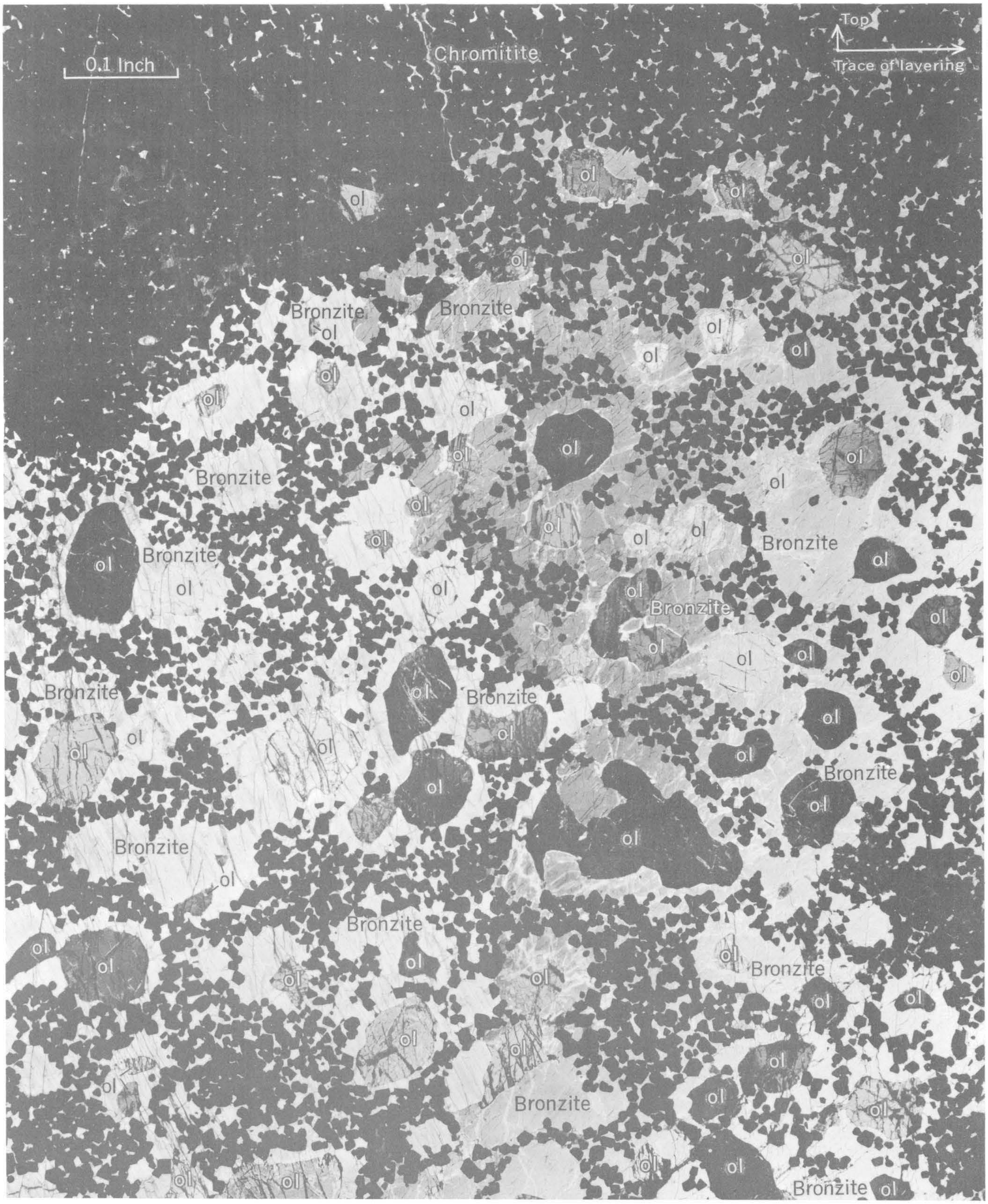


FIGURE 53.—Photomacrograph of reaction replacement texture in poikilitic chromite harzburgite. The original size and shape of the olivine crystals is outlined by the rims of formerly contiguous chromite crystals. In some areas outlined by chromite, olivine has been completely reacted out. ol=olivine. Crossed nicols.

as well as olivine. Textural relations between olivine and augite are identical with those between olivine and bronzite: olivine crystals within augite oikocrysts are rounded, embayed, and smaller than those surrounded by interstitial plagioclase (fig. 52). Examples of chromitite layers a few grains thick passing through augite hosts without interruption have been observed.

BRONZITE ⟶ CHROMIAN AUGITE

All bronzitite contains ⅜- to ⅝-inch clinopyroxene oikocrysts scattered evenly throughout the rock. Textural relations within and between the oikocrysts are identical with those described between olivine and bronzite and between olivine and augite (fig. 54). Single settled crystals of bronzite at the margins of poikilitic augite crystals show euhedral forms against plagioclase, and embayed contacts against clinopyroxene (fig. 55). Similar reaction textures between hypersthene and clinopyroxene in the main zone of the Bushveld complex have been described by Lombaard (1934, p. 26–27), Van den Berg (1946, p. 163), and Wells (1952, p. 919–920).

VOLUME RELATIONS

Relative proportions of settled olivine and bronzite within and between the bronzite and augite oikocrysts have been determined by means of separate modal counts on large etched slabs by the method described by Jackson and Ross (1956, p. 648–651). A total of 53 specimens of poikilitic harzburgite and bronzitite were investigated, and results are tabulated in table 4.

TABLE 4.—*Volume percentages of constituents within and between pyroxene oikocrysts in poikilitic harzburgite and bronzitite*

Poikilitic harzburgite

Specimen No.	Constituents between pyroxene oikocrysts		Constituents within bronzite oikocrysts		Constituents within chromian augite oikocrysts		Amount of olivine replaced within oikocrysts	
	Olivine	Plagioclase	Olivine	Bronzite	Olivine	Chromian augite	Bronzite	Chromian augite
52WF-4	94	6	68	32	--------	--------	28	--------
14	80	20	50	50	--------	--------	37	--------
18	82	18	67	33	--------	--------	18	--------
27	85	15	55	45	69	31	35	19
29	90	10	57	43	71	29	37	21
52BE-8	82	18	48	52	66	34	41	20
15	87	13	71	29	--------	--------	18	--------
52AL-4	75	25	42	58	55	45	44	27
52NL-13	78	22	34	66	57	43	56	27
52MV-8	70	30	36	64	50	50	49	29
20	91	9	55	45	70	30	40	23
55MV-1	78	22	53	47	--------	--------	32	--------
3	86	14	54	46	58	42	37	33
25	87	13	58	42	--------	--------	33	--------
26	89	11	55	45	67	33	38	25
27	81	19	50	50	63	37	38	22
63	82	18	57	43	--------	--------	30	--------
69	83	17	52	48	--------	--------	37	--------
72	85	15	--------	--------	71	29	--------	16
54EDJ-73	72	28	30	70	--------	--------	58	--------

Bronzitite

Specimen No.	Constituents between chromian augite oikocrysts		Constituents within chromian augite oikocrysts		Amount of bronzite replaced within chromian augite oikocrysts
	Bronzite	Plagioclase	Bronzite	Chromian augite	
51MV-7	87	13	50	50	43
9	91	9	53	47	42
11	87	13	48	52	45
13	90	10	52	48	42
15	88	12	51	49	42
55MV-9	81	19	48	52	41
10	76	24	37	63	51
12	79	21	31	69	61
32	88	12	55	45	38
33	91	9	63	37	31
68	87	13	54	46	38
77	91	9	61	39	33
78	89	11	57	43	36
52WF-2	90	10	60	40	33
8	99	1	64	36	35
12	99	1	73	27	26
20	93	7	62	38	33
35	93	7	66	34	29
40	89	11	48	52	46
42	90	10	49	51	46
44	89	11	45	55	49
47	85	15	42	58	51
48	80	20	34	66	57
52BE-29	85	15	48	52	44
31	85	15	51	49	40
34	88	12	46	54	47
35	83	17	46	54	45
55BE-2	66	34	12	88	82
4	59	41	9	91	85
5	73	27	25	75	66
7	85	15	38	62	55
53IM-12	87	13	50	50	43
EDJ-52-7	85	15	42	58	51

Modal counts outside of oikocrysts, where the interstitial material is plagioclase, are reproducible within about 2 percent, but counts within the poikilitic crystals are no better than about 5 percent. In most rocks the oikocrysts contain higher proportions of included bronzite or olivine near the margins, and adequate samples within nonhomogeneous spheres larger than about one-half inch in diameter cannot be made, even on large slabs. Some of the rocks investigated contain from 1–3 percent chromite, which was assigned during counting to the mineral within which it occurred, so that only two constituents need be dealt with.

In the 20 specimens of poikilitic harzburgite listed in table 4, the average volume of olivine between oikocrysts is 83 percent, the average volume of olivine within bronzite oikocrysts is 52 percent, and the average volume of olivine within augite oikocrysts, where these are present in the rocks, is 63 percent. In the 33 specimens of bronzitite investigated, the average volume of bronzite between the augite oikocrysts is 85 percent, and the average volume of bronzite within the oikocrysts is 48 percent. Assuming that the settled bronzite and olivine crystals in the individual rocks were the same size and shape when deposited in the layers, and that the volume percentage of olivine where surrounded by plagioclase represents the volume percentage of olivine in the crystal mush before crystallization of the trapped interprecipitate magma, then

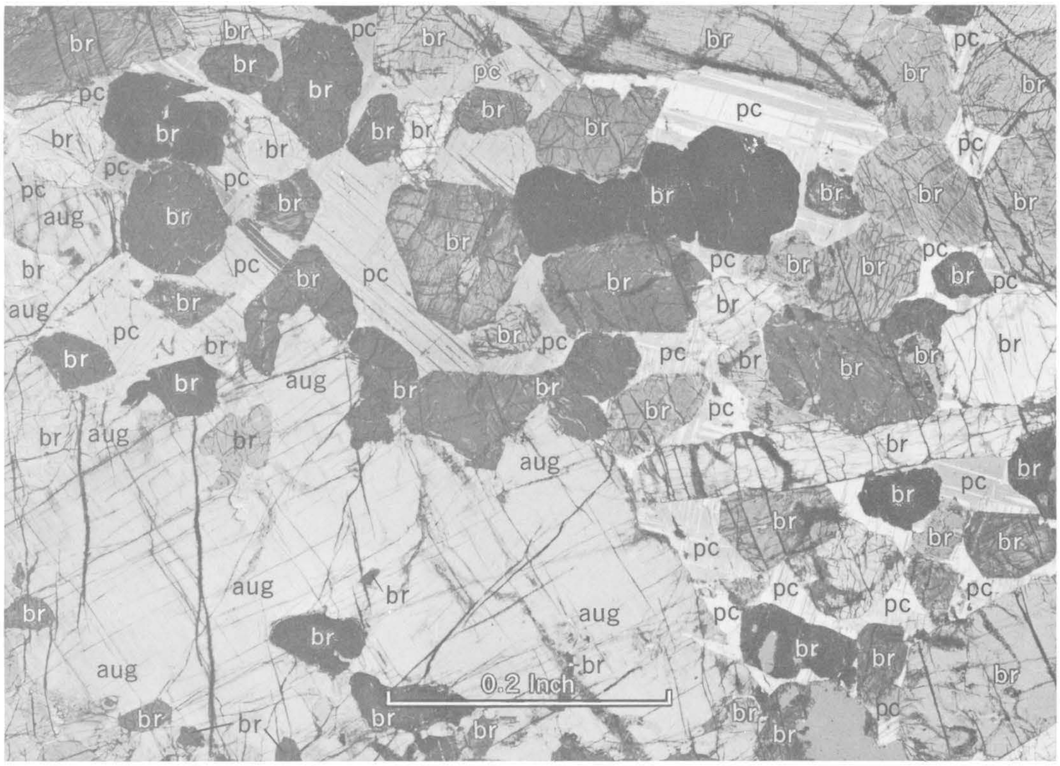


FIGURE 54.—Reaction replacement of settled bronzite in bronzitite. Bronzite crystals surrounded by plagioclase (upper right half of photograph) are euhedral; bronzite grains within augite oikocryst (lower left) are rounded, embayed and islanded. br=bronzite; aug=augite; pc=plagioclase. Note subparallel alinement of two elongate bronzite crystals. Crossed nicols.

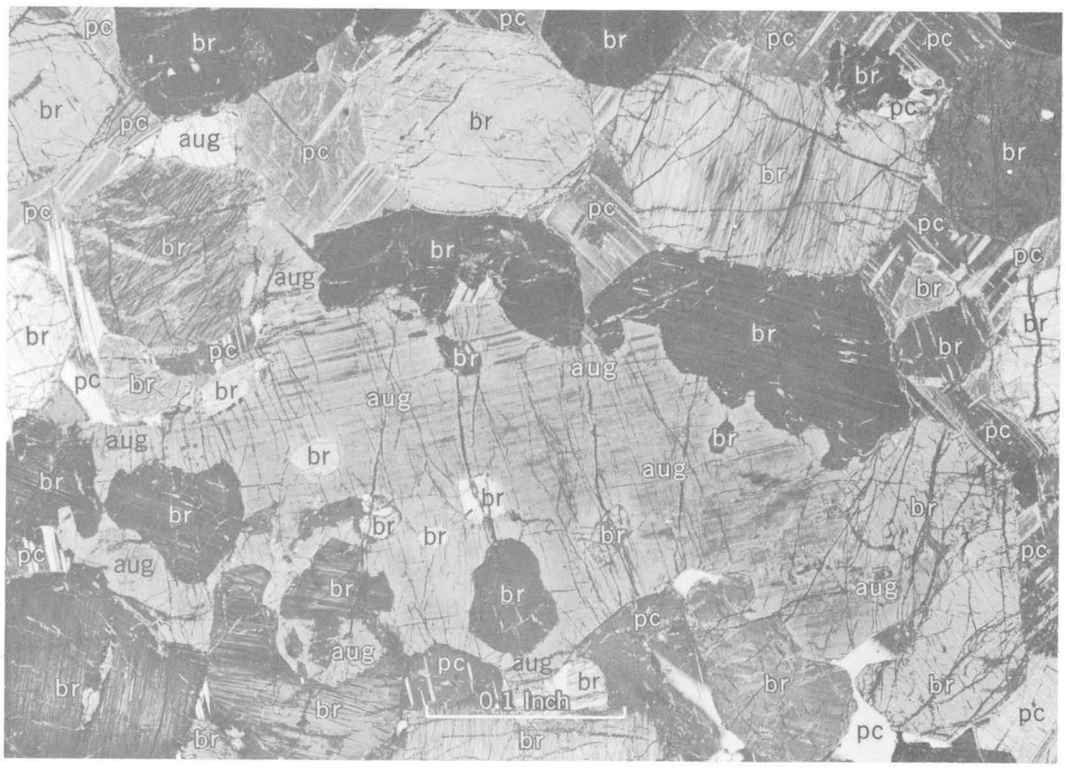


FIGURE 55.—Reaction replacement of settled bronzite by augite. Single bronzite crystals around periphery of augite oikocryst show crystal faces against plagioclase, but they are partially replaced where in contact with augite. br=bronzite; aug=augite; pc=plagioclase. Crossed nicols.

PHOTOMACROGRAPHS OF BRONZITE → AUGITE REACTION TEXTURES the averages indicate that more than 35 percent of olivine in contact with bronzite has been replaced, that about 25 percent of olivine in contact with augite has been replaced, and that more than 40 percent of bronzite in contact with augite has been replaced. The ability of augite to replace more bronzite than olivine is also suggested qualitatively in granular harzburgites, where settled bronzite in augite oikocrysts is noticeably smaller and more embayed than contiguous olivine in the same oikocrysts.

The amounts of settled olivine and bronzite resorbed within the area of replacing pyroxenes have been computed for each specimen and are tabulated in table 4. These values have been plotted against the volume percentage of settled minerals lying between the pyroxene oikocrysts for the individual specimens in figure 56. A rough but significant linear trend can be observed in each of the three sets of data. The slopes of these trends for olivine-bronzite and bronzite-augite relations are the same, and although the data for olivine-augite relations are not definitive, a similar slope seems possible. Again assuming that the volume of settled minerals lying between the oikocrysts represents the volume of olivine and bronzite present prior to the crystallization of either interstitial pyroxene or plagioclase, then these curves indicate that the higher the porosity of the crystal mush, the more olivine and bronzite were resorbed within the area of the oikocrysts, regardless of the relative percentages of the two interstitial minerals in the rock.

DISCUSSION

In view of the well-known reaction relation between olivine and orthopyroxene, the poikilitic bronzite enclosing and partly replacing olivine is best explained as a reaction product between settled olivine crystals and the interprecipitate magma with which they were in contact. The trapped magma at the same time precipitated bronzite between the olivine crystals, and the reaction stopped when the proportionally small volume of magma had exhausted its mafic constituents. Plagioclase crystallizing from the interprecipitate magma simply filled interstices between olivine grains without reaction. The extension of this mechanism to explain identical textures between olivine–augite and bronzite–augite is hampered by incomplete data on the crystallization behavior of clinopyroxenes. In synthetic melts, clinopyroxenes form solid solutions from clinoenstatite to diopside, and Osborn and Tait (1952, p. 429) state that clinopyroxenes over most of the composition range in the system diopside-forsterite-anorthite-silica have reaction boundaries with olivine. Poldervaart and Hess (1951, p. 472–489), however, consider that only limited solid solution exists in the pyroxene field of natural magmas, and that lime-rich pyroxenes are separated from olivines and lime-poor pyroxenes by cotectic boundaries. They conclude that although olivine may have a reaction relation with orthopyroxene, neither olivine nor orthopyroxene has a reaction relation with augite. Without questioning the general validity of this conclusion, it would appear that if cotectic relations between augite and olivine-bronzite were invariably operative, then augite crystallizing from the interprecipitate magma in the Ultramafic zone would simply fill interstices between settled olivine and bronzite as plagioclase is observed to do. The consistent development of replacement textures would seem to indicate that, under the particular conditions obtaining, augite was formed in part by reaction of previously settled bronzite and olivine with the interprecipitate magma.

Relative volume measurements indicate that only about one-third of the interprecipitate pyroxene in the Ultramafic zone fills spaces between settled crystals, and that the remainder crystallized at the expense of the settled crystals by reaction replacement. The measurements also suggest that the ability of the trapped magma to react with and replace the outer peripheries of settled crystals is restricted by low porosity in the crystal mush and enhanced by high porosity.

SECONDARY ENLARGEMENT

Individual crystals of chromite, olivine, and bronzite, although as a general rule euhedral, are commonly observed with partially developed mutual interference boundaries and, in a few rocks, are completely anhedral against each other. Mutual interference between these crystals is inversely related to the amount of interstitial minerals present in the rocks, so that crystals range from perfectly euhedral, in rocks with 30 percent or more matrix, to completely anhedral, in rocks with less than 5 percent matrix.

In certain areas of the complex characterized by plastically deformed layers, undulatory olivine, and strained bronzite, these relations are believed to be caused by deformational filter pressing prior to the final crystallization of the interstitial material. In other areas, however, where no evidence of early deformation exists, mutual interference seems best explained as being caused by continued growth of the settled crystals in certain layers after deposition, as proposed by Hess (1939, p. 431). The term secondary enlargement is used here to describe phenomena believed caused by this second mechanism.

Several independent criteria indicating secondary enlargement are recognized: (1) All gradations exist

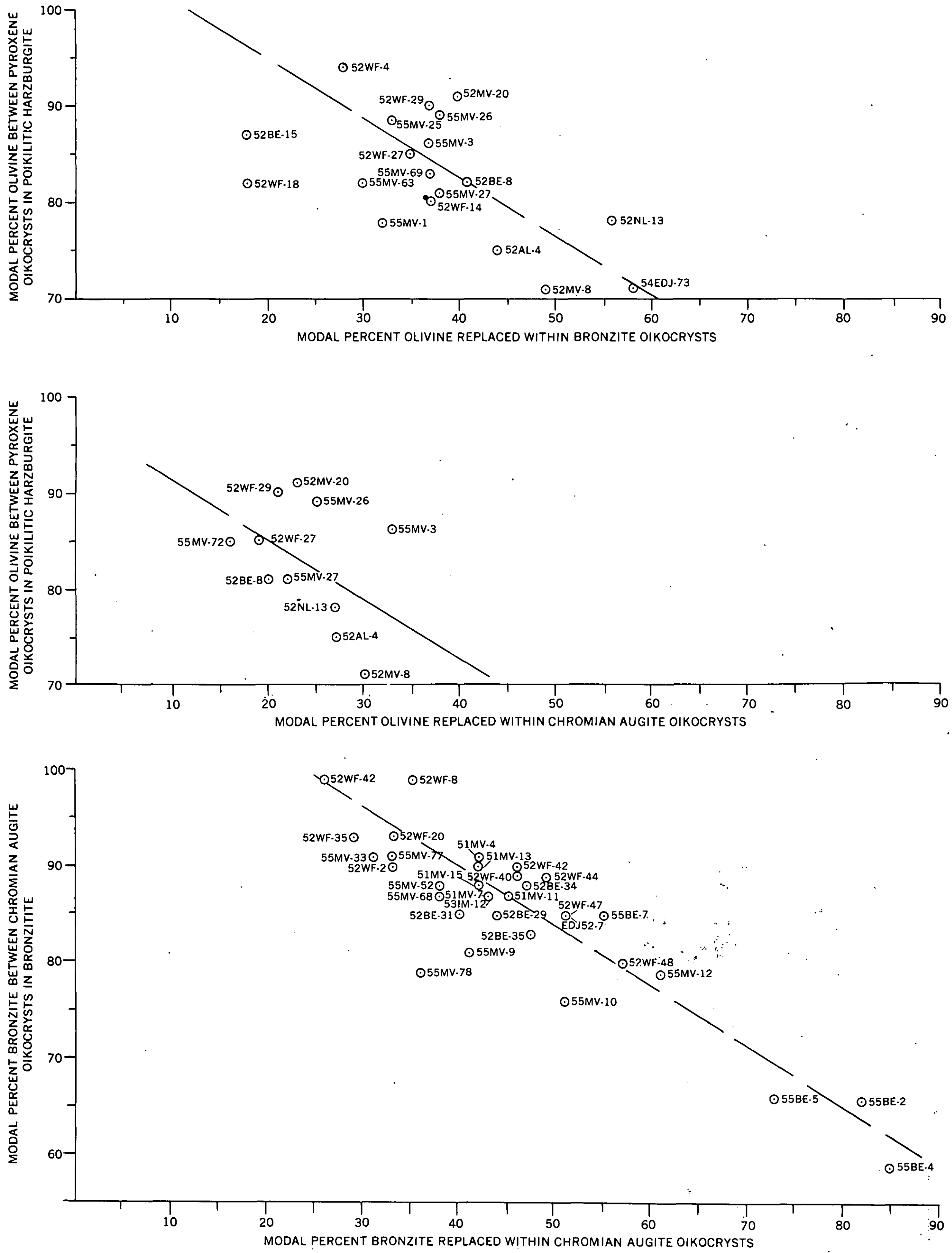


Figure 56.—Relations of volumes of settled minerals lying between pyroxene oikocrysts to volumes of settled minerals replaced within pyroxene oikocrysts.

between rocks with perfectly euhedral settled crystals and those with mosaic textures. (2) The degree of euhedrism of individual crystals of olivine, bronzite, or chromite is related to the layering plane, so that a bronzitite with euhedral bronzite may be succeeded in the section by a dunite with mosaic texture, which may itself be succeeded by a granular harzburgite with partially interfering olivine and bronzite, each of these units retaining its character along the strike. (3) Individual crystals of olivine and bronzite in a few rocks have euhedral cores surrounded by slightly more iron-rich, mutually interfering rims, which are suggestive of authigenic overgrowths in sedimentary rocks. The general absence of peripheral zoning in rocks where secondary enlargement is believed to have occurred is attributed to the growth of the settled crystals in contact with magma from which crystals of the same composition were being precipitated.

The simplest and most regular development of secondary enlargement occurs in rocks composed of only one settled mineral: poikilitic harzburgite, dunite, bronzitite, and chromitite. In rocks composed of two settled minerals (olivine chromitite, poikilitic chromite harzburgite, olivine bronzitite, and granular harzburgite), secondary enlargement is dependent on the relative proportions of settled minerals present, and relations are more complicated.

POIKILITIC HARZBURGITE AND DUNITE

The transition from rocks containing automorphic to those containing xenomorphic olivine is accompanied by concomitant decrease in matrix minerals. For example, the specimen shown in figure 57 is composed of 70 percent perfectly euhedral olivine crystals and 30 percent interstitial plagioclase. In the rock illustrated in figure 58 the olivine-plagioclase ratio has increased to 82:18, and the olivine shows some mutually interfering boundaries. The plagioclase, however, still perfectly fills interstices between the partially interfering olivine, and shows no evidence of being replaced. The specimen illustrated in figure 59 contains no interstitial plagioclase, and the olivine is completely anhedral. The absence of replacement textures between olivine and plagioclase is considered to indicate that the mutual interference between olivine grains occurred prior to the crystallization of the interstitial material, and that interprecipitate magma was displaced in the process of overgrowth.

In a few rocks the outermost margins of secondarily enlarged olivine are slightly more iron rich than the cores, but, in general, no zoning can be detected.

BRONZITITE

Progressive increase of interference boundaries with decreasing interstitial material content occurs with bronzite exactly as it does with olivine (figures 60–62).

Zoning of peripheral parts of secondarily enlarged bronzite is, as with olivine, rare, but it is somewhat more easily recognized because of bronzite's lower birefringence. In rocks where such zoning is observed (fig. 82), the central core of the bronzite commonly has a euhedral shape. Exsolution lamellae generally extend continuously from the cores into the peripheries of the grains, indicating that enlargement occurred prior to exsolution.

CHROMITITE

In some chromitite layers chromite behaves like olivine and bronzite in that mutually interfering grains are distributed evenly throughout the layer. In others, however, the distribution of mutually interfering chromite grains is heterogeneous and the layers are composed of two textural types: (1) aggregations of nearly pure, massive chromite grains with polygonal shapes; and (2) normal euhedral or subhedral chromite crystals, which comprise about 70 percent by volume of the rock, and which are separated by interstitial silicates. Chromite crystals in the massive clots are about one-third larger than those in the more disseminated areas. Transitions between the massive and more disseminated chromitite areas are sharp, and the irregular attitudes of their contacts have no relation to the layering plane (figs. 63, 64). Wagner (1923, p. 228, 232) describes a similar texture in the chromitites of the Bushveld complex, which he calls "pseudo-porphyritic poikilitic", and concludes that the more disseminated clots fell to the floor as aggregates, whereas the chromite crystals of the more massive areas fell as individuals. Several aspects of this texture in the Stillwater complex do not seem to conform with Wagner's hypothesis: (1) Through-going layers of olivine crystals and thin chromitite layers parallel to the general structure cut across both massive and disseminated clots. (2) In many occurrences the more disseminated clots are very irregular in shape and long dimensions are not in the layering plane. (3) The dense packing and polygonal mutual boundaries of the chromite grains in the massive areas would seem to preclude an origin by simple accumulation of individuals. It seems most likely that the "pseudo-porphyritic poikilitic" texture of Stillwater chromitites is caused by irregularly distributed secondary enlargement subsequent to deposition. The chromitite layers probably originally consisted of closely packed chro-

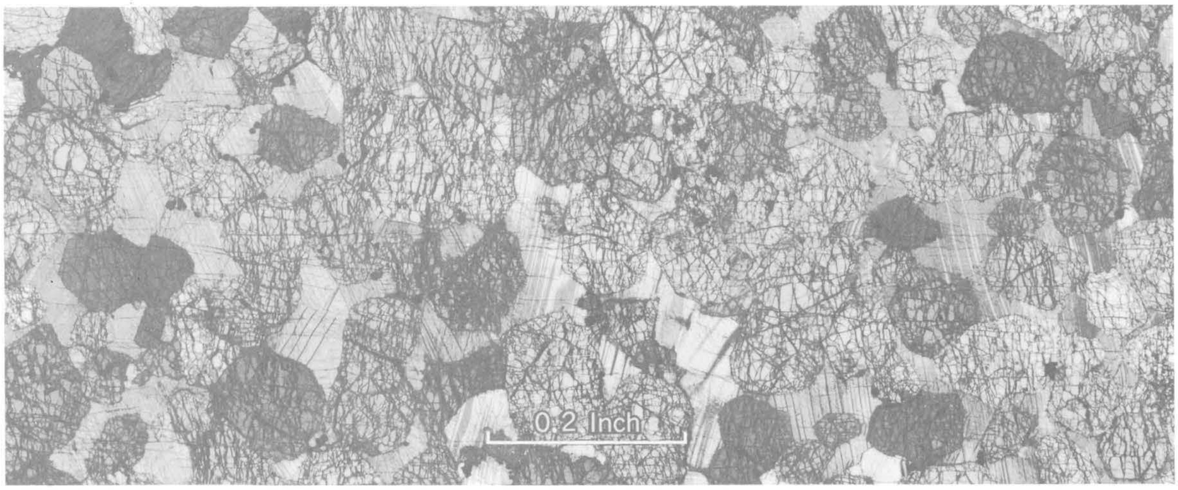


FIGURE 57.—Poikilitic harzburgite virtually unaffected by secondary enlargement. Euhedral olivine crystals are separated by interstitial plagioclase. Texture is automorphic poikilitic. Crossed nicols.

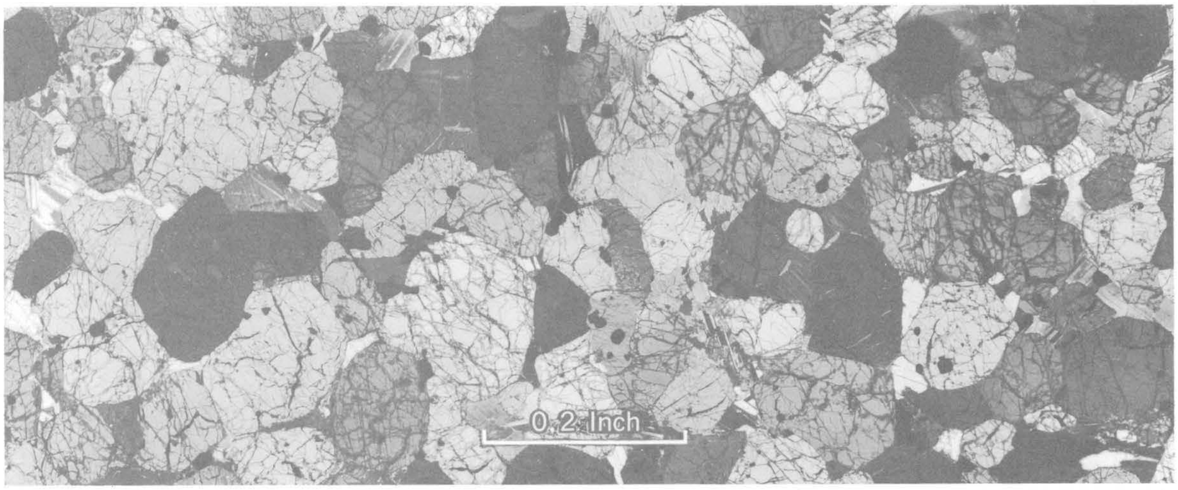


FIGURE 58.—Poikilitic harzburgite affected by intermediate secondary enlargement. Subhedral olivine crystals show some mutual interference, but are partially separated by interstitial plagioclase. Texture is hypautomorphic granular. Crossed nicols.

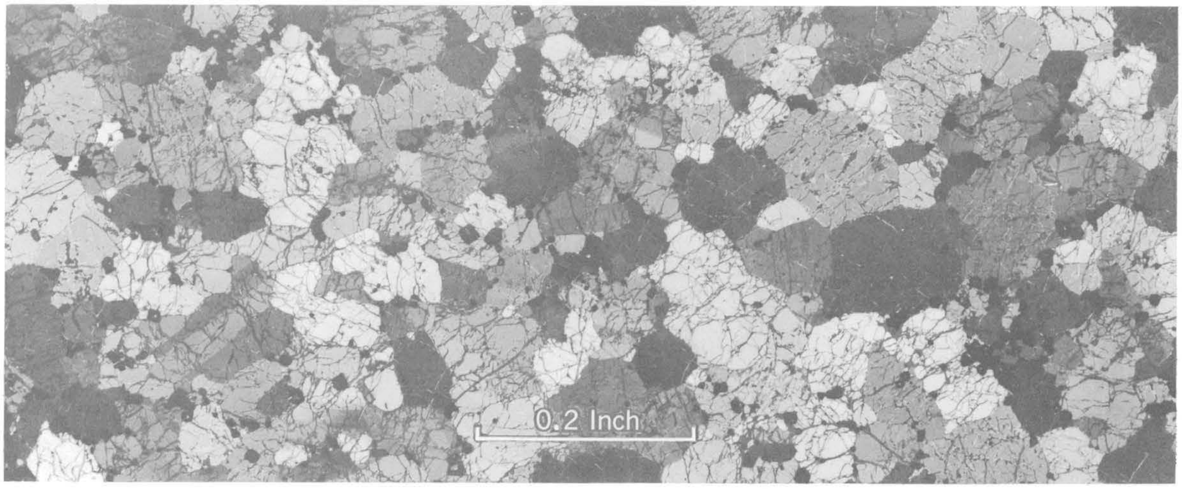


FIGURE 59.—Dunite showing complete secondary enlargement. Anhedral olivine grains show well-developed mutual interference. The rock contains no plagioclase. Texture is xenomorphic granular. Crossed nicols.

PHOTOMACROGRAPHS OF OLIVINE-RICH ROCKS SHOWING PROGRESSIVELY ADVANCED DEGREES OF SECONDARY ENLARGEMENT

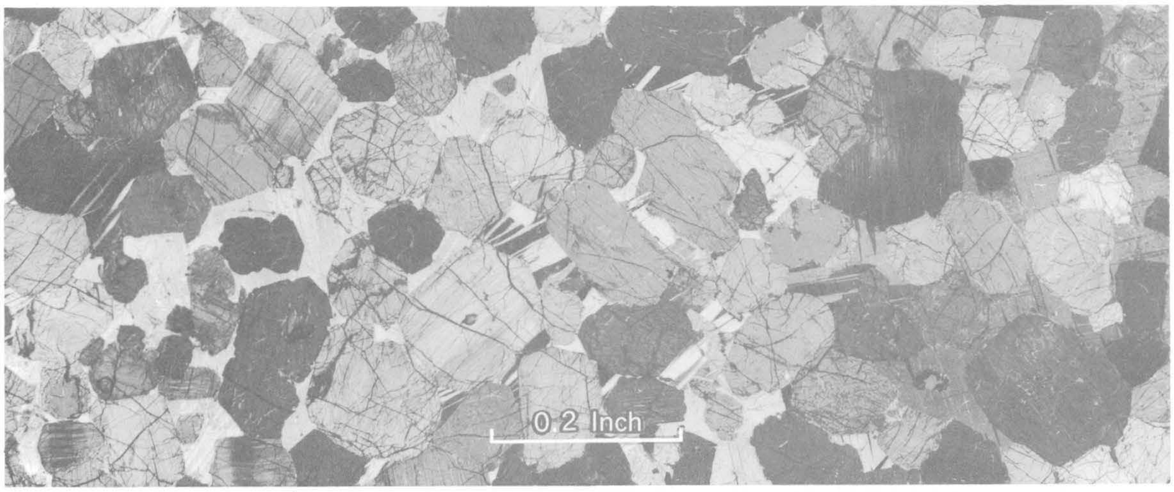


FIGURE 60.—Bronzitite virtually unaffected by secondary enlargement. Euhedral bronzite crystals are separated by interstitial plagioclase. Texture is automorphic poikilitic. Crossed nicols.

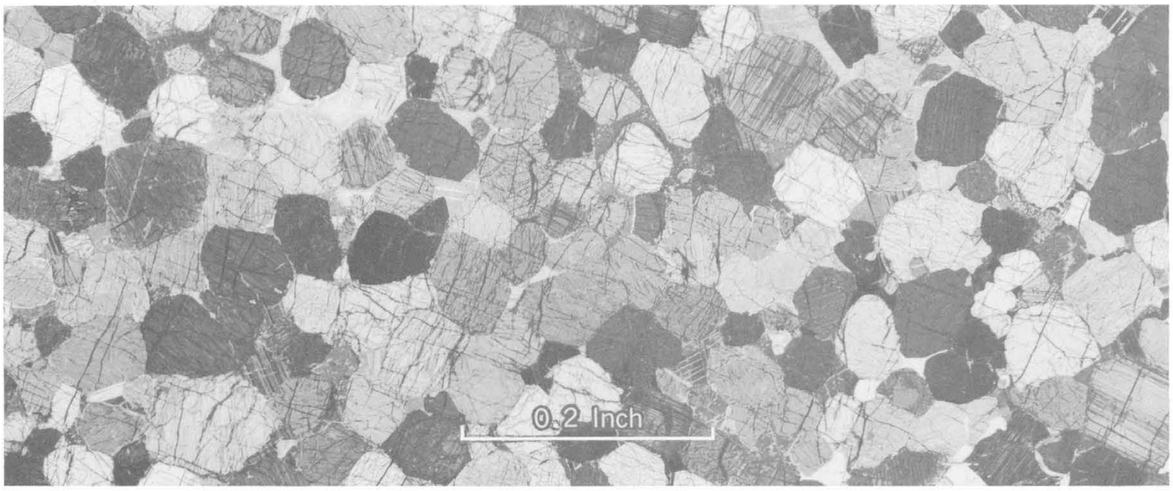


FIGURE 61.—Bronzitite affected by intermediate secondary enlargement. Subhedral bronzite crystals show some mutual interference but are partially separated by interstitial plagioclase. Texture is hypautomorphic granular. Crossed nicols.

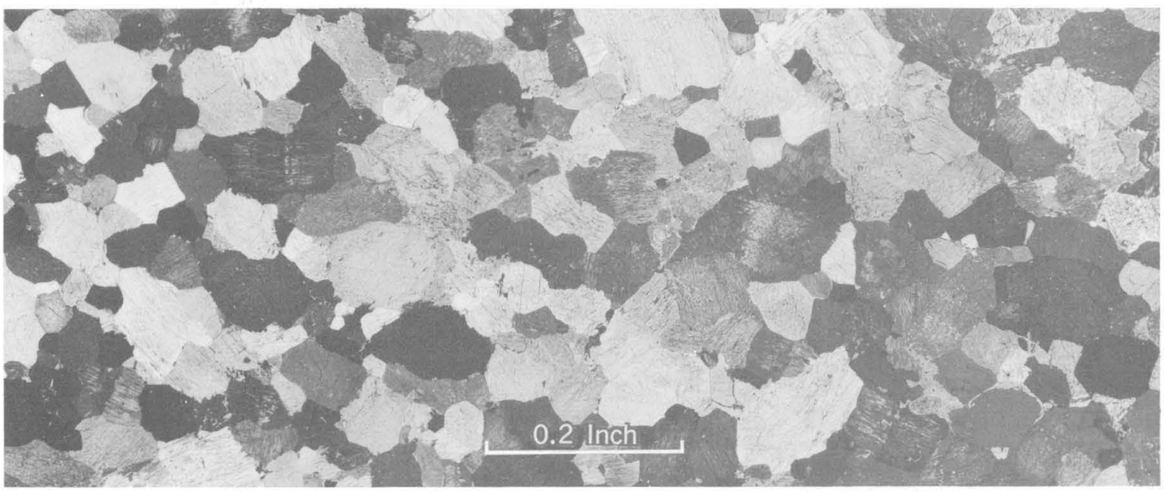


FIGURE 62.—Bronzitite showing complete secondary enlargement. Anhedral bronzite grains show well-developed mutual interefence. The rock contains no plagioclase. Texture is xenomorphic granular. Crossed nicols.

PHOTOMACROGRAPHS OF BRONZITITES SHOWING PROGRESSIVELY ADVANCED DEGREES OF SECONDARY ENLARGEMENT

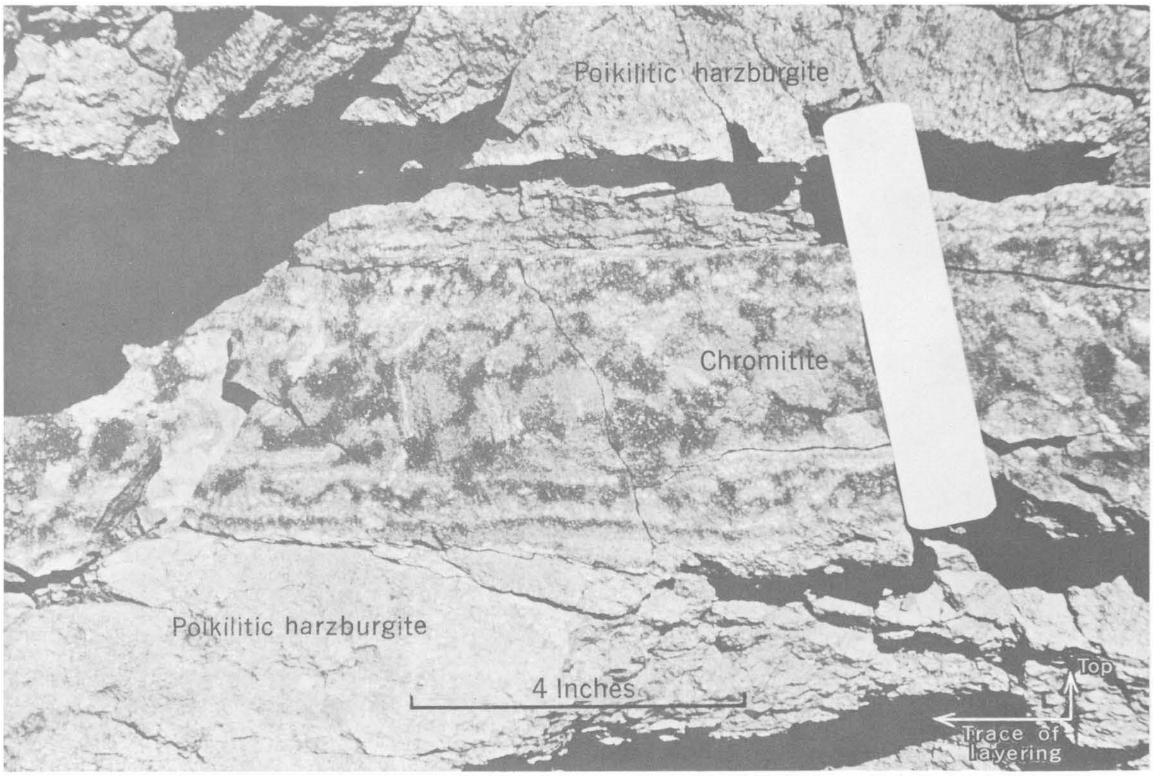


FIGURE 63.—Field photograph of massive and disseminated clots in chromitite layer.

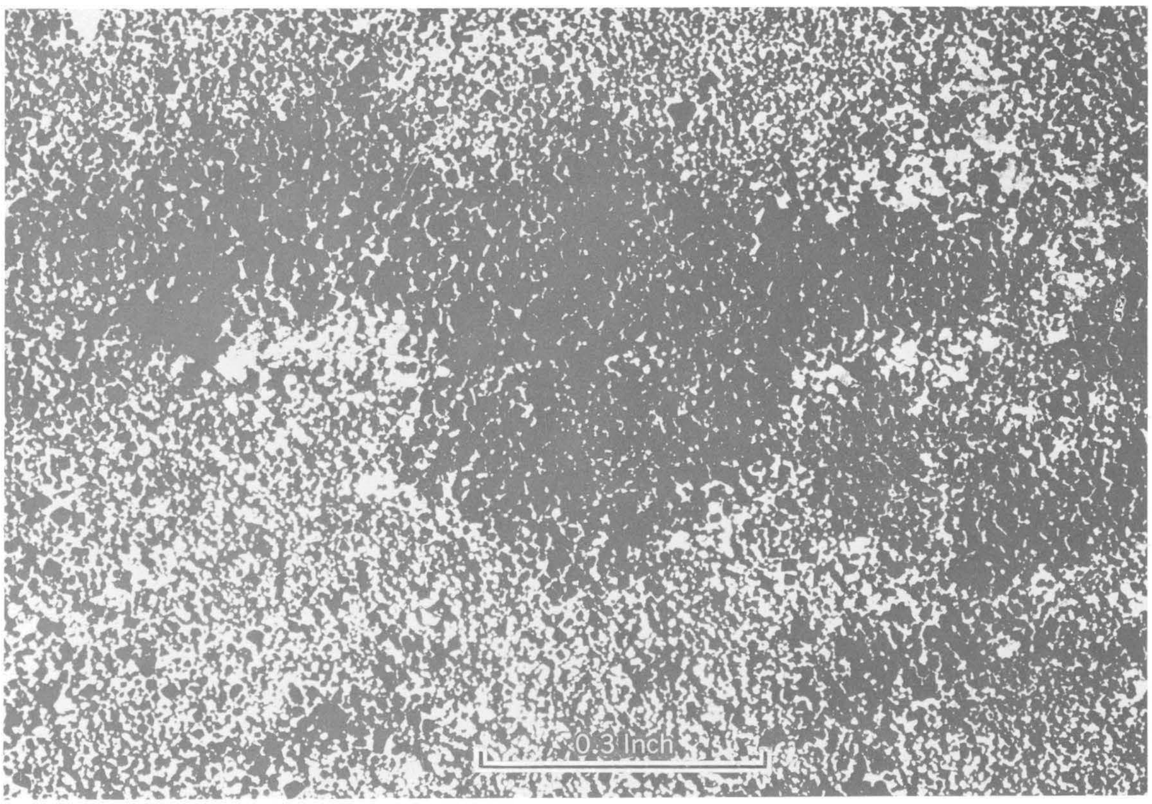


FIGURE 64.—Photomicrograph of massive and disseminated clots in chromitite. Light material interstitial to chromite grains in disseminated clots is pyroxene and plagioclase. Plane polarized light.

EXAMPLES OF HETEROGENEOUS SECONDARY ENLARGEMENT IN CHROMITITES mite euhedra containing about 40 percent interstitial magma. In part these chromite crystals were secondarily enlarged, and elsewhere the undisplaced interstitial magma crystallized to silicate minerals. Zoning at the outer margins of enlarged chromite individuals has not been observed.

OLIVINE CHROMITITE AND POIKILITIC CHROMITE HARZBURGITE

In many specimens of olivine chromitite and poikilitic chromite harzburgite, chromite crystals are commonly euhedral, whereas olivine commonly shows evidence of secondary enlargement. In many of the rocks the peripheral parts of olivine grains are crowded with inclusions of chromite identical in size with the chromite located between olivine grains (fig. 65). The clear inner core of such olivine is thought to represent the original settled crystal, and the periphery is believed to represent secondary enlargement of the olivine after deposition. Enlargement of the chromite in many of these rocks, however, apparently did not occur.

In other olivine chromitite and poikilitic chromite harzburgite specimens, particularly in those with high chromite-olivine ratios, these relations are reversed. Chromite grains commonly show interference boundaries with each other, and olivine crystals are nearly euhedral or are partially replaced by interprecipitate bronzite (fig. 53). In these rocks chromite was apparently precipitated from the interstitial liquid or at the mush surface, whereas olivine crystals were not enlarged.

In some olivine chromitite both olivine and chromite show evidence of having been enlarged subsequent to deposition. It is not clear from textural evidence whether enlargement of olivine and chromite occurred simultaneously or sequentially.

OLIVINE BRONZITITE AND GRANULAR HARZBURGITE

The character of enlargement in rocks containing mixtures of settled olivine and bronzite, like that in olivine-chromite rocks, seems dependent on the relative proportions of settled minerals in the layer. In olivine-rich granular harzburgites, olivine crystals commonly show considerable mutual interference. Bronzite crystals in these rocks are also enlarged, but the outer peripheries have replacement textures against the olivine (fig. 66). In olivine bronzitite, olivine crystals are generally euhedral, whereas the bronzite may show considerable mutual interference (fig. 36). In both types, olivine enlargement, where present, appears to have been completed before bronzite enlargement began.

VOLUMETRIC RELATIONS

The original pore space in the crystal mush that formed at the floor of the intrusion during the accumulation of the Ultramafic zone is now composed of material that was added to settled crystals after deposition, plus interstitial precipitates of other minerals. If the original pore-space volume in the crystal mush is known, a measure of the amount of secondary enlargement in any rock can be obtained by subtracting the volume of interstitial material from the initial porosity.

Variations in the initial porosity of the crystal mush are discussed in the following section, and estimates of the average initial porosities for the various rock types are listed in table 5. No single average value for initial porosity of olivine chromitites can be given because of their bimodal size characteristics and variable proportions of olivine and chromite.

Measurements of the amount of interstitial material in specimens of the various rock types, made by modal counts, are presented graphically in figure 69. The amount of interstitial material in harzburgite and bronzitite was determined on those parts of large etched slabs where plagioclase was in contact with the settled minerals; areas within pyroxene oikocrysts, where much of the material formed by reaction replacement, were avoided. Interstitial chromite in these rocks was tabulated as settled material, even though it occupies parts of the interstices between the larger settled olivine and bronzite crystals. Measurements in chromitite, where no reaction textures have been observed, were made on the entire area of 2- by 2-inch thin sections. The frequency histograms in figure 69 suggest a normal distribution of the amount of interstitial material, but the number of measurements is, in all cases, insufficient to establish this definitely. Arithmetic mean percentages of the average amounts of interstitial material are listed in table 5.

TABLE 5.—*Average amount of enlargement of settled crystals in the principal rock types, in volume percent*

Rock type	Estimated average initial porosity	Average amount of interstitial material	Average amount of secondary enlargement
Poikilitic harzburgite	35	15	20
Bronzitite	35	14	21
Chromitite	40	20	20
Granular harzburgite and olivine bronzitite	30	10	20
Olivine chromitite and poikilitic chromite harzburgite	25–40	14	11–26

The average amount of secondary enlargement for the rock types is calculated by subtraction in table 5. Differences in estimated initial porosity tend to bal-

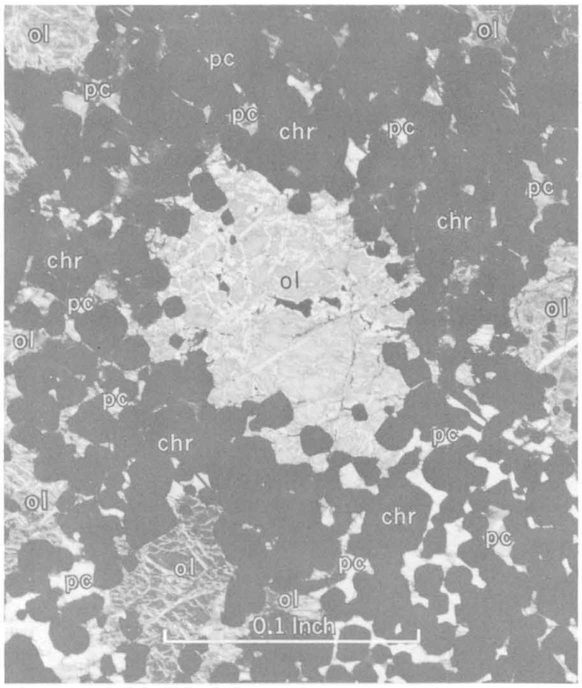


FIGURE 65.—Secondary enlargement of settled olivine in olivine chromitite. Olivine has grown outward after deposition to include neighboring settled chromite grains. Some enlargements of chromite have also occurred. ol=olivine; chr=chromite; pc=plagioclase. Crossed nicols.

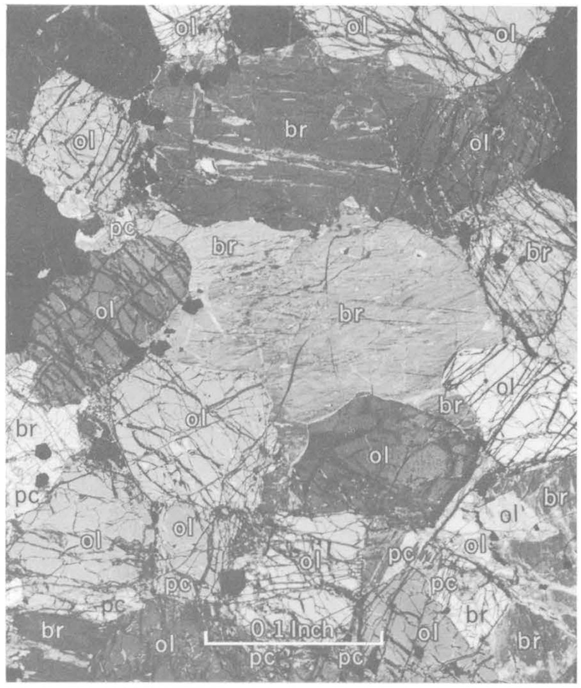


FIGURE 66.—Secondary enlargement of settled bronzite in olivine-rich granular harzburgite. Bronzite has grown out to fill interstices and partially to replace olivine. ol=olivine; br=bronzite; pc=plagioclase. Crossed nicols.

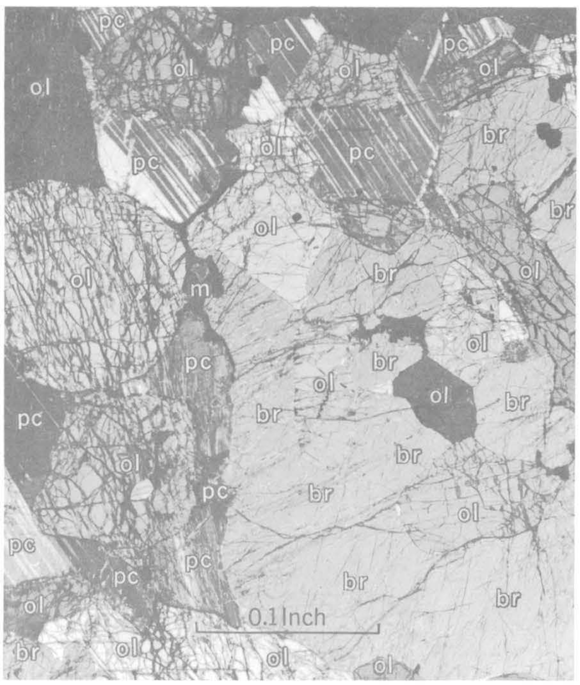


FIGURE 67.—Details of contact between interstitial plagioclase and interstitial bronzite in poikilitic harzburgite. Where the two minerals are in contact, small-scale mutual embayment occurs. m=biotite; other symbols as in figure 66. Crossed nicols.

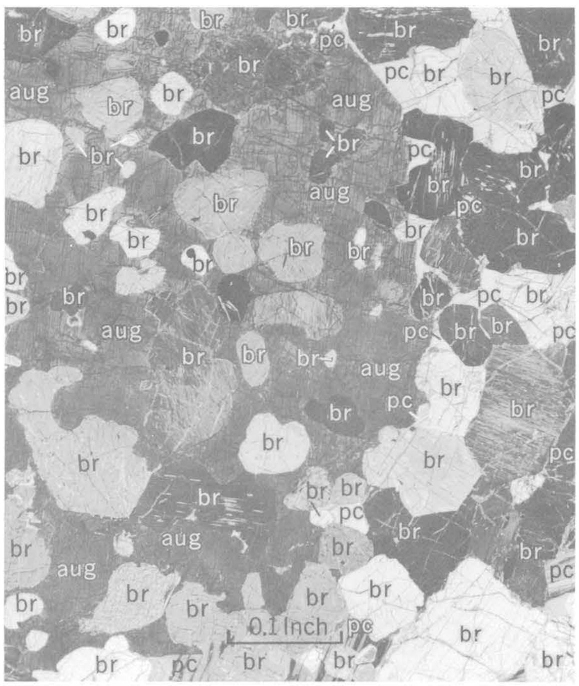


FIGURE 68.—Details of contact between interstitial plagioclase and interstitial augite in bronzitite. Locally the augite has developed segments of prism and dome faces against plagioclase, but along most of the contact there is mutual embayment. aug.=augite; other symbols as in figure 66. Crossed nicols.

PHOTOMICROGRAPHS SHOWING DETAILS OF SECONDARY ENLARGEMENT AND RELATIONS BETWEEN INTERPRECIPITATE MINERALS IN THE ULTRAMAFIC ZONE

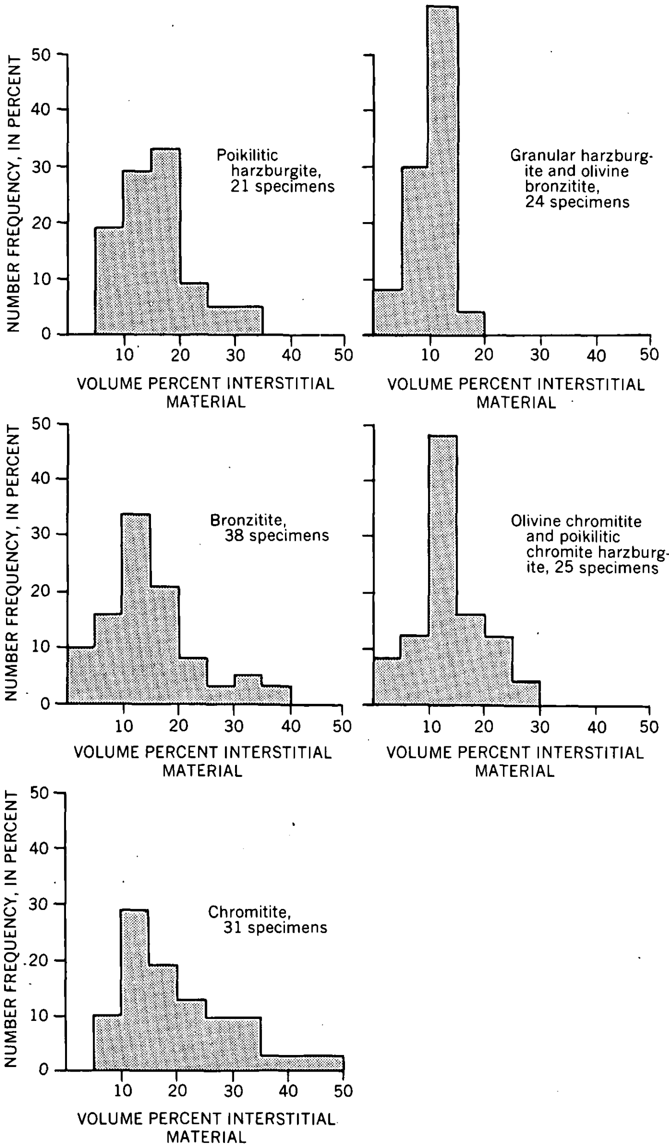


FIGURE 69.—Frequency distribution of volume of interstitial material, by rock type.

ance the differences in average amounts of interstitial constituents. Within the limits of measurements and assumptions, therefore, there seems to be no significant difference in the amount of secondary enlargement between the five principal rock types of the Ultramafic zone.

STRATIGRAPHIC AND AREAL DISTRIBUTION

Determinations of the amount of secondary enlargement material within the cyclic units of the Peridotite member show no smooth pattern of variation. Of the three cyclic units shown in table 6, units 9 and 15 show reasonably consistent values considering the limits of accuracy of the method used to determine the amount of secondary enlargement, and cyclic unit 2 shows an irregular variation. Furthermore, no simple upward

TABLE 6.—*Intracycle stratigraphic distribution of amount of secondary enlargement in the Mountain View section of the Peridotite member, in volume percent*

Cyclic unit No.		Specimen No.	Interstitial material	Secondary enlargement material[1]
15	Bronzitite	55MV-77	9	26
	Granular harzburgite	55MV-76	10	20
		-75	12	18
		-74	10	20
	Poikilitic harzburgite	55MV-73	13	22
		-72	15	20
		-69	12	23
9	Bronzitite	55MV-33	9	26
		-32	12	23
		-31	13	22
	Granular harzburgite	55MV-30	8	22
		-29	8	22
		-28	8	22
	Poikilitic harzburgite	55MV-27	17	18
		-26	9	26
		-25	9	26
2	Bronzitite:			
	fine-grained	55MV-12	21	14
		-10	24	11
	coarse-grained	52MV-11	17	18
		55MV-9	19	16
	Granular harzburgite	55MV-8	15	15
		-7	19	11
		52MV-9	14	16
	Poikilitic harzburgite	52MV-8	29	6
		55MV-3	12	23
		-2	14	21
		-1	20	15

[1] Assuming an initial porosity of 35 percent in bronzitite and poikilitic harzburgite, and 30 percent in granular harzburgite.

variation between cycles could be detected in either the West Fork or Mountain View sections. If simple intercycle variation does exist, an excessively large number of measurements would be required to define it because of the large deviation in amount of interstitial material within single layers.

Although a pattern of stratigraphic variation in the amount of secondary enlargement cannot be established, gross changes in the amount of interstitial material along the strike were observed in the field and have been confirmed to some extent by measurements. In the field, it was observed that in areas where the Peridotite member is stratigraphically thick, the rocks contained more interstitial material than rocks in thinner sections. Within the Bronzitite member of the Ultramafic zone, which is considerably more consistent in thickness than the Peridotite member, no significant changes in interstitial material content along the strike were detected in the field. Measurements were made of the amount of interstitial material in a number of specimens from correlative subunits in the Mountain View and West Fork sections, and the amount of secondary enlargement was calculated. These values are listed in table 7. In the lower part of the Peridotite member, the West Fork section is about one-third as thick as the Mountain View section and contains 1.5 times as much secondary-enlargement material; above the main chromitite layer, the West Fork section is about one-half as thick and contains about 1.1 times as much

TABLE 7.—*Average amount of interstitial and secondary enlargement material in correlative subunits of the Ultramafic zone*

Subunit	West Fork section				Mountain View section			
	Stratigraphic thickness (feet)	Interstitial material (volume percent)	Secondary enlargement material (volume percent)	Number of specimens averaged	Stratigraphic thickness (feet)	Interstitial material (volume percent)	Secondary enlargement material (volume percent)	Number of specimens averaged
Bronzitite member	2, 120	12	23	6	3, 060	13	22	6
Peridotite member:								
Main chromitite to top of Peridotite member	500	12	21	12	1, 035	14	19	19
Base of Peridotite member to main chromitite	1, 000	9	24	15	2, 975	16	17	28

enlargement material; in the Bronzitite member, the West Fork section is about two-thirds as thick as the Mountain View section and contains only very slightly more enlargement material. These relations are illustrated graphically in figure 70.

The average amount of enlargement material in the bronzitite of the Basal zone, which is sporadically developed between the chilled gabbro and the base of the Peridotite member, is considerably less than the average anywhere within the Ultramafic zone. The average of four determinations from the Benbow area, where the basal bronzitite reaches its maximum development, is 7 percent enlargement material, and the range is 20 percent to none. Lateral variation within the basal bronzitite was not investigated.

Secondary enlargement of settled crystals in the Ultramafic zone may be summarized as follows: (1) No significant difference in amount of enlargement between rock types can be established. (2) The amount of enlargement may change abruptly and on a small scale with stratigraphic position. (3) No systematic trends in this change within layers, within cyclic units, or between cyclic units could be established. (4) The average amount of secondary enlargement seems to be related to relative thickness of stratigraphic section, so that in two correlative sections believed to have been formed in the same interval of time, the thinner stratigraphic section shows more enlargement than the thicker. (5) There is considerably less enlargement in the bronzitite of the Basal zone than in any investigated part of the Ultramafic zone.

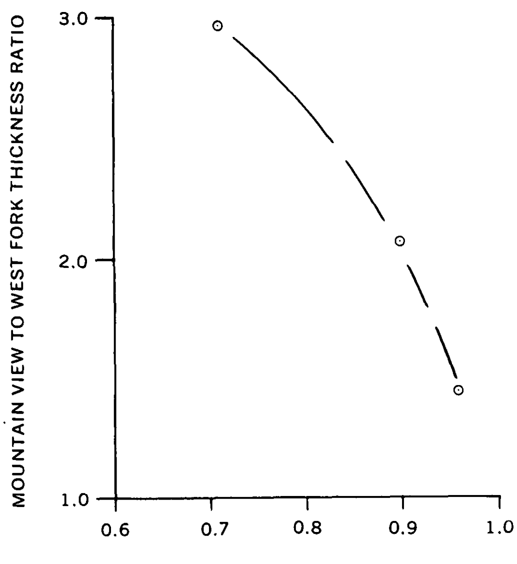


FIGURE 70.—Relations between thickness of correlative subunits and amount of secondary enlargement.

DISCUSSION

Wager and Deer (1939, p. 127–128) postulate that primary precipitate minerals in the Skaergaard intrusion had been enlarged subsequent to their deposition. They state:

> That part of the interprecipitate material which crystallized as the same minerals as the primary crystals, is found as outer zones of increasingly lower temperature solid solutions, and such outer zones often occupy interstices. Neglecting the outer fringe, the primary precipitate may be found to have an idiomorphic relation to a certain mineral, but taking into consideration the outer fringe, the crystals would be put down as allotriomorphic to the same mineral.

Enlargement of settled minerals caused only by continued precipitation of the same minerals from the trapped interstitial magma should be limited in amount and characterized by strong peripheral zoning. Such a mechanism cannot account for completely monomineralic dunites, bronzitites, and chromitites in the Ultramafic zone of the Stillwater complex without calling upon olivine, bronzite, and chromite magmas, for which there is no other evidence of existence. To account for these relations, Hess (1939, p. 430–431) has proposed a more complicated mechanism involving diffusion. On the basis of slump structures in the gabbroic rocks, Hess considers the unconsolidated mush on the floor of the complex to have been about 10 feet thick throughout the period of accumulation. Diffusion between the main body of magma and the magma trapped within this crystal mush allowed crystallization of solid phases in the interstices which were identical in composition with the settled crystals. Hess has concluded that the amount of diffusion was controlled by the rate of accumulation of crystals: where the rate of accumulation was slow, diffusion was operative; where rapid, the original magma was effectively trapped.

The relative efficacy of diffusion in causing secondary enlargement in the Ultramafic zone seems open to some question. The quantity of a material that diffuses in the steady state is proportional to its concentration at the front (Garrels, Dreyer, and Howland, 1949, p. 1826–1827); assuming that diffusion is capable of supplying olivine or bronzite to dunite or bronzitite layers in the mush, the supply of chromite to associated chromitites should be much less. The average amount of secondary enlargement in chromitite, however, does not seem to be significantly less than in silicate layers. In some sequences, 1- to 2-inch chromitite layers contain less interstitial material than the olivine-rich rocks immediately above and below, and the mechanism for accomplishment of this selective overgrowth after burial is difficult to visualize. Furthermore, detailed mapping of the Ultramafic zone has resulted in discovery of small-scale slump structures involving units as thin as six inches. It would therefore seem possible that some secondary enlargement, at least, took place at or near the surface of the mush, in contact with the magma from which the crystals were precipitating.

Regardless of whether optically continuous overgrowth occurred at the surface of the mush or at depths of several feet, Hess' concept of a direct relation between amount of overgrowth and rate of crystal accumulation seems equally valid. Field estimates throughout the Ultramafic zone as well as laboratory measurements indicate that in areas where the stratigraphic section is relatively thin, the rocks contain less interstitial material than rocks in areas where the stratigraphic section is relatively thick. Because these "shelf" and "basin" sections are believed to have accumulated in the same interval of time, the amount of overgrowth would seem to be related to rate of accumulation.

Assuming that the measurements are representative and that a qualitative relation between secondary enlargement and accumulation rate is established, the following observations can be made: (1) Accumulation of bronzite to form the bronzitite of the upper part of the Basal zone was sufficiently more rapid than crystal accumulation with the Ultramafic zone, proper, to appreciably inhibit secondary crystal enlargement. (2) In some parts of the Ultramafic zone the rate of crystal accumulation changed erratically on a small scale. (3) The average rate of crystal accumulation in the Mountain View section was greatest near its base and gradually decreased throughout the section, whereas the average rate in the West Fork section was initially very slow but increased near the main chromitite and maintained a steady rate at least through the Bronzitite member (table 7).

INITIAL POROSITY

The original porosity of settled crystals in the accumulating mush can be estimated in some rocks by means of modal counts of individual crystals and interstitial material, but distinction between what were originally settled crystals and interprecipitate material is commonly difficult because of secondary enlargement and reaction replacement of the settled material. The apparent porosity is, of course, decreased where settled material has been enlarged, and increased where the settled material has been resorbed. Modal counts of areas where relations are most clearly definable indicate that original porosities in the crystal mush ranged between about 20 and 50 percent by volume, and that the average for the zone was probably about 35 percent. Packing relations are similar to those in comparable sedimentary rocks: the finer grained chromitites apparently had slightly higher initial porosities than the coarser harzburgites and bronzitites, and bimodal associations of chromite and olivine in general had lower initial porosities than assemblages containing minerals of uniform size.

Estimates of maximum, minimum, and average porosities are considered below. For a given rock type, the maximum original porosity is based on the maximum observed amount of interstitial material in any rock of that type; the minimum estimate is based on the amount of interstitial material in rocks showing very slight mutual interference effects between settled crystals; and the estimated average porosity is a guess limited by these two extremes.

BRONZITITE

In bronzitite composed of anchiequidimensional bronzite, the greatest measured amount of interstitial material was 41 percent; the amount of interstitial material in bronzite showing the beginnings of mutual interference boundaries between bronzite crystals is about 30 percent. The range of original porosity was probably, therefore, about 10 percent. Differences in original porosity in bronzitite of this type are more probably a result of differences in packing than of differences in grain size or sorting, because the observed ranges in the latter properties are relatively small. The average porosity of bronzitite with nearly equidimensional grains is estimated to have been 35 percent.

The much less abundant bronzitite composed of tabular or broad prismatic bronzite is observed to have considerably less interstitial material than bronzitite with nearly equidimensional grains. This is presumably an effect of grain shape on original porosity similar to the decrease in porosity of sands with disk-shaped particles observed by Fraser (1935, p. 937). No numerical estimate of the average original porosity of bronzitite with flattened bronzite crystals can be given because the ratio of intercepts of these minerals varies widely among individual specimens, and, presumably, so would the initial porosity. The largest amount of interstitial material measured in bronzitite of this type was 15 percent, but the specimen showed some mutual interference between the bronzite grains. The initial porosity of this bronzitite is estimated to have been about 20 percent.

POIKILITIC HARZBURGITE

The maximum amount of interstitial material measured in poikilitic harzburgite was 30 percent, and this specimen shows slight effects of mutual interference between the olivine crystals. Presumably, both the maximum porosity and the average porosity were greater than 30 percent. The grain shape, sorting, and size range of olivine in poikilitic harzburgite do not differ appreciably from those of anchiequidimensional bronzite in bronzitite. Furthermore, the average amount of interstitial material for all measured poikilitic harzburgite is slightly greater than the average for bronzitite, a difference that may be related to the inclusion of several specimens of bronzitite with broad prismatic crystals into the average. It seems reasonable, therefore, that the porosity of crystal mush composed of olivine crystals and liquid was very nearly equal to the porosity of anchiequidimensional bronzite crystals and liquid, and the original porosity of the poikilitic harzburgite is assumed to have been about 35 percent. Neither grain size, sorting, nor shape variations within the poikilitic harzburgite seem large enough to have caused much variation in original porosity. However, the presence of accessory chromite in poikilitic harzburgite lowered the original porosity slightly, because of its location between olivine grains.

CHROMITITE

The maximum amount of interstitial material in any massive chromitite investigated was 50 percent; beginnings of mutual interference boundaries are observed in chromitite with about 30 percent interstitial material. The amount of interstitial material in three of the specimens measured exceeded the 41 percent recorded for the maximum amount in the bronzitite. The range of porosity in chromitite, therefore, exceeded that of bronzitite, and the average porosity was probably higher. An average porosity of 40 percent would seem to be a reasonable estimate. That fine-grained aggregations of chromite crystals should have a higher porosity than aggregations of olivine or bronzite crystals 10 times as large is in accord with the observations of Ellis and Lee (1919, p. 121), Trask, (1931, p. 273), and others, that, contrary to the theoretical behavior of spheres, the porosity of sands decreases as grain size increases. Variations in grain size, shape, and sorting within the chromitite, as in the poikilitic harzburgite, is probably too small to effect porosity changes of any great magnitude between layers. If an original porosity range of 15 to 20 percent did exist, as indicated, the major part of the variation is most likely caused by differences in packing and bridging.

GRANULAR HARZBURGITE

The maximum observed amount of interstitial material in a granular harzburgite is 19 percent, in a specimen that shows considerable mutual interference. The average amount of interstitial material in all specimens of granular harzburgite measured is 3 percent lower than the average for bronzitite (fig. 69). In granular harzburgite composed of bronzite and olivine crystals of equal size, the original porosity should have been in the same range as the original porosity in bronzitite and poikilitic harzburgite. In most granular harzburgite, however, the settled olivine and bronzite crystals have different sizes (fig. 19), and, although these minerals considered individually have good sorting, the degree of sorting of the rock as a whole is reduced by the inclusion of two sizes of material (fig. 28). The effect of this poorer sorting should be lowered original porosity (Fraser, 1935, p. 922–930); the amount of lowering is dependent on the relative proportions and the relative sizes of settled olivine and bronzite in the rock. The decrease in average original porosity caused by these bimodal size distributions was probably relatively small, because at the observed size ratios between olivine and bronzite most of the smaller grains are incapable of filling voids between the larger ones. The average porosity of granular harzburgite, therefore, should have been somewhat less than that of bronzitite and poikilitic harzburgite, possibly about 30 percent.

OLIVINE CHROMITITE AND POIKILITIC CHROMITE HARZBURGITE

The maximum observed amount of interstitial material in a rock composed of a mixture of settled olivine and chromite is 26 percent. This specimen, which has an olivine chromite ratio of 69:31, shows no mutual interference, and the observed amount of interstitial material is believed to agree closely with the initial porosity. The average amount of interstitial material in the 20 specimens measured was 14 percent, about the same as that for bronzitite.

It seems reasonable that mushes composed of mixtures of olivine and chromite had considerably lower porosities than mushes composed of either mineral alone. The sorting of olivine chromitite is strictly bimodal (fig. 29) and the average size ratios of chromite to olivine range from 0.07 to 0.38, with an average of 0.19 (table 3). In all these rocks, the chromite is small enough to exist in voids between the olivine crystals; the size ratios are less than what Fraser (1935, p. 919) calls the "critical ratio of occupation." In most of the 16 olivine chromitite specimens for which size measurements have been made, the chromite-olivine diameter ratio is also within what Fraser (1935, p. 919) calls the "critical diameter of entrance" and finds to be 0.414 for loosest packing, and 0.154 for tightest packing (in the case of spheres). Assuming that octahedral chromite grains and nearly equidimensional olivine did behave essentially as spheres, the observed diameter ratios indicate that chromite grains in most olivine chromitite are small enough to have passed between tightly packed olivine crystals and are therefore capable, at least, of having been sifted down in the mush. At any rate, the original porosity of olivine chromite was much reduced by small chromite grains filling spaces between olivine grains at the expense of interstitial magma. The extent of this reduction would be greatest where olivine constitutes about 65 percent of the rock, and the porosity of the mush with these proportions would seem to have been about 25 percent. With decrease in chromite content, the porosity would approach that of poikilitic harzburgite. With increase of chromite the porosity would approach that of chromitite. The range of porosity was probably between 25 and 40 percent.

DISCUSSION

The original porosity variation of the mush, which is from 20 to 50 percent in the Ultramafic zone, is most probably caused by two independent factors: (1) the physical properties of the crystal aggregate making up the mush, and (2) the amount of compaction of the mush prior to cementation. Crystal shape differences are apparently responsible for the porosity difference between equidimensional and tabular collections of bronzite; average size differences for porosity differences between silicate layers and massive chromitite layers; and differences in sorting for porosity differences between olivine-chromite mixtures and monomineralic accumulations. Indicated porosity differences of 10 to 20 percent within bronzitite and chromitite with nearly equal size and shape, however, cannot be accounted for by changes in physical properties of the grains, and these differences would seem to be caused by variations in amount of compaction prior to cementation.

Bronzitite and poikilitic harzburgite make up about 88 percent of the Ultramafic zone, and the remaining 12 percent is composed largely of granular harzburgite. The estimated average porosity of the Ultramafic zone as a whole, therefore, is only slightly less than 35 percent. In consideration of the high viscosity and density of the magma, and the generally uniform sizes and nearly equidimensional shapes of the settled crystals, even an average porosity of 35 percent seems somewhat low compared with measured porosities of experimentally settled and freshly deposited sands, which, in the 0.2 to 1.0 mm size grades, generally range between 40 and 46 percent (Ellis and Lee, 1919, p. 121; Trask, 1931, p. 273; Hamilton and Menard, 1956, p. 756). Fraser (1935, p. 936), however, has shown that the porosity of quietly settled wet natural sands can be reduced by 5.5 to 8 percent by continued jarring.

The porosity of the complex as a whole is probably considerably less than 35 percent because of the prevalence of broad prismatic and tabular minerals in the thick section of norites, gabbros, and anorthosites stratigraphically above the Ultramafic zone. In contrast, the Ultramafic zone is characterized by a preponderance of nearly equidimensional settled crystals.

Within the limits imposed by a small number of significant measurements, the settled crystals in the Ultramafic zone obey the general physical laws of particle packing with regard to grain size, sorting, and shape. Numerical estimates of the original porosity agree very well with porosity measurements of well-packed sedimentary rocks in the same size range. The generally good packing of the settled crystals, like the packing in sandstones, was probably effected near the surface of deposition, perhaps by periodic jarring of the floor by minor tectonic disturbances during deposition. Failure of the mush to pack is recorded in a few layers by abnormally large amounts of interstitial material in the rocks.

INTERPRECIPITATE MATERIAL

The interprecipitate material is defined as including all minerals that crystallized in place in the rocks. Under this definition, it may be divided into three types: (1) the material added on to settled crystals by secondary enlargement after deposition; (2) the material which simply fills space between the original or secondarily enlarged settled crystals; and (3) the material which has partly replaced settled crystals by postdepositional reaction replacement. The first two types of material, taken together, occupy what originally was pore space in the crystal mush. The third type, however, now occupies space which originally was taken up by precipitated crystals, and, although it is not descriptively "interprecipitate", it is so classified because it formed in place.

The relative proportions of these three types of material differ from layer to layer. Development of secondary enlargement and interstitial space-filling minerals are reciprocal: At one extreme are the completely monomineralic rocks whose entire original pore space has been filled by secondary enlargement of the settled crystals; at the other are certain layers of bronzitite and chromitite that contain 40 to 50 percent of interstitial space-filling material. Development of reaction replacement in rocks containing olivine or bronzite is greatest in rocks with minimal secondary enlargement.

The exact distinction between the precipitate and interprecipitate constituents of every rock cannot be made by simple inspection because of the absence, in most rocks, of internal boundaries in secondarily enlarged crystals and in replacing minerals. The distinction between individual grains and interstitial material, however, is evident by change of minearology, and the following descriptive material will deal in large part with interstitial grains.

SHAPE OF THE INTERSTITIAL MATERIAL

The interstices between settled crystals are continuously interconnecting. Some interstitial material is confined to the space defined by 3 or 4 adjacent settled crystals, which may be termed a unit interstice, and differs from the material in the adjoining interstice either in composition or optical orientation. In other instances, the interstitial material is in common optical orientation over many hundreds of these interstices, and the texture is said to be poikilitic. A distinction must be made, therefore, between the shapes of the unit interstices, which may or may not define the boundaries of an optically continuous interstitial mineral, and the exterior shape of poikilitic crystals, where these occur.

SHAPE OF THE INTERSTICES

The interstices are invariably concave polygons, entirely bounded by the crystal faces of the settled minerals. In cross section the interstices are cuspoid, terminating in 4 to 8 sharp points, or continuing along narrow throats between settled crystals. Crystals that have continued to grow after deposition develop interference boundaries against their neighbors but retain their crystal faces where growing into pore spaces, so that in rocks with moderate amounts of overgrowth material the interstices are the same in shape but decreased in volume. This effect is illustrated in figure 71*A*, a tracing of olivine-plagioclase relations in a poikilitic harzburgite. Modal counts indicate that the olivine crystals of this rock have been enlarged about 15 percent after deposition, and, although olivine crystals are in contact in many areas, the shapes of the interstices occupied by plagioclase retain their sharp boundaries. Where the interstitial material has not only filled spaces between settled crystals, but partially replaced them, the material is increased in volume and the interstices lose their characteristic shapes. In rocks where such replacement has been extensive,

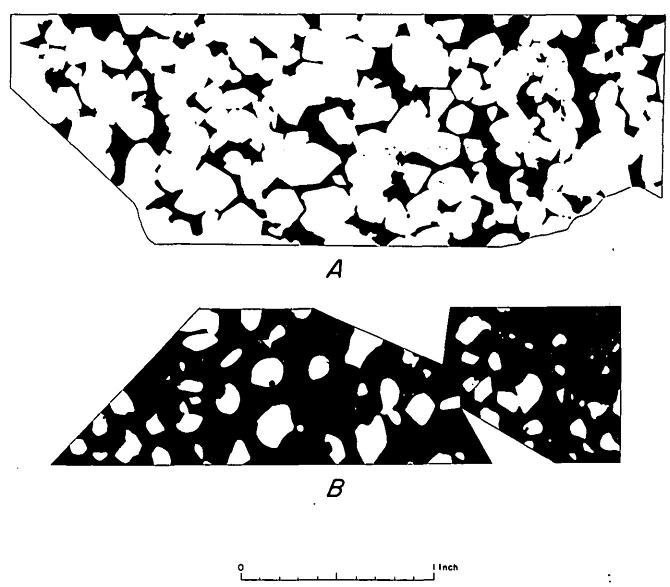


FIGURE 71.—Sectional shapes of interstitial minerals in poikilitic harzburgite. *A*, Interstitial plagioclase (black) surrounding olivine crystals (white) between bronzite oikocrysts; *B*, Interstitial bronzite (black) surrounding olivine crystals (white) within bronzite oikocrysts. Traced from etched slab.

the interstitial material becomes the dominant element in the texture and is, in aggregate, sponge shaped. The sectional relations for settled olivine partly replaced by interstitial bronzite is shown in figure 71*B*.

Local restriction of any of the interstitial minerals to one interstice has been observed, but the tendency to form connecting, poikilitic crystals is pronounced and varies with mineralogy and mineral abundance. Quartz has been observed to surround 3 or 4 bronzite grains, but generally occurs in widely separated single grains. Plagioclase crystals generally occupy one to five connecting interstices but uncommonly develop into large poikilitic crystals. Bronzite, chrome augite, and olivine all have strong tendencies toward development of large oikocrysts and are rarely seen in single grains confined to individual interstices. Biotite, where relatively abundant, also prefers the poikilitic habit but commonly is restricted to single interstices because of its scarceness.

SHAPE OF THE POIKILITIC CRYSTALS

Bronzite oikocrysts in poikilitic harzburgite are perhaps the most striking textural feature of the Ultramafic zone. Less obviously, they are also well developed in chromitite. In both rock types, the poikilitic bronzite grains are, with rare exceptions, grossly spherical (fig. 4). In detail, the spherical boundaries are irregular; olivine crystals project across the contacts, and where the bronzite is in contact with interstitial plagioclase the boundary is generally irregular with small-scale mutual embayments (fig. 67). In some highly feldspathic poikilitic harzburgite, however, the bronzite develops smooth crystal boundaries along short segments of its contact with plagioclase. Several examples of elliptical rather than spherical development of bronzite oikocrysts occur where thin poikilitic chromite harzburgite layers exist between two chromitite layers. Some of the bronzite oikocrysts have apparently been restricted in vertical development.

Chromian augite oikocrysts tend to have prismatic rather than spherical shapes, so that cross sections are imperfect rectangles or squares. In detail the outer margins of augite oikocrysts, like those of bronzite, are irregular, with settled crystals extending across the contacts. In many rocks the boundaries of the poikilitic crystals against surrounding plagioclase are completely irregular, but euhedral crystal terminations of augite against plagioclase are developed to a greater extent than in the case of bronzite. In rocks containing minimal amounts of secondarily enlarged material, particularly in bronzitite, augite oikocrysts terminate against plagioclase with what appear to be sharp prism and dome faces (fig. 68). When examined in detail, however, the augite-plagioclase contacts are, for the most part, mutually embayed and curved and only short segments of the augite oikocrysts are actually euhedral. The augite oikocrysts, therefore, have a strong tendency to maintain a prismatic form but at their outer margins develop interference boundaries with plagioclase. In feldspathic bronzitite, where replacement of bronzite by augite has been extreme, these prismatic forms give the rocks the appearance of porphyritic texture. Where augite is in contact with interstitial bronzite, the boundaries of the bronzite are commonly embayed.

Interstitial olivine occurs only in certain chromitite specimens; in these, it is commonly poikilitic. In the restricted number of specimens where they have been observed, olivine oikocrysts have prismatic, nearly equidimensional shapes. Boundaries with continuous olivine are irregular and interfering, and contacts with pyroxene are irregularly embayed. Contacts between interstitial olivine and plagioclase are not common in chromitite because of the tendency for all minerals to fill completely the smaller interstices, because much chromitite with relatively abundant interstitial olivine contains no plagioclase, and because olivine is commonly rimmed by pyroxene. In the few places where relations are observable, interstitial olivine is completely euhedral against plagioclase.

Biotite occurs in very minor amounts in all the rock types, but poikilitic crystals have been observed only in a few poikilitic harzburgites and chromitites. Oikocrysts tend to be strongly tabular parallel to the micaceous cleavage and are generally less than 0.1 mm thick. In sections parallel to the cleavage the biotite is roughly circular in shape but irregular in detail, and apparently it surrounds several settled crystals. Perpendicular to the cleavage, however, settled crystals extend through both sides of the oikocryst. Pinacoid faces, or segments of them, are developed against all the other interstitial materials, but prismatic or pyramidal terminations have not been observed.

Poikilitic plagioclase, where it is seen, is roughly spherical in bronzitite and granular harzburgite. In poikilitic harzburgite and chromitite, however, the plagioclase oikocrysts are irregular in shape and tend to conform to hour-glass-shaped or large cuspate areas between pyroxene oikocrysts. The outer contacts of the poikilitic plagioclase are scalloped by extension of settled crystals across the contacts. Where it is in contact with other interstitial minerals, the plagioclase either has interference boundaries or is controlled by crystal boundaries of interstitial pyroxene; plagioclase has not been observed to be terminated by its own crystal faces.

Quartz, in its uncommon occurrences as a poikilitic mineral, has roughly spherical outlines and irregular boundaries against all the other interstitial constituents.

Poikilitic olivine, bronzite, and augite crystals in chromitite, and, to a lesser extent, bronzite and augite crystals in harzburgite and bronzitite, are locally modified by narrow apophyses that envelop settled crystals far beyond the roughly spherical limits of the oikocryst. Narrow rims of these three minerals surround settled crystals at considerable distances from the centers of the oikocrysts, coating the walls of the interstices with optically continuous material (fig. 72). The centers of the interstices are filled with plagioclase. The reverse of this textural development has been observed in a few chromitite specimens, where plagioclase plates the faces of chromite crystals outwards from the margins of plagioclase oikocrysts, and augite or bronzite fills the central parts of the outlying interstices (fig. 73). Where these peripheral platings of settled crystals are well developed, the coating material decreases in abundance away from the center of the oikocrysts, so that the rims become increasingly narrow, although the whole remains in optical continuity.

DISCUSSION

There is a striking similarity between the sectional shapes of unit interstices defined by the closely packed settled crystals and the section shapes of unit voids between spheres illustrated by Graton and Fraser (1935, figs. 14, 17–20). If arcuate boundaries are substituted for angular ones, many of the shapes correspond exactly.

The tendency of the interstice walls to maintain their angularity, even where the settled crystals have grown considerably after deposition, suggests that secondary enlargement was virtually completed by the time the interstitial minerals crystallized. Where bronzite forms a part of the interstitial material, for instance, its boundaries with plagioclase are for the most part irregular and interfering, whereas secondarily enlarged bronzite has euhedral terminations against plagioclase. However, the homogeneity of interstitial material formed in part by reaction replacement suggests that reaction occurred simultaneously with space filling. Within the greatly enlarged interstices no trace of the original pore-space boundaries can be detected.

The characteristic equidimensional or prismatic forms of bronzite, augite, and olivine oikocrysts dominate the texture of the interstitial material, suggesting that these minerals grew outward from central nuclei, displacing the interprecipitate magma without local entrapment. The generally irregular contacts of augite and bronzite with plagioclase at the peripheries of the oikocrysts suggest mutual interference in the final stages of crystallization. Local segments of crystal faces of these minerals against plagioclase probably record the local parts of the outer peripheries that completed crystallization prior to plagioclase. Although the relative power of automorphism of olivine and plagioclase cannot be evaluated, I prefer to believe that the interstitial olivine in chromitite completed crystallization prior to precipitation of plagioclase.

Envelopment and plating of chromite crystals at the margins of some oikocrysts, although almost identical with reaction textures between chromite and gabbro described by Thayer (1946, p. 203–205), would seem to have a different origin for the following reasons: (1) No consistent zonal arrangement is recognized. (2) The enveloping rims are optically continuous with, and connected to, large oikocrysts, which fill the entire space between chromite crystals. (3) The width and therefore volume of the rims decreases away from the oikocrysts. (4) The euhedral shape of the chromite is not altered. It seems most likely that the enveloping rims are skeletal outgrowths from the poikilitic crystals with which they are connected, and that the magma was unable to supply enough of the constituent to fill the interstices completely.

DISTRIBUTION OF THE INTERPRECIPITATE MATERIAL

In most rocks of the Ultramafic zone, the interstitial material is evenly distributed along the plane of the layering and ranges in volume from less than 1 percent, in the uncommon rocks where secondary enlargement is nearly complete, to 50 percent, in abnormally porous chromitite with no secondary enlargement. Exceptions to the rule of even distribution of interstitial material occur in the clotted chromitite, where secondary enlargement is irregularly developed, and in some piokilitic harzburgite, which contains relatively large quantities of bronzite formed by reaction.

The mineralogy and distribution of interstitial material varies with the amount of oriented overgrowth on settled crystals, and because of this they also vary areally and stratigraphically. In rocks in which the settled crystals have been considerably enlarged after deposition, interstitial minerals do not have characteristic poikilitic textures. Oikocrysts become progressively smaller as enlargement increases, until, in nearly monomineralic rocks, the interstitial constituents are confined to single widely spaced interstices and are not

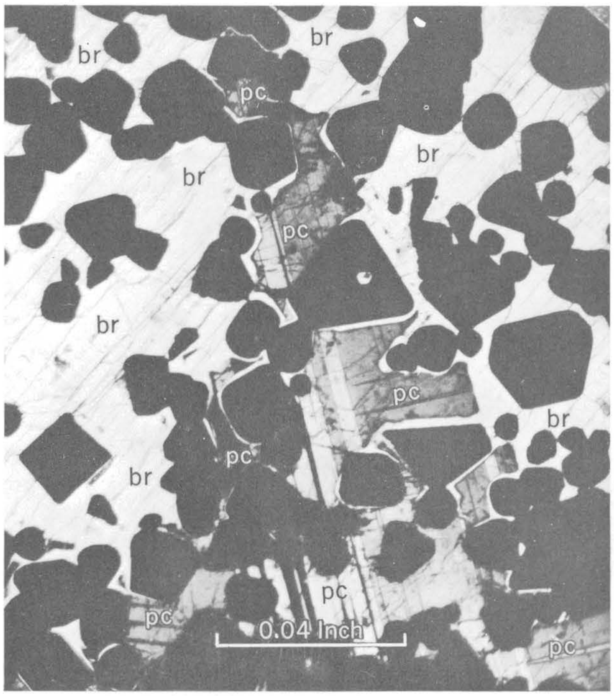


FIGURE 72.—Plating of chromite by bronzite. Narrow shells of bronzite surround settled chromite crystals near margin of bronzite oikocryst. br=bronzite; pc=plagioclase. Crossed nicols.

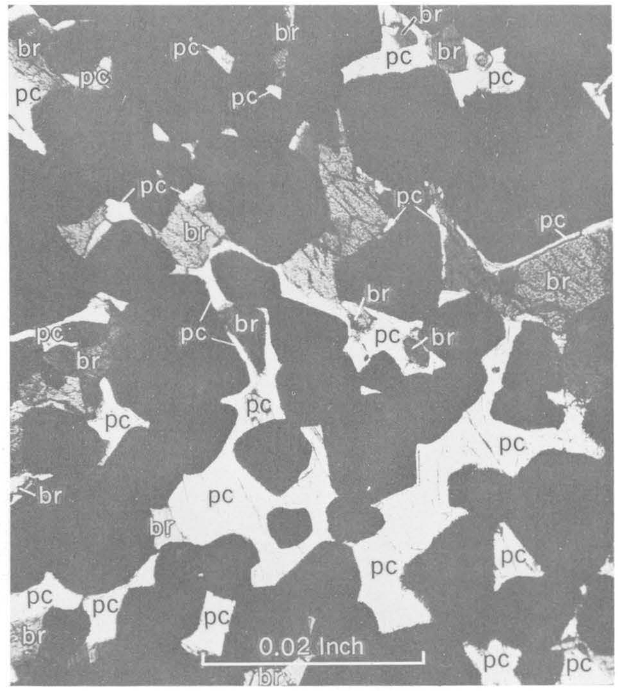


FIGURE 73.—Plating of chromite by plagioclase. Narrow shells of plagioclase surround settled chromite crystals near margin of plagioclase oikocryst. br=bronzite; pc=plagioclase. Crossed nicols.

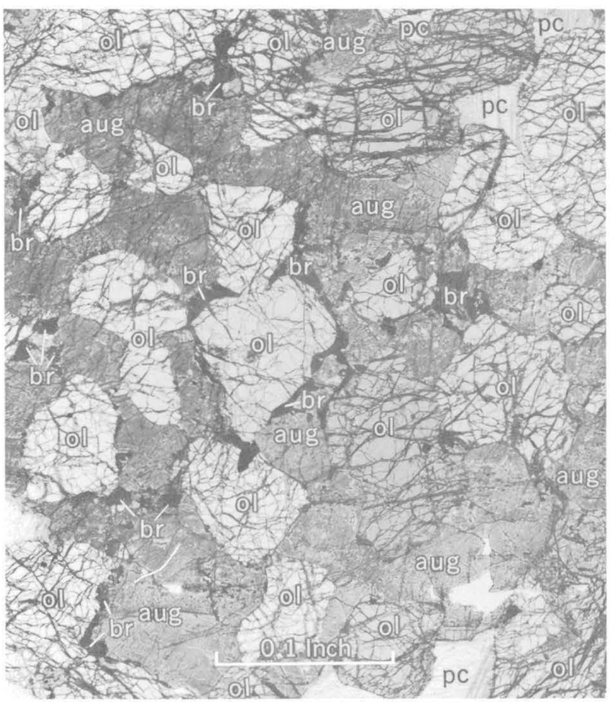


FIGURE 74.—Augite replacing bronzite in poikilitic harzburgite. Remnants of uniformly oriented bronzite oikocryst occur within augite oikocryst near boundaries of olivine crystals. ol=olivine; aug=augite; br=bronzite; pc=plagioclase. Crossed nicols.

FIGURE 75.—Biotite in poikilitic harzburgite. Biotite has partly replaced included portion of chromite crystal. Note that plagioclase is strongly zoned near biotite. m=biotite; chr=chromite; ol=olivine; pc=plagioclase. Crossed nicols.

PHOTOMICROGRAPHS OF TEXTURES OF INTERPRECIPITATE MINERALS IN THE ULTRAMAFIC ZONE in contact or in optical continuity. Presumably this restriction of poikilitic development is caused by cementation and consequent closing of the throats of interstices, thus decreasing the permeability of the mush.

The character of the interstitial material also varies independently with change in mineralogy of the settled crystals and with stratigraphic position. The variation of the character of interstitial material with change in mineralogy of settled crystals seems the most fundamental, and for this reason the descriptions will be considered separately for the various rock types. The mineralogy of these rocks is summarized in table 8.

TABLE 8.—*Settled and interstitial minerals in Ultramafic zone rocks having relatively small amounts of secondary enlargement*

[Parentheses indicate minerals not always present]

Major rock types	Settled constituents	Interstitial constituents	
		Generally abundant (in order of average abundance)	Generally <1 percent of rock
Poikilitic harzburgite	Olivine Chromite	Bronzite Plagioclase Augite	Biotite
Granular harzburgite and olivine bronzitite.	Olivine Bronzite (Chromite)	Plagioclase Augite (Bronzite)	(Biotite)
Bronzitite	Bronzite (Chromite)	Plagioclase Augite	(Quartz) (Biotite) (Grossularite-pyrope)
Chromitite	Chromite (Olivine)	(Plagioclase) (Augite) (Bronzite) (Olivine)	Biotite
Olivine chromitite and poikilitic chromite harzburgite.	Chromite Olivine	Bronzite (Augite) (Plagioclase)	(Biotite)

POIKILITIC HARZBURGITE

The settled constituents of poikilitic harzburgite are olivine and accessory chromite; the recognized interstitial constituents are bronzite, plagioclase, augite, and very minor amounts of biotite. Quartz has not been observed. Interprecipitate olivine occurs where settled crystals have been secondarily enlarged.

Bronzite invariably occurs in poikilitic crystals partially replacing included olivine in amounts up to 58 percent. In some bronzite oikocrysts the amount of replacement seems constant throughout, but in others olivine is more highly resorbed in the central part of the bronzite oikocrysts. Augite is present only in extremely minor amounts in many specimens of poikilitic harzburgite, and it is nearly always subordinate in amount to bronzite. Its most general form of occurrence is as minute grains in the cusps or throats of interstices occupied largely by strongly zoned plagioclase. In rocks where augite is slightly more abundant, it also occurs in poikilitic crystals very much smaller than, and generally located between, bronzite oikocrysts in the same rock. Poikilitic augite partially replaces olivine, but to a lesser extent than bronzite does. In a few layers augite is nearly as abundant as bronzite and the rocks are properly poikilitic lherzolites. In these rocks augite occurs in oikocrysts the same size as those of bronzite, and spaced equally with them throughout the rock. Microscopic examination shows that the central part of each augite oikocryst of this type contains irregular isolated inclusions of uniformly oriented bronzite (fig. 74). Apparently, therefore, the augite in these rocks is in part formed at the expense of bronzite, which had previously crystallized from the interprecipitate magma. Bronzite and augite oikocrysts in individual specimens of poikilitic harzburgite tend to have equal size and roughly equidistant spacing along the strike of the layers.

Plagioclase fills the interstices between pyroxene oikocrysts; for the most part, it occurs as small grains occupying a single interstice or as small poikilitic grains including, in section, 3 or 4 olivine crystals. The poikilitic grains are generally larger near the centers of the areas of plagioclase in the specimen—that is, at some distance from the pyroxene oikocrysts. Scattered throughout the area of interstitial plagioclase, but generally concentrated near the margins of pyroxene oikocrysts, are small pockets of plagioclase which occupy single interstices or parts of interstices, and which are characterized by extreme zoning (fig. 76). In most poikilitic harzburgite interstitial pyroxene is about 3 times more abundant than plagioclase, but examples in which plagioclase is dominant are known. The problem of estimating the proportions is greatly complicated by the extremely large grain size of the bronzite oikocrysts; in some rocks a representative mode would involve an area of about 75 square feet.

Biotite generally occurs within the pockets of strongly zoned plagioclase, either along the wall of an interstice in contact with olivine or adjacent to chromite grains, if these are present (fig. 75). It commonly occurs in single tablets 0.5 to 1.0 mm in diameter and 0.05 to 0.1 mm thick, so that the entire crystal commonly is confined within a single interstice. Development of larger poikilitic crystals which cross several interstices are not common, occurring only in poikilitic harzburgite where mica is abnormally abundant. Rarely, however, mica plates cut transversely across boundaries between plagioclase and olivine, where they have apparently formed by replacement of both minerals. A small percentage of chromite crystals in contact with mica are serrate at the margins (fig. 75), and small volumes of chromite are replaced.

FIGURE 76.—Granular harzburgite with pockets of plagioclase characterized by extreme zoning. The two noses of augite that extend into the interstice at left center of photograph are also zoned. ol=olivine; br=bronzite; aug=augite; pc=plagioclase. Crossed nicols.

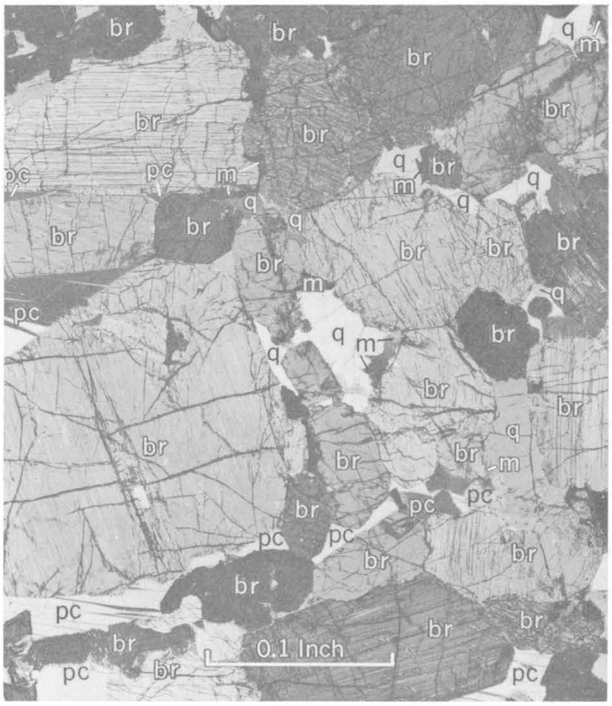


FIGURE 77.—Interstitial quartz in bronzitite. Note that nearly all quartz-filled interstices contain some biotite near their margins. m=biotite; q=quartz; br=bronzite; pc=plagioclase. Crossed nicols.

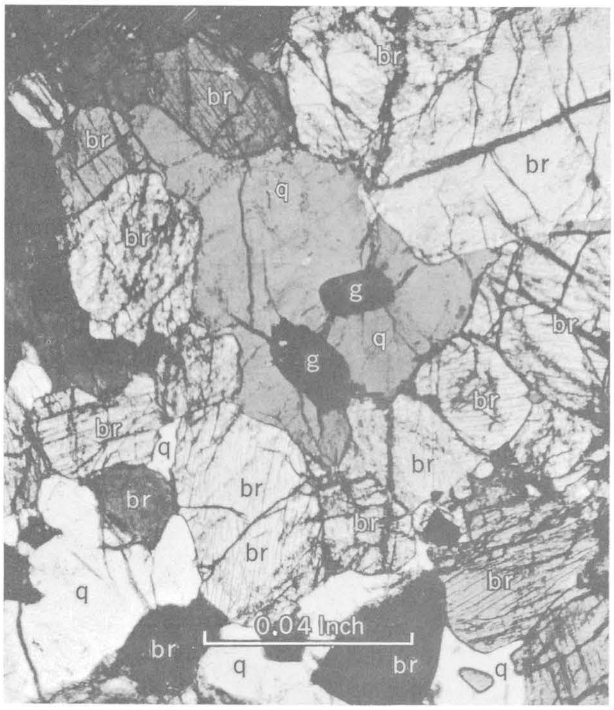


FIGURE 78.—Grossularite-pyrope associated with quartz in bronzitite. Two crystals within interstitial quartz are illustrated. g=grossularite-pyrope; br=bronzite; q=quartz. Crossed nicols.

FIGURE 79.—Grossularite-pyrope associated with plagioclase in bronzitite. Garnet is partly replacing bronzite. Note suggestions of dodecahedral shapes. br=bronzite; g=grossularite-pyrope; pc=plagioclase. Crossed nicols.

PHOTOMICROGRAPHS OF FINAL INTERPRECIPITATE CRYSTALLIZATION PRODUCTS IN ROCKS OF THE ULTRAMAFIC ZONE

GRANULAR HARZBURGITE

The settled constituents of granular harzburgite are olivine, bronzite, and accessory chromite; the interstitial constituents are plagioclase, augite, bronzite, and accessory biotite. Quartz has not been observed. Varied amounts of interprecipitate olivine and bronzite occur where these minerals have been secondarily enlarged.

In the upper parts of granular harzburgite layers, where settled bronzite is equal to or exceeds olivine in volume, the bronzite tends to be euhedral toward plagioclase, even where it is secondarily enlarged, (figs. 34, 36). In the lower parts of granular harzburgite layers, however, where olivine is more abundant than bronzite, the bronzite is irregular, generally terminating in cuspoid shapes controlled by surrounding crystals (fig. 66). Such bronzite grains have interference boundaries where they are in contact with plagioclase, and have grown out to replace partly the neighboring olivines. These relations are interpreted to indicate that in olivine-rich granular harzburgite, settled bronzite continued to grow after deposition until joined by plagioclase, filling interstices between and partly replacing settled olivine, whereas in the bronzite-rich granular harzburgite, bronzite enlargement was essentially completed before plagioclase crystallized, and no interstitial bronzite occurs in the rock.

Chromian augite typically occurs in small poikilitic crystals or in grains filling one or two interstices between settled crystals, with oikocrysts more commonly developed in the bronzite-rich granular harzburgite. Margins of included settled silicates are partially replaced, bronzite to a greater extent than olivine (fig. 52). In rocks where oikocrysts are developed, the augite grains tend to have nearly equal size and spacing along the strike of the layering. Augite also occurs independently, in minute grains, in the cusps or throats of many interstices occupied by plagioclase, accompanied, in some rocks, by biotite. The plagioclase adjacent to these small augite crystals commonly is strongly zoned, and the areas are interpreted as pockets of relatively late crystallization.

Plagioclase distribution is much like that in poikilitic harzburgite. It occurs in single grains and small poikilitic crystals, which are generally larger away from augite oikocrysts; pockets of fine-grained, highly zoned plagioclase are also scattered throughout the rocks. In granular harzburgite, plagioclase is considerably more abundant than interstitial pyroxene.

Biotite is much less abundant in granular harzburgite than in poikilitic harzburgite, and it cannot be detected at all in 2- by 2-inch thin sections of many specimens. Where observed, it does not form poikilitic crystals but occurs as tiny tablets, generally within areas of strongly zoned plagioclase.

BRONZITITE

The settled constituents of bronzitite are bronzite and, in a few rocks, a little chromite; the observed interstitial constituents are plagioclase, augite, biotite, quartz, and extremely minor amounts of grossularite-pyrope. Of the interstitial constituents only plagioclase and augite are ubiquitous. Biotite is spottily developed throughout the Ultramafic zone, but quartz and grossularite-pyrope, which generally occur together, occur only in the Basal zone and in the upper part of the Bronzitite member.

Augite very commonly occurs in poikilitic crystals replacing included bronzite in amounts up to 85 percent. As with bronzite oikocrysts in poikilitic harzburgite, augite commonly replaces larger amounts of bronzite near the center and lesser amounts near the edge of the oikocrysts. Poikilitic crystals of augite tend to have nearly equal size and spacing along the strike of the layers. Augite also occurs as thin selvages on bronzite in the throats and cusps of some interstices occupied by plagioclase.

Plagioclase distribution in bronzitite is identical with that in the harzburgite. It is invariably more abundant than interstitial pyroxene.

Biotite is even less abundant in bronzitite than in granular harzburgite; where present, it is generally associated with strongly zoned plagioclase, as in the other rock types. Generally it is confined to the interstices between settled bronzites, but in some cases it has replaced the preexisting minerals.

Quartz occurs in clear, internally homogeneous single grains or in small poikilitic crystals scattered throughout bronzite layers (fig. 77), and it is generally closely associated with biotite. Like biotite, quartz is slightly more abundant near the margins of pyroxene oikocrysts, but it maintains a fairly even distribution through the rock even where it is an extremely minor constituent. Where quartz occurs in amounts less than about 0.5 percent, it shares the corners of interstices with strongly zoned plagioclase; where more abundant, it fills entire interstices. Quartz seems to be entirely space filling, and it has not been observed with replacement relations.

Very minor amounts of grossularite-pyrope garnet have been observed in six specimens of quartz-bearing bronzitite. In thin section the mineral is colorless, locally very weakly birefringent with sectoral extinction, and in places has suggestions of dodecahedral boundaries. Other physical properties of the garnet were difficult to determine because of the extreme scarcity of the mineral in the rocks in which it occurs. About one-fourth of a gram of material containing roughly 10 percent garnet and altered garnet was obtained from a 2-pound sample of bronzitite, by hand panning in methlyene iodide. Garnet grains in this concentrate were pale pink to pale amber in color and ranged in refractive index from 1.73 to 1.755, with single grains commonly variable over much of this range. Unit cell size, calculated from X-ray diffraction patterns, proved to be 11.74±0.04 angstrom units. Average values of n and a_0 plotted on Sriramadas' (1957, p. 294–298) determinative diagrams reveal two possible compositions: grossularite$_{70}$–pyrope$_{20}$–almandite$_{10}$ and grossularite$_{60}$–pyrope$_{30}$–andradite$_{10}$. Winchell's (1958, p. 595–600) diagrams confirm these two alternatives and add a third: grossularite$_{65}$–pyrope$_{20}$–spessartite$_{15}$. Although the physical properties do not provide a definitive composition, it seems clear that in first approximation the garnet is predominantly grossularite, with subordinate pyrope. The grossularite–pyrope is closely associated with quartz, either occurring in 0.2- to 0.6-mm subhedral crystals within the quartz (fig. 78) or in plagioclase near quartz concentrations. In some instances the garnet is concentrated at the contacts between plagioclase and settled bronzite, with its boundaries partly controlled by the outlines of the bronzite and partly replacing it (fig. 79). The textures, mineral associations, and stratigraphic distribution of this mineral are strong evidence for its occurrence as a primary constituent in the Ultramafic zone.

CHROMITITE

The interstitial constituents of chromitite include bronzite, augite, olivine, plagioclase, and small amounts of mica. Quartz and garnet have not been observed.

Olivine occurs as an interstitial mineral only in about one-half of the chromitite examined. Where it does occur it is commonly in small poikilitic crystals. Chromitite containing interstitial olivine commonly also contains both pyroxenes, and the amount of olivine may exceed or be less than total pyroxene. In some specimens, interstitial olivine is separated from plagioclase by a shell of bronzite that commonly replaces the olivine near its periphery; but in a few, interstitial olivine is directly in contact with the feldspar.

Bronzite and augite are apparently absent in some chromitite, but not simultaneously. Where present, bronzite occurs in evenly spaced poikilitic crystals about one-half inch in diameter, filling space between chromite crystals without evidence of replacement. Augite typically occurs in irregular oikocrysts either rimming or partially enclosing poikilitic bronzite, with replacement textures where the two minerals are in contact (fig. 81). As in the silicate rocks, augite is also found in tiny grains in corners of interstices. The two pyroxenes generally occur together and, in most rocks, in nearly equal amounts, although rocks with either in excess are known.

Plagioclase in chromitite layers, although not appreciably different in grain size from that in silicate layers, is almost invariably poikilitic because of the relatively fine grain size of included chromite crystals. As in silicate layers, plagioclase occurs between the sharply defined pyroxene oikocrysts, but in chromitite, the size of the plagioclase oikocrysts commonly is nearly the same as poikilitic crystals of bronzite and augite. Most commonly plagioclase is about one-half as abundant as total interstitial ferromagnesian minerals, but layers are known where, at least locally, plagioclase is well in excess of total bronzite, augite, and olivine. In some chromitite, plagioclase is apparently absent.

Biotite is relatively abundant in chromitite. Traces can be found in nearly all specimens and, in a few rocks, concentrations up to nearly two percent have been observed. As in the silicate layers, biotite occurs as tiny grains between settled chromite crystals, and, much less commonly, as small poikilitic plates. Generally, biotite is associated with strongly zoned plagioclase, and locally replaces edges of contiguous chromite.

OLIVINE CHROMITITE AND POIKILITIC CHROMITE HARZBURGITE

The interstitial constituents of rocks containing mixtures of settled olivine and chromite are bronzite, augite, plagioclase, and biotite. Of these, only bronzite is invariably present.

The proportions and distribution of interstitial minerals in these rocks are more similar to those of poikilitic harzburgite than chromitite. Olivine does not occur as an interstitial mineral but does surround some chromite as a consequence of secondary enlargment of settled olivine. Bronzite, which commonly occurs in 1- to 2-inch oikocrysts, partially replacing olivine and surrounding large numbers of chromite crystals, is considerably more abundant than augite or plagioclase. Where present, augite occurs as in chromitite, but it is much less abundant and is absent in a few specimens.

Plagioclase occurs in very small poikilitic crystals, and is confined to the chromite-rich part of the rock between olivine crystals. Plagioclase is less abundant in olivine chromitite and poikilitic chromite harzburgite than in any other rock types in the Ultramafic zone; it was not found in about one-third of the specimens examined.

Biotite occurs with strongly zoned plagioclase in chromite-rich parts of the rocks, but it is less abundant than in either chromitite or poikilitic harzburgite.

STRATIGRAPHIC DISTRIBUTION

As is apparent from the foregoing descriptions, the mineralogy, texture, and proportions of the interstitial constituents are strongly dependent on the character of the settled minerals present. Because the settled minerals tend to be regularly disposed in cycles, the interstitial minerals have, to the same extent, a cyclic stratigraphic variation. Thus, poikilitic bronzite is an important constituent of the poikilitic harzburgite in the lower parts of the cyclic units; it decreases in abundance in the lower part of the granular harzburgite layer in the central part of the unit; it is completely absent from the upper half where settled bronzite becomes an abundant mineral. Augite has a reciprocal distribution, being generally of minor importance in poikilitic harzburgite, increasing in size and abundance in the upper part of granular harzburgite, and reaching maximum development in the bronzitite at the stratigraphic tops of the cycles. Plagioclase is ubiquitous, but the ratio of plagioclase to interstitial pyroxene increases markedly upward in the cyclic unit. Although concentrations of biotite in excess of three percent in any rock have not been observed, it is nevertheless more abundant in the lower parts of cycles than in the upper.

Several anomalous stratigraphic variations in distribution of interstitial minerals between cycles have been observed. In the western half of the complex, augite is abnormally abundant in the harzburgite immediately above the cyclic unit 2 chromitite layer in the lower middle part of the Peridotite member. In this poikilitic harzburgite (properly a feldspathic lherzolite), augite and bronzite occur in nearly equal amounts; in the overlying granular harzburgite, augite also occurs in greater than normal abundance. A second anomaly occurs in the lower half of the Peridotite member in the West Fork section, where plagioclase is unusually scarce, and the plagioclase-interstitial pyroxene ratio is exceptionally low. The chromitite in this area contains abundant interstitial olivine and little or no plagioclase. A third anomalous stratigraphic variation concerns the distribution of quartz and grossularite-pyrope, which have been observed only in the upper two-thirds of the Bronzitite member and in the bronzitite of the Basal zone. Neither mineral has been found in rocks containing settled olivine or chromite, nor have they been observed in bronzitite within the Peridotite member. Where present in the Bronzitite member neither mineral exceeds one-tenth percent by volume; in the Basal zone grossularite-pyrope similarly does not occur in measurable amounts, but quartz is present in amounts up to 5 percent. Quartz apparently occurs alone in some of these bronzitites, but grossularite-pyrope is found only in bronzitite that contains some quartz.

DISCUSSION

Several deductions concerning the order of crystallization in the interprecipitate magma can be made on the basis of mineral distribution. As previously pointed out, the idiomorphism of crystal faces on secondarily enlarged settled crystals contiguous to interstitial minerals indicates that enlargement was virtually complete before crystallization of the interstitial phases. This is not true, however, of bronzite enlargement in olivine-rich granular harzburgite, where the outer margins of enlarged bronzite crystals partially replace contiguous olivines, and interfere with plagioclase. Interstitial bronzite in these rocks does not form new centers of crystallization as it does in the poikilitic harzburgite immediately below, but adds on to settled crystals and continues to crystallize with plagioclase.

It is apparent from textures in the chromitite that the reaction replacement of settled olivine by interstitial bronzite continues to occur between these two minerals even where both are interstitial constituents, and thus crystallization of interstitial olivine must cease before bronzite can appear. Similarly, in the poikilitic harzburgite, where both augite and bronzite appear as interstitial constituents, there is abundant evidence that augite occurs in part as a replacement of bronzite. A reaction, rather than cotectic, relation between these minerals therefore continues in the interprecipitate magma, and interstitial bronzite ceased crystallizing prior to deposition of augite.

When plagioclase began to precipitate in the crystallization sequence of the interstitial magma is not entirely clear. In chromitite containing interstitial olivine, the olivine apparently finished crystallizing prior to the appearance of feldspar, but both pyroxenes in these rocks show mutually interfering boundaries with plagioclase. In poikilitic harzburgite, the bronzite oikocrysts control the textures by their even-spaced poikilitic development, and it seems likely that bronzite began to crystallize before plagioclase. The same argument suggests that augite in bronzitite began to crystallize before feldspar. In rocks that contain both augite and bronzite as interstitial constituents, the bronzite has interference boundaries with plagioclase, indicating that feldspar must have begun to crystallize before augite.

The pockets of strongly zoned plagioclase and isolated augite gains in all the rock types suggest that augite and plagioclase were the final crystallization products of the interstitial magma throughout the section, and their association with biotite, quartz, and grossularite-pyrope indicates that they were joined, in some rocks, by these new mineral phases.

On the basis of the foregoing observations on shape, distribution, and mutual relations, diagrammatic sequences of crystallization for the principal rock types are presented in figure 80.

INTERNAL CHARACTER OF THE INTERPRECIPITATE MATERIAL

INCLUSIONS

Settled crystals excepted, primary inclusions in interstitial minerals are rare. One example of inclusions of previously formed interstitial material has been described: uniformly oriented bronzite occurs in augite in a few augite-rich poikilitic harzburgites. Minor inclusions of accessory minerals in the interstitial material are even less common. Grossularite-pyrope inclusions in quartz and plagioclase have been described. Apatite crystals in plagioclase, although relatively abundant in the chilled border rocks, are not common within the Ultramafic zone.

ORIENTED INTERGROWTHS

Clinopyroxene exsolution lamellae in interprecipitate bronzite, like those of settled bronzite, are observed only on (100) crystal planes of the host. In settled bronzite these lamellae are ubiquitous; but in parts of the interprecipitate bronzite, lamellae apparently are completely lacking. Even where they are well developed, lamellae in interprecipitate bronzite tend to be slightly narrower and more widely spread than those of settled crystals.

The lamellae of bronzite that occurs as euhedral settled crystals in granular harzburgite and bronzitite commonly extend all the way to the outer margin of the grain and pinch out sharply. In rocks where settled bronzite crystals have been secondarily enlarged, however, the lamellae begin to die out at considerable distances from the margin, leaving an outer shell of nonlamellar bronzite (fig. 82). In most grains this outer shell of clear bronzite is zoned, but in a few grains the bronzite appears to be in perfect optical continuity throughout the grain.

The lamellae of bronzite that occurs as an interstitial mineral in poikilitic harzburgite and some granular

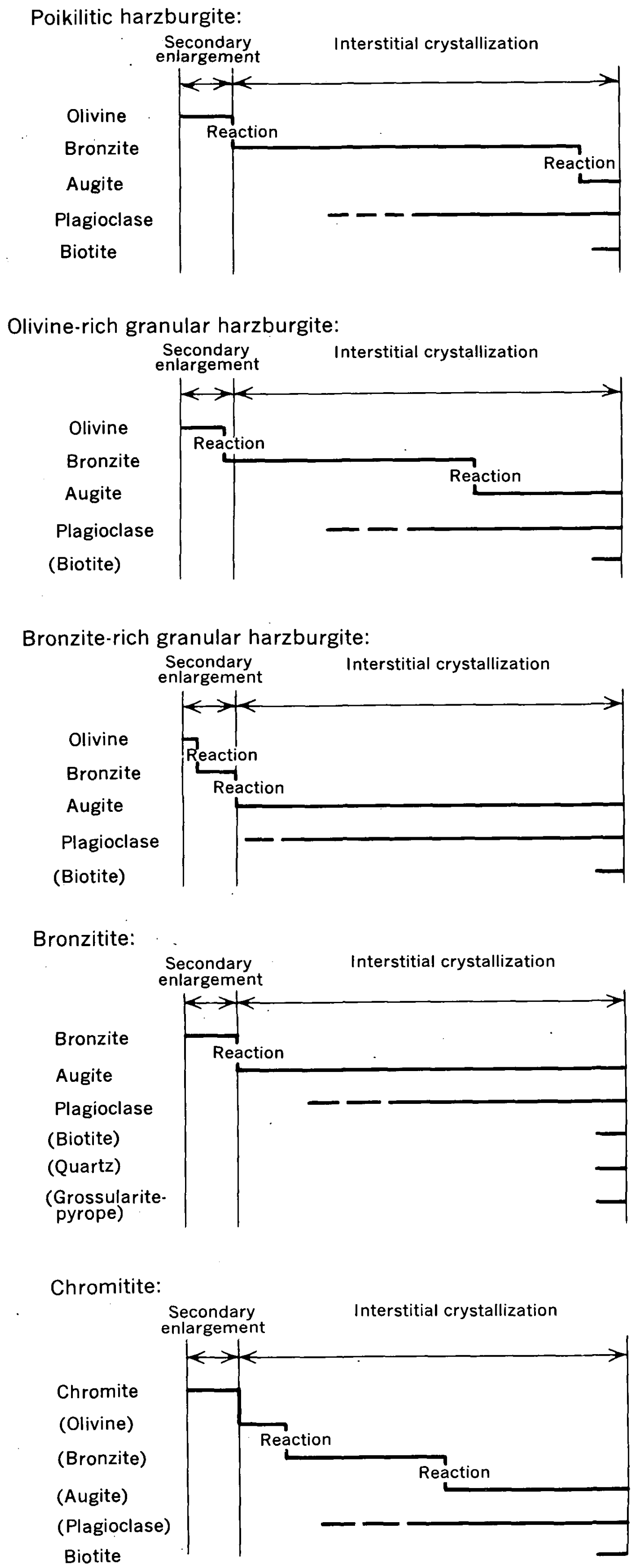


FIGURE 80.—Diagrammatic illustrations of order of crystallization from the interprecipitate magma. Parentheses indicate minerals not invariably present.

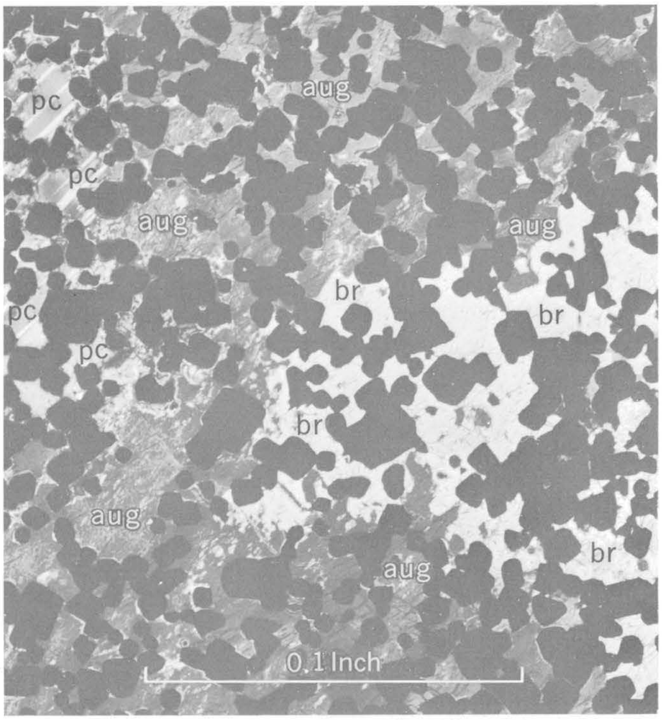


FIGURE 81.—Interstitial augite replacing interstitial bronzite in chromitite. Black grains are chromite. Tongues of augite extending into bronzite are zoned. br=bronzite; aug=augite; pc=plagioclase. Crossed nicols.

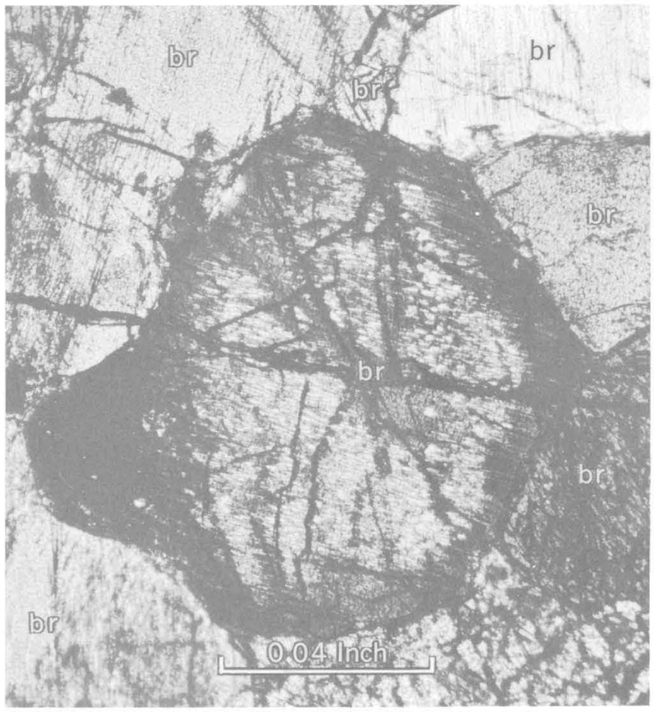


FIGURE 82.—Clinopyroxene lamellae in secondary enlarged bronzite crystal. Lamellae die out at considerable distances from the margin. Bronzite is zoned and in photograph is darker (more iron rich) at margin. br=bronzite. Crossed nicols.

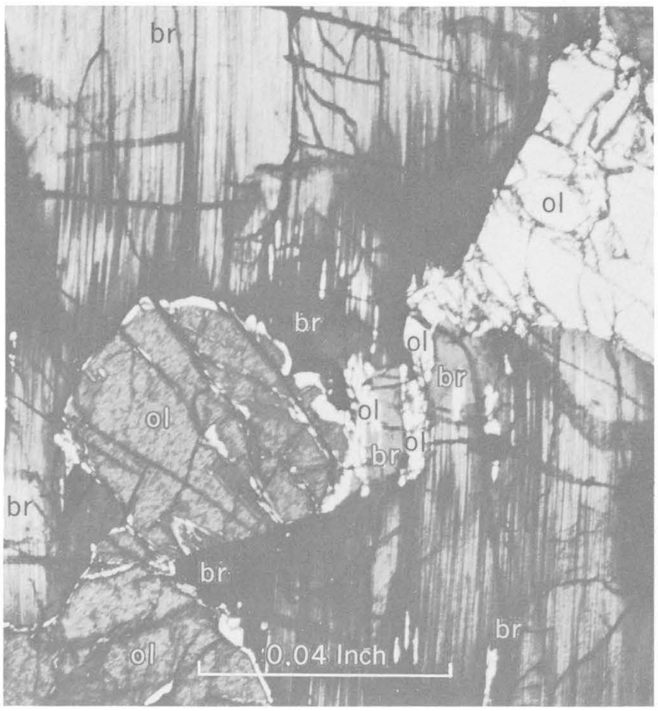


FIGURE 83.—Clinopyroxene lamellae in interprecipitate bronzite. Lamellae continue to margins of some included olivine grains but die out at considerable distances from others. Absence of lamellae corresponds with maximum zoning. ol=olivine; br=bronzite. Crossed nicols.

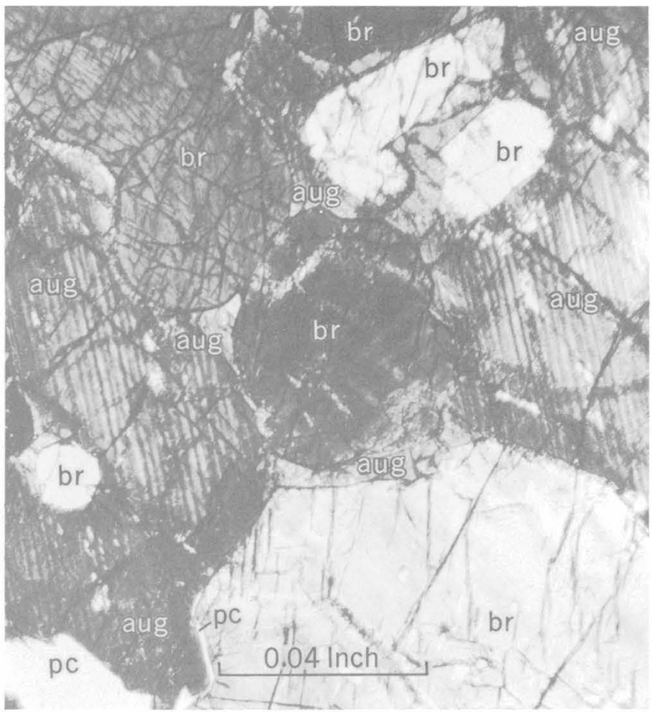


FIGURE 84.—Orthopyroxene lamellae in interprecipitate augite. Lamellae die out in areas of extreme zoning. br=bronzite; pc=plagioclase; aug=augite. Crossed nicols.

PHOTOMICROGRAPHS OF TEXTURES OF INTERPRECIPITATE MINERALS IN THE ULTRAMAFIC ZONE harzburgite are most commonly continuous throughout the grain and pinch out sharply at the grain margins and around inclusions of olivine. In many rocks, however, lamellae are absent from zoned parts of the interstitial bronzite, and these clear areas are commonly concentrated near the margins of the poikilitic crystals and in narrow rims around included settled crystals (fig. 83). In a very few layers, interstitial bronzite has poorly developed, irregularly distributed lamellae throughout. The absence of lamellae in certain parts of interprecipitate bronzite must be related either to migration of the exsolved material during exsolution, or to a deficiency of diopside molecule in the original crystallization product, inasmuch as the plutonic environment precludes retention of diopside molecule owing to rapid cooling. Lime deficiencies in parts of the interprecipitate bronzite could occur in two ways: (1) by crystallization of the nonlamellar bronzite in a lime-free environment, as proposed by Walker (1940, p. 1090) to explain similar bronzites in the Palisades diabase; or (2) by crystallization at low magma temperatures where diopsidic material is less soluble in orthopyroxene, as proposed by Hess and Phillips (1940, p. 282-283). Hess and Phillips' explanation is favored because plagioclase is almost invariably present in the final crystallization product. It is also possible that exsolution began near the centers of bronzite grains and that exsolved material moved from the margins toward the centers during this process, as proposed by Brown (1957, p. 521, 528) to explain similar relations in inverted pigeonites from the Skaergaard intrusion, but this hypothesis does not explain the general association of absence of lamellae with zoning.

Narrow orthopyroxene lamellae are abundantly developed on the (100) plane of interstitial augite, and these pinch out sharply at grain boundaries and around inclusions in the same manner as do clinopyroxene lamellae in bronzite. Exsolution plates on (001) of augite, indicating primary exsolution of pigeonite, have not been observed. Augite oikocrysts tend to be peripherally zoned, and the outer margins of these zoned crystals are generally free of lamellae. On oikocrysts oriented perpendicular to Y of augite, where zoning can be observed by change in interference colors, the lamellae become progressively less abundant and more poorly developed in areas of increasing birefringence (fig. 84).

The absence of lamellae from the outer parts of many augite oikocrysts is probably due to a deficiency of orthopyroxene molecule in the original crystallization product. Again, relatively low temperatures during the final stages of consolidation of the rocks would decrease the solubility of the orthopyroxene molecule in augite and explain the distribution of lamellae-free areas.

ZONING

Compositional zoning in settled crystals is not at all common; in contrast, the interprecipitate minerals characteristically show well-developed compositional variation.

The secondarily enlarged outer peripheries of some settled crystals show minor continuous compositional changes, and these seem to be related to the amount of overgrowth that has occurred. In some bronzitite and dunite, characterized by xenomorphic texture, the margins of bronzite and olivine become gradually more iron rich outward, especially where the amount of enlargement has been relatively great (fig. 82). Where the amount of enlargement has been relatively small, constituent grains of olivine and bronzite are homogeneous in composition throughout. Zoning in secondarily enlarged outer margins of chromites has not been observed, in either transmitted or reflected light.

Smoothly gradational, nonoscillatory zoning is well developed in interstitial plagioclase, augite, and bronzite. In areas where plagioclase grains are confined to single interstices, the most calcic part of the grain generally lies adjacent to a settled crystal forming part of the boundary, and the feldspar becomes more sodic toward the opposite side of the interstice. In some specimens, however, the more sodic part lies in the center of the interstice (fig. 76). The pattern of compositional change in larger, poikilitic plagioclases is more complex. In these, the most calcic portion commonly lies adjacent to one of the included settled crystals, or in narrow areas between two adjacent settled crystals, located near the center of the oikocryst. Plagioclase of intermediate composition surrounds the calcic portion and fills the central parts of nearby interstices. The most sodic plagioclase surrounds the intermediate portion and thus lies adjacent to most of the settled crystals included within the plagioclase oikocryst.

The zoning pattern of poikilitic augite is similar to that of poikilitic plagioclase. Small but continuous increases in birefringence, $2V$, and extinction angle occur roughly concentrically outward from the center of the augite oikocrysts, accompanied by similar increases around the margins of many of the included settled crystals. The magnesium-poor zones at the edges of the oikocrysts and around settled crystals are commonly characterized by absence of orthopyroxene lamellae. Zoning of augite oikocrysts around settled crystals is about equally developed in chromitite, where nearly all of the augite simply fills pore space in bronzitite and harzburgite, where augite occurs partly at the expense of bronzite or olivine. In the latter case, zoning follows the embayed boundaries of the partially replaced chadacrysts.

Bronzite oikocrysts appear to be considerably more uniform in composition than those of augite, but weak enrichment of iron near the extreme margins and surrounding settled inclusions can be detected in many individuals.

If the advance of crystallization of poikilitic crystals of plagioclase and pyroxene was outward from the center, as indicated by their distribution and mutual boundaries, then the general concentric compositional distribution indicates a soda and iron enrichment outward during growth. The secondary pattern of zoning around many of the settled inclusions may indicate that, once inaugurated, crystallization advanced more rapidly through the central portions of the interstices, so that crystallization lagged immediately adjacent to inclusions.

The absence of zoning in settled crystals has been interpreted as indicating growth of these crystals while suspended in a large volume of magma; the prevalence of zoned interstitial minerals is believed to be a result of growth from small volumes of trapped or partially trapped magma surrounding the settled crystals. The consequence of this entrapment is differentiation on a small scale, and it is interesting to note that the general chemical direction of differentiation of the complex as a whole is presaged in the interstices of its stratigraphically lowest layers.

SIZE AND SIZE DISTRIBUTION OF POIKILITIC CRYSTALS

The grain-size range within the interstitial material is extreme compared with that of settled crystals in the same rocks. In many poikilitic harzburgites that contain settled olivines of a size range of about four Udden size grades, the sizes of single interstitial crystals range from bronzite oikocrysts 8 inches long to plagioclase crystals 0.004 inch in length. Despite this extreme size range, qualitative variations in average grain dimensions can be observed, particularly when observations are confined to poikilitic crystals of one mineral in a particular rock type.

The size of poikilitic crystals is relatively constant along the layering plane, and several consistent variations occur across the layering. The size distribution of poikilitic crystals is influenced by stratigraphic position, and by the grain size and amount of secondary enlargement in settled crystals.

Maximum and minimum dimensions of oikocrysts were measured, whenever possible, in the field, and "average" dimensions and variability along the strike of layers were estimated at the same time. More refined descriptions of size and sorting were impractical because of the large crystal dimensions involved.

GRAIN SIZE

The occurrence and diameter ranges of poikilitic crystals of bronzite, augite, and plagioclase are summarized in table 9. The minimum observed diameters for all three minerals are arbitrary; each of the minerals occupies single interstices in some rocks, and three-sixteenths inch is about the minimum diameter at which a crystal can be said to be poikilitic.

TABLE 9.—*Diameter of poikilitic crystals in rocks of the Ultramafic zone*

Poikilitic mineral	Principal occurrence	Maximum observed diameter range (inches)	Normal diameter range (inches)
Bronzite	Poikilitic harzburgite Chromitite	3/16–15	3/4–4
Augite	Granular harzburgite Bronzitite Chromitite	3/16–1 1/4	3/8–5/8
Plagioclase	All rock types in Ultramafic zone.	3/16–8	3/8–5/8

SIZE DISTRIBUTION

The most obvious feature of the size distribution of poikilitic crystals is that the size variation of oikocrysts along layers is less than one-half that across layers. Individual layers can therefore be characterized by "average" values for the sizes of their poikilitic crystals.

Study of stratigraphic variation in poikilitic crystals has been confined to bronzite in poikilitic harzburgite, because such bronzite oikocrysts are easily observed in the field, and because they have a relatively large size range. Within individual poikilitic harzburgite layers, no consistent variation in oikocryst size has been observed. In some layers, bronzite oikocrysts increase in size from bottom to top; in others, size decreases from bottom to top; in most layers, no perceptible change occurs.

A rough overall variation in size of bronzite oikocrysts in poikilitic harzburgite throughout the Peridotite member seems to exist, as illustrated in figure 85. In a general way, poikilitic harzburgite layers in the lower part of the section contain smaller bronzite oikocrysts than do such layers in the upper part. It has been noted that the settled olivine crystals in these poikilitic harzburgite layers increase in mean size in much the same way.

In areas where sharp breaks in size of settled olivine crystals occur within layers, the size of bronzite oiko-

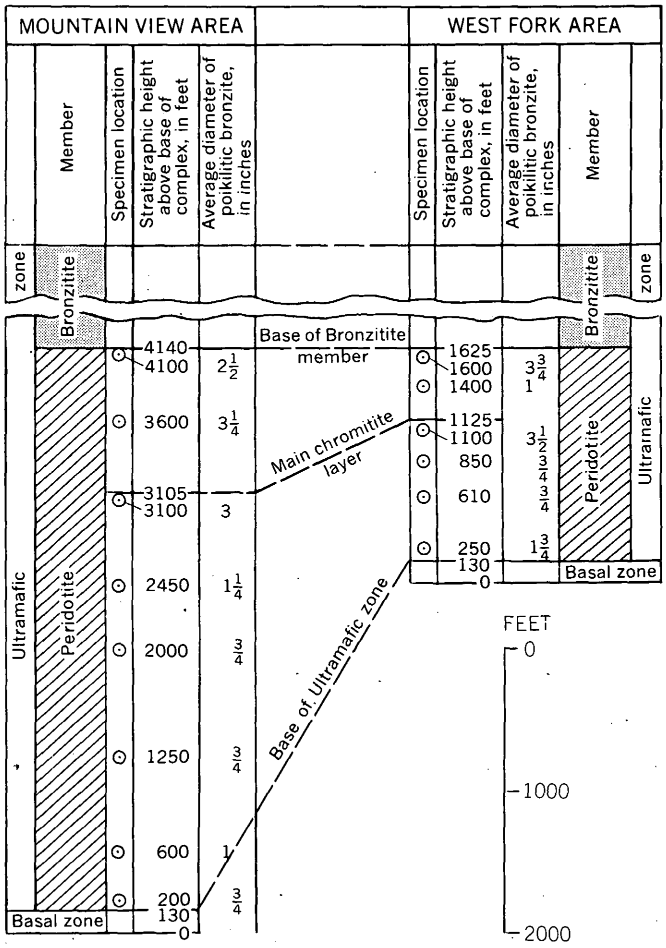


FIGURE 85.—Stratigraphic distribution of diameters of bronzite oikocrysts in poikilitic harzburgite layers in the Mountain View and West Fork areas.

crysts responds in the same direction, so that larger olivine crystals are associated with larger oikocrysts, and vice versa (fig. 21). Bronzite oikocrysts with diameters from 5 to 15 inches are largely confined to the poikilitic harzburgite layers immediately below the two thickest chromitite layers, and these harzburgite layers are also characterized by the extreme grain size of their settled olivine. In order to check the interdependence of size of settled olivine and interstitial bronzite in the same rocks, the average sizes of both constituents in 22 specimens of poikilitic harzburgite were measured and are simultaneously plotted in figure 86. Errors in determining the "average" size of oikocrysts are probably large; nevertheless, the plot suggests a broad direct relation.

Oikocrysts are smaller in chromitite than in layers composed of settled olivine or bronzite, and it is not common for crystals of any of the three principal poikilitic minerals to exceed one-half inch in diameter. In chromitite, bronzite and augite tend to occur in nearly equal-sized crystals.

In a general way, the size of poikilitic crystals decreases in rocks whose settled crystals have been secondarily enlarged. Poikilitic harzburgite and bronzitite that contain relatively small amounts of interstitial material are characterized by small poikilitic crystals of bronzite and augite. In dunite, where the interstitial material has been reduced to less than 10 percent of the rock, bronzite oikocrysts are commonly less than one-half inch in diameter.

Another type of variation in size of poikilitic crystals is apparently concerned with the amount of the interstitial mineral present in the rock. In rocks where biotite is relatively abundant, it occurs in poikilitic crystals; but where biotite is scarce, it occurs in scattered grains within single interstices. Similarly, augite oikocrysts tend to be larger in bronzitite, where augite is relatively abundant, then in harzburgite, where augite is less abundant.

DISCUSSION

The sizes of oikocrysts and settled crystals in poikilitic harzburgite appear to be interdependent. Two mechanisms for explaining this correlation are suggested: (1) changes in the magmatic environment caused increases or decreases in the size of both settled olivine and poikilitic bronzite; and (2) the size variations in accumulated settled olivine caused size variations in bronzite by changes in the permeability of the crystal mush. The relative influence of these two mechanisms is not clear. The consistently small oikocrysts in the relatively fine-grained and hence relatively impermeable chromitite suggest that the physi-

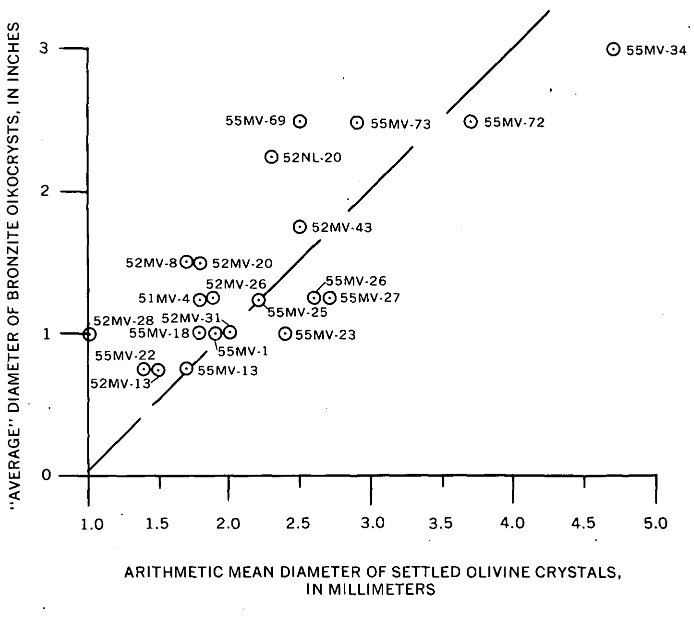


FIGURE 86.—Relation between size of settled olivine and size of poikilitic bronzite in 22 specimens of poikilitic harzburgite.

cal properties of the mush had some influence on poikilitic development.

Two other factors apparently restrict the growth of poikilitic crystals: (1) secondary enlargement of settled crystals presumably limits size of poikilitic crystals by reducing the pore volume and permeability; and (2) the abundance of material available to form the poikilitic mineral limits its final attained size.

ORIENTATION OF POIKILITIC CRYSTALS

No statistical study of orientation of poikilitic crystals had been made because of their extreme dimensions. On the basis of qualitative observations, however, no strong or consistent optical or dimensional orientation is believed to exist.

No relation between the optical orientation of oikocrysts and the optical or dimensional orientation of settled crystals has been observed, even where there is a reaction relation between the two. Similarly, no relation between the optical orientation of oikocrysts and the layering plane have been observed. Cleavage reflections on poikilitic crystals within compositional layers are apparently random.

Except for the ellipsoidal dimensions of bronzite oikocrysts in a few chromitite specimens described on p. 66, dimensional orientation in bronzite oikocrysts has not been observed.

DEVELOPMENT OF DOMINANT TEXTURES IN THE ULTRAMAFIC ZONE

The coarse granular textures and abundant examples of crystal settling in the Ultramafic zone may be attributed primarily to the extremely slow cooling of the thick intrusion, inasmuch as no abnormalities in composition or physical properties of the saturated basaltic parent magma are apparent. In the lower part of the Basal zone, where the effects of rapid cooling can be observed, the rocks are fine grained and the texture is generally ophitic (fig. 87), pyroxene and plagioclase being present in about equal amounts. According to Walker (1957, p. 9), ophitic textures in rocks similar in composition to the chilled gabbro of the Stillwater complex indicate that both pyroxene and plagioclase began crystallization at a very early stage and continued to crystallize in ophitic relationship throughout the cooling history of the rock. Within the Basal zone above the chilled rocks, a rapid transition from ophitic to settled textures occurs, and the rocks consist of packed euhedral pyroxenes in a predominantly feldspar mesostasis. It is proposed that, in the Stillwater complex, this texture indicates primary precipitation, settling, and burial of bronzite prior to interprecipitate crystallization of plagioclase.

The Ultramafic zone is characterized throughout by settled textures in which the primary precipitate and the interprecipitate material can generally be distinguished. However, modifications of simple settled-interstitial relations have occurred throughout the zone, and the dominant textures range from automorphic-poikilitic to xenomorphic. Rocks with minor secondary enlargement have interposition fabrics, in which the settled crystals are euhedra or partially resorbed euhedra and the interstitial material is largely poikilitic. Rocks with much secondary enlargement have mosaic fabrics and contain little or no interstitial material. All gradations between these two textural extremes occur.

The wide range of textural variation is caused by the behavior of the interprecipitate magma. In those parts of the crystal mush where this magma has crystallized constituents different from the settled crystals, textures are dominantly automorphic poikilitic; where the magma crystallized material of the same composition as the settled constituents, textures are xenomorphic. In many rocks, where the interprecipitate magma has partly crystallized as enlargements on settled crystals and partly crystallized as different phases, the textures are best described as hypautomorphic-poikilitic or intergranular.

AUTOMORPHIC-POIKILITIC TEXTURE

Rocks composed predominantly of euhedral settled crystals are accompanied by poikilitic mesostasis textures. Such textures are common in each of the rock types of the Ultramafic zone except dunite (figs. 57, 60, 72), but are perhaps best exemplified by chromitite because of the absence of resorption effects between precipitate and interstitial material. In rocks where resorption textures are marked, particularly in poikilitic harzburgite, the automorphic character of the settled crystals is partially destroyed, but only those crystals that lie within the boundaries of the poikilitic reaction product are affected, and the other settled crystals in the rock retain their euhedral character. Automorphic-poikilitic textures are most abundant in the stratigraphically thickest sections of the Ultramafic zone.

The euhedral nature of the settled crystals is attributed to their uninhibited crystallization in a large volume of free magma, and the preservation of their euhedral forms is a result of the failure of the interprecipitate magma to crystallize large amounts of material of the same composition as the settled crystals, or to react with the crystals to form other minerals. Secondary enlargement was not effective in completely filling the interstices between settled crystals where burial was too rapid for diffusion to be operative between the main magma and the interprecipitate magma. The trapped interstitial liquid was therefore incapable of supplying much material the same composition as the settled crystals, and proceeded to differentiate in place, giving rise to new minerals.

The absence of secondary enlargement in these rocks produced buried crystal mushes characterized by both high porosity and permeability. As a result, poikilitic crystallization of the mesostasis minerals was favored, and the rocks are characterized by large volumes of coarse-grained interstitial material. Crystallization and differentiation in the trapped magma proceeded independently of, but in the same direction as, that of the free magma, and the interstices were filled with minerals not encountered as primary precipitates until much later in the crystallization history.

HYPAUTOMORPHIC TEXTURE

Rocks composed predominantly of subhedral settled crystals are, like those with euhedral settled crystals, generally accompanied by poikilitic mesostasis textures, but these are more poorly developed, and individual oikocrysts are commonly smaller in size. Most of the rocks of the Ultramafic zone are characterized by such textures, and all gradations between automorphic and xenomorphic textures are recognized (figs. 58, 61, 13).

The subhedral nature of the settled crystals in these rocks is primarily due to partial mutual interference between grains; this interference is believed to be caused by continued growth of settled crystals subsequent to deposition. Such loss in automorphism by secondary enlargement is confined to those parts of settled crystals which are in contact with neighboring crystals, and those parts in contact with interstitial minerals retain their crystal faces. From this and other evidence it is concluded that secondary enlargement was completed prior to precipitation of new minerals from the interprecipitate magma. The rate of burial in rocks with textures of this type was apparently slow enough to allow some enlargement of settled crystals, either at the surface of the mush, or, as suggested by Hess (1939, p. 431) by diffusion between the main magma and the interprecipitate magma. The volume of the interprecipitate magma was reduced by continued crystallization of the settled minerals. The remaining interprecipitate magma was trapped by continued burial, so that it crystallized and differentiated in much the same way as in rocks with no secondary enlargement.

Porosity and permeability in the buried crystal mush were reduced proportionally to the amount of secondary enlargement, and both volume and grain size of interstitial minerals are smaller than in rocks with little or no enlargement. Where the amount of enlargement is small, poikilitic textures are well developed; where relatively large, the tendency for interstitial minerals to occupy adjoining interstices is reduced and textures of the rocks are perhaps better described as hypautomorphic-intersertal.

XENOMORPHIC TEXTURE

Rocks predominantly composed of anhedral settled crystals generally contain little or no mesostasis minerals. Such rocks, whether dunite, harzburgite, bronzitite or chromitite, have typical peridotite even-grained mosaic textures (figs. 59, 62, 64). Rocks with xenomorphic textures can be correlated with rocks of the same type which contain abundant interstitial material in other parts of the Ultramafic zone, and the mosaic texture is best developed in the stratigraphically thinnest areas of the zone.

The anhedral nature of the constituent grains is attributed to the nearly complete secondary enlargement of originally euhedral settled crystals to the point where all grains are mutually interfering. In rocks with xenomorphic texture, almost the entire original pore space in the crystal mush is composed of secondarily enlarged material and little or no interprecipitate magma was trapped to form interstitial minerals. This process is believed to have been favored by relatively slow rates of accumulation and burial, so that the settled crystals had ample opportunity to continue growth after deposition, either in contact with the main magma or by diffusion through the slowly accumulating crystal pile.

In the Ultramafic zone of the Stillwater complex, the large compositional and textural differences between rocks with automorphic-poikilitic textures and those with xenomorphic textures are believed to be caused by local conditions of deposition and burial, and these differences are not related to any fundamental variation in composition, or crystallization sequence of the parent magma. Thus, poikilitic harzburgite is genetically closely related to dunite, for both formed from accumulations of olivine crystals. Poikilitic harzburgite, on the other hand, differs in origin to a greater degree from granular harzburgite, even though it may have the same mineralogic composition, because the latter contains settled bronzite and the former does not. Similarly, automorphic bronzitite with substantial amounts of interstitial feldspar and augite are closely related to monomineralic bronzitite with xenomorphic textures, because both rocks formed from a bronzite crystal mush; their textural and compositional differences are attributed to their postdepositional history, and especially to their rate of burial.

DEVELOPMENT OF THE ULTRAMAFIC ZONE

In a study of Ultramafic rocks, the problem of origin invites speculation at all stages of the investigation. Some tentative conclusions regarding the development of the Ultramafic zone can be drawn from the preceding data on texture and mineral associations in the rocks. Even though such conclusions must necessarily be incomplete without consideration of detailed data on stratigraphy and chemistry, and will no doubt require subsequent revision, it appears worthwhile to summarize them in this report.

CONDITIONS OF CRYSTALLIZATION AND DEPOSITION

The layered rocks composing the Ultramafic zone of the complex are believed to have formed during crystallization of a single magma, by accumulation of crystal precipitates that fell to the floor of the magma chamber and were enlarged or cemented after deposition. The various magmatic processes influencing the final rock products can be divided into three groups: (1) those that affect the character and growth of the primary precipitate crystals prior to deposition; (2) those that affect the distribution of the primary precipitate during descent and arrival at the floor of the magma chamber; and (3) those that largely affect the crystallization of the interprecipitate material after deposition. At any instant of time, of course, free growth, deposition, and consolidation went on simultaneously at different horizons in the intrusion, and the level of all three rose gradually as the pile of crystals accumulated.

PREDEPOSITIONAL CONDITIONS

Some tentative conclusions regarding the properties of the Stillwater magma and its early free crystallization products can be assembled, partly from the present investigation, and partly from the result of earlier investigations.

THE MAGMA

The composition of the Stillwater magma, on the basis of a chill-zone analysis reported by Peoples[6] (1932, p. 45) and on more recent analyses by the U.S. Geological Survey, most nearly resembles a saturated normal basalt. Magma of this composition therefore apparently furnished the crystals composing the lower part of the Ultramafic zone. During crystallization of the zone the magma became progressively enriched in silica owing to the subtraction of olivine and chromite, and the effects of this change in composition are apparent even within the Ultramafic zone by the increased abundance of bronzite at the expense of olivine upward in the section. From exsolution phenomena in the pyroxenes and from experimental work by Bowen and Schairer (1935, p. 200–201), Hess (1941, p. 582–583) estimates that the initial temperature of the Stillwater magma was about 1120°C, and that after about 60 percent of the volume of the magma had crystallized, the temperature was about 1100° C. These figures are based on dry measurements at one atmosphere of pressure. Recent studies of the crystallization behavior of a natural tholeiitic basalt by Yoder and Tilley (1956, p. 169–171) showed that at 1090° C and 5000 bars water pressure, pyroxene disappeared. Brown (1957, p. 541) assumes from this data that the Skaergaard magma began to crystallize at about 1090° C. The apparent agreement between these figures arises because increasing pressures tend to increase the melting point, whereas water dissolved in the magma tends to depress it. The absolute temperature value should be considered subject to further experimental work. Comparison of known compositions of bronzites in the Ultramafic zone with Brown's (1957, fig. 5) crystallization curve for calcium-poor pyroxenes indicates that the magma temperature in the Stillwater complex decreased no more than about 20°C during the crystallization of the entire Ultramafic zone. This is in accord with the estimates of Hess (1941, p. 583) and with the experimental results of Yoder and Tilley (1957, p. 158–159).

The density of the magma throughout the crystallization and accumulation of the Ultramafic zone was less than that of olivine and bronzite, which readily sank in it. By the time the Ultramafic zone had accumulated and calcic plagioclase first appeared as a primary precipitate, the magma density was below that of the plagioclase, which was deposited in the norites immediately above the Bronzitite member. Very little information is available on which to base estimates of the viscosity of the Stillwater magma. In a recent discussion of the viscosity of dolerite sills with compositions similar to that of the Stillwater chilled margin, Jaeger and Joplin (1956, p. 445) suggest limits between 40,000 and 280 poises. Hess (1956, p. 448) gives a preferred value of 3,000 poises. As a first approximation, the viscosity of the Stillwater magma probably lay within an order of magnitude above or below 3,000 poises.

[6] Peoples, J. W., 1932, Geology of the Stillwater complex: unpublished doctoral thesis, Princeton University, 180 p.

PRIMARY CRYSTALLIZATION PRODUCTS

The primary crystallization products of the magma that were formed during the entire course of crystallization of the Ultramafic zone are olivine, chromite, and bronzite. Augite was not a primary precipitate, for it has about the same density as bronzite, and, if present, would have been recorded as a settled mineral in the rocks. Plagioclase either was not a primary precipitate or it floated. The probability is strong that plagioclase did not crystallize from the free magma for the following reasons: (1) Not a single settled crystal of plagioclase has been observed in the Ultramafic zone, and even if plagioclase had floated, a considerable number of grains would have been forced to the floor by settling olivine and bronzite. (2) Plagioclase does not occur as inclusions in the settled minerals of the Ultramafic zone, except in one specimen of bronzitite collected a few feet below the layered norites. (3) No evidence of rafting of plagioclase has been observed either in the Ultramafic zone or in the norite and gabbro above it. (4) There is no settled plagioclase in the upper part of the Bronzitite member, even though the magma density could not have been significantly different than in the settled plagioclase rocks immediately above it. The contact between the Bronzitite member and the overlying norite is not caused by density change in the magma, inasmuch as density change must be gradual and the bronzitite-norite contact is so sharp that it involves only one layer of crystals. Furthermore, some settled plagioclase is present in local norite layers in the Basal zone, indicating that plagioclase was capable of settling in the original magma.

The euhedral shapes, equidimensional habits, absence of zoning, and paucity of inclusions in the three settled minerals indicate that they grew freely while falling slowly in saturated solution, and that the magma had no rapid fluctuations in equilibrium. The crystals themselves were apparently present in the magma in logarithmic size distributions, and they apparently continued to grow as they settled toward the floor. The generally smooth grain-size changes of settled minerals within the cyclic units suggest that crystallization and deposition were continuous during their accumulation. The sharp grain-size breaks accompanying compositional changes at the bases and tops of the cyclic units, on the other hand, suggest hiatuses of crystallization.

DEPOSITIONAL CONDITIONS

During deposition, conditions were such as to produce layering. The extensive lateral continuity of layers, the gravity structures within the complex, and the generally conformable relations between the complex and overlying Paleozoic sedimentary rocks indicate that the layering was originally formed in a nearly horizontal position. In the following section, certain conclusions about the forces responsible for the transport and deposition of the primary precipitate, and about the origin of the various types of layers are summarized.

AGENTS OF TRANSPORTATION AND DEPOSITION

Textures and structures in the Ultramafic zone suggest that the magma above the gradually rising floor of the magma chamber was essentially stagnant throughout the period of accumulation of the entire Ultramafic zone, and only very locally did relatively weak currents disturb its quiescence. Local areas where currents were strong enough to sort crystals are marked by scour, local unconformities, and abnormal sorting characteristics in the settled grains. Still weaker currents are indicated in some rocks by crude lineations of elongate grains. The general absence of currents at the site of deposition is indicated by the extreme scarcity of the above features throughout the Ultramafic zone, and by the absence of hydraulic equivalence between coexisting settled crystals in nearly all the rocks in the zone that contain two or more settled minerals. Convection currents, therefore, do not appear to have been active during deposition of settled crystals. Furthermore, magma currents do not appear capable of accounting for the distribution of settled crystals. They cannot have caused the rhythmic layering, most of which is hydraulically upside down. The characteristic thick-bedded, predominantly monomineralic compositional layering in the Ultramafic zone also does not appear to be a result of current sorting of a mixture of floating crystals; currents or pulsatory variations in current velocity could not have sorted olivine from bronzite of nearly the same size and specific gravity, to form the thick poikilitic harzburgite and bronzitite layers. Currents also cannot have brought about the repetitive order of the compositional layers. In particular, current sorting seems incapable of producing the Bronzitite member, a unit 2,000-feet thick, containing no settled mineral other than bronzite.

Hess (1956, p. 449) has pointed out that crystals fall through relatively viscous magma at very slow rates, and that, in the absence of currents, crystals cannot be expected to sink appreciable distances in moderate lengths of time. Calculations of absolute settling rates are subject to considerably more error than consideration of relative settling rates (p. 30–35), but, with certain assumptions, orders of magnitude can be obtained. Assuming that the falling crystals obey Stokes' law (as their Reynolds numbers indicate), that the magma density is 2.7, and the viscosity of the magma is 3,000 poises, then olivine and bronzite crystals 2 mm in diameter would fall about 140 meters per year, and 0.2-mm chromite crystals would fall about 4 meters per year. If it were assumed that crystallization occurred at the top of the intrusion, then crystals falling at such rates would not reach the bottom of the intrusion during the largest part of the cooling history. If, however, crystallization occurred at the bottom of the intrusion rather than at the top, then gravity settling of the crystallization products could explain the depositional nature of the textures without recourse to magma currents. The physical aspects of bottom crystallization will be discussed in a subsequent section.

ORIGIN OF THE LAYERING

The genesis of the various types of layering in the Ultramafic zone will be discussed in greater detail in a subsequent publication, but those aspects of origin that are in some respect illuminated by the textures of the rocks will be briefly discussed here. All the varieties of layering in the Ultramafic zone of the complex are fundamentally related to the action of gravity on dispersed crystals of the three primary precipitate minerals. Thus, all layers are parallel to the floor of the intrusion; layers never crosscut; sedimentary structures such as scour and slump occur locally; individual grains lie with their long dimensions in the layering plane. That these particles were discrete is shown by the general absence of clumping.

The planar orientation of settled minerals is believed to be partly a result of simple gravitational forces, which caused settled crystals to assume their most stable positions, and partly a result of post-depositional compaction. Such layering is developed only where settled crystals have elongate or platy habits, and planar structure is most pronounced where platy or elongated crystals are most prominent. Lineation of long crystal axes within the layering plane is commonly lacking. Planar dimensional distribution of crystals, where present, is similar to that observed in the plagioclases of the Skaergaard intrusion, called "igneous lamination" by Wager and Deer (1939, p. 37–38). These authors note, however, that where Skaergaard plagioclase crystals are elongate, a lineation of long axes occurs in the layering plane, and they ascribe the layering to the action of convection currents sweeping across the floor of the intrusion. Although such currents undoubtedly would have intensified the platy parallelism of settled crystals in the Ultramafic zone of the Stillwater complex, it seems likely that they would also have imparted a strong lineation to the fabric.

If the rocks of the Ultramafic zone were formed by the successive accumulation of crystals, then the compositional layers are a result of a changing supply of primary precipitate minerals available for deposition at the floor of the intrusion. The character of this changing supply was such that contacts between layers are generally knife sharp (fig. 88) and that about 85 percent of the rocks of the zone are composed essentially of only one of the three settled minerals. Furthermore, these layers—defined by the abrupt appearance and disappearance of the settled minerals—are repeated many times throughout the section, and in a regular order. The size ranges and densities of olivine and bronzite in the rocks are identical, yet for the most part they occur in mutually exclusive layers. As stated above, this type of layering could not have been produced by gravity sorting or convection currents. One must conclude, therefore, that the rhythmically repeated compositional layers reflect repeated changes in the supply of crystallization products of the Stillwater magma, and that each layer represents the crystallization products available for deposition at that time. As a corollary, the sequence of the layers represents the order of crystallization of the settled minerals. Not only does current sorting fail to provide an explanation for the distribution of settled minerals in the Ultramafic zone, but current transportation of crystallization products from the roof to the floor of the intrusion seems incompatible with lack of current structures, lineation, and hydraulic equivalence in the rocks. As Hess (1956, p. 449) has pointed out, convection currents in the Stillwater magma must have existed. The present evidence, however, indicates that they were not active where the settled minerals were deposited at the floor of the intrusion during the accumulation of the Ultramafic zone.

The layering caused by changing proportions of settled minerals in the Ultramafic zone is believed to have several modes of origin. In a few places, thin layers composed of gradually changing proportions of olivine and chromite are developed with chromite increasing upward. These layers, which are hydraulically similar to the rhythmic layering of Wager and Deer (1939, p. 37) may be caused by differences in relative settling rates of suspended mixtures of large olivine crystals and small chromite crystals, as proposed by Hess (1938a, p. 266) and Wager and Deer (1939, p. 272–273) for similar layering involving pyroxene and plagioclase. The normal sequence of such layering in the Ultramafic zone, however, is from predominantly

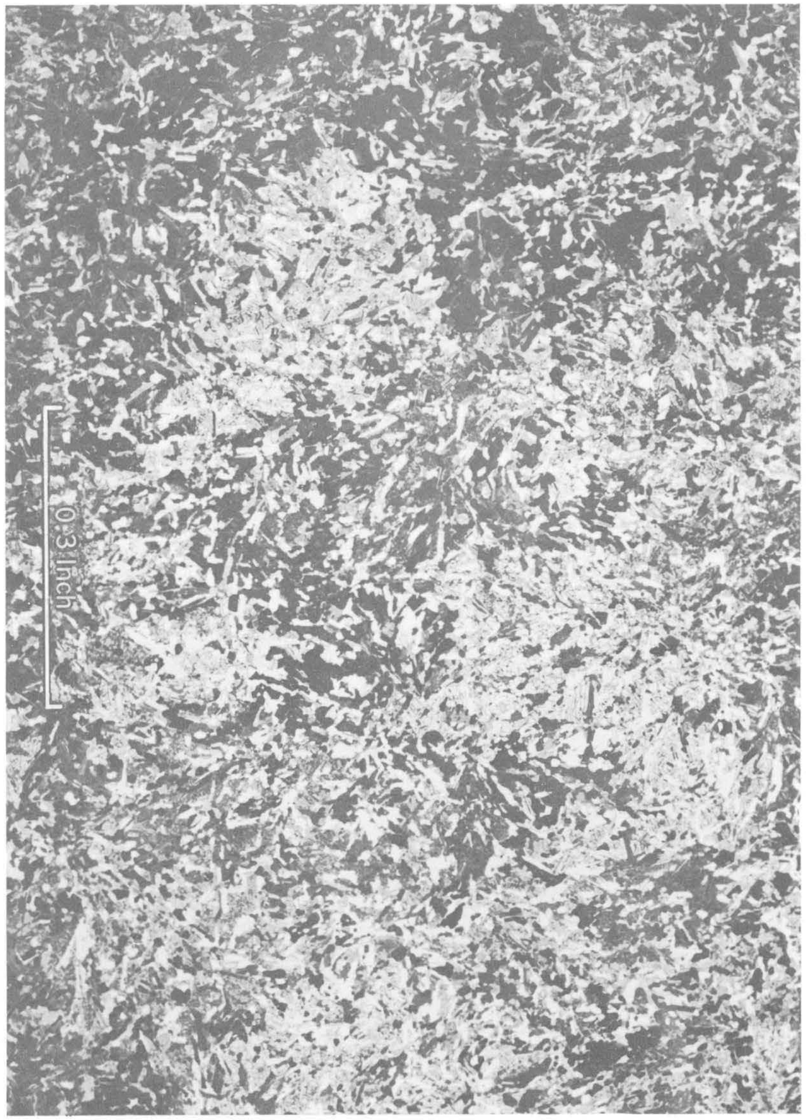


FIGURE 87.—Photomicrograph of chilled gabbro at base of the Stillwater complex. Texture is ophitic; plagioclase laths make up about one-half of the specimen, ophitic hypersthene and augite the remainder. Crossed nicols.

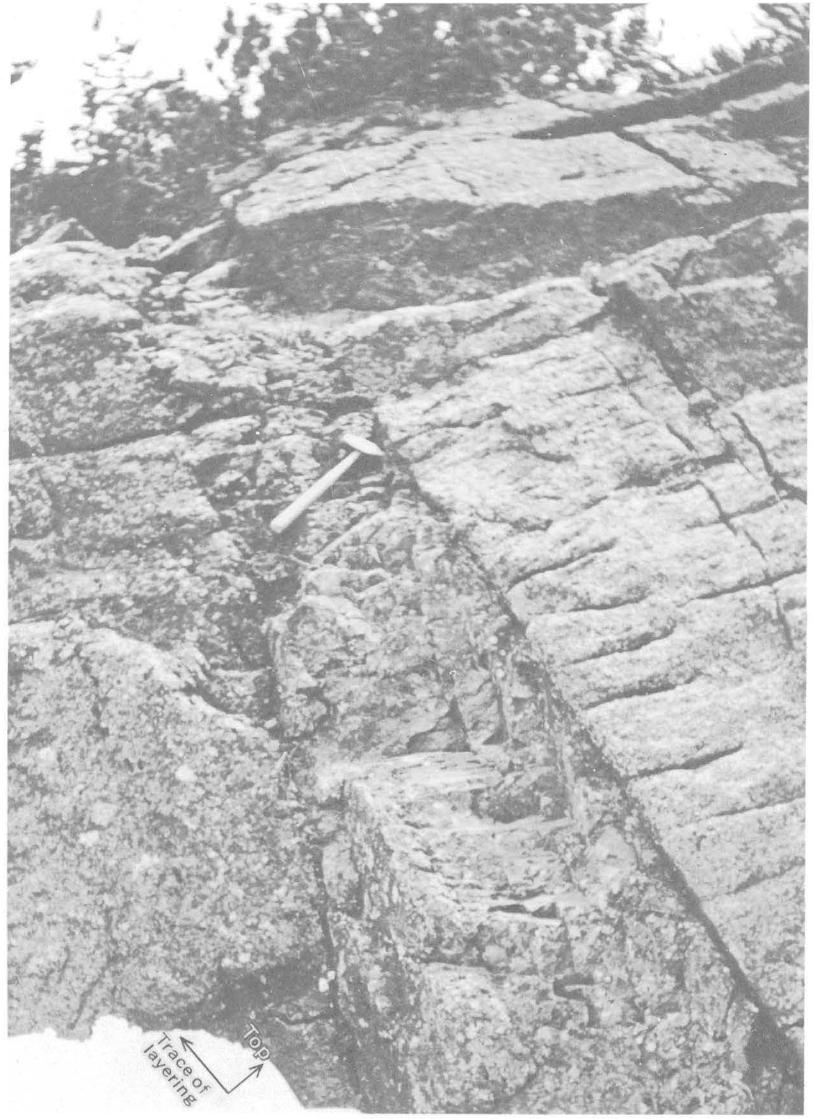


FIGURE 88.—Photograph of contact between poikilitic harzburgite (at left) and granular harzburgite (at right). The rocks are nearly identical in grain size. Olivine is the only constituent in the poikilitic harzburgite; settled bronzite and olivine occur in about equal amounts in the granular harzburgite.

EXAMPLES OF OPHITIC TEXTURE IN THE CHILLED GABBRO AND LAYERING IN THE ULTRAMAFIC ZONE small chromite crystals at the base to predominantly larger olivine crystals at the top. Layers of this type are hydraulically upside-down, and could not have been produced by differential settling. The most probable explanation is that they form as a result of changing proportions in the supply of settled olivine and chromite to the deposition surface, owing to a gradual cessation of chromite crystallization and concomitant inauguration of olivine crystallization. A third type of layering caused by gradually changing proportions of settled minerals upward in the rocks of the Ultramafic zone is developed on a larger scale in most granular harzburgite layers. In these rocks, the bronzite typically increases in amount stratigraphically upward at the expense of settled olivine (fig. 11), and this change is accompanied by an increase in bronzite grain size and a decrease in olivine grain size (fig. 19). Again, this layering is not easily explained in terms of differential settling rates, because the two minerals involved have nearly equal specific gravities and are in hydraulic equivalence only at those horizons within the layers where the grain sizes of the two minerals are equivalent. In view of their consistent stratigraphic position between poikilitic harzburgite and bronzitite, the granular harzburgite layers seem best explained as crystal accumulations that reflect a gradual decrease in the amount of olivine crystallized by the magma, as bronzite becomes the dominant crystallization product.

The several varieties of size layering described earlier in this paper are also, for the most part, probably a result of changing crystallization conditions in the magma, rather than a result of mechanical sorting; but the uncommon current-bedded layers described on page 31 are an exception to this general hypothesis. The sharp size breaks accompanying mineralogical changes at the bottoms of the poikilitic harzburgite layers are believed to represent hiatuses of deposition. The fact that there is no mixing of fine bronzite with the coarser olivine overlying it at these contacts is taken to indicate that all the bronzite had an opportunity to fall to the floor before olivine crystals were available for deposition. The gradual size increases and decreases of settled minerals within layers and within cyclic units suggest that deposition was continuous throughout their accumulation.

In summary, the types of layering and the textural features of these layers indicate that: (1) simple crystal settling occurred from magma near the floor of the intrusion; (2) the magma from which the settling occurred was essentially stagnant during crystal deposition, and magma currents did not materially effect either the transportation or deposition of such crystals; (3) single layers contain all the settled minerals being crystallized at the time of their deposition, and the stratigraphic sequence, therefore, parallels the order of crystallization in the magma; and (4) deposition and, therefore, crystallization were continuous during the deposition of the individual layers and cyclic units, but discontinuous between cyclic units.

POSTDEPOSITIONAL CONDITIONS

The primary precipitate formed a crystal mush on the floor of the intrusion, and the interstices of this mush were filled with the basaltic magma from which the primary precipitate had crystallized. The textures of the rocks provide some evidence as to the character of the mush, and the composition and crystallization course of the interprecipitate magma.

CHARACTER OF THE CRYSTAL MUSH

The porosity of the crystal mush on the floor of the intrusion during the accumulation of the rocks of the Ultramafic zone is estimated to have ranged from about 20 to 50 percent and to have averaged about 35 percent. Differences in initial porosity can be assigned to the physical properties of the crystal aggregate—size, sorting, shape—and to the amount of compaction prior to cementation. The permeability of the mush presumably was influenced by the packing and by the grain size of the individual layers. The thickness of unconsolidated mush at any one time on the floor of the intrusion apparently ranged from about 6 inches to about 10 feet, because beds of this range of thickness are involved in slump structures. Interprecipitate magma, however, probably existed at much greater depths in the mush, since it would take only a small amount of secondary enlargement to weld the settled crystals and impart a rigidity to the crystal pile.

INTERPRECIPITATE MAGMA

The composition and physical properties of the interprecipitate magma within the unconsolidated mush on the floor of the intrusion must be initially identical with those of the main magma immediately above it. At greater depths in the mush, however, two processes operate to change its character: diffusion and crystallization-differentiation. At shallow or intermediate depths in the mush, where interconnecting pore spaces are available, diffusion between the interprecipitate magma and the main magma is possible. The effect of such diffusion, as pointed out by Hess (1939, p. 431) would be to crystallize interprecipitate minerals of the same phase and composition as were being generated in the main magma above the floor of the intrusion. If only one phase was being precipitated by the main magma, and if accumulation rates were slow enough for diffusion to operate at maximum efficiency, completely monomineralic rocks would probably result. At deeper levels in the mush, or where continuous pore spaces were blocked by welding or impermeable layers, diffusion between the main and interprecipitate magma would not be operative, and the interprecipitate magma would be trapped. Textural and mineralogic relations indicate that the order of crystallization in this trapped magma is such that successive residual fractions are enriched in sodium, silicon, iron, and volatiles.

The relatively lower temperature crystallization products, the absence of exsolution lamellae in the latest crystallized parts of interstitial augite and bronzite, and the zoning—all indicate falling temperature of crystallization as the trapped interprecipitate magma solidifies. An inference as to the final consolidation temperatures in those rocks which contain grossularite-pyrope as a very late crystallization product may be drawn from Yoder's (1950, p. 250) conclusion that the assemblage quartz-grossularite-anorthite is incompatible at temperatures above about 650°C.

CRYSTALLIZATION OF THE INTERPRECIPITATE MATERIAL

Results of the present investigation substantiate Hess' (1939, p. 431) hypothesis that the course of crystallization in the interstices of the crystal mush is largely controlled by the rate of accumulation of that mush. Where the rate of accumulation and burial was rapid, the interprecipitate magma was effectively trapped and crystallized in place, with the formation of new mineral phases not encountered as primary precipitates until much higher in the section. Where the rate of accumulation and burial was slow, diffusion between the main and interprecipitate magma was relatively effective and all or much of the pore space between settled crystals was filled by material of the same composition as the primary precipitate.

MINERAL ASSOCIATIONS IN THE ULTRAMAFIC ZONE

Because the constituent minerals of Ultramafic zone rocks can be readily divided into primary precipitate and interprecipitate material, it is possible to examine separately the mineral assemblages produced during the early stages of crystallization of the main Stillwater magma, and the mineral assemblages produced by the same magma where differentiation was spatially restricted by entrapment in the crystal mush.

PRIMARY PRECIPITATE

The most striking feature of the primary precipitate assemblage is the tendency for the three settled minerals to occur singly rather than in combination with one another. In the case of olivine-bronzite associations, for instance, poikilitic harzburgite, which contains no settled bronzite, and bronzitite, which contains no olivine, are considerably more abundant rock types than granular harzburgite, which contains a mixture of the two minerals. In order to derive a quantitative expression of this tendency, stratigraphic thicknesses of each of these three rock types were measured, totaled, and recalculated to 100 percent in three complete sections of the Ultramafic zone; results are presented in table 10. Settled olivine and bronzite occur together in about 12 percent of the rocks of the zone; they are mutually exclusive in about 88 percent.

TABLE 10.—*Relative stratigraphic thicknesses of harzburgite and bronzitite in three complete sections of the Ultramafic zone*

Rock type	West Benbow section		Mountain View section		West Fork section		Average ratio
	Total thickness (feet)	Ratio	Total thickness (feet)	Ratio	Total thickness (feet)	Ratio	
Poikilitic harzburgite	1,370	27.4	1,675	23.8	750	20.8	24.0
Granular harzburgite	840	16.8	860	12.2	280	7.8	12.3
Bronzitite	2,785	55.8	4,515	64.0	2,580	71.4	63.7
Total	4,995	100.0	7,050	100.0	3,610	100.0	100.0

The tendency toward monomineralism of settled minerals is also evident in olivine-chromite mixtures. Although the two minerals apparently occur in all proportions, much of the chromite in the Ultramafic zone is concentrated into massive layers containing no other settled mineral.

Where settled minerals do occur as mixtures, there is a strong tendency for bimineralic associations. In rocks composed of mixtures of olivine and chromite, settled bronzite does not occur; in rocks composed of mixtures of olivine and bronzite, chromite occurs only in amounts less than 3 percent of the rock or 5 percent of the settled constituents.

The rocks of the Ultramafic zone contain only three settled minerals, so that it is possible to outline their fields of coexistence on a triangular plot. In order to establish their true proportions, it is necessary to subtract the amount of interprecipitate material in the individual specimens and recalculate to 100 percent, but in view of the practically universal occurrence of secondary enlargement and reaction replacement a certain care must be exercised in making the calculations. In most chromitite and bronzitite, only one settled mineral is present, and the recalculation may be made directly. In bronzitites which contain chromite, and in poikilitic harzburgites, it is necessary to make modal counts in areas where plagioclase is the interstitial mineral, in order to avoid the effects of reaction replacement. In granular harzburgites, the same procedure is generally followed, but in cases where this is impractical it is necessary to compute the original proportions of the settled minerals from the mode of the entire rock. In olivine chromitites and poikilitic chromite harzburgites, the original boundaries of olivine crystals are outlined by the closely packed chromite around them, and it is possible to measure the proportions directly. In rocks which contain two or more settled crystals, the assumption is made that the amount of secondary enlargement of each mineral is the same. This assumption is not invariably valid, but the error involved is not believed to be large enough to change the boundaries of the fields of occurrence.

Modes of 141 specimens of rocks of the Ultramafic zone, measured and recalculated by the methods described above, were plotted individually in figure 89. Chromitite, olivine chromitite, and poikilitic chromite harzburgite are disproportionally represented in order to outline their fields of occurrence. Nevertheless, the monomineralic tendencies of the settled minerals are obvious from the crowding at the apices of the diagram. Most bronzitite, which contains no olivine by definition, also contains no chromite. Nine of the 38 bronzitite specimens measured contain chromite in amounts less than 0.5 percent. Three bronzitite specimens contain between 1 and 4 percent settled chromite. Each of these three specimens occurs within 100 feet of the top of the Bronzitite member, and the significance of this abnormal chromite concentration at this particular horizon is discussed in a subsequent section of this report.

Mixtures of olivine and bronzite apparently occur in all proportions between $br_{100}ol_0$ and $br_{20}ol_{80}$. About two-thirds of the olivine bronzitite and granular harzburgite specimens contain measurable chromite, but the total amount in any one specimen does not exceed 5 percent. In a general way, the chromite content increases with increasing amounts of olivine. Specimens containing proportions of olivine and bronzite between $br_{20}ol_{80}$ and br_0ol_{100} were looked for but not found, and it is believed that a gap in the field occurs in this range.

Olivine and chromite apparently occur in all proportions over the range $ol_{100}chr_0$ to ol_0chr_{100}. The

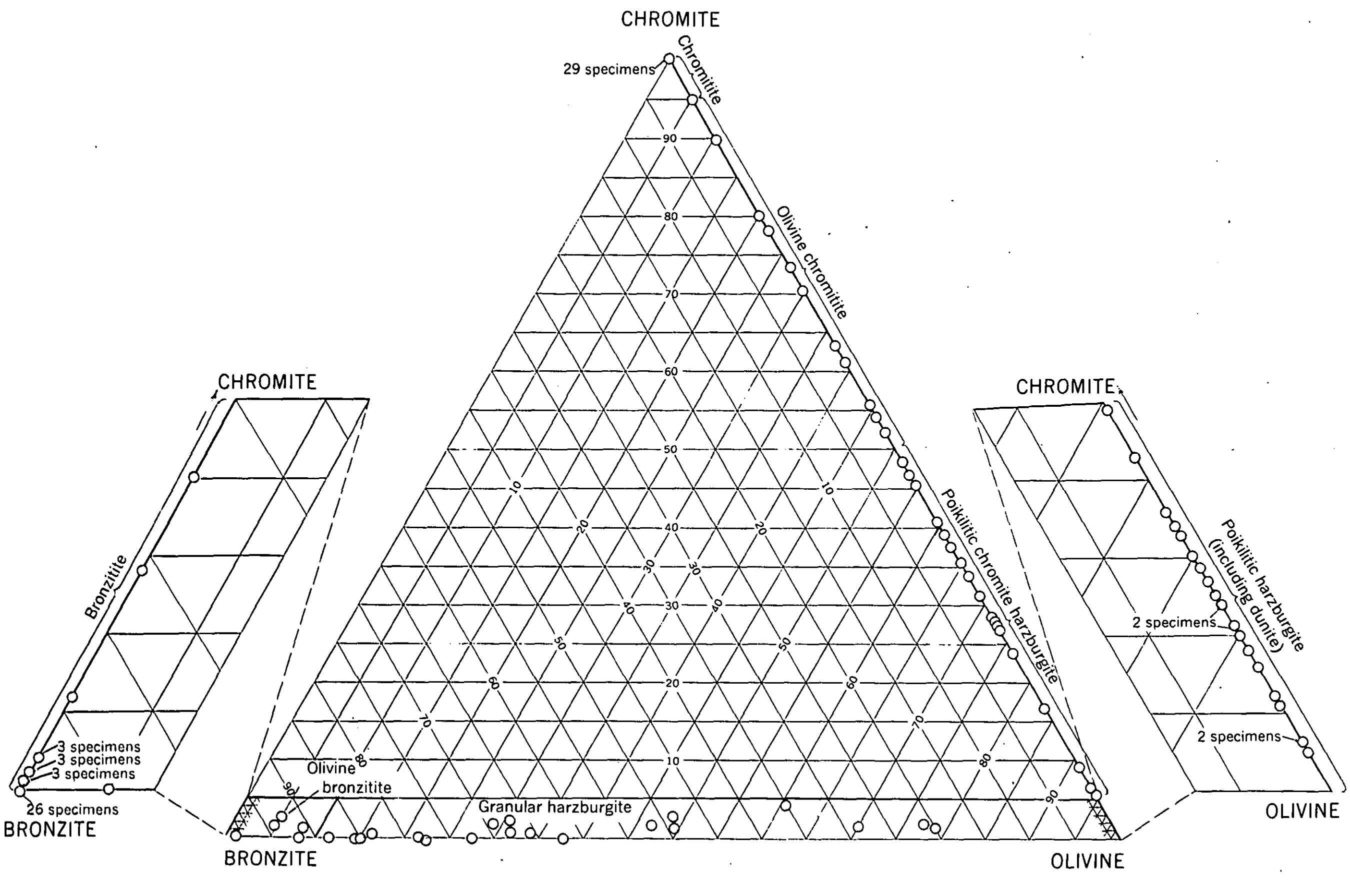


FIGURE 89.—Ratios of settled minerals in rocks of the Ultramafic zone.

line of variation between chromitite and poikilitic harzburgite contains no settled bronzite.

The fields of settled mineral associations shown in figure 89 indicate the minerals which accumulated simultaneously, and not necessarily those which crystallized together. The restriction of associations does indicate, however, which minerals typically could not have been crystallizing together. Thus, during the accumulation of the chromite mushes now represented by the massive chromitites, no olivine or bronzite was crystallizing; had they been, their size and density would have caused their incorporation into the mush. Similarly, during the accumulation of most bronzitite, no mineral other than bronzite was crystallizing within settling distance of the floor of the intrusion. Such monomineralic crystallization could take place over considerable periods of time: during the accumulation of the 1,500- to 3,000-foot thickness of the Bronzitite member, the only mineral crystallizing from the Stillwater magma was bronzite.

If the presence of thick layers containing only one settled mineral connotes monomineralic crystallization from the magma, the presence of layers containing mixtures of settled minerals does not necessarily connote cotectic relationships between them. There appear to be three mechanisms whereby the observed distributions of two or more settled minerals might occur: (1) by cotectic crystallization, (2) by mechanical mixture of minerals crystallized at different times or places, and (3) by simultaneous crystallization at different horizons in the magma.

The distribution of chromite inclusions in olivine in a few rocks suggests a cotectic relation between these two minerals. In the great majority of such rocks, however, inclusions do not occur, and it is not possible to estimate the quantity of rocks or the relative proportions of the two minerals through which a cotectic relationship existed. The constant association of a small amount of chromite with all rocks formed from olivine crystal mushes, and the localization of all chromitite layers within poikilitic harzburgite layers certainly suggests that the crystallization fields of olivine and chromite are adjoining. The general absence of rocks containing mixtures of chromite and bronzite, on the other hand, suggests that the crystallization fields did not adjoin in the part of the field where crystallization occurred, at least until nearly the entire Ultramafic zone had crystallized, and the original magma had been considerably modified by differentiation, including depletion of the magma in chromium.

It is obvious from inspection of figure 89 that the efficacy of mechanical mixing of settled crystals cannot be large. Current mixing has, however, changed proportions of settled minerals in a few current-bedded olivine chromitite and granular harzburgite layers, and differences in settling velocity no doubt account for some of the olivine-chromite graded beds. Neither current deposition nor suspension, however, appear to be capable of producing the thick, internally homogeneous olivine chromitite and poikilitic chromite harzburgite layers, nor do these mechanisms readily explain the olivine-bronzite size-proportion relations in granular harzburgite layers.

The association of olivine and bronzite in the granular harzburgite and olivine bronzitite layers, in fact, demands a special explanation. It is abundantly demonstrated in the Stillwater rocks that olivine and bronzite have a reaction relationship and consequently cannot crystallize at the same time and place in the magma. It is proposed, therefore, that during certain conditions of crystallization olivine and bronzite crystallized simultaneously at slightly different horizons above the floor of the intrusion. The abrupt appearance of bronzite in relatively small quantities at the bases of the granular harzburgite layers suggests that bronzite began crystallizing at a higher level than the olivine, fell through the zone of olivine crystallization, and became incorporated in the crystal mush. Upward in the granular harzburgite layers, olivine becomes smaller and less abundant, which suggests that olivine crystallization was restricted to increasingly narrow zones near the floor of the intrusion. Such a mechanism would not only provide an explanation for the regular grain-size and abundance variations of the two minerals, but would explain the absence of bronzite reaction shells on the olivine in the rocks. A similar process may account for some olivine chromitite and poikilitic chromite harzburgite layers, because many of these layers gradually increase in olivine at the expense of chromite upward in the section; however, the relative effect of cotectic crystallization in these rocks cannot be evaluated.

INTERPRECIPITATE MATERIAL

If the settled crystals represent the early crystallization products, or solidus, of the Stillwater magma, then the interprecipitate material should in a broad sense represent the liquidus, or the magma from which the settled crystals were precipitated. It would seem reasonable, therefore, that one could determine magma compositions layer by layer, stratigraphically upward in the section, by measurement of the volume and composition of the interprecipitate material in the various layers. Unfortunately, it can be shown that the interprecipitate material does not necessarily represent the composition of the liquids trapped in the interstices of the crystal mush, and, furthermore, that the trapped magma in individual layers is not necessarily of the same composition as the main magma from which the settled crystals in that layer were precipitated. It would be possible, however, to obtain an approximate overall composition for the trapped magma if that portion of the interprecipitate material which crystallized from it could be recognized.

The interprecipitate material may be divided into (1) the secondary enlargement material, (2) the reaction replacement material, and (3) the interstitial minerals. Of these, the secondary enlargement material properly belongs, mineralogically and chemically, with the primary precipitate, because it grew in equilibrium with the main magma. Reaction replacement material and interstitial minerals, for the most part, represent new phases caused by entrapment and later crystallization of the magma. Those portions of the reaction replacement minerals which formed from previously existing settled crystals, however, were not entirely constituted from the trapped magma; where bronzite replaced olivine, for instance, only SiO_2 was added. The interstitial material, including those portions of reaction minerals which fill interstices, is entirely a product of the trapped magma. The interstitial material alone should furnish an approximation of the composition of the trapped magma, but this approximation does not include elements provided in reaction replacement, nor does it include that small portion of the trapped magma that crystallized to form minerals already present as settled constituents.

A serious limitation in obtaining approximations of the composition of trapped magma is the problem of obtaining significant measurements of interstitial minerals. Reproducible proportions of the relatively fine-grained and evenly distributed settled minerals may be obtained from small slabs or thin sections, but the extreme grain-size ranges in the interstitial material make equivalent accuracy impossible to obtain, even where large slabs were used. Furthermore, the interstitial material makes up only a small part of the rocks, and errors are considerably magnified by recalculation to 100 percent.

Although significant measurements of interstitial material in individual specimens is generally impractical, an average value for a large number of specimens is probably reasonably representative. Qualitatively, the variation in proportions of interstitial constituents is greater between rock types than within them. In order to obtain quantitative data, the amounts of interstitial minerals in 94 specimens containing greater than 10 percent total interstitial material were measured, recalculated to 100 percent, averaged by rock type, and plotted in figure 90. In most rocks, more than 95 percent of the total interstitial material is composed of the three minerals—bronzite, chromian augite, and plagioclase—so that averages are plotted for simplicity on a triangular diagram. The only major exception occurs in the chromitite specimens, in which olivine constitutes an average of about 20 percent of the interstitial material. This was combined directly with bronzite for purposes of plotting on the diagram.

The ratios of interstitial minerals in the three major rock types of the Ultramafic zone—poikilitic harzburgite, granular harzburgite, and bronzitite—fall nearly on a straight line in figure 90, and are arranged in the same sequence as their appearance in the cycles. Chromian augite makes up about 10 percent of the average interstitial material in all three rock types, and plagioclase replaces bronzite as an interstitial constituent as settled olivine gives way to settled bronzite. The ratios of interstitial minerals in chromitite and olivine chromitite layers, which lie stratigraphically within the poikilitic harzburgite layers, do not fall on this curve. Both contain relatively greater amounts of chromian augite and relatively less plagioclase than the averages for the major rock types.

Assuming that the plotted data are representative of the average proportions of interstitial minerals in the various rock types, and that the interstitial minerals are reasonably representative of the composition of the trapped magma, the gross changes in interstitial mineralogy indicate the broader chemical trends in the liquid once present in the crystal mush. The trapped magma in the average chromitite apparently contained slightly larger amounts of iron and magnesium, and less aluminum, than the trapped magma in the average poikilitic harzburgite. The compositional trend of the three major rock types is toward strong calcium and aluminum enrichment in passing from poikilitic harzburgite through granular harzburgite to bronzitite. Because the major rock types occur in a regular order of succession, this variation coincides with the variation within the cyclic units and is repeated some 15 times throughout the Ultramafic zone.

If it is further assumed that the composition of the trapped magma in some measure reflects the composition of the main magma—an assumption that cannot at present be verified—then there appear to be at least two possible explanations for this variation: (1) The composition of the trapped magma reflects the composition of the main magma from which the settled crystals precipitated, and its compositional change within the cycle reflects the changing composition of the main

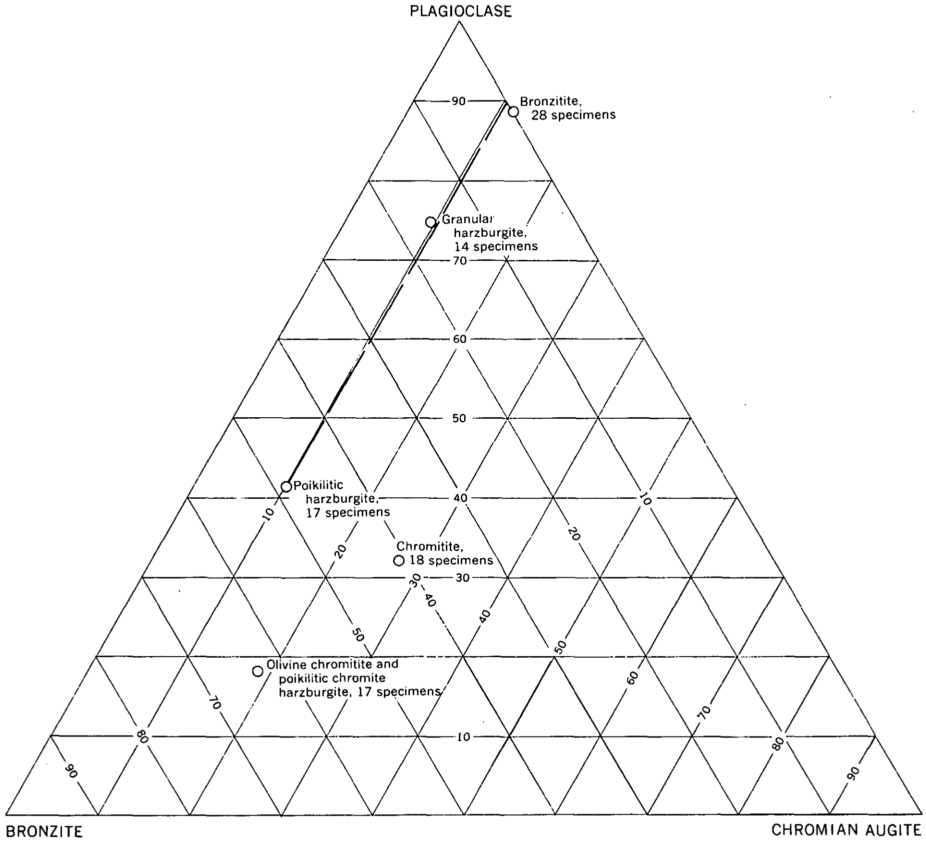


FIGURE 90.—Ratios of principal interstitial minerals in rocks of the Ultramafic zone.

magma as it precipitates new phases of settled crystals. (2) The composition of the trapped magma in the entire cycle represents the average composition of the main magma, but the trapped magma has differentiated in place, first forming bronzite in the lower olivine-rich layers and leaving a plagioclase-rich residuum to crystallize in the uppr bronzite-rich layers. A choice between these hypotheses cannot be made until additional data on the chemical composition of the interstitial minerals are available.

CLASSIFICATION OF ROCK PRODUCTS

The rocks of the Ultramafic zone are generally made up of about 65 percent settled minerals and 35 percent interprecipitate minerals. The interprecipitate material may be all or in part of the same composition as the settled minerals, the remainder being made up of new phases precipitated from magma trapped in the interstices of the crystal mush.

The mineralogic composition of individual specimens can be expressed as modes, and the specimens can be assigned rock names on the basis of their total mineral constituents. This normal basis of classification, which suffices to distinguish many igneous rocks, fails to provide a breakdown suitable for field distinctions in the Stillwater complex for two reasons: (1) A standard mode does not differentiate between settled and interstitial minerals, so that many granular and poikilitic harzburgite specimens, for instance, have identical modes. (2) The variability of interstitial constituents in the rocks complicates the classification and leads to a multiplicity of rock names based on minor constituents that are not consistent along the strike of the layers.

The problem of classification in Stillwater rocks is therefore similar to that in sedimentary, rather than igneous rocks. The bulk composition of the rocks does not represent the composition of the magma from which they crystallized and is not, therefore, of direct genetic importance. As with sediments, the allogenic minerals of the Ultramafic zone are spread out in mappable beds, and the interstitial constituents are dependent on postdepositional factors that may vary from place to place along the beds. The fundamental basis for a field classification of Stillwater rocks must, therefore, be the presence, absence, and proportions of the settled crystals in the rocks.

Ideally, new terms expressing the various fields of settled mineral associations should be coined, or rock names should be avoided altogether in the manner of Shand (1942, p. 409–428), to avoid confusion with existing compositional terminology. Standard ultramafic rock names have, however, been applied to Stillwater rocks in previous publications, and precedence for their use has been set. Rather than burden the literature with new names, therefore, the existing terminology for rocks of the Ultramafic zone of the complex is here more rigidly defined.

The fields of the various rock types are based entirely on presence, absence, and proportions of settled minerals; these are shown diagrammatically in figure 89. The sequence of rocks made up of mixtures of settled olivine and chromite are arbitrarily divided on the basis of ratios of the two minerals in the rocks. Chromitites range from chr_{100} to ol_5chr_{95}, olivine chromitites from ol_5chr_{95} to $ol_{50}chr_{50}$, and poikilitic chromite harzburgites from $ol_{50}chr_{50}$ to $ol_{95}chr_5$. The poikilitic harzburgite field ranges from $ol_{95}chr_5$ to ol_{100}, although no rocks are at present known that contain less than 0.5 percent chromite. Rocks composed of mixtures of olivine and bronzite commonly contain some chromite, so that the fields are two dimensional. Granular harzburgites occur within the field bounded by br_0ol_{100}, $br_{90}ol_{10}$, $br_{85}ol_{10}chr_5$, and $ol_{95}chr_5$, although specimens containing less than 20 percent settled bronzite have not been observed. Olivine bronzitites occur within the field bounded by $br_{90}ol_{10}$, br_{100}, $br_{95}chr_5$ and $br_{85}ol_{10}chr_5$, and bronzitites range from br_{100} to $br_{95}chr_5$. Other fields, such as chromite bronzitites or granular chromite harzburgites, could be added to the general classification if specimens with corresponding ratios of settled minerals are subsequently observed.

The term dunite is a useful one, and it has been used in previous publications to describe certain layered rocks of the Ultramafic zone in the Stillwater complex. It is retained as a term to describe rocks composed of 95 or more percent olivine. Dunite is, therefore, a particular variety of poikilitic harzburgite, whose settled constituents are olivine and accessory chromite, and which is characterized by extreme secondary enlargement of olivine.

This system of nomenclature leads to some unconventional classifications—for instance, one specimen containing only 50 percent modal bronzite must be placed in the bronzitite field. In addition, some rocks that in terms of strict mineralogic nomenclature are websterite, lherzolite, gabbro, or norite are included as bronzitite or harzburgite. Wherever the total mineralogic composition of the rocks is pertinent to the discussion, however, individual modes will be presented.

SIGNIFICANCE OF THE DEPOSITIONAL CYCLES

The cyclic units are the building blocks of the Ultramafic zone, and any attempts at reconstructing the genesis of the zone must primarily be concerned with their origin.

SUMMARY OF SALIENT FEATURES

The cyclic units are internally continuous, repetitive stratigraphic layers in which the settled minerals appear and disappear in a regular order. Minerals were continuously being deposited during the cycles, but the boundaries between cyclic units represent hiatuses. Based on the law of superposition, the stratigraphic sequence of settled minerals represents their order of accumulation within the cyclical unit. Further, in the absence of rafting and current sorting, the order of accumulation within the cycles represents the order of crystallization of the settled crystals from the magma above the floor of the intrusion.

Within the Peridotite member, the order of crystallization of primary precipitate minerals during accumulation of the cyclic unit was olivine, chromite, olivine, bronzite, as represented by the rock types poikilitic harzburgite, chromitite, olivine chromitite, poikilitic harzburgite, granular harzburgite, and bronzitite. The order of disappearance within the cycle was chromite, olivine. Although the order of succession of the rock types is consistent, not all cyclic units within the Peridotite member are complete: some are terminated within the poikilitic harzburgite layer and some within the granular harzburgite, so that bronzitite is not developed. The character of the cyclic units changes gradually upward in the Peridotite member: stratigraphically lower cyclic units contain more poikilitic harzburgite relative to bronzitite, and higher cyclic units are proportionally enriched in bronzitite. In a few cyclic units near the top of the Peridotite member, the rock type at the base of the unit is granular harzburgite.

Within the Bronzitite member there appear to be two possibilities regarding cyclic units: (1) the Bronzitite member represents a single continuously deposited upper portion of the highest cyclic unit of the Ultramafic zone, and differs from bronzitite layers within the Peridotite member only in its thickness; or (2) an unknown number of cyclic units consisting only of settled bronzite occur within the member, concealed by its monotonous lithology. The apparently continuous size changes of bronzite crystals within the member seem to favor the first possibility, but the samples are widely spaced, and sharp small-scale size changes are known to exist. The presence of two thin, apparently lenticular layers of granular harzburgite in the Bronzitite member in the Mountain View section, where it reaches its maximum development, favor the second possibility. In either case, virtually the only primary

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precipitate of the Stillwater magma during the accumulation of the member was bronzite.

Near the top of the Bronzitite member, a new cyclic unit consisting of a lower layer of coarse bronzitite with accessory chromite, and an upper layer of norite, can be recognized. The order of crystallization within this unit was therefore essentially bronzite, plagioclase.

CHEMICAL ASPECTS

Assuming that deductions as to the order of crystallization of the primary precipitate within the cyclic units are valid, certain phase boundary relationships can be deduced. The investigated chemical field most nearly resembling the composition of the chilled gabbro of the Stillwater complex is the system diopside–forsterite–anorthite–silica (Osborn and Tait, 1952, p. 425–432). If iron is assigned to magnesium, the chilled gabbro composition plots at about $di_{20}fo_{30}an_{40}q_{10}$, near the anorthite–forsterite–silica face of the tetrahedron. This point is within the forsterite field near the spinel boundary. The primary crystallization product would therefore be forsterite, and this would next be joined by spinel. Following forsterite--spinel crystallization, however, the magma would precipitate forsterite–anorthite and dissolve spinel. If the natural system resembles the investigated one, then the chromite field of the former must be larger than the spinel field of the latter and must extend as far as pyroxene, for no settled feldspar is found in the cyclic units of the Ultramafic zone. In the investigated system the forsterite–clinoenstatite join is a reaction boundary, and the same situation is indicated in the cyclic units by the early disappearance of olivine. The system anorthite–forsterite–silica (Andersen, 1915, p. 407–454) accurately predicts the order of crystallization in the final cyclic unit of the Ultramafic zone. Assuming that the Stillwater magma had been enriched in SiO_2 by the precipitation and settling of considerable quantities of olivine and chromite, the diagram predicts that bronzite will then crystallize, followed by bronzite plus plagioclase, and this is the observed relation. It is of interest to note that in preliminary investigations of the crystallization behavior of Kilauean tholeiite basalts compositionally similar to the chilled gabbro of the Stillwater complex, Yoder and Tilley (1956, p. 169; 1957, p. 157–158) found the order of crystallization to be olivine, bronzite, plagioclase.

Several features of the cyclic units cannot, however, be explained in terms of the investigated systems. If the magma began crystallization in the olivine field during the formation of the Peridotite member units, then no simple explanation for the massive chromitite layers indicating slightly later monomineralic crystallization of chromite is apparent. Nor does the system explain the ubiquitous small quantities of chromite that occur with olivine in the poikilitic harzburgite layers above and below the chromitite layers. Further, the vertical disappearance of chromite before the appearance of a third solid phase, and the absence of resorption textures involving chromite, do not correspond with the experimental system, but this may be a result of the early exhaustion of the small chromium content of the magma.

The textures of the granular harzburgites—the rocks which lie between the layers representing the crystallization of olivine alone and bronzite alone—are also not what one would expect to find at a reaction boundary, in that euhedral olivine and bronzite crystals exist side by side throughout the rock. Bowen (1928, p. 58–59), however, emphasizes that:

> There is nothing in the existence of a reaction relation between two crystal species to prevent the occurrence of both as perfectly formed crystals with no evidence of a resorption of the earlier member of the reaction pair . . . under certain conditions of rapid cooling the liquid may ignore the olivine crystals and pass immediately into the pyroxene field with formation of crystals of that phase.

Still, several granular harzburgite layers exceed one hundred feet in thickness, and it seems probable that olivine continued to crystallize after bronzite had begun to precipitate. For this reason, it has been proposed that two different crystallization layers existed briefly in the magma above the floor of the accumulating crystal mush.

HISTORY OF THE CYCLE

In view of the chemical complexity of the natural magma compared to the investigated systems, the correspondence between crystal products and their order of appearance and disappearance is surprisingly good; this correspondence, combined with textural evidence, perhaps justifies a preliminary reconstruction of the history of accumulation of a cycle. The many evidences, assumptions, and inferences involved have been stated elsewhere in the text and need not be repeated here.

The cycle began with the precipitation of olivine crystals from the magma near the floor of the intrusion, and these immediately began to sink. Crystals that formed near the floor had less opportunity for growth, and thus the grain size of the olivine in the mush was finer near the floor. After 5 to 100 feet of mush had formed, olivine crystallization ceased abruptly and chromite was temporarily the only crystallization product of the magma, perhaps as a result of supersaturation and excursion of the liquid into the chromite field. A thin, relatively impermeable layer of fine-grained chromitite was then formed in the crystal mush—a layer that later acted as a cap rock to interstitial solutions attempting to rise as the mush compressed slightly—resulting locally in the formation of gabbroid pegmatites along its base. As with olivine, the growth of chromite crystals forming nearest the floor was arrested by deposition, so that the basal chromite crystals were slightly finer grained than those near the center of the layer. Olivine then joined chromite as a crystallization product and the two crystallized together, olivine increasing in amount and chromite decreasing until the chromium content of the magma was virtually exhausted.

Olivine then continued to crystallize alone, its crystal diameters increasing upward as crystals arrived from increasingly greater distances above the floor. Bronzite began to crystallize at a higher level in the magma, fell through the zone of olivine crystallization, and, at a sharp boundary in the mush, the two minerals began to accumulate simultaneously. Olivine crystallization became restricted to narrower and narrower zones above the floor and thus began to decrease in size and total amount, whereas bronzite increased in both. Along a gradational contact olivine finally ceased to be a crystallization product, and bronzite continued to precipitate alone. Bronzite crystals gradually decreased in size to the top of the cyclic unit, perhaps due to a combination of gradual cessation of crystallization and differential settling of the finer crystallization products. The crystallization had ended and all crystal products had reached the floor before olivine of the succeeding cycle began to precipitate. During the entire time of accumulation and primary crystallization of the cyclic unit the magma was stagnant, or nearly so.

Once collected, most settled crystals continued to grow somewhat into the interstices of the mush and against their neighbors, the amount of secondary enlargement being largely a function of the rate of accumulation. This enlargement tended to produce a rigidity in the mush by welding grains together and, for the most part, prevented the squeezing out of the magma trapped in the remaining interstices of the mush. However, the mush was not so rigid as entirely to prevent loss of porosity by compressional weight of overburden, inasmuch as voids caused by contraction during change from liquid to solid state have not been observed. The crystallization behavior of this trapped liquid on cooling depended a great deal on the settled crystals with which it was choked: where it surrounded olivine, the magma attempted to make olivine over into bronzite, but it lacked the volume to accomplish this entirely and finally crystallized plagioclase and augite. Similarly in bronzitite, the magma on cooling reacted with bronzite to form augite and finally crystallized plagioclase, accompanied by a small amount of quartz in a few rocks.

Two major problems remain in establishing the possibility of this simplified mode of origin: (1) to establish that bottom crystallization is physically reasonable, and (2) to derive a mechanism capable of causing repetitive cyclical deposition.

BOTTOM CRYSTALLIZATION

The nature of the layering suggests that crystallization of the primary precipitate of the Ultramafic zone occurred at the bottom, rather than the top of the intrusion. Had the settled minerals formed at the top and settled directly through 5 or 6 miles of magma, the rocks would exhibit features of extreme differential settling. Furthermore, Hess (1956, p. 449) has shown that, at reasonable magma viscosities, the time of fall from roof to floor is large, considering the probable solidification rate of the intrusion. Transportation of high-level crystallization products to the floor of the magma chamber by magma currents fails to explain the mineralogic, rather than size-density, sorting that occurs in individual layers and cycles. The most reasonable explanation for the observed textures and structures, therefore, would seem to be that the primary precipitate crystallized near the bottom of the intrusion and accumulated by simple crystal settling on the floor as rapidly as it formed.

Many authors have postulated nonconvective cooling and crystal settling as probable or possible mechanisms for differentiation and layering in mafic sill-like intrusions (Tyrrell, 1916, p. 123–128; Bowen, 1919, p. 411–423; Walker, 1940, p. 1083–1089; Edwards, 1942, p. 603–604; and Cornwall, 1951, p. 190–193). Subsequent to initial chilling effects, cooling in nonconvecting, moderately thick horizontal bodies not in an infinite medium must be predominantly from the upper surface, where thermal gradients are increased by the proximity of the earth's surface, which is maintained at constant temperature by atmospheric processes. Lovering (1935, p. 86) has demonstrated that, after an appreciable time, temperatures in the country rock below a tabular body may actually exceed those in the body itself. The major site of crystallization in such bodies depends on the relative magnitudes of the actual thermal gradient and the melting-point gradient in the magma. Disregarding the early chill effects, crystallization in a stagnant magma may: (1) proceed inward from both the upper and lower surfaces at essentially equal rates providing the body is relatively thin or deeply buried (Jaeger, 1957, p. 311–312); (2) proceed in all parts of the magma simultaneously if the body has its upper surface at shallow depths and a compositional gradient is established (Cornwall, 1951, p. 192); or (3) proceed predominantly downward from the top if the body is extremely thick.[7]

The heat relations and site of major crystallization subsequent to early chill effects are, however, considerably different in convecting magmas (Jaeger, 1957, p. 317). Wager and Deer (1939, p. 266–270) proposed a theory of convection circulation in the Skaergaard intrusion in which crystallization began in the upper part of the intrusion, owing to cooling, and continued during the descent in the convection current, owing to increase in pressure. The growing crystals contributed to the mean density of the magma, and, at the bottom of the continuous cycle, they spread out over the floor of the intrusion. This process has been illustrated diagrammatically by Wager (1953, p. 346). Hess (1956, p. 449) has stated that he favors the same mechanism to explain the crystallization process in the Stillwater complex.

Wager and Deer base their ideas of crystallization at depth in the magma on the assumption that, in a convecting magma, the melting point increases with depth faster than the actual temperature of the magma, and these authors (1939, p. 268–269) state:

> If the upper part of the Skaergaard magma is regarded as on the point of precipitating crystals of the primary phases, plagioclase, olivine and pyroxene, then the increase in pressure as the magma is carried down by the convective circulation should cause some crystallization, since the thermal gradient is about 0.3° centigrade per kilometre and the raising of the melting point for these minerals lies between 1° and 5° centigrade per kilometre of descent.

Wager and Deer's figure for the adiabatic gradient is derived from Jeffreys (1929, p. 138–139), and their melting-point gradient from measured or calculated data for the minerals forsterite, fayalite, diopside, and anorthite.

The relative values of the adiabatic and melting-point gradients are extremely important in determining the site of crystallization in a convecting magma, and a review of their nature seems warranted here. The equation for the adiabatic gradient in a perfectly convecting magma may be derived from the first law of thermodynamics, and the solution requires a knowledge of the temperature, specific heat at constant pressure, and coefficient of volume expansion of the magma. From this equation, Adams (1924, p. 462) determined the adiabatic gradient in a postulated molten mantle to be "something less than 1°C. per kilometer of depth." Jeffreys (1929, p. 138), using in the same equation the parameters: temperature 1400°K, specific heat 0.2 calories per gram-degree, and coefficient of volume expansion 2×10^{-5} per degree, determined the thermal gradient of the mantle to be about 0.3°C. per kilometer. The application of Adams' and Jeffreys' values to the mantle as a whole have been criticized (Verhoogen, 1956, p. 30, 33–34), but the equation for adiabatic gradient and even the parameters used by Jeffreys would seem to express very adequately the thermal distribution in a convecting magma in the upper levels of the crust. An expression for the melting-point gradient may be derived from the Gibbs free energy and Clausius-Clapeyron equations, and Jeffreys (1952, p. 272), using fairly typical values for igneous rocks, calculated the gradient to be about 3°C per kilometer. More recently, Yoder (1952, p. 364–374) experimentally determined the change in melting point in diopside with pressure, and he, on the basis of this experimental work, estimated the gradient for basalt to be 10°C per 1000 bars, or about 3°C per kilometer. Thus, it would appear that in a convecting basalt sill, the increase of melting point of the basalt at depth would be about 10 times the increase in temperature.

If these gradients are of the right order of magnitude, then Adams' (1924, p. 459–472) argument on solidification of the earth may be applied to solidification of the Stillwater magma; crystallization must have begun at the bottom of the relatively thick sill, once the initial chill effects were overcome, and convection established on an adiabatic gradient. This relation is illustrated in figure 91, a diagrammatic representation of the heat relations in an initially molten sill 8 kilometers thick (the assumed initial thickness of the Stillwater magma). At t_1 it is assumed that the magma has established its adiabatic gradient above the melting-point gradient, and no crystallization occurs. As heat is lost from the top of the sill, the temperature of the magma decreases uniformly, and the adiabatic gradient is maintained. At t_2 the temperature curve in the cooling magma intersects the melting-point temperature curve at the bottom of the sill, and crystallization begins, while the temperature at the top is still more than 20 degrees above the melting point. At t_3, after considerable convective cooling and consolidation have taken place, the zone of crystallization has moved upward although remaining near the floor of the intrusion. In relatively thin sills, or in thick ones which have reduced their thickness by precipitation and building at the floor, these conditions may not obtain. At the chosen gradients, a sill 2 kilometers thick beginning to crys-

[7] Hunter (1958, p. 20–24) has recently proposed a mechanism whereby very hydrous magmas cooling by conduction would crystallize from the bottom upward.

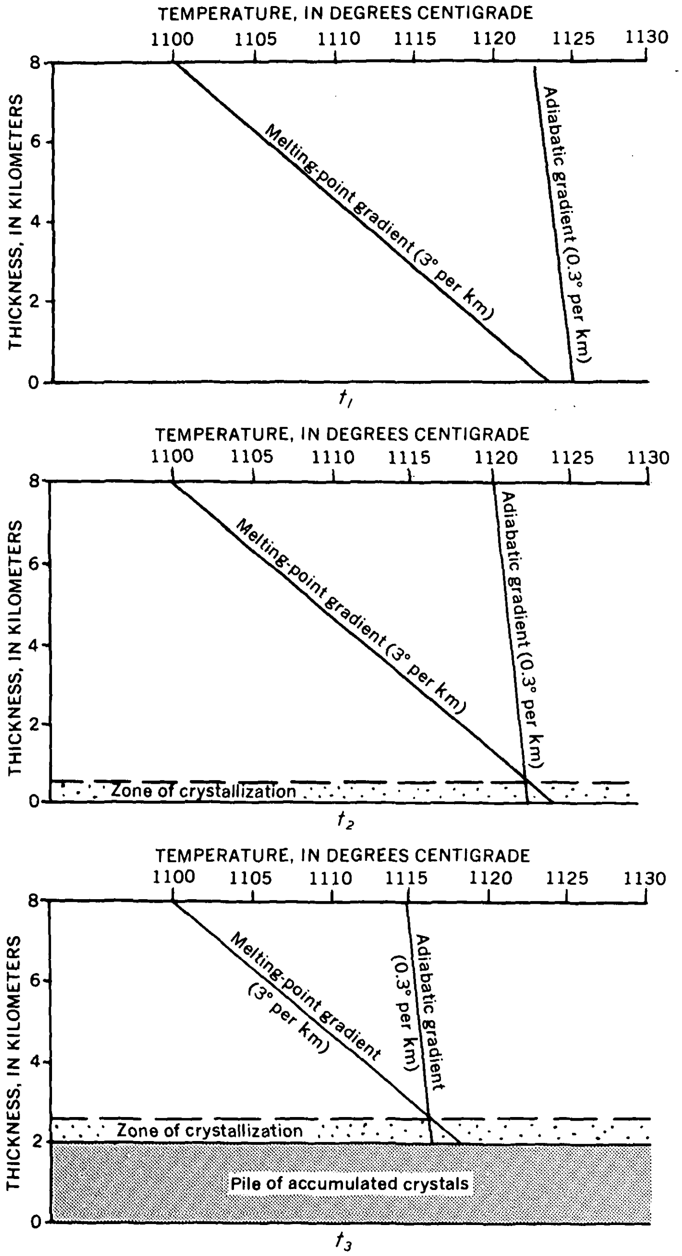

FIGURE 91.—Hypothetical crystallization behavior in a thick convecting sill.

tallize would be only about 5 degrees above its melting point at the top, and if the gradients near the top are slightly superadiabatic, the cooling might cause crystallizations like those pictured by Wager and Deer, and Hess. Through the Ultramafic zone of the Stillwater complex, at least, the available evidence suggests that crystallization of the primary precipitate occurred entirely at the bottom if the magma was thoroughly mixed.

The question remains whether convection did, in fact, exist in the Stillwater magma during crystallization and accumulation. The abundant current structures cited by Wager and Deer (1939, p. 262–266) as evidence for current deposition in the Skaergaard intrusion are for the most part lacking in the Ultramafic zone of the complex. A theoretical discussion of convection is hampered by lack of knowledge concerning original shape and dimensions of the Stillwater magma chamber, but, ideally, a Newtonian fluid cooling predominantly from the top is unstable by reason of increased density of the surface layers and will convect, provided the viscosity is not so great as to prevent it. Scheidegger (1953, p. 144) uses the product of the Grashoff and Prandtl numbers to predict convection in the mantle, and although there is some doubt as to the significance of this product in highly viscous materials, it should at least be more applicable to liquid magmas than to solid substances. Calculation of the Grashoff-Prandtl product for the Stillwater magma, assuming a cell diameter of 15 miles and a temperature difference of only one degree, shows that convection would not be damped unless the viscosity were about 3×10^{16} poises, a figure some 13 orders of magnitude greater than the expected viscosity. Inasmuch as any crystallization at the top of the intrusion would serve to increase the probability of overturn, convection appears to be theoretically compelling.

INTERMITTENT CRYSTALLIZATION

An attempt has been made to show that the cyclic units are the fundamental building blocks of the Ultramafic zone, and that each cyclic unit represents a single crystallization sequence that occurred near the bottom of the intrusion chamber. A brief and tentative discussion of mechanisms capable of producing the repetition of these crystallization sequences is necessary in order to complete a preliminary outline of origin for the lower portion of the complex. Two such mechanisms will be considered. The first, multiple intermittent injections of magma during crystallization, which was proposed by Lombaard (1934, p. 40–52) to explain certain oscillations in the stratigraphy of the Bushveld complex, appears to have serious limitations in application to the Stillwater. The second, a process which involves continuous convection at the top and intermittent crystallization at the bottom during the consolidation of a single intrusion, is proposed by me, for it appears, at this stage of the investigation, to be the most probable mechanism to account for the cyclical distribution of compositional layers in the Ultramafic zone.

INTERMITTENT MAGMA INJECTION

Lombaard's multiple injection hypothesis, which was later adopted by Kuschke (1939, p. 71–73) and Van der Walt (1941, p. 111), involved differentiation and remelting of successive crystal products in a subcrustal magma chamber, and injection of these liquids in pulses to form the Bushveld complex.[8] This process was criticized by Turner and Verhoogen (1951, p. 223), who objected to the coincidence of preintrusive differentiation in an elusive, hidden chamber. Cooper (1936, p. 44–45) postulated repeated injections of original magma to account for repetitive stratigraphy in the Bay of Islands complex, and this seems a more reasonable process.

A superficially plausible explanation for cyclic variation in the Ultramafic zone of the Stillwater complex can be constructed using a mechanism similar to Cooper's. A portion of the magma was injected, formed the chill zone, began to convect, and crystallized olivine and then pyroxene at the base of the magma chamber, forming cyclic unit 1. A second pulse of the same magma was then injected into the upper part of the chamber. The fresh magma supplied heat, stopped convection, and terminated crystallization at the base. After mixing, convection was reinaugurated, crystallization began once more, and cyclic unit 2 was deposited. This process was then repeated some 15 times during the accumulation of the Peridotite member. The injections thereupon ceased and allowed the remaining magma to crystallize bronzite alone until, with continued cooling, the mineral was joined by plagioclase.

Hess' (1940, p. 377; 1941, p. 584) mineral variation curves for the Stillwater complex indicate that no fresh magma was injected into the Stillwater system subsequent to the first appearance of settled plagioclase at the top of the Ultramafic zone, and the simple mineralogy of the Bronzitite member indicates that a similar situation prevailed. New influxes of magma, if such occurred at all, must therefore have ceased early in the history of the complex. The possibility that magma injection occurred during the accumulation of the Peridotite member cannot be eliminated, but several strong objections to the theory exist: (1) The initial injection of the complex was accompanied by emplacement of considerable amounts of iron-copper-nickel sulfides along the base, and there is no reason to suppose that subsequent injections would be lacking in similar amounts of sulfur, but no sulfide concentrations at the bases of the cyclic units have been observed. (2) Magma injections forming stratigraphically higher cyclic units would be emplaced after consolidation of the lower cyclic units, but no intrusive disturbances of layers of the Ultramafic zone have been observed. (3) The total olivine-bronzite ratio in the cyclic units of the Peridotite member changes slightly and gradually from bottom to top, so that Lombaard's coincidental theory of simultaneous differentiation in a hidden chamber must, to some extent, still be called upon. Brown's (1956, p. 44–45) recent "reflux" theory, which involves not only successive emplacement of magma but concomitant extrusion, seems to account very satisfactorily for the rhythmic units at Rhum, but, when applied to the cyclic units of the Stillwater complex, it is also subject to the three objections listed above.

[8] More recently, Worst (1958, p. 334–345) has elaborated on Lombaard's theory and adopted it to explain the formation of the Great Dyke.

VARIABLE-DEPTH CONVECTION

In consideration of the objections to multiple injection as an explanation, it seems preferable to turn to a hypothesis based on single magma injection to account for the repetitive distribution of the cyclic units in the Peridotite member. A mechanism involving variable-depth convection and periodic refreshment of stagnant bottom magma undergoing crystallization seems to fit the observed facts, at least within the Ultramafic zone of the complex. A tentative outline of this mechanism will be made here, and a more detailed treatment will be presented in a subsequent publication.

It is presumed that the magma was injected within a relatively short period of time, and essentially as a single pulse, into relatively cool wall rocks. Conduction of heat by the wall rocks resulted in an initial depression of temperature in the magma at both top and bottom of the intrusion, producing fine-grained chilled gabbro at the margins. During this initial stage of crystallization, the magma presumably was relatively stagnant, and hotter in the central portion than at either top or bottom. At this stage, the rates of heat loss from the top and bottom were much the same, magma temperatures decreased nearly symmetrically, and supercooling resulted near both margins. At both the top and bottom of the chamber the magma was dense, not only because of the relatively lower temperatures obtaining, but because clouds of early precipitates began to form in the magma near the margins, which substantially increased the effective density. At the top of the intrusion, the magma was unstable—that is, its temperature gradient was superadiabatic—and convection commenced almost immediately. Free crystals that might have formed near the upper contact were re-fused when carried into the hot interior by convection, because the amount of magma in the sill was very large compared to the amount of crystallization at the top—at least at this

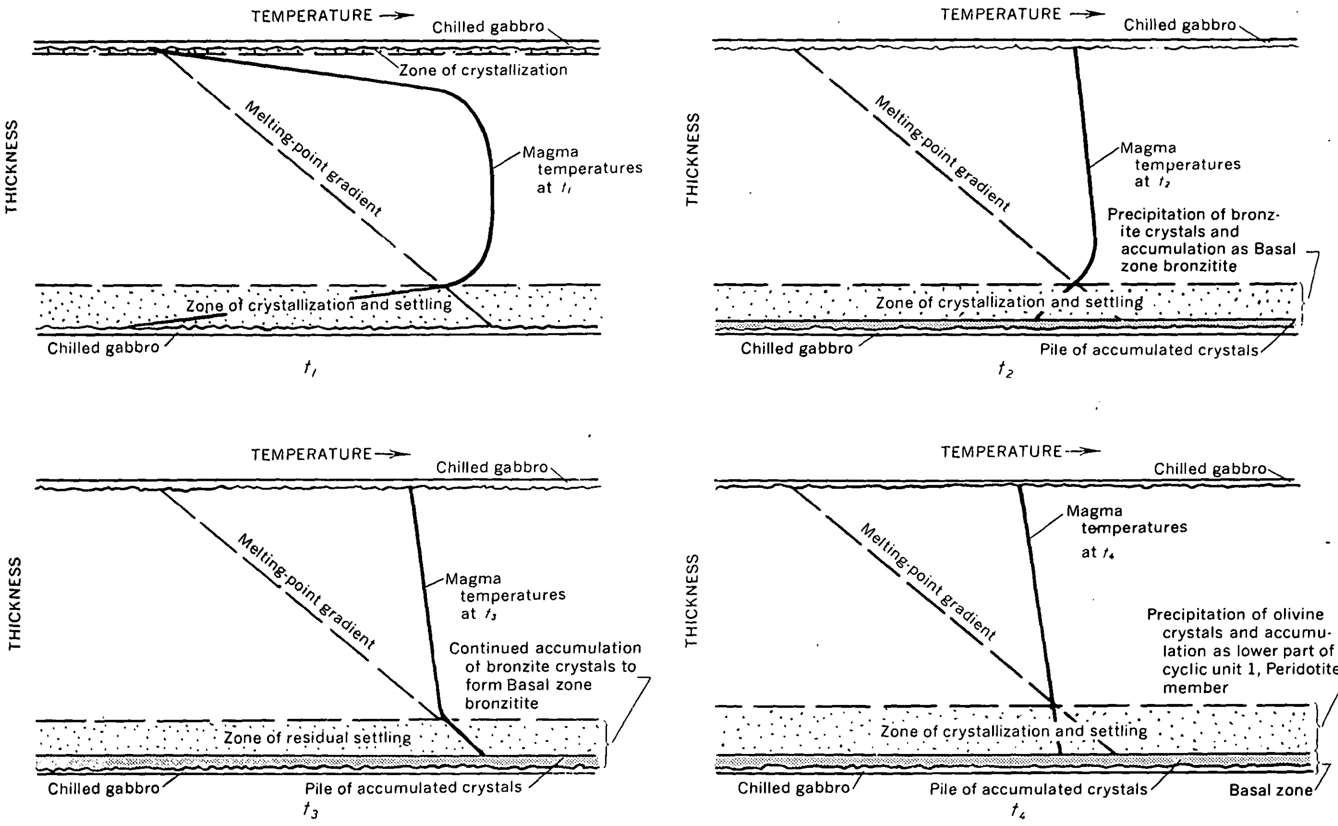

FIGURE 92.—Diagrammatic illustrations of proposed mechanism for crystallization in the lower part of the Stillwater complex.

early stage of the history of the intrusion. Near the base of the intrusion, however, the situation was considerably different. Relatively cool, crystal-charged magma near the bottom was stable, and its crystal products were preserved by settling to the floor of the chamber. Furthermore, the amount of supercooling and the amount of crystal precipitation near the bottom was greater than that near the top, by reason of the slope of the melting-point curve. A schematic diagram of temperature relations hypothetically existing at this time (t_1) is shown on figure 92.

On the basis of the foregoing discussion it is therefore presumed: (1) that convective overturn occurred in the upper portion of the intrusion; (2) that the convective cycle extended to considerable depths in the intrusion; and (3) that magma near the bottom of the chamber did not join in this circulation.

Convection in the upper part of the magma would have established a true adiabatic temperature gradient there. Convective overturn thus would have raised the temperature of the magma near the upper contact and maintained it at high values. High temperatures resulted in (1) a high rate of conductive heat loss at the top and (2) virtual cessation of crystallization there, because the adiabatic magma temperature exceeded the melting-point temperature for pressures at that depth (fig. 92, t_2). During this period, heat lost through the upper contact was supplied by a uniform decrease in the temperature of the convecting portion of the magma.

Crystallization in the lower stagnant magma would continue at gradually increasing temperatures (fig. 92, t_2) as the originally supercooled magma was warmed by latent heat of crystallization until a two-phase crystal–liquid equilibrium condition was reached (fig. 92, t_3). The crystal products of this process settled to form the Basal zone bronzitites.[9]

During this period, heat loss through the lower contact was supplied locally by latent heat of crystallization in the stable bottom layer. Presumably, an equilibrium state would have been approached in the bottom layer, the temperature would have followed the pressure-melting relation, and the rate of crystallization would have been just sufficient to supply the conductive heat lost through the bottom. As the rate of such conductive heat loss through the floor of the intrusion diminished, and as latent heat supply produced by crystallization of the interstitial magma in the accumulating crystal mush became appreciable, the

[9] Preliminary investigations of the composition of these layered bronzitites show the predicted relation: higher temperature phases occur upward in the section.

amount of crystallization of primary precipitate from the stable bottom layer would have decreased, with attendant decrease in density of the layer. At the same time, the temperatures of the magma in the bottom layer would have risen to and have been maintained at the melting-point curve by supply of latent heat of crystallization. The original temperature gradient in the lower stagnant layer would at this time have been reversed (fig. 92, t_3).

Hypothetically then, at the stage in the cooling history numbered t_3 in figure 92, temperatures in the upper convecting portion of the magma were determined by the true adiabatic gradient and the progressively decreasing upper-contact temperatures, and were still greater than melting-point temperatures in that part of the sill. Temperatures in the lower, stagnant portion, on the other hand, had been raised to or slightly above the melting point at depth, and crystallization had virtually stopped. The melting-point gradient is superadiabatic, and conditions were therefore favorable for the lower, stagnant magma to join in the convective overturn; but owing to the high density of the crystal-laden magma, this could not be accomplished until the residual suspended crystals in the lower layer had settled out. As this residual settling progressed, the circulation of the upper convecting portion of the magma would penetrate to progressively increasing depths, until the bottom layer of magma, partially fractionated by its crystallization of early mineral phases, was completely incorporated into the convective system.

When the heretofore stagnant lower layer did, eventually, gradually join the upper convecting system, fresh, relatively cool magma would have been brought to the bottom as an adiabatic gradient was established there (fig. 92, t_4). This would reinitiate crystallization at the bottom in that portion of the fresh magma brought below the melting-point temperatures. A cloud of crystalline precipitate would form, again increasing the density of the bottom layer and causing it to stagnate while convective circulation was maintained in the upper part of the intrusion. Due to the decreased thermal gradient in the rocks below the floor of the sill, this second stagnant magma was not supercooled to the same extent as the magma that produced the bronzitites of the Basal zone, and the initial depression of temperatures below the melting point was caused by overshoot rather than rapid conduction. First olivine, then chromite, then bronzite would have been precipitated and successively dropped to form cyclic unit 1 of the Ultramafic zone. Crystallization would virtually stop when the temperature of the bottom layer was raised uniformly to the melting point by latent heat of crystallization, but the bottom layer would not again join the circulation until its density was reduced by crystal settling. This process is presumed to have been repeated, with the crystallization and deposition of the stratigraphically higher cyclic units from successive stagnant magma layers, each considerably thicker than the pile of crystals precipitated from it. The transition to the stagnant state of the bottom layer would not be expected to take place under conditions of thermodynamic equilibrium, owing to inertia of the deeply convecting system and supercooling prior to nucleation. Thus, layers of finite thickness, as postulated, might be expected to have been brought below the melting-point temperature before the increased density due to crystal precipitation brought about stagnation.

A variation of the above hypothesis, which appears less probable at this time, concerns intermittent rather than variable-depth convection. It seems possible that crystallization in the lower layer might have stagnated the entire magma column during precipitation and settling. In such a case, adiabatic temperature gradients would not have been maintained in the upper portion of the intrusion, and magma near the top would have been conductively cooled to a considerable extent. After cessation of crystallization and settling in the bottom layer, the unstable column would have overturned one-half cycle, at which time the cool magma from the top would have reached the region of higher melting point at the bottom and crystallization would have once more stabilized the magma. Intermittent convection would require a much longer cooling time for the intrusion as a whole than would variable-depth convection, and a considerably thicker upper chill zone would be expected.

In the favored hypothesis, the cyclic units are pictured as depositional products of periodically refreshed stagnant magma which became stabilized by bottom crystallization. Because the bottom magma during each crystallization cycle was stagnant, it became enriched in silica as crystallization proceeded, and the early chromite and olivine were followed by bronzite. Each overturn brought a fresh supply of magma to the bottom and the cycle was repeated; but after such selective crystallization of a number of overturns, the composition of the entire magma was gradually but appreciably changed, so that higher cycles in the Peridotite member systematically contained smaller proportions of olivine. In this manner olivine and chromite finally ceased altogether to be crystallization products, and the magma crystallized bronzite alone in the Bronzitite member, and bronzite plus plagioclase at the base of the norite section above.

An important assumption made in developing the foregoing theory is that crystallization at the top of the Stillwater magma was minor during the formation of the Ultramafic and Basal zones, and that crystal phases forming at the top did not reach the floor of the intrusion and did not become incorporated in the layered rocks. Two points may be made in support of this assumption: (1) it seems theoretically probable, and (2) it supports the field relations. Theoretically, it must be admitted that the maintainance of single-phase adiabatic temperatures up to the roof of the intrusion as illustrated in figure 92—t_2, t_3, and t_4—seems very unlikely. Not only would extremely rapid convection be required, but the marginal rocks would begin to melt. No doubt magma temperatures near the roof decreased markedly to the melting point, and some free crystals were produced there while the rocks of the Basal and Ultramafic zones were accumulating at the bottom. The fate of such crystals would be remelting, as long as magma above the melting-point gradient remained in the center of the intrusion. Preliminary considerations of the probable heat-flow relations indicate that considerably more crystallization took place at the bottom of the intrusion than at the top during the early cooling history. After all of the Ultramafic zone rocks had accumulated, some 6 to 7 km of magma still remained in the intrusion; and, even if the assumption is made that equal amounts of crystals were produced at both margins, it seems unlikely that the magma temperatures would have been driven down to the melting-point gradient by this time.

It must be emphasized, however, that as the crystal pile increased in thickness above the Ultramafic zone and as magma temperatures decreased during the continued fractionation and cooling of the complex, crystallization from the top must have become increasingly important. The amount of specific heat available for remelting crystals would progressively decrease. The magma temperatures would approach and maintain the melting-point gradient for whatever mineral phases were precipitating at that time, and a two-phase crystal–liquid equilibrium would result. Under these conditions, the temperature gradient would be superadiabatic, and the whole magma would have been able to overturn, precipitating crystals throughout. Crystals which began to grow at all levels in the magma would be carried to the bottom and deposited. This is essentially the mechanism proposed by Wager and Deer (1939, p. 266–270) to account for the observed relations in the Skaergaard intrusion, and adopted by Hess (1956, p. 449) to explain the origin of the Stillwater complex.

The theory of variable-depth convection and bottom crystallization as outlined here appears capable of accounting for the repetitious stratigraphy, general absence of current features, compositional rather than size-density layering, absence of hydraulic equivalence, and size distributions and other previously described features of the Ultramafic zone. The theory of continuous convection and crystallization appears capable of explaining layered igneous rocks characterized by current structures, size-density layering, lineation of primary precipitate mineral axes, and continuous differentiation toward lower temperature mineral phases. The two theories are not mutually exclusive, and it seems likely that conditions of variable-depth convection, bottom crystallization, and magma refreshment in the lower part of the Stillwater complex gave way to continuous convection and deposition in the upper part as the magma volume and, particularly, the magma thickness diminished.

SIMILARITY TO CHEMICAL SEDIMENTS

Several authors, particularly Wager and Deer (1939, p. 271) and Turner and Verhoogen (1951, p. 236) have compared the origin of rocks of layered intrusions to that of detrital sediments. Thus, Wager and Deer, who offer an explanation of origin of layers by what might be called igneous density currents, state:

> There is a close analogy between the structural features of the layered series and of sedimentary rocks. The igneous lamination of the layered series is similar to the lamination of a micaceous silt; in both cases it is due to the lamellar form of the material deposited. The unlaminated material of melanocratic bands in the layered series, like sandstone is composed of fragments with a general rounded shape and in both there is no fissility. . . . In other ways the rhythmic layering is comparable with rhythmic variation of sandstones and shales, the light bands of the layered series being comparable with the shale because they represent material carried by feeble currents, while the dark bands are comparable with sandstone composed of heavy grains only transported by vigorous currents.

Brown (1956, p. 44–45) has, however, suggested that the layered ultrabasic rocks of Rhum originated in a manner analagous to evaporites, and I propose the same comparison for the rocks of the Ultramafic zone. The Stillwater ultramafics and evaporites appear to have the following common features: (1) both have a bedded distribution acquired by crystallization and settling of primary precipitates from a saturated solution; (2) both are constructed of compositional layers, commonly monomineralic or bimineralic, which are derived by fractional crystallization [10] (Pettijohn, 1957,

[10] To my knowledge, no one has as yet proposed halite or anhydrite magmas.

p. 428, 484); (3) in both, the compositional layers are commonly repeated in a cyclic fashion (Stewart, 1951, p. 446, 460; Schaller and Henderson, 1932, p. 8); and (4) primary settled grains within the layers are single crystals, although more material of the same composition may be added as crystallographically oriented overgrowths after deposition (Dellwig, 1955, p. 88–93). To account for saline deposits and also the lower part of the Stillwater complex, appeal must be made to physico-chemical rather than mechanical processes to explain the composition and distribution of the rocks.

REFERENCES CITED

Adams, L. H., 1924, Temperatures at moderate depths within the earth: Washington Acad. Sci. Jour., v. 14, p. 459–472.

Andersen, Olaf, 1915, The system anorthite–forsterite–silica: Am. Jour. Sci., 4th ser., v. 39, p. 407–454.

Bastin, E. S., 1950, Interpretation of ore textures: Geol. Soc. America Mem. 45, 101 p.

Berg, J. J. van den, 1946, Petrofabric analysis of the Bushveld gabbro from Bon Accord: Geol. Soc. South Africa Trans., v. 49, p. 155–208.

Borg, I. V., and Maxwell, J. C., 1956, Interpretation of fabrics of experimentally deformed sands: Am. Jour. Sci. v. 254, p. 71–81.

Bowen, N. L., 1915, Crystallization-differentiation in silicate liquids: Am. Jour. Sci., 4th ser., v. 39, p. 175–191.

——— 1919, Crystallization-differentiation in igneous magmas: Jour. Geology, v. 27, p. 393–430.

——— 1928, The evolution of the igneous rocks: Princeton University Press, 322 p.

Bowen, N. L., and Schairer, J. F., 1935, The system MgO–FeO–SiO_2: Am. Jour. Sci., 5th ser., v. 29, p. 151–217.

Bowen, N. L., and Tuttle, O. F., 1949, The system MgO–SiO_2–H_2O: Geol. Soc. America Bull., v. 60, p. 439–460.

Brown, G. M., 1956, The layered ultrabasic rocks of Rhum, Inner Hebrides: Royal Soc. [London] Philos. Trans., B., v. 240, p. 1–53.

——— 1957, Pyroxenes from the early and middle stages of fractionation of the Skaergaard intrusion, East Greenland: Mineralog. Mag., v. 31, p. 511–543.

Buckley, H. E., 1951, Crystal growth: New York, John Wiley & Sons, 571 p.

Christiansen, J. E., 1935, Distribution of silt in open channels: Am. Geophys. Union Trans., v. 16, pt. 2, p. 478–485.

Cooper, J. R., 1936, Geology of the southern half of the Bay of Islands igneous complex: Newfoundland Dept. Nat. Res. Bull. 4, 62 p.

Cornwall, H. R., 1951, Differentiation in lavas of the Keweenawan series and the origin of the copper deposits of Michigan: Geol. Soc. America Bull., v. 62, p. 159–202.

Dapples, E. C., and Rominger, J. F., 1945, Orientation analysis of fine-grained clastic sediments: Jour. Geology, v. 53, p. 246–261.

Dellwig, L. F., 1955, Origin of the Salina salt of Michigan: Jour. Sed. Petrology, v. 25, p. 83–110.

Edwards, A. B., 1942, Differentiation of the dolerites of Tasmania: Jour. Geology, v. 50, p. 451–480, 579–610.

Ellis, A. J., and Lee, C. H., 1919, Geology and ground waters of the western part of San Diego County, California: U.S. Geol. Survey Water-Supply Paper 446, 321 p.

Fraser, H. J., 1935, Experimental study of the porosity and permeability of clastic sediments: Jour. Geology, v. 43, p. 910–1010.

Fuller, R. E., 1939, Gravitational accumulation of olivine during the advance of basalt flows: Jour. Geology, v. 47, p. 303–313.

Garrels, R. M., Dreyer, R. M., and Howland, A. L., 1949, Diffusion of ions through intergranular spaces in water-saturated rocks: Geol. Soc. America Bull., v. 60, p. 1809–1828.

Graton, L. C., and Fraser, H. J., 1935, Systematic packing of spheres—with particular relation to porosity and permeability: Jour. Geology, v. 43, p. 785–909.

Greenman, N. N., 1951a, On the bias of grain-size measurements made in thin-section—a discussion: Jour. Geology, v. 59, p. 268–274.

——— 1951b, The mechanical analysis of sediments from thin-section data: Jour. Geology, v. 59, p. 447–462.

Hamilton, E. L., and Menard, H. W., 1956, Density and porosity of sea-floor surface sediments off San Diego, California: Am. Assoc. Petroleum Geologists Bull., v. 40, p. 754–761.

Hess, H. H., 1938a, Primary banding in norite and gabbro: Am. Geophys. Union Trans., v. 19, pt. 1, p. 264–268.

——— 1938b, A primary peridotite magma: Am. Jour. Sci., 5th ser., v. 35, p. 321–344.

——— 1939, Extreme fractional crystallization of a basaltic magma—The Stillwater igneous complex [abs.]: Am. Geophys. Union Trans., v. 20, pt. 3, p. 430–432.

——— 1940, An essay review—The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: Am. Jour. Sci., v. 238, p. 372–378.

——— 1941, Pyroxenes of common mafic magmas, pt. 2: Am. Mineralogist, v. 26, p. 573–594.

——— 1949, Chemical composition and optical properties of common clinopyroxenes, pt. 1: Am. Mineralogist, v. 34, p. 621–666.

——— 1956, The magnetic properties and differentiation of dolerite sills—discussion: Am. Jour. Sci., v. 254, p. 446–451.

Hess, H. H., and Phillips, A. H., 1938, Orthopyroxenes of the Bushveld type: Am. Mineralogist, v. 23, p. 450–456.

——— 1940, Optical properties and chemical composition of magnesian orthopyroxenes: Am. Mineralogist, v. 25, p. 271–285.

Howland, A. L., 1954, Relations of regional and thermal metamorphism near the base of the Stillwater complex, Montana (abs.): Geol. Soc. America Bull., v. 65, p. 1264–1265.

——— 1955, Chromite deposits in the central part of the Stillwater complex, Montana: U.S. Geol. Survey Bull. 1015–D, p. 99–121.

Howland, A. L., Garrels, R. M., and Jones, W. R., 1949, Chromite deposits of the Boulder River area, Sweetgrass County, Montana: U.S. Geol. Survey Bull. 948–C, p. 63–82.

Huang, W. T., and Merritt, C. A., 1952, Preferred orientation of olivine crystals in troctolite of the Wichita Mountains, Oklahoma: Am. Mineralogist, v. 37, p. 865–868.

Hunter, H. E., 1958, A study of the Tow Lake gabbro: Manitoba Mines Branch Pub. 53–5, p. 1–47.

Jackson, E. D., Howland, A. L., Peoples, J. W., and Jones, W. R., 1954, Geologic maps and sections of the eastern part of the Stillwater complex, in Stillwater County, Mont.: U.S. Geol. Survey open-file report.

Jackson, E. D., and Ross, D. C., 1956, A technique for modal analysis of medium- and coarse-grained (3–10 mm) rocks: Am. Mineralogist, v. 41, p. 648–651.

Jaeger, J. C., 1957, The temperature in the neighborhood of a cooling intrusive sheet: Am. Jour. Sci., v. 255, p. 306–318.

Jaeger, J. C., and Joplin, Germaine, 1956, The magnetic properties and differentiation of dolerite sills—discussion: Am. Jour. Sci., v. 254, p. 443–446.

Jeffreys, Harold, 1929, The earth: 2d ed., Cambridge Univ. Press, 278 p.

——— 1952, The earth: 3d ed., Cambridge Univ. Press, 392 p.

Jones, W. R., Peoples, J. W., and Howland, A. L., 1960, Igneous and tectonic structures of the Stillwater complex, Montana: U.S. Geol. Survey Bull. 1071–H, p. 281–335.

Krumbein, W. C., 1935, Thin-section mechanical analysis of indurated sediments: Jour. Geology, v. 43, p. 482–496.

——— 1938, Size frequency distributions of sediments and the normal phi curve: Jour. Sed. Petrology, v. 8, p. 84–90.

——— 1939, Preferred orientation of pebbles in sedimentary deposits: Jour. Geology, v. 47, p. 673–706.

——— 1942, Flood deposits of Arroyo Seco, Los Angeles County, California: Geol. Soc. America Bull., v. 53, p. 1355–1402.

Kuenen, P. H., 1951, Properties of turbidity currents of high density: Soc. Econ. Paleontologists and Mineralogists, Special Pub. 2, p. 14–33.

Kuschke, G. S. J., 1939, The critical zone of the Bushveld igneous complex, Lydenburg District: Geol. Soc. South Africa Trans., v. 42, p. 57–81.

Lombaard, B. V., 1934, On the differentiation and relationships of the rocks of the Bushveld complex: Geol. Soc. South Africa Trans., v. 37, p. 5–52.

Loveland, R. P., and Trivelli, A. P. H., 1927, Mathematical methods of frequency analysis of size of particles; pt. 1—Methods: Franklin Inst. Jour., v. 204, p. 193–217.

Lovering, T. S., 1935, Theory of heat conduction applied to geological problems: Geol. Soc. America Bull., v. 46, p. 69–94.

MacDonald, G. A., 1944, The 1840 eruption and crystal differentiation in the Kilauean magma column: Am. Jour. Sci., v. 242, p. 177–189.

Martens, J. H. C., 1939, Beaches, *in* Trask, P. D., ed., Recent marine sediments: Tulsa, Okla., Am. Assoc. Petroleum Geologists, p. 207–218.

Nanz, R. H., 1955, Grain orientation in beach sand as a possible means of predicting reservoir trend [abs.]: Jour. Sed. Petrology, v. 25, p. 130.

Osborn, E. F., and Tait, D. B., 1952, The system diopside–forsterite–anorthite: Am. Jour. Sci., Bowen volume, pt. 2, p. 413–433.

Overbeek, J. T. G., 1952, Phenomenology of lyophobic systems, *in* Kruyt, H. R., ed. Colloid Science: Amsterdam, Elsevier Pub. Co., v. 1, p. 58–89.

Peoples, J. W., 1936, Gravity stratification as a criterion in the interpretation of the structure of the Stillwater complex, Montana: Internat. Geol. Cong., 16th, United States 1933, Rept., v. 1, p. 353–360.

Peoples, J. W., and Howland, A. L., 1940, Chromite deposits of the eastern part of the Stillwater complex, Stillwater County, Montana: U.S. Geol. Survey Bull. 922–N, p. 371–416.

Peoples, J. W., Howland, A. L., Jones, W. R., and Flint, Delos, 1954, Geologic map, sections, and map of underground workings of the Mountain View Lake area, Stillwater County, Montana: U.S. Geol. Survey open-file report.

Pettijohn, F. J., 1957, Sedimentary rocks: New York, Harper & Bros., 718 p.

Phillips, F. C., 1938, Mineral orientation in some olivine-rich rocks from Rum and Skye [Scotland]: Geol. Mag., v. 75; p. 130–135.

Poldervaart, A., and Hess, H. H., 1951, Pyroxenes in the crystallization of basaltic magma: Jour. Geology, v. 59, p. 472–489.

Rittenhouse, Gordon, 1943, Transportation and deposition of heavy minerals: Geol. Soc. America Bull., v. 54, p. 1725–1780.

Sampson, Edward, 1932, Magmatic chromite deposits in southern Africa: Econ. Geology, v. 27, p. 113–144.

Schaller, W. T., and Henderson, E. P., 1932, Mineralogy of drill cores from the potash field of New Mexico and Texas: U.S. Geol. Survey Bull. 833, 124 p.

Scheidegger, A. E., 1953, Examination of the physics of theories of orogenesis: Geol. Soc. America Bull., v. 64, p. 127–150.

Schmidt, E. R., 1952, The structure and composition of the Merensky reef and associated rocks of the Rustenburg platinum mine: Geol. Soc. South Africa Trans., v. 55, p. 233–279.

Shand, S. J., 1942, Phase petrology in the Cortlandt complex, New York: Geol. Soc. America Bull., v. 53, p. 409–428.

Sriramadas, A., 1957, Diagrams for the correlation of unit cell edges and refractive indices with the chemical composition of garnets: Am. Mineralogist, v. 42, p. 294–298.

Stewart, F. H., 1951, The petrology of the evaporites of the Eskdale no. 2 boring, east Yorkshire: Mineralog. Mag., v. 29, p. 445–475.

Thayer, T. P., 1946, Preliminary chemical correlation of chromite with the containing rocks: Econ. Geology, v. 41, p. 202–217.

Trask, P. D., 1931, Compaction of sediments: Am. Assoc. Petroleum Geologists Bull., v. 15, p. 271–276.

Turner, F. J., 1942, Preferred orientation of olivine crystals in peridotites, with special reference to New Zealand examples: Royal Soc. New Zealand Proc. and Trans., v. 72, p. 280–300.

Turner, F. J., and Verhoogen, Jean, 1951, Igneous and metamorphic petrology: New York, McGraw-Hill Book Co., 602 p.

Tyrrell, G. W., 1916, The picrite-teschenite sill of Lugar (Ayrshire): Geol. Soc. London Quart. Jour., v. 72, p. 84–129.

van den Berg, J. J., *see* Berg, 1946.

van der Walt, C. F. J., *see* Walt, 1941.

Verhoogen, Jean, 1956, Temperatures within the earth *in* Ahrens, L. H., Rankama, Kalervo, and Runcorn, S. K., eds. Physics and chemistry of the earth, v. 1: New York, McGraw-Hill Book Co., p. 17–43.

Vogt, J. H. L., 1921, The physical chemistry of the crystallization and magmatic differentiation of igneous rocks: Jour. Geology, v. 29, p. 318–350.

Wager, L. R., 1953, Layered intrusions: Dansk Geol. Forening Meddelelser, Bd. 12, p. 335–349.

Wager, L. R., and Deer, W. A., 1939, Geological investigations in East Greenland; pt. 3—The petrology of the Skaergaard intrusion, Kangerdlugssuaq, East Greenland: Meddelelser om Grønland, v. 105, no. 4, 335 p.

Wagner, P. A., 1923, The chromite of the Bushveld igneous complex: South African Jour. Sci., v. 20, p. 223–235.

Walker, Frederick, 1940, Differentiation of the Palisade diabase, New Jersey: Geol. Soc. America Bull., v. 51, p. 1059–1106.

Walker, Frederick, 1957, Ophitic texture and basaltic crystallization: Jour. Geology, v. 65, p. 1–14.

Walt, C. F. J. van der, 1941, Chrome ores of the western Bushveld complex: Geol. Soc. South Africa Trans., v. 44, p. 79–112.

Wells, A. K., 1952, Textural features of some Bushveld norites: Mineralog. Mag., v. 29, p. 913–924.

Wimmler, N. L., 1948, Investigation of chromite deposits of the Stillwater complex, Stillwater and Sweetgrass Counties, Montana: U.S. Bur. Mines Rept. Inv. 4368, 41 p.

Winchell, Horace, 1958, The composition and physical properties of garnet: Am. Mineralogist, v. 43, p. 595–600.

Worst, B. G., 1958, The differentiation and structure of the Great Dyke of Southern Rhodesia: Geol. Soc. South Africa Trans. and Proc., v. 61, p. 283–354.

Yoder, H. S., Jr., 1950, Stability relations of grossularite: Jour. Geology, v. 58, p. 221–253.

——— 1952, Change of melting point of diopside with pressure: Jour. Geology, v. 60, p. 364–374.

Yoder, H. S., Jr., and Tilley, C. E., 1956, Natural tholeiite basalt–water system: Carnegie Inst. Wash. Year Book 55, p. 169–171.

——— 1957, Basalt magmas: Carnegie Inst. Wash. Year Book 56, p. 156–161.

NOTE: While this publication was in press, the following important paper was published: "The Stillwater Igneous Complex, Montana, A Quantitative Mineralogical Study": Geol. Soc. America Memoir 80, 230 p., 1960, by H. H. Hess. Although it is unfortunate that reference to Hess's memoir could not be made in this publication, many of his ideas had been outlined in earlier papers that are heavily cited here.

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